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

Durand R. Begault
Human Factors Research and Technology Division
NASA Ames Research Center

Moffett Field, California
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 reverberation 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

\[ T = 0.049 \frac{V}{A} \]  (room volume in cubic feet)
\[ T = 0.16 \frac{V}{A} \]  (room volume in cubic meters)

(where \( A = \sum S_i + \sum S_1 + \ldots + \sum S_N \) + mV (air absorption > 2 kHz)

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

<table>
<thead>
<tr>
<th>Surface</th>
<th>Material</th>
<th>Area (sq. ft)</th>
<th>500Hz</th>
<th>A (sabins)</th>
</tr>
</thead>
<tbody>
<tr>
<td>walls ceiling</td>
<td>gyp brd</td>
<td>1125</td>
<td>0.1</td>
<td>112.5</td>
</tr>
<tr>
<td>floor</td>
<td>carpet</td>
<td>2525</td>
<td>0.05</td>
<td>126.25</td>
</tr>
</tbody>
</table>

\[ T = 0.049 \frac{V}{A} \]
\[ = 0.049 (11,250) / 238.75 \]
\[ = 2.31 \text{ seconds} \]

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

a: Absorptive seating area
   Short reverberant decay

Sound source
Receive position
Examples of coupled spaces

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

(a) Absorptive seating area
   Short reverberant decay

(b) Undamped stagehouse
   Long reverberant decay

Sound source
Receive position
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.
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.

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

Measure the binaural room impulse response via a dummy head recording
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
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

- 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
<table>
<thead>
<tr>
<th>Location</th>
<th>Wavelength (feet)</th>
<th>Freq. (Hz)</th>
<th>Pitch</th>
<th>Nearest audible Freq. (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>elevation (nave floor to attic)</td>
<td>121</td>
<td>9.26</td>
<td>D</td>
<td>36.7</td>
</tr>
<tr>
<td>width (across nave)</td>
<td>95</td>
<td>11.79</td>
<td>F#</td>
<td>23.1</td>
</tr>
<tr>
<td>elevation (nave floor to ceiling)</td>
<td>90</td>
<td>12.44</td>
<td>G</td>
<td>24.5</td>
</tr>
<tr>
<td>width (across apse)</td>
<td>45</td>
<td>24.89</td>
<td>G</td>
<td>24.5</td>
</tr>
<tr>
<td>length (apse to vestibule)</td>
<td>310</td>
<td>3.61</td>
<td>A#</td>
<td>29.1</td>
</tr>
<tr>
<td>width (across transept)</td>
<td>139</td>
<td>8.06</td>
<td>C</td>
<td>32.7</td>
</tr>
<tr>
<td>Octave band</td>
<td>T30</td>
<td>T20</td>
<td>T15</td>
<td>EDT</td>
</tr>
<tr>
<td>------------</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>63 Hz</td>
<td>7.5</td>
<td>8.7</td>
<td>9.0</td>
<td>2.3</td>
</tr>
<tr>
<td>125 Hz</td>
<td>6.2</td>
<td>6.4</td>
<td>5.8</td>
<td>2.1</td>
</tr>
<tr>
<td>250 Hz</td>
<td>5.6</td>
<td>5.5</td>
<td>5.2</td>
<td>0.8</td>
</tr>
<tr>
<td>500 Hz</td>
<td>5.2</td>
<td>5.1</td>
<td>5.1</td>
<td>2.3</td>
</tr>
<tr>
<td>1 kHz</td>
<td>4.6</td>
<td>4.4</td>
<td>4.2</td>
<td>2.0</td>
</tr>
<tr>
<td>2 kHz</td>
<td>3.8</td>
<td>3.7</td>
<td>3.6</td>
<td>2.8</td>
</tr>
<tr>
<td>4 kHz</td>
<td>1.9</td>
<td>1.8</td>
<td>1.8</td>
<td>0.4</td>
</tr>
</tbody>
</table>
Apse-Nave: fast decays superimposed on slow decay
Front-back movement for sound source at apse
Front-back movement for sound source at apse

![Graph showing sound level over time for different locations: above apse, above altar, above nave, and labyrinth. The x-axis represents time in seconds, and the y-axis represents relative level in dB. Different lines indicate different locations, with arrows pointing to specific time points for comparison.]
Front-back movement for sound source at apse: zoom in
Vertical movement for sound source at altar

Source at altar: vertical movement, at altar, nave

- Relative level (dB)
- Time (s)

Legend:
- altar, lower
- altar, upper
- nave, lower
- nave, upper
Vertical movement for sound source at altar

Source at altar: vertical movement, at altar, nave

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Relative level (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>altar, lower</td>
</tr>
<tr>
<td></td>
<td>altar, upper</td>
</tr>
<tr>
<td></td>
<td>nave, lower</td>
</tr>
<tr>
<td></td>
<td>nave, upper</td>
</tr>
</tbody>
</table>

Diagram showing the vertical movement for sound source at altar with relative levels at different time points.
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

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Relative Level (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>125</td>
<td>-45</td>
</tr>
<tr>
<td>250</td>
<td>-50</td>
</tr>
<tr>
<td>500</td>
<td>-55</td>
</tr>
<tr>
<td>1000</td>
<td>-60</td>
</tr>
</tbody>
</table>
Source at transept, receiver in nave: 125 Hz - 1 kHz oc. band

Time (s)

Relative level (dB)

125 Hz
250 Hz
500 Hz
1 kHz
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*