Measurement and auralization of ‘moving’ late reverberation

3rd IWSM, Aizu-Wakamatsu, Japan 2003
Bang & Olufsen, Struer, DK 2003
McGill University, Montreal 2003
AES SF Section meeting 2003

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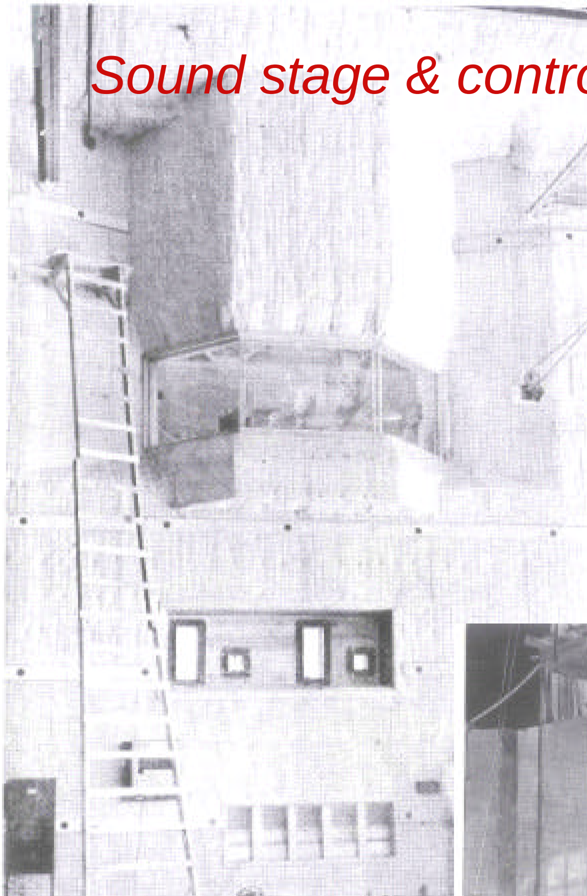
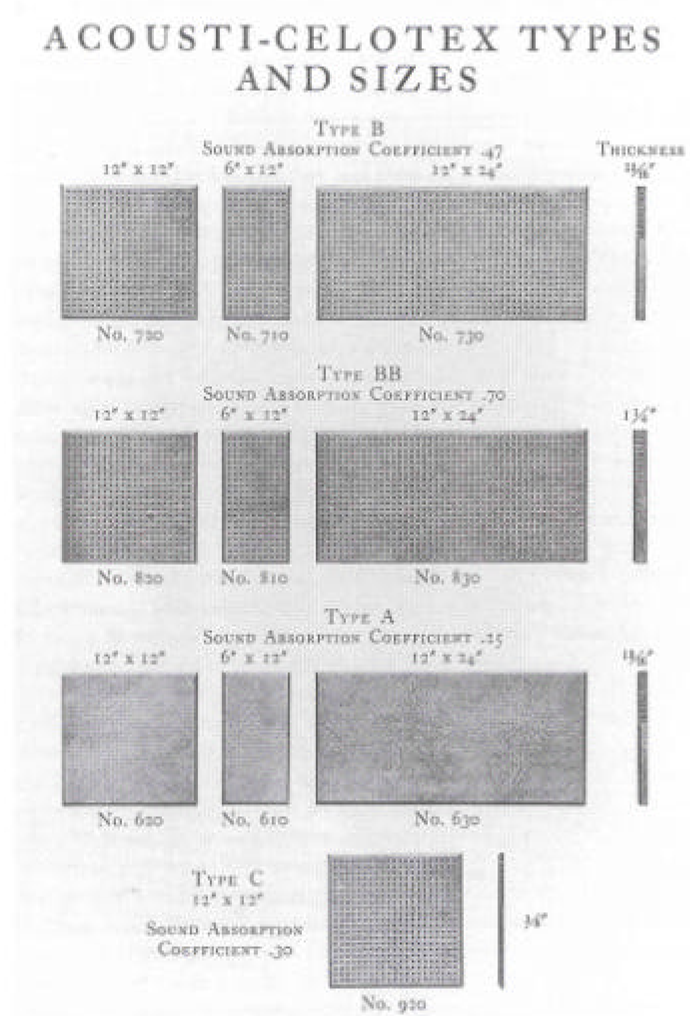
Historically, the use of acoustical absorption to ‘neutralize’ acoustical characteristics of rooms began ca. 1930s

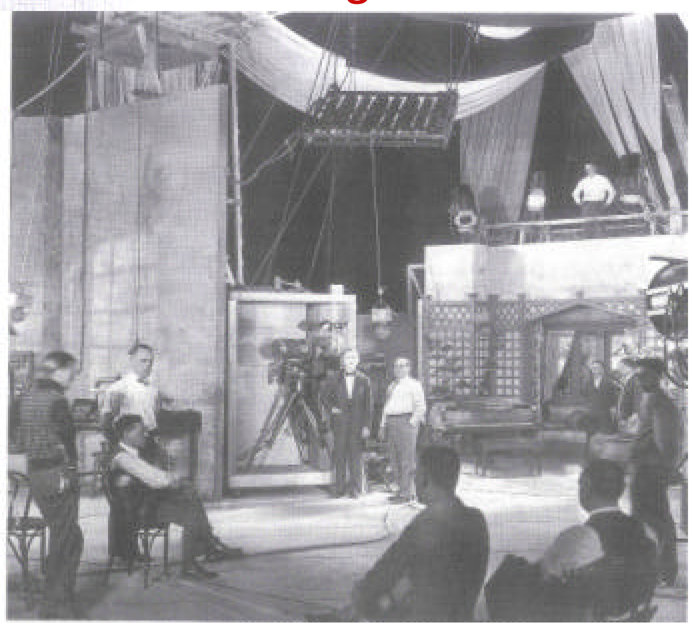
Sound stage & control room



Acoustical wall/ceiling panels



Recording for film



…but highly-reverberant environmental contexts have always been important for music performance, particularly for “western art music” tradition from 13th-19th centuries.

- Concert halls with apx. 2 sec. RT for symphonic music (balance between articulation and blending of instrumental choirs)

- Sacred music within cathedrals: > 4 sec. RT (“dramatic” reverberant effect)

An ideal “Sabinian space” has a linear dB decay over time.

- Occurs in spaces with uniformly-distributed absorption, and “uniform” exchange of acoustical energy within a single volume

- Reverberation time in diffuse field of a Sabinian space is a ‘meaningful’ descriptor

- No ‘directionality’ exists within a diffuse field: late reveberation doesn’t move

REVERBERATION TIME (RT)

Time required for a sound to decay 60 dB below steady state level
T30= estimated from -5 to -35 dB decay (x2)

SABINE EQUATION $T = 0.049\ V/A$ (room volume in cubic feet)
$T = 0.16\ V/A$ (room volume in cubic meters)

(where $A = ?_1 S_1 + ?_1 S_1 + \dots\dots\dots ?_N S_N) + mV$ *(air absorption > 2 kHz)*

example: 25 x 45 x 10 foot room (11,250 cubic feet)

Surface	Material	Area (sq. ft)	? 500Hz	A (sabins)
walls ceiling	gyp brd	1125	0.1	112.5
floor	carpet	2525	0.05	126.25
				=238.75 sabins

$T = 0.049\ V/A$
$= 0.049\ (11{,}250) / 238.75$
$= 2.31$ seconds

Depends on uniform exposure of acoustical energy to absorptive materials

In a “coupled space”, a non-linear dB decay over time results.

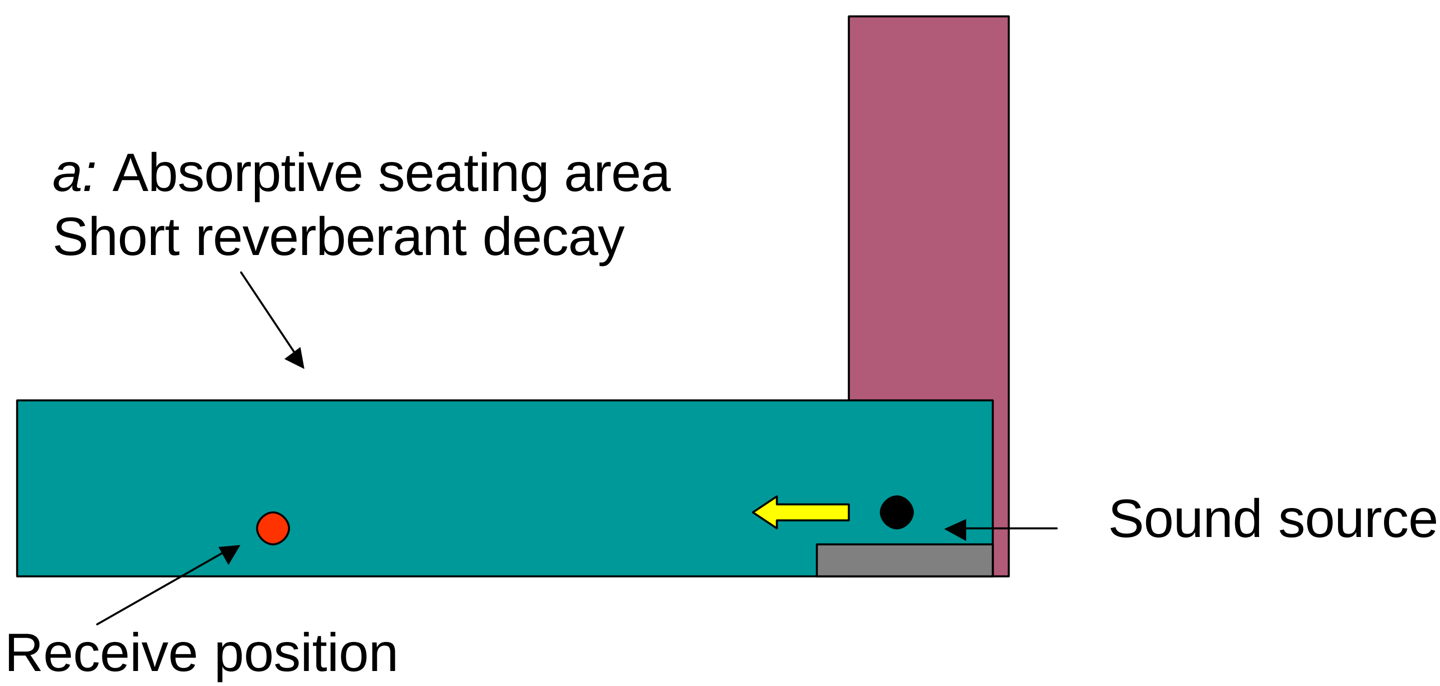
- Occurs when two or more adjacent areas with different volume or absorption are simultaneously excited by an acoustic source, via doorways, windows, apertures.

- Acoustical energy measured at a single receiving point can be viewed as result of exchange of energy between volumes

- Single value for reverberation time does not capture physical or perceptual characteristics of coupled spaces.

Examples of coupled spaces

-Absorptive theater with undamped stagehouse
-Reverberation chambers surrounding concert halls
-Subway tunnels with branching passages



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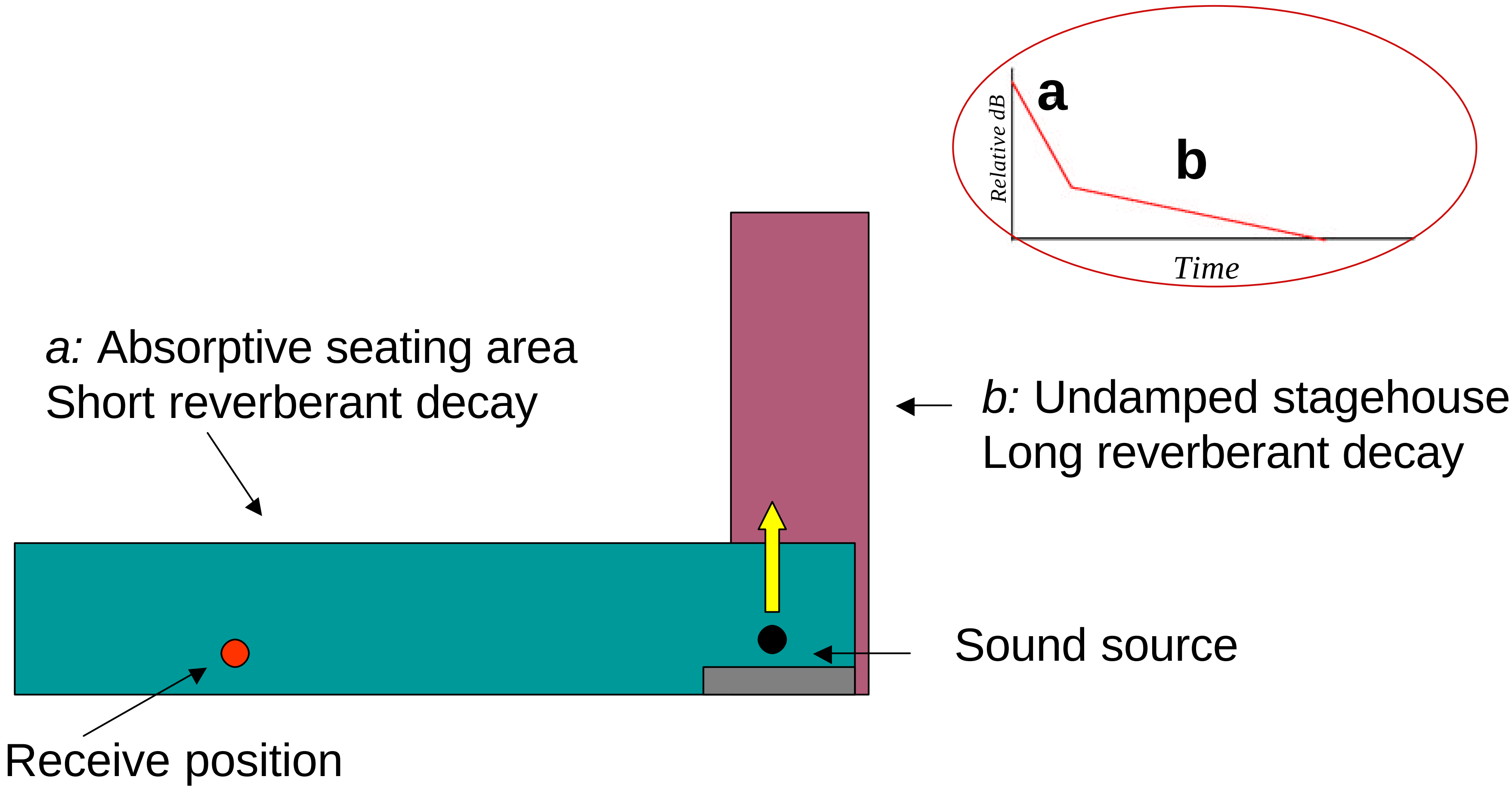
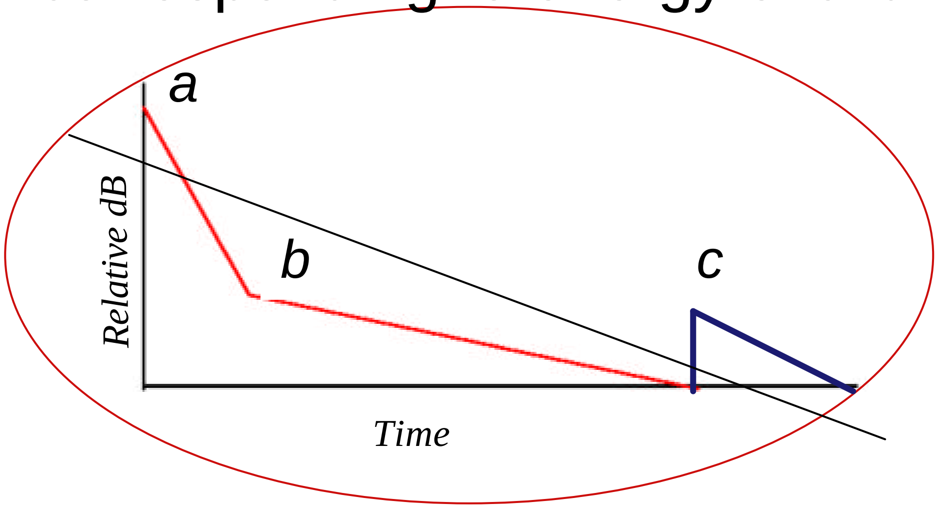
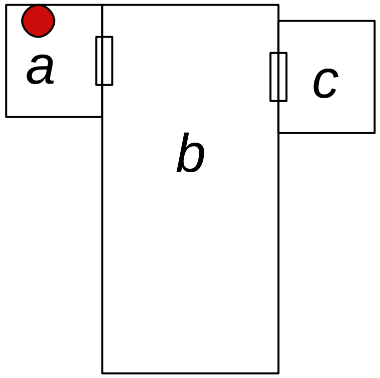


A coupled space's reverberant decay can be understood as an average linear decay, modulated by a complex waveform corresponding to energy exchange of the coupled spaces





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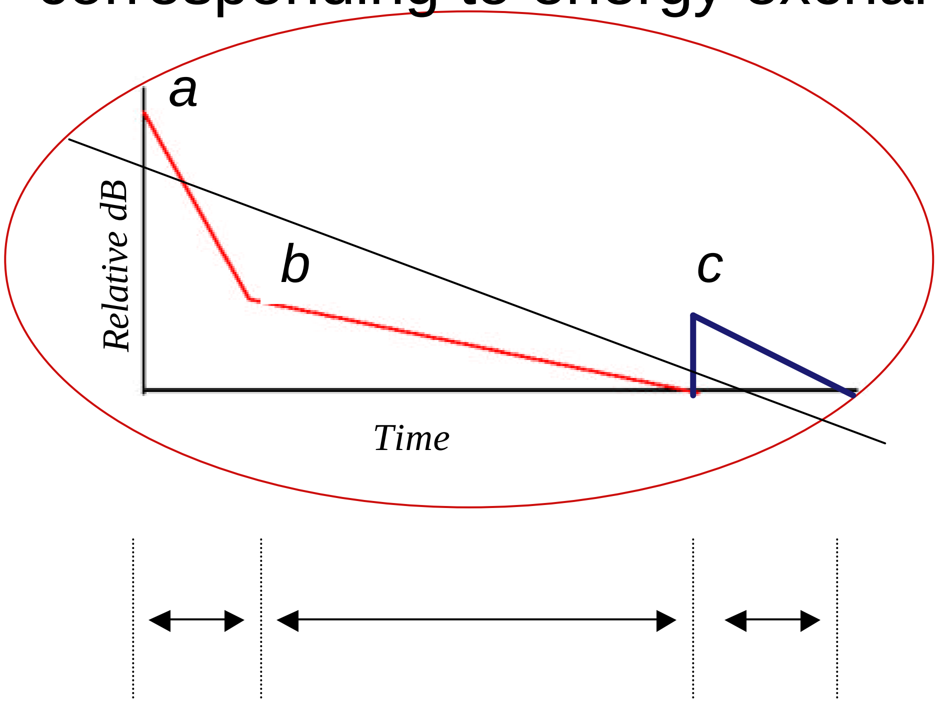
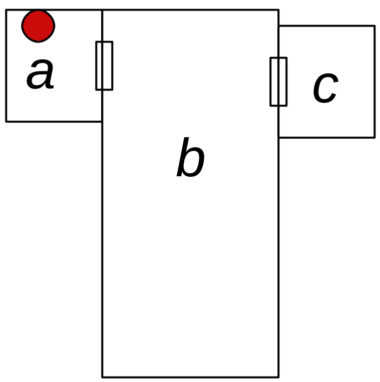


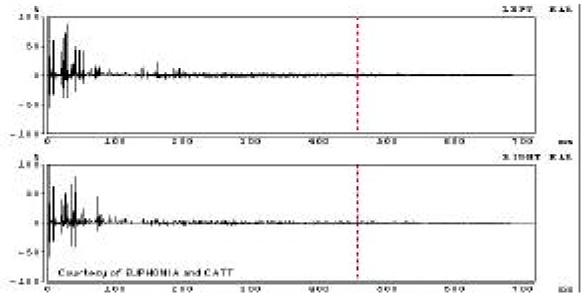


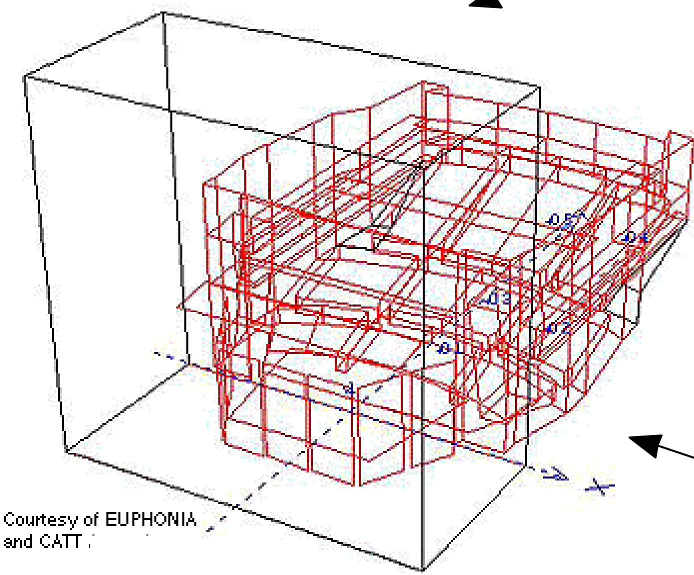
Working theory: within a given frequency band, when (1) duration between modulation peaks (*a* - *c*) > 50 ms or (2) differences in decay rate (*a* - *b*) > 300 ms occur between different spatial locations, the late reverberant field can be heard to as moving between the locations

Measurement of spatial reverberation

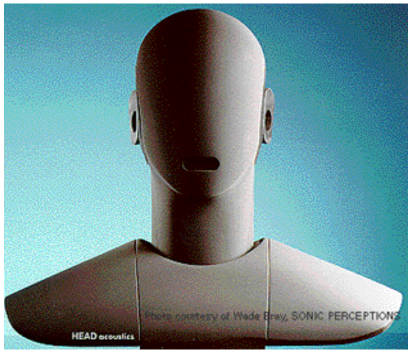
Spatial room impulse responses can be obtained from a existing room by…

1. Calculating the response from a room model (ray tracing, image modeling)



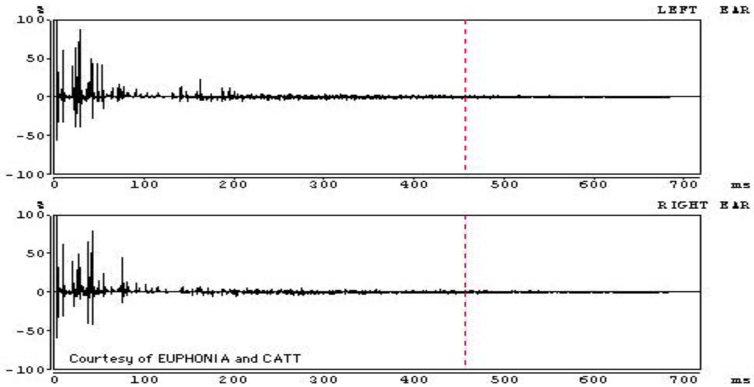


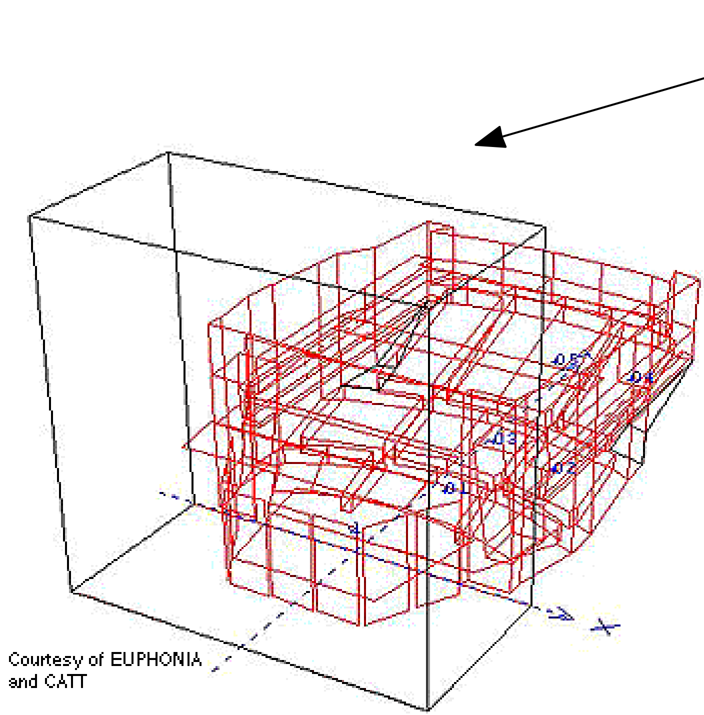
2. Recording the binaural impulse response



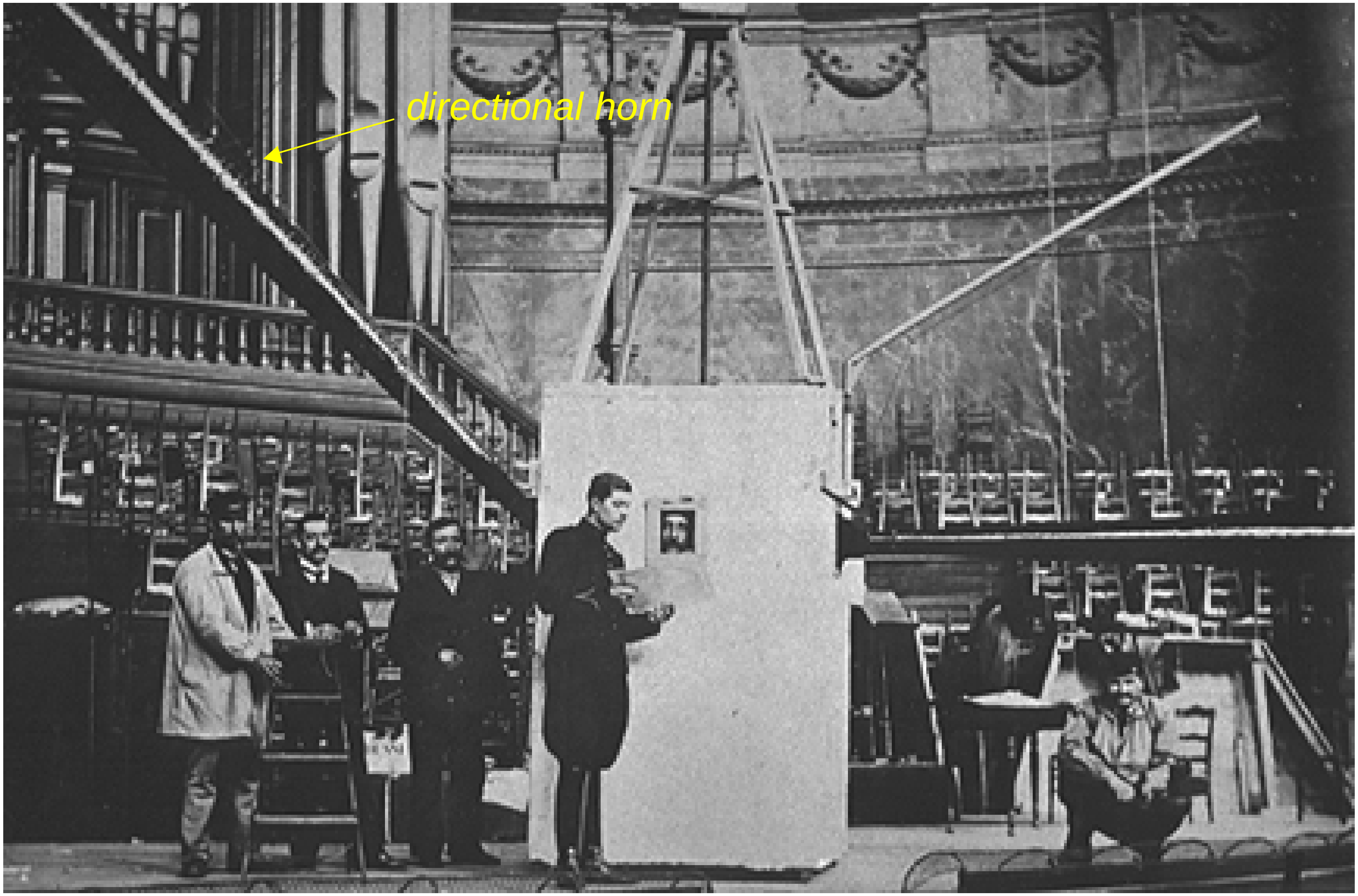
3. Recording a directional impulse response for processing and analysis

Calculate the impulse response
from a room model
(using ray tracing, image modeling)



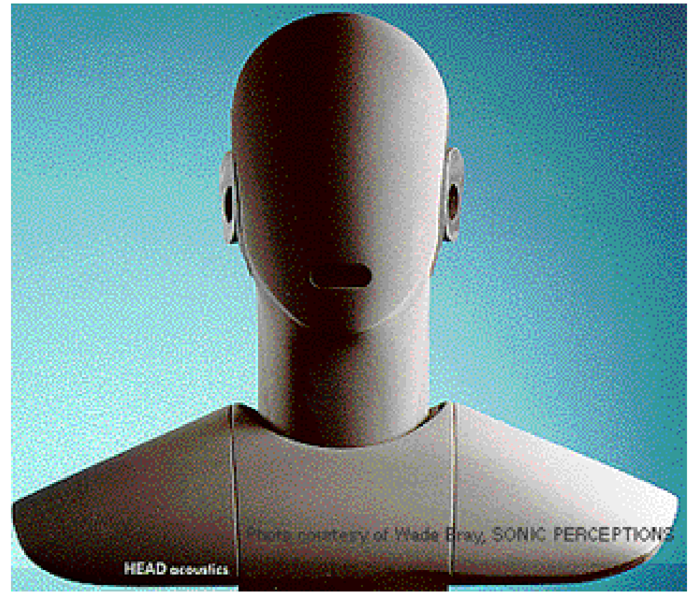


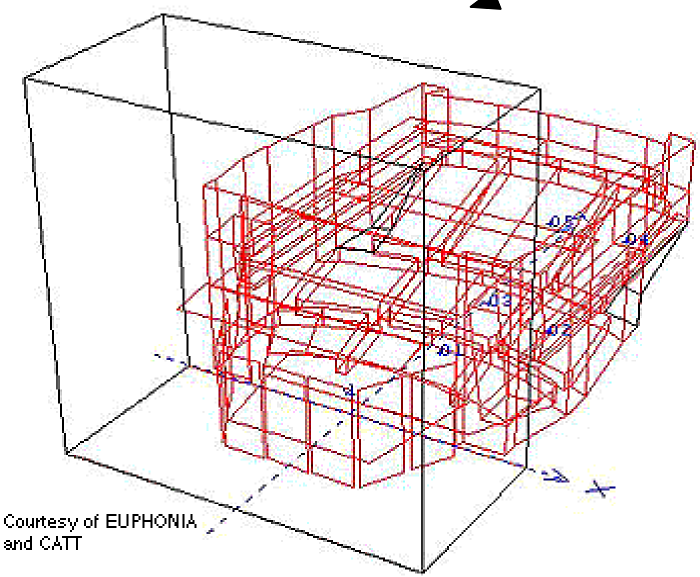
Challenges:
-adequate yet reasonable
 sampling of sources & receivers
-directivity data for sound sources
 limited; sound source movement
 usually unaccounted for
-modeling low frequency behavior
-coupled spaces difficult to model



Ray tracing, while imperfect, can be an efficient means for finding the location of disturbing echoes

Measure the binaural
room impulse response
via a dummy head recording





Courtesy of EUPHONIA
and CATT

Challenges:
-localization error due to non-individualized HRTF
-deriving spatial information from
 a 2-channel source
-multiple measurements for each
receiver position required

Directional mic room impulse response.

Essert (1996) used a B-format output from a *SoundField* MKV microphone to obtain one omnidirectional (W) and three dipole IRs (oriented left-right X, back-front Y, and down-up Z, respectively)

The omnidirectional response reveals the arrival time of significant early reflections;

Cross-correlations between the monopole and dipole responses indicate reflection direction of arrival.

Individualized HRTFs can be applied during the synthesis phase to significant early reflections

Intensity measurements have also been investigated in the literature.

Synchronized, multi-mic measurements in Grace Cathedral, San Francisco

- Gothic-style cruciform design, mid-band RT = 4.7 s
- Noted for excellent acoustics for choir, organ
- Complex arrangement of coupled spaces

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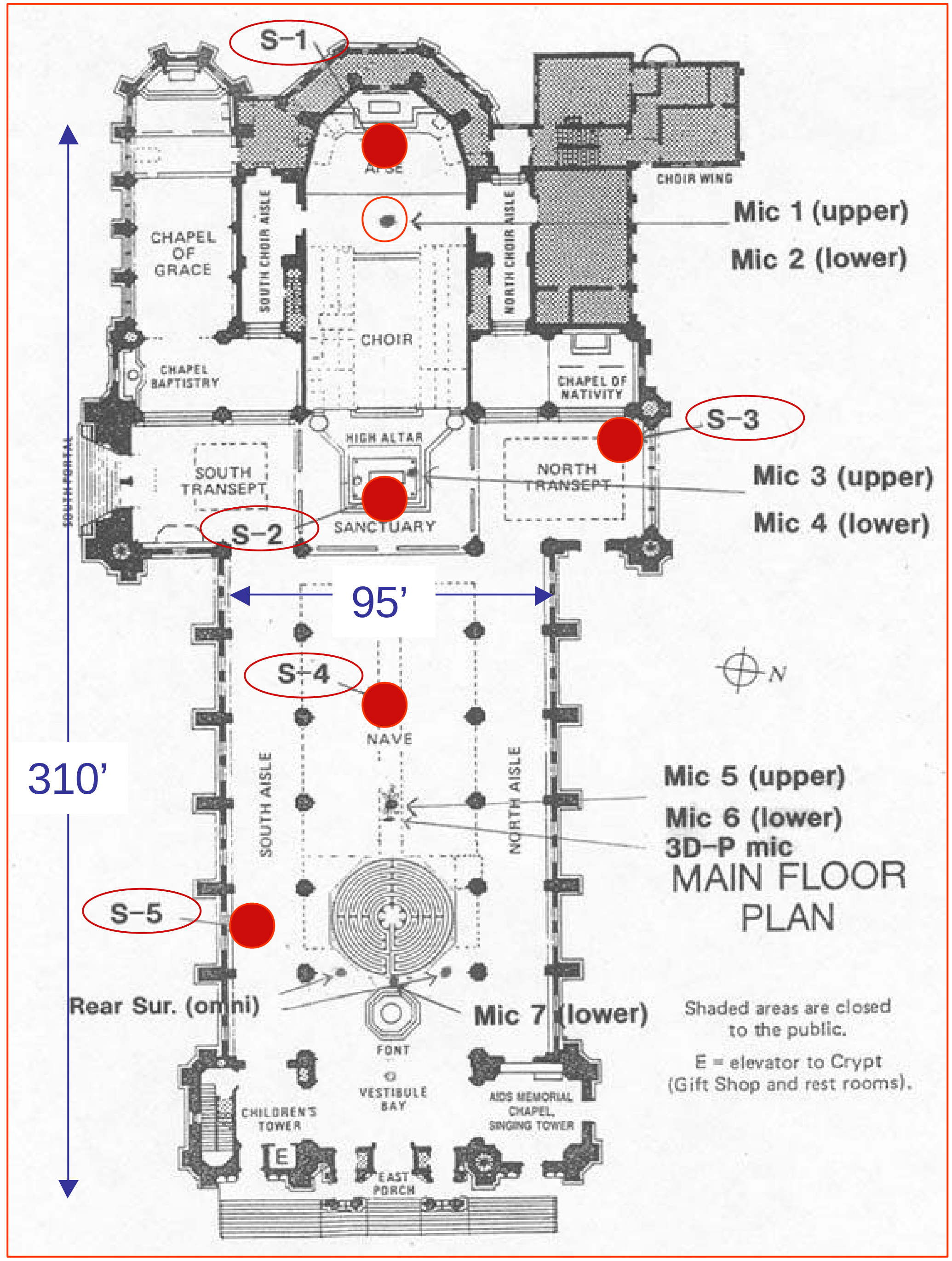
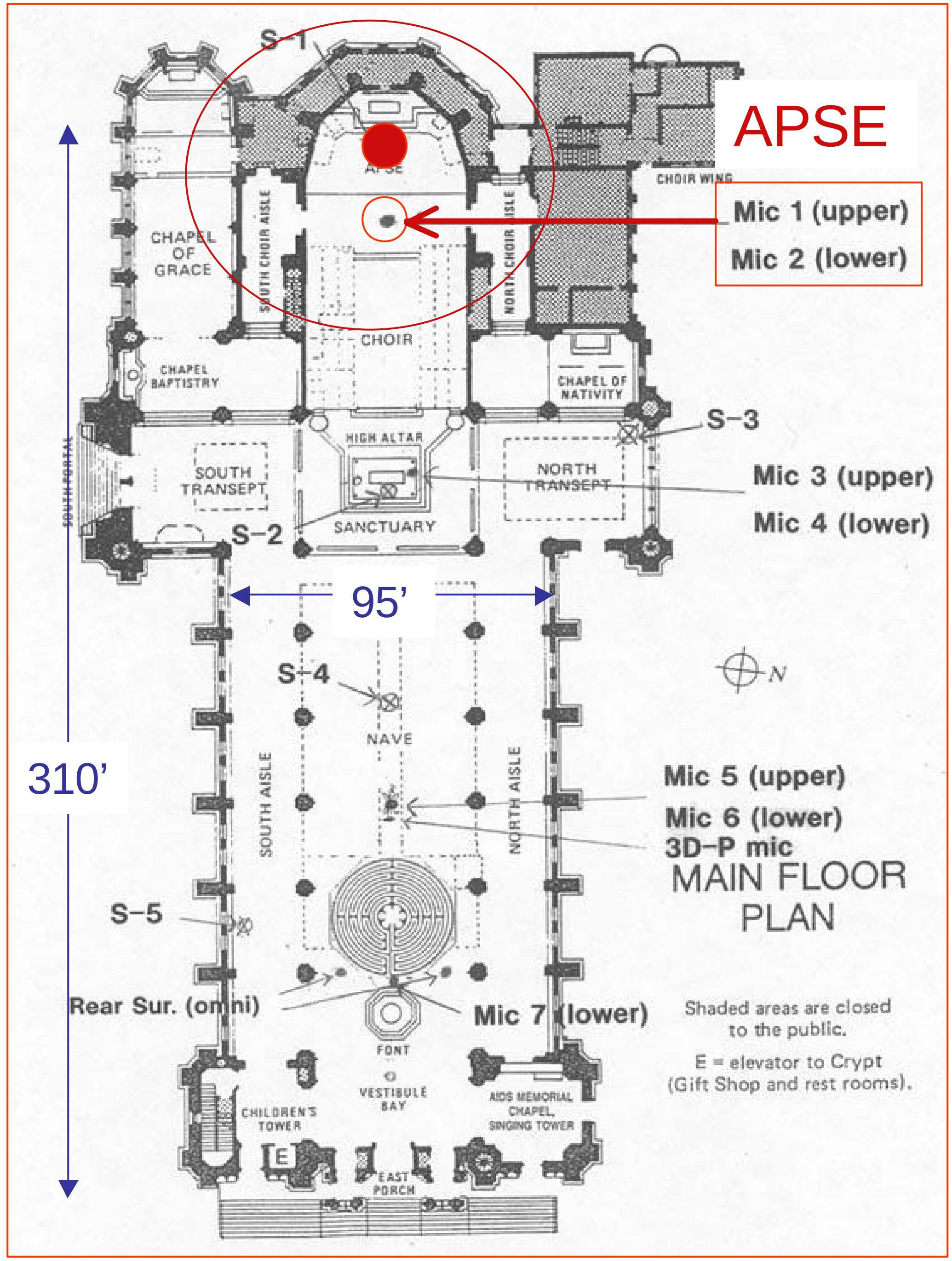
- Seven measurement microphones simultaneously recorded with synch pulse to ‘spatially sample’ a complex acoustical space
- Mics co-located vertically at 5’ and 85’ above floor
- Five sound sources located throughout space measured
- Superior to binaural measurement since location/time can be tracked

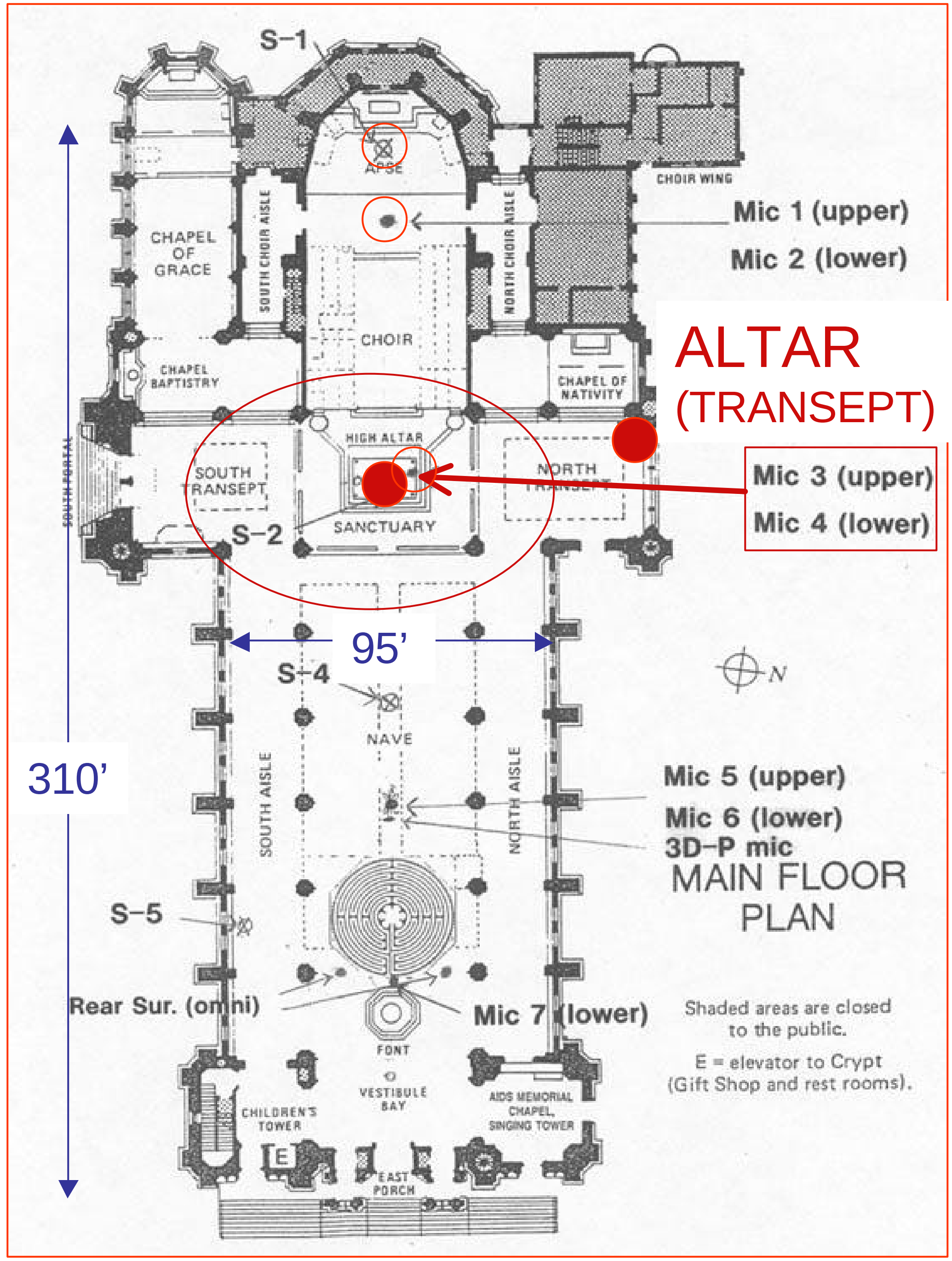
-starter pistol sound source at 5 locations



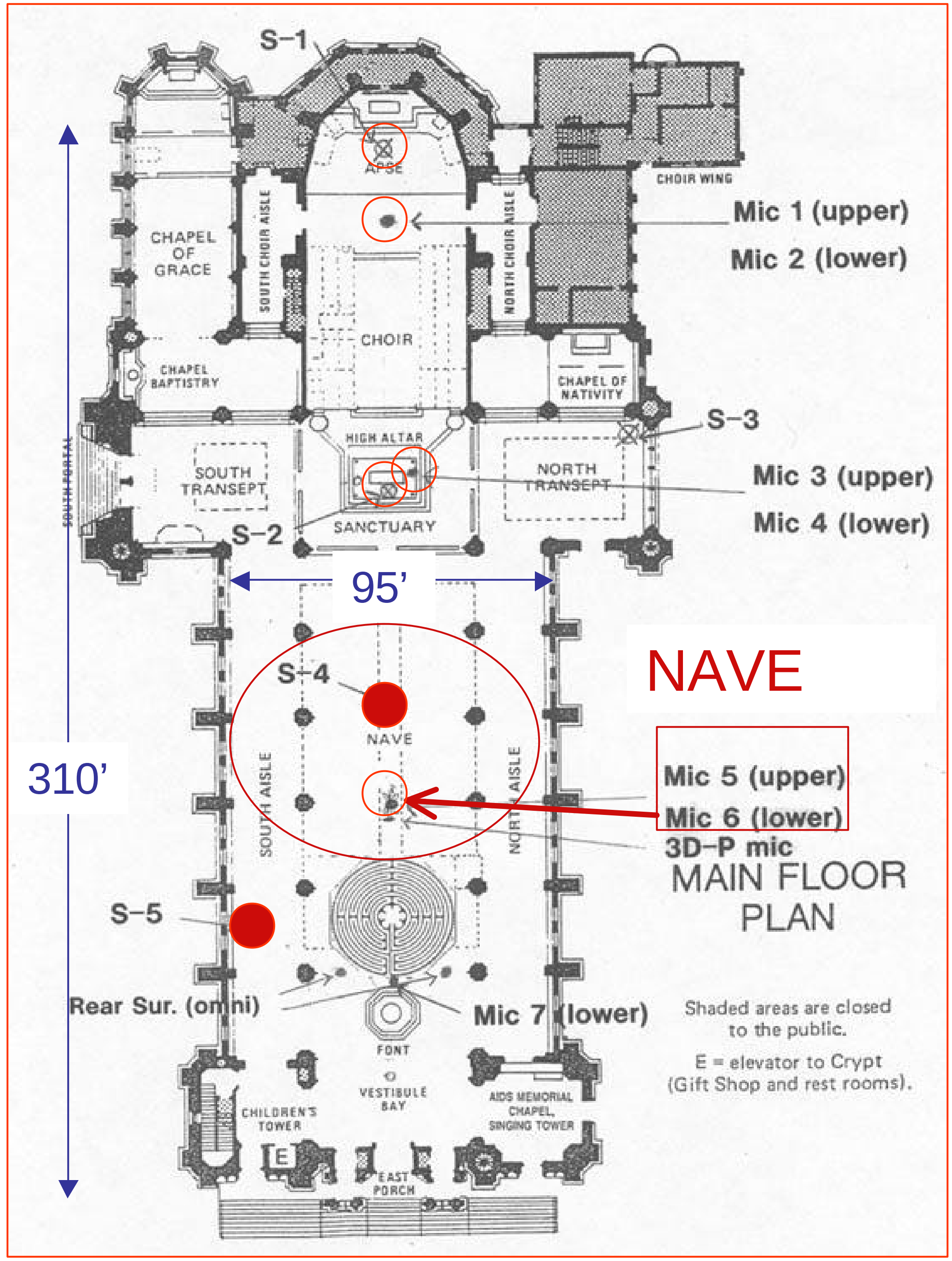
-Vertical mic pair
and sound source at apse



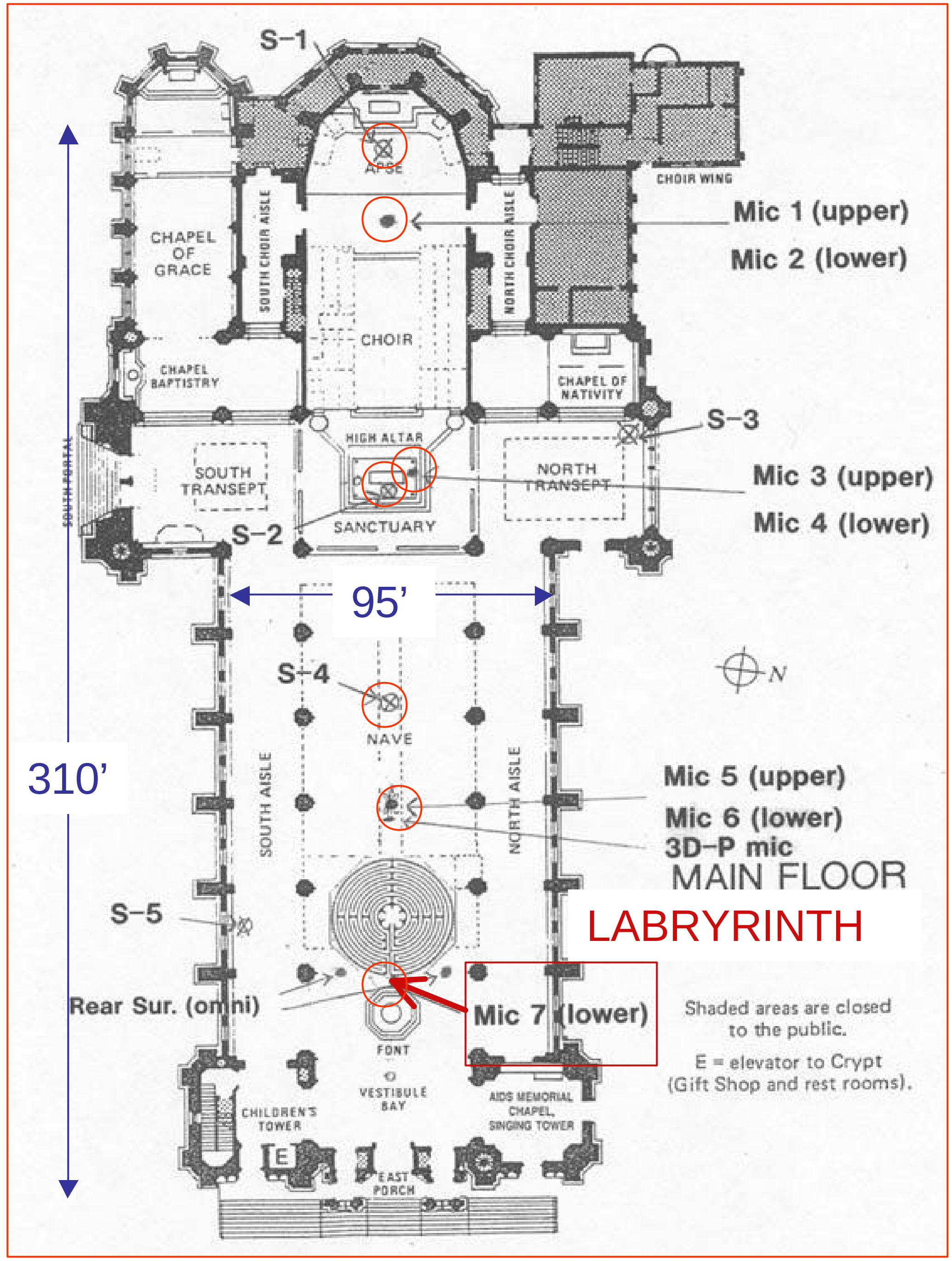
-Vertical mic pair
at altar; sound sources at
altar and end of transept

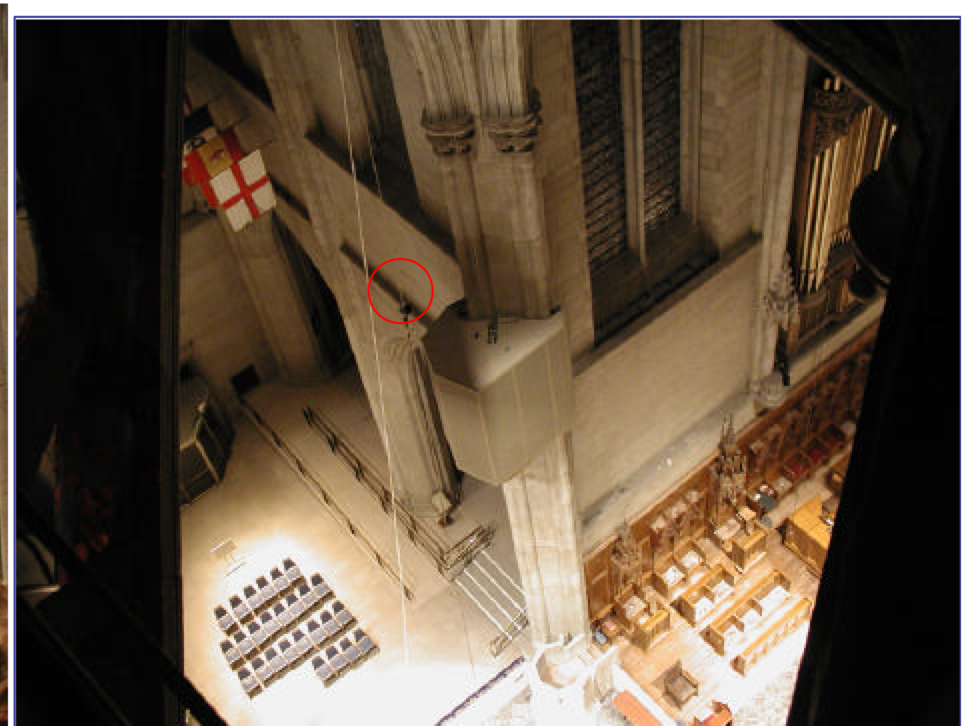


-Vertical mic pair
at nave; sound sources at
nave and nave gallery



-mic behind labyrinth

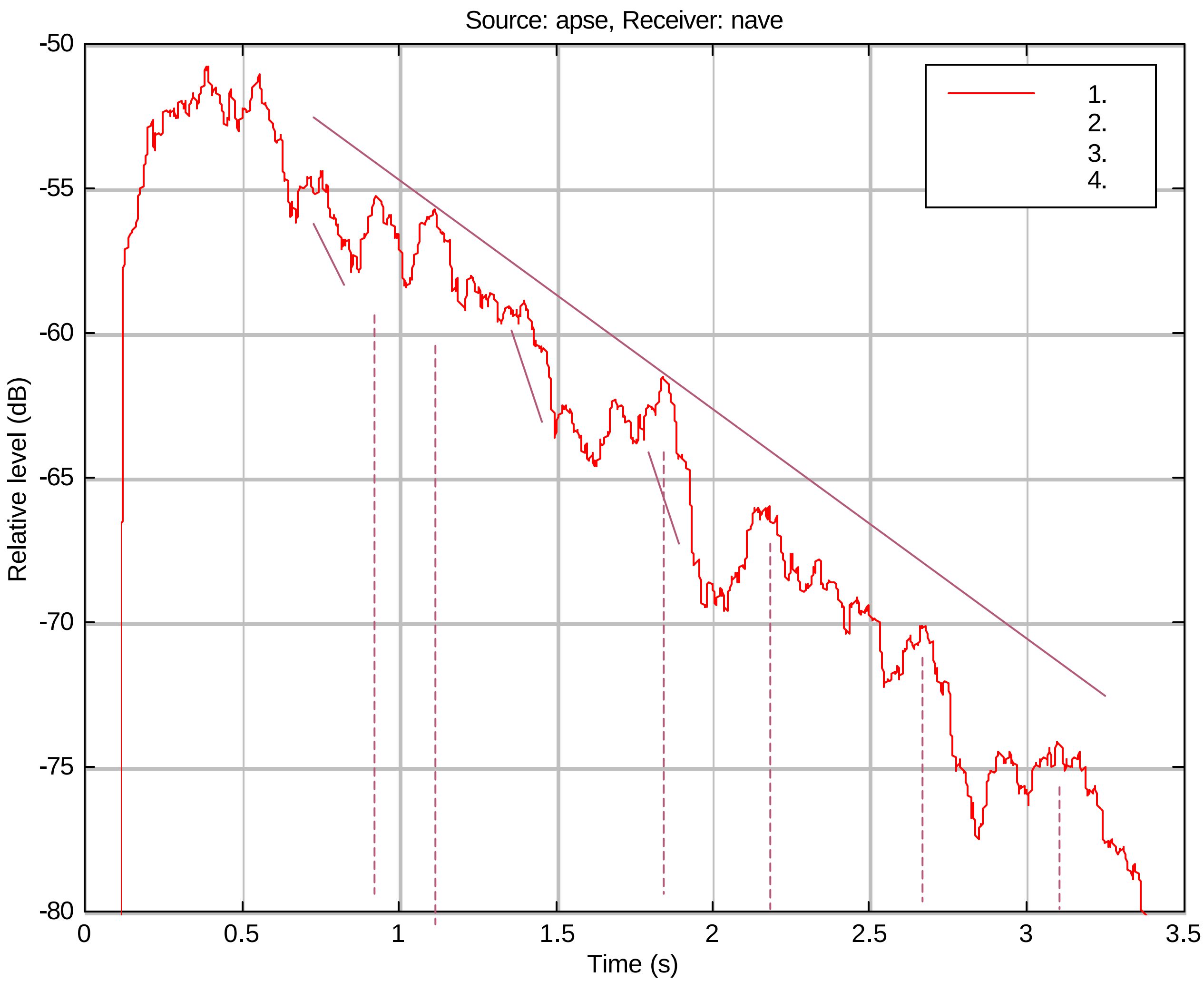




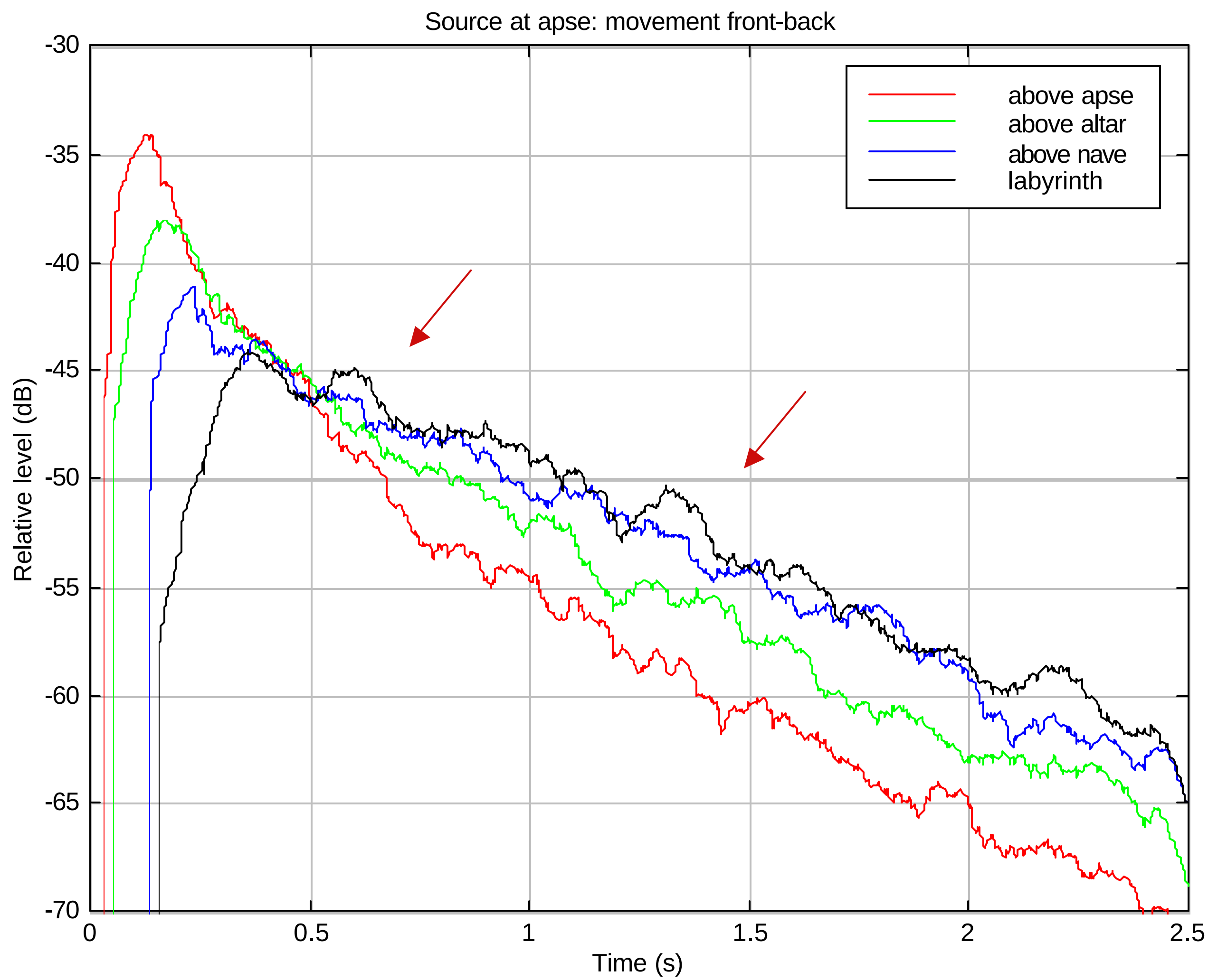
location	Wavelength (feet)	Freq. (Hz)	Pitch	Nearest audible Freq. (Hz)
elevation (nave floor to attic)	*121*	*9.26*	***D***	*36.7*
width (across nave)	95	11.79	**F#**	23.1
elevation (nave floor to ceiling)	90	12.44	**G**	24.5
width (across apse)	45	24.89	**G**	24.5
length (apse to vestibule)	310	3.61	**A#**	29.1
width (across transept)	139	8.06	**C**	32.7

Octave band	T30	T20	T15	EDT
63 Hz	7.5	**8.7**	9.0	2.3
125 Hz	6.2	**6.4**	5.8	2.1
250 Hz	5.6	**5.5**	5.2	0.8
500 Hz	5.2	**5.1**	5.1	2.3
1 kHz	4.6	**4.4**	4.2	2.0
2 kHz	3.8	**3.7**	3.6	2.8
4 kHz	1.9	**1.8**	1.8	0.4

Apse-Nave: fast decays superimposed on slow decay



Front-back movement for sound source at apse



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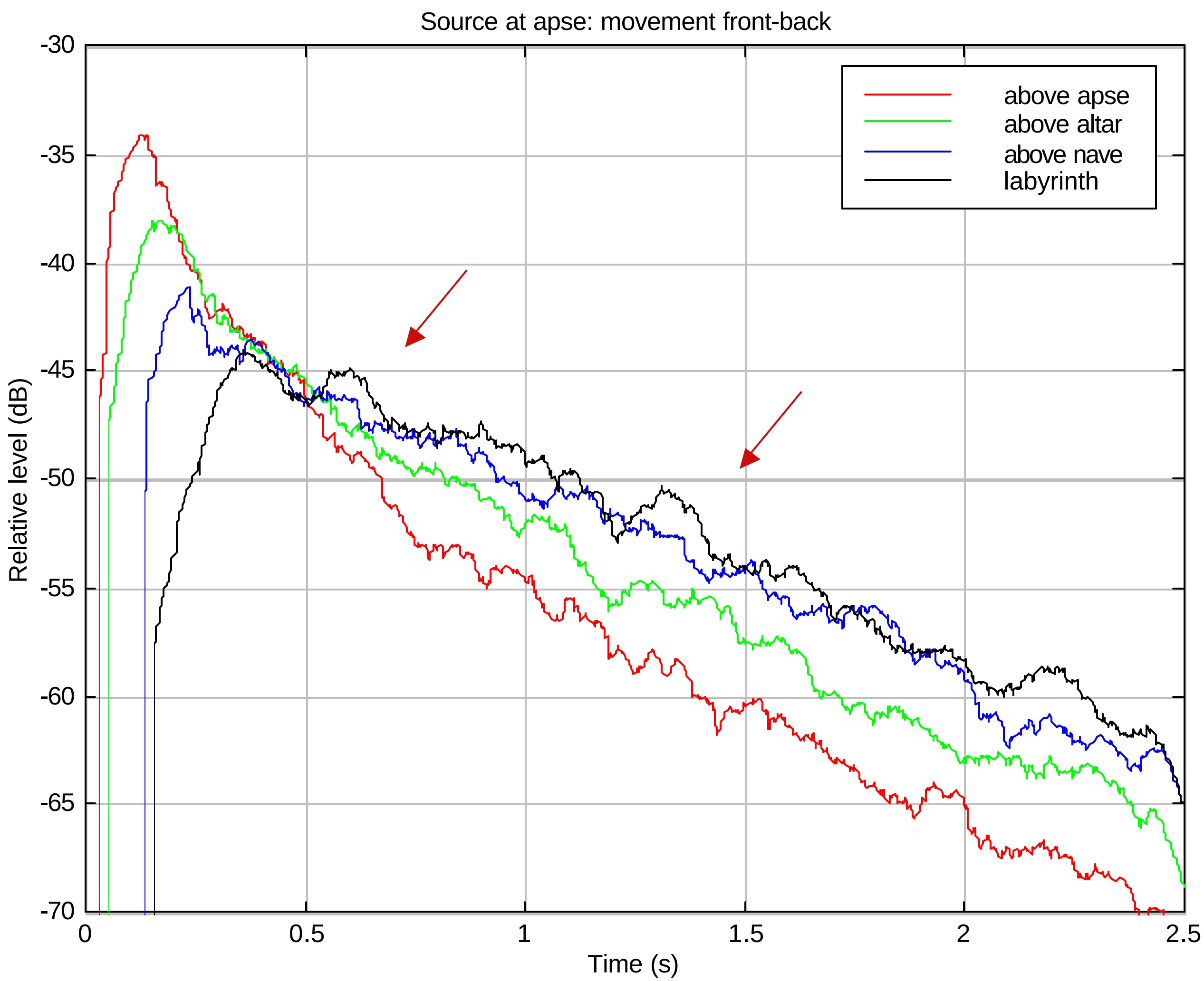
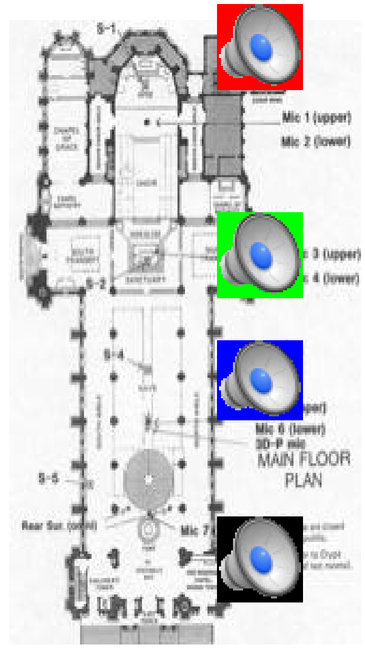
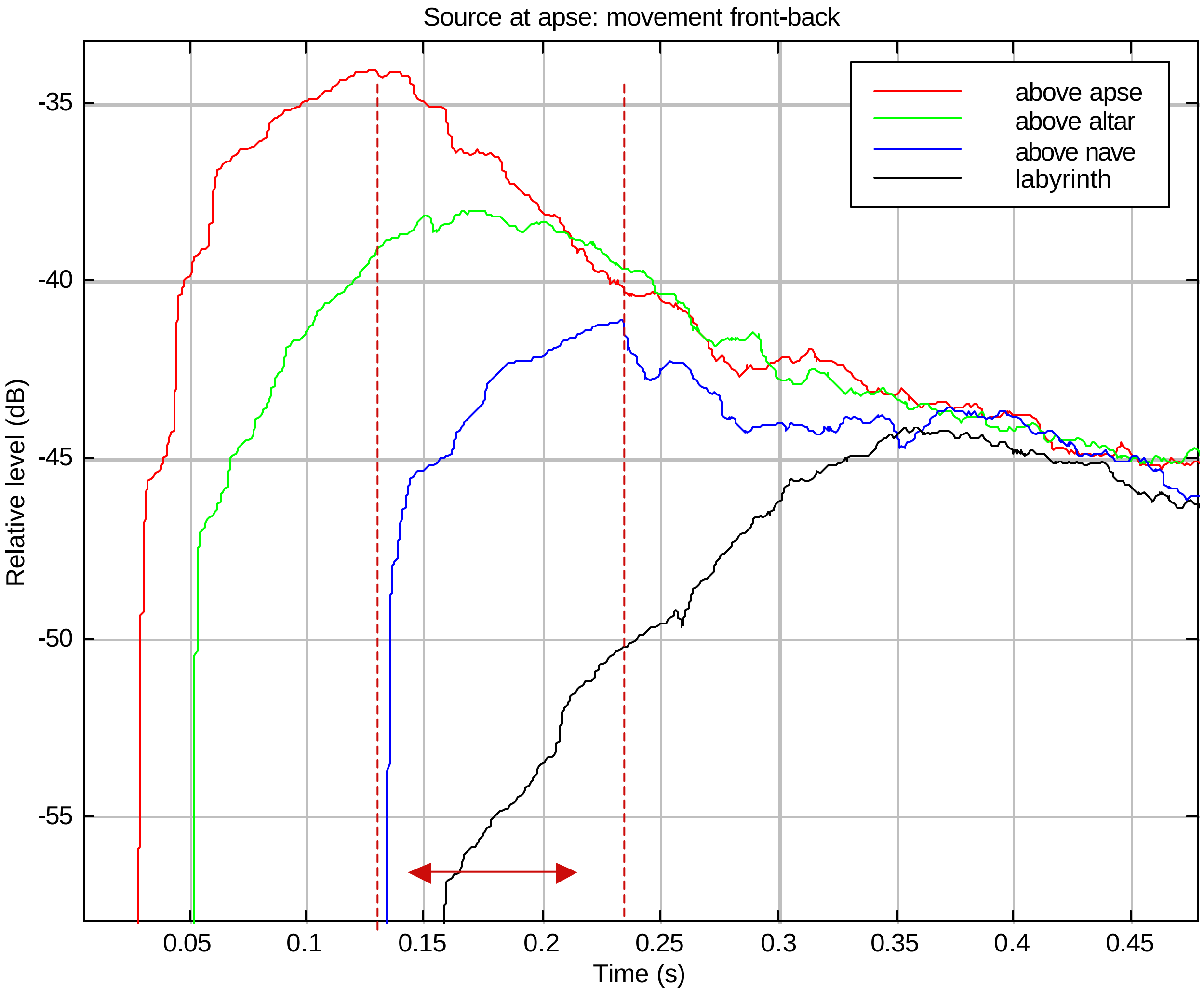
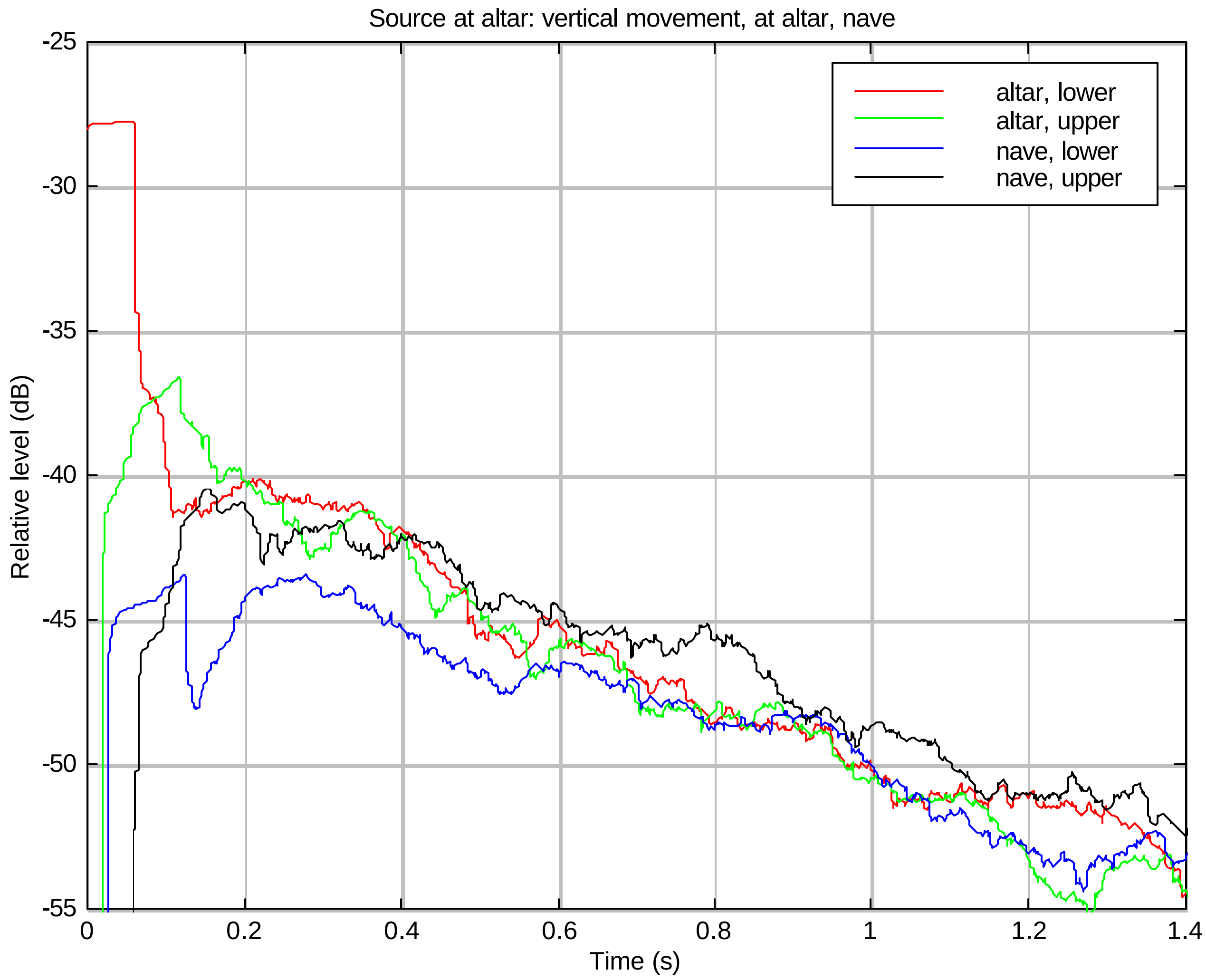




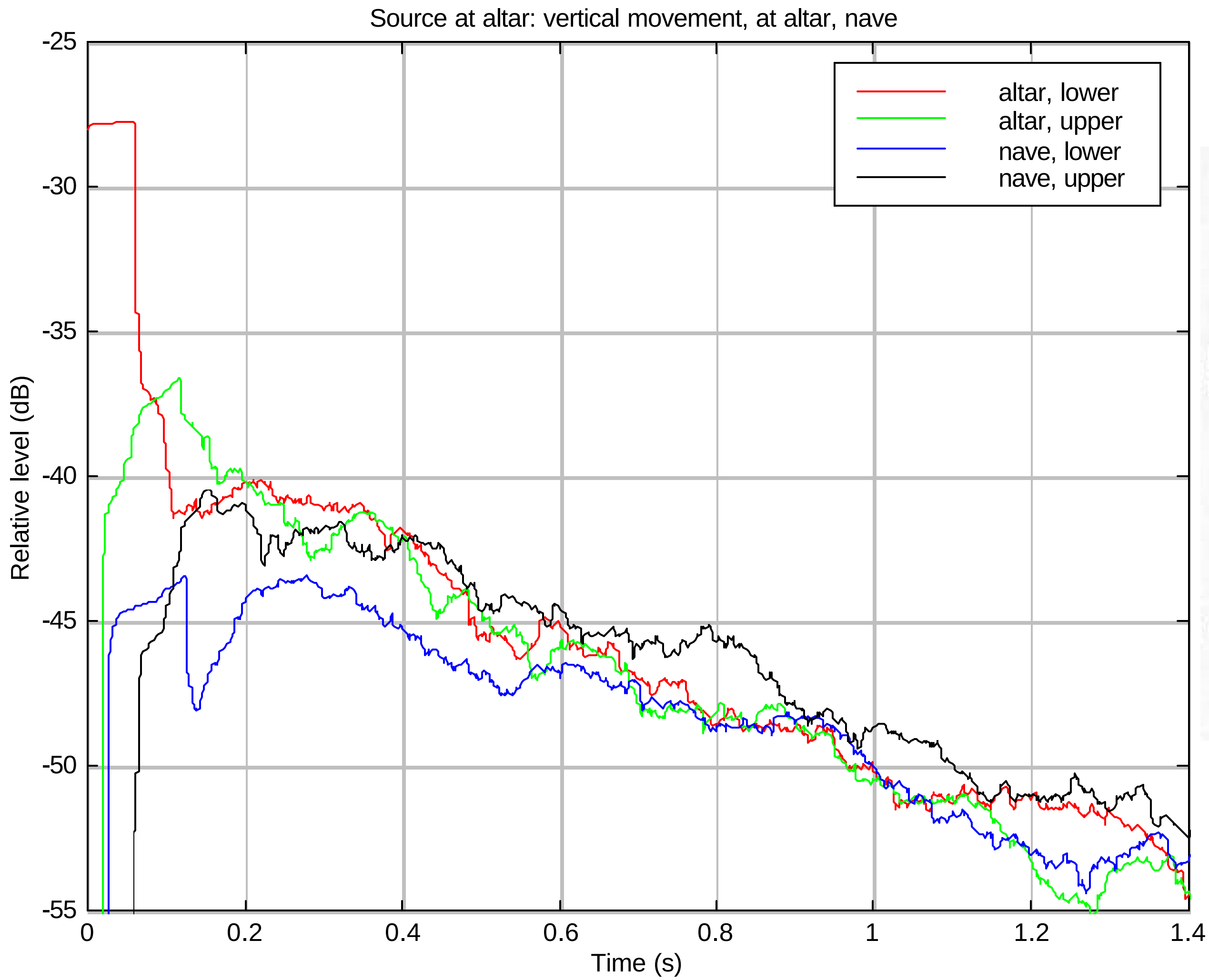
Front-back movement for sound source at apse: zoom in

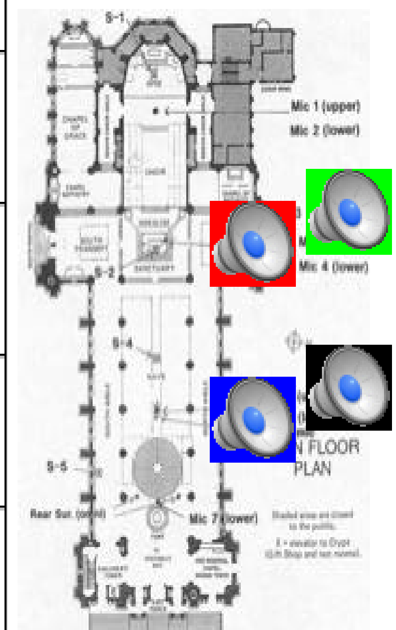


Vertical movement for sound source at altar



Vertical movement for sound source at altar

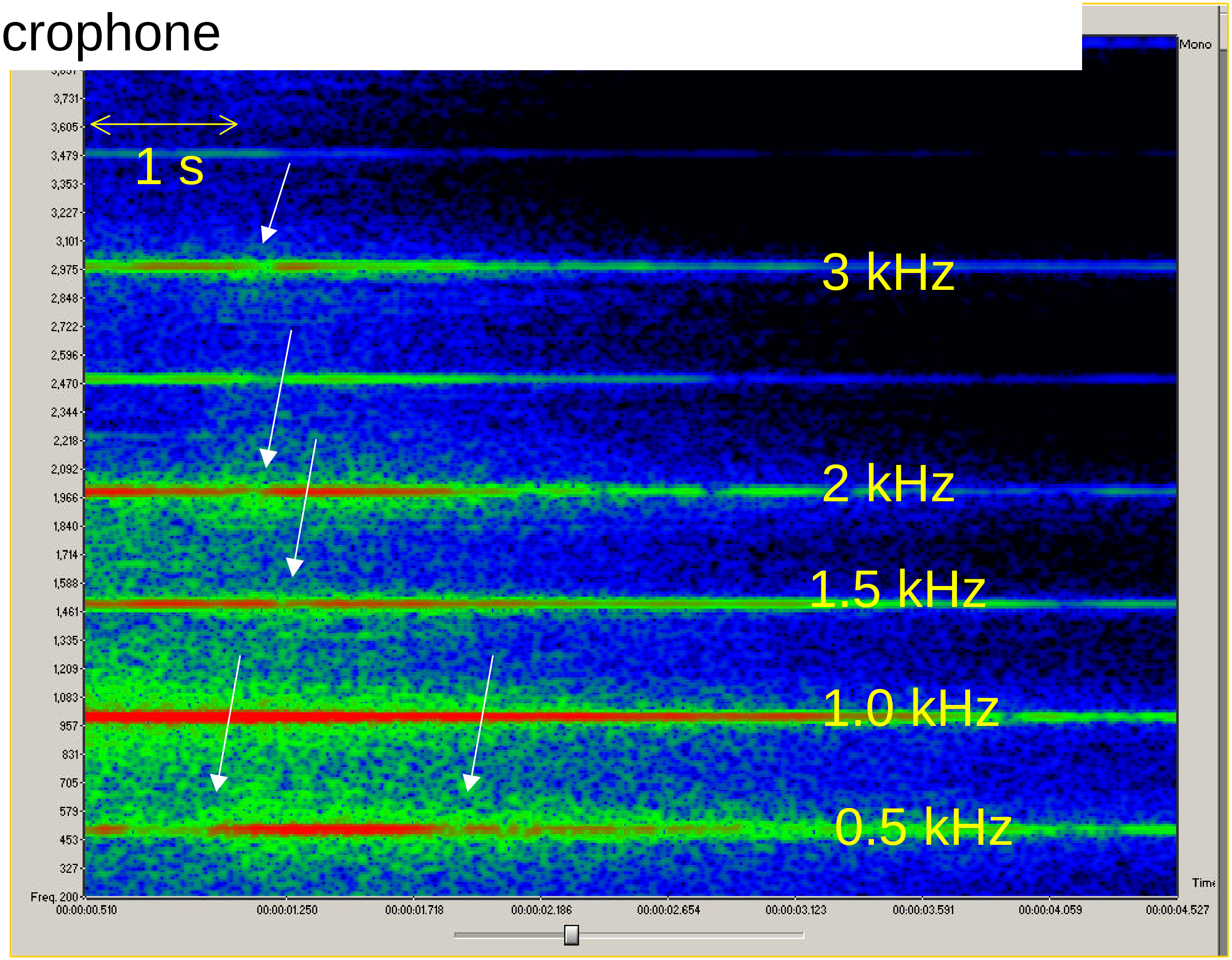


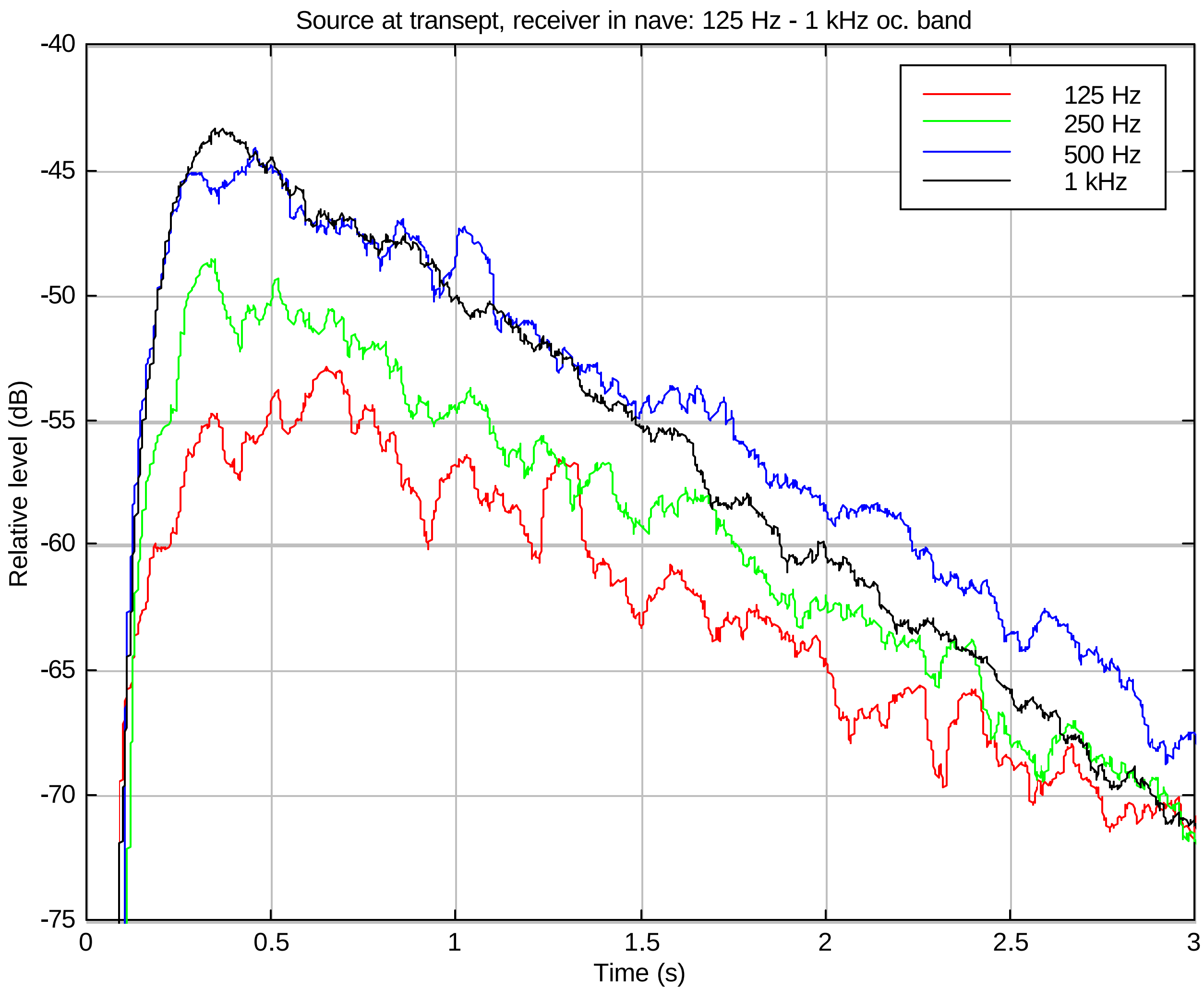


In addition to spatial modulation:
At each measured location, there is also differential amplitude modulation between frequency bands

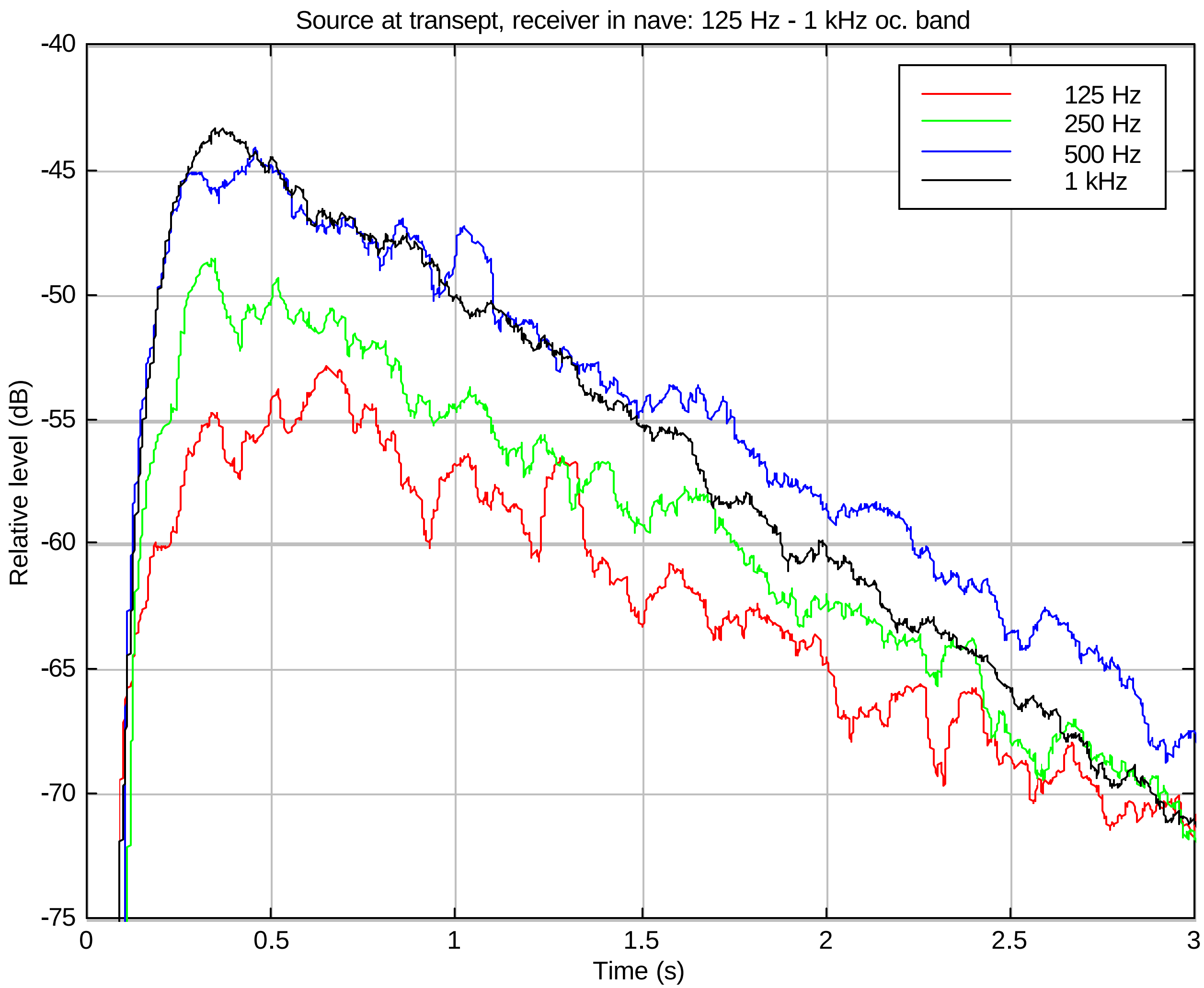
Sonogram of stopped organ tone decay

Arrows indicate differential amplitude modulation between frequency regions at one microphone





Source at transept, receiver in nave: 125 Hz - 1 kHz oc. band
125 Hz
250 Hz
500 Hz
1 kHz
-40
-45
-50
-55
-60
-65
-70
-75
0
0.5
1
1.5
2
2.5
3
Relative level (dB)
Time (s)



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125 Hz
250 Hz
500 Hz
1 kHz
Relative level (dB)
-40
-45
-50
-55
-60
-65
-70
-75
0
0.5
1
1.5
2
2.5
3
Time (s)

Tentative conclusions

Sensation of movement of late reverberation within a coupled space caused when

(1) duration between modulation peaks> (?) ms or

(2) differences in decay rate (*a* - *b*) > 300 (?) ms

occurs between different spatial locations within a given frequency band

Characteristic 'ragged' decays found in large spaces

Future psychoacoustic investigations for verification

Differential modulation between frequency bands occurs at given measurement locations

Provides additional cues about the character of a space