Modeling and Auralization:

Past and Progress

Kurt Graffy
But first, a bit of history, from 27 years ago:

6th AES Conference on Sound Reinforcement
Nashville, Tennessee May 1988

And the software buzz then was:
6th AES Conference on Sound Reinforcement
Nashville, Tennessee May 1988

Altec AcoustaCADD

ARUP
Figure 1 - Grey Shade: White boxes showing the speaker location for a two-dimensional view of the listener's area.

Figure 2 - Physical Plan: White boxes showing the listener's area.

Figure 3 - 3D view: Grey Shade: White boxes showing the speaker location for a three-dimensional view of the listener's area.

Figure 4 - 3D view: White boxes showing the listener's area.

Figure 5 - 3D view: Grey Shade: White boxes showing the speaker location for a three-dimensional view of the listener's area.

Figure 6 - 3D view: White boxes showing the listener's area.

Figure 7 - 3D view: Grey Shade: White boxes showing the speaker location for a three-dimensional view of the listener's area.

Figure 8 - 3D view: White boxes showing the listener's area.

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Figure 10 - 3D view: White boxes showing the listener's area.

Figure 11 - 3D view: Grey Shade: White boxes showing the speaker location for a three-dimensional view of the listener's area.

Figure 12 - 3D view: White boxes showing the listener's area.

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Figure 54 - 3D view: White boxes showing the listener's area.
6th AES Conference on Sound Reinforcement
Nashville, Tennessee May 1988
Not at the 6th AES Conference on Sound Reinforcement
Nashville, Tennessee May 1988

PHD

ARUP
A mere 10 years later....

Here’s what was going on...

Auralization for new LA Cathedral:
Cathedral of Our Lady Of Angels, Los Angeles - 1998
Cathedral of Our Lady Of Angels, Los Angeles - 1998

1. View from Front of Nave
2. View from Mid-Nave
3. View from Rear of Nave
4. View from Chancel
5. View from Transept (choir)
Volume is 3,247,000 cubic feet or 1,080 cubic feet per seat
Cathedral of Our Lady Of Angels, Los Angeles

What we had to do to create the IR for Auralization:
Computer Farm!
(5) Computers @300 MHz
1 computer per listener location
Computers were on UPS, running 24/7 for 5 weeks to generate impulse responses
1998 Our Lady Of Angels Cathedral Los Angeles

Presentation to the Cardinal and Architect:

Impulse Response fed Lake Huron Convolver BUT
Huron did not have enough taps for the length of the IR!
Consequently Convolved IR was fed through Lexicon 480 to
develop the reverberant tail necessary for the decay time.
Convolution was “live” via a live talker (KMG) on wireless microphone
Listeners heard “real-time” binaural auralizations via IR wireless headphones
No acoustic “time zero” so latency effects negated.

Preparation:

Room model “built” and “skinned”.
Impulse Response generated for:
Five Listener Locations
Each listener location was modeled with 3 different sources
   Human talker, Distributed Arrays, Pewback system
Each listener location modeled with 3 different acoustical conditions
   No Treatment, Current Treatment, Recommended Treatment
So just Build ‘em, what Could Be Simpler?
Perhaps just a few things...

MODELS

- Parametric Analysis
- Materials Data
- Diffusion (Data?)
- Coupled Spaces
- IR Spectrum
- Level of Detail

- Architectural Entry?
- Loudspeaker Data
- Complex?
- Far-Field
- In Near-Field
- Diffraction

- Schroeder Freq Modal/BEM?
- Audience Block or Plane?
- Model vs Measured
5 Key Things to Consider

1. Level of Detail to Use

2. Application / Approach to Diffusion/Diffraction

3. How to handle frequencies below 125 Hz (below Schroeder)

4. Mapping Patch Size, Length of Echogram re Room

5. Note: GA Prediction methods are best suited to investigate main impacts of room size and shape...and distribution of absorbing and diffusing surfaces.

6. And oh yeah....Level of Detail to Use
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Models - Just Build 'em, what Could Be Simpler?
Modeling – What Level of Detail?

Schematic Curve of: Model Complexity vs Geometric Acoustic Accuracy

“Engineering Principles and Techniques in Room Acoustic Prediction”, Dahlenback_BNAM 2010
Modeling - Detail and Realization

One can consider Geometric Acoustics (GA) Applicable if:

• The wavelength $\lambda$ is much smaller than smallest dimension of the surface ($d$)
  • Such that $\lambda \ll d$
• In practice this expanded to be simply $\lambda < d$
• But...what’s crept in now are claims like:
  • Detailed geometry is relevant, and will provide diffusion
  • LF where $\lambda \gg d$ can be modeled with GA

“Engineering Principles and Techniques in Room Acoustic Prediction”, Dahlenback_BNAM 2010
Modeling - Detail and Realization

So. Let’s Consider the Two Claims regarding Detail and Diffusion:

• With sufficient modeling of detail the diffusing effect of surfaces can be generated,
  versus

• Use Frequency Dependent Scattering (FDS) coefficients on flat surface and omit the details

How does that work out?…how does it compare to a measured “real-world” situation?

“Engineering Principles and Techniques in Room Acoustic Prediction”, Dahlenback_BNAM 2010
Consider Two Claims regarding Detail:

Highly Detailed Will Geometry Work?

Planar surface + FDS Direct plus diffuse tail

Yup...it’s a better way to Go

Referenced Against Measured Direct plus diffuse tail

“Engineering Principles and Techniques in Room Acoustic Prediction”, Dahlenback_BNAM 2010
Modeling - Blended Models

Blending Revit Model And EASE Model
Modeling - Blended Models

Steel Forestage framing from Revit in EASE to check occlusions to array
Modeling - Blended Models
Modeling - Blended Models

• Occluding Elements to be Revised
Modeling - Blended Models

STAGE LEFT ARRAY ONLY

STAGE RIGHT ARRAY ONLY

CENTER ARRAY ONLY

IMPACT OF FORESTAGE SCREEN FRAME ON 3RD BALCONY COVERAGE
ORIGINAL ARRAY LOCATIONS
Modeling - Blended Models

FORESTAGE SCREEN FRAMING IN PLACE

STAGE LEFT ARRAY ONLY  CENTER ARRAY ONLY  STAGE RIGHT ARRAY ONLY

NO FORESTAGE SCREEN FRAMING

IMPACT OF FORESTAGE SCREEN FRAMING ON 3RD BALCONY COVERAGE
ORIGINAL ARRAY LOCATIONS
Modeling - Blended Models

MAPPING OF AUDIO INTENSITY ON FORESTAGE SCREEN FRAMING

STAGE LEFT ARRAY ONLY
BLACK AREAS ARE OCCLUDED BY FORESTAGE SCREEN FRAMING

STAGE RIGHT ARRAY ONLY
AREAS OF FORESTAGE SCREEN FRAMING OCCLUDING UPPER ARRAYS
ORIGINAL ARRAY LOCATIONS
Models - Just Build 'em, what Could Be Simpler?

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- MODELS
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Modeling - Parametric Analysis
Modeling - Parametric Analysis

Parametric Mapping in Model vs Illuminated Reflected Energy in Room
Modeling - Parametric Analysis

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Parametric Mapping in Model vs Illuminated Reflected Energy in Room
Modeling - Parametric Analysis

Parametric Mapping in Model for Balcony Geometry Shaping
Modeling - Parametric Analysis

Parametric Mapping in Model for Balcony Geometry Shaping

Time Delay from Direct Sound (ms)
MODELS - Just Build 'em, what Could Be Simpler?

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Model vs Measured
# Modeling - Measured vs Modeled

<table>
<thead>
<tr>
<th>Facts</th>
<th>Measurements</th>
<th>Simulations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room geometry</td>
<td>Fully included by definition</td>
<td>Approximated</td>
</tr>
<tr>
<td>Alteration of room geometry</td>
<td>Difficult</td>
<td>Easy</td>
</tr>
<tr>
<td>Wave phenomena (phase information, diffraction)</td>
<td>Fully included – inherent in the real sound field</td>
<td>Approximated with varying accuracy</td>
</tr>
<tr>
<td>Wall properties</td>
<td>Fully included – inherent in the real room</td>
<td>Absorption - scattering coefficients have to be measured or estimated, with limited accuracy</td>
</tr>
<tr>
<td>Air absorption (a function of temperature and humidity)</td>
<td>Fully included but may vary significantly in different measurements</td>
<td>Calculated, but very accurate</td>
</tr>
<tr>
<td>Source directivity</td>
<td>Not perfect: Lobes at high frequencies</td>
<td>Perfectly omni-directional</td>
</tr>
<tr>
<td>Dynamic range of source</td>
<td>Insufficient at very low and very high frequencies. Distortion at high levels</td>
<td>Unlimited dynamic range at all frequencies. No distortion</td>
</tr>
<tr>
<td>Calibration of source</td>
<td>Special procedure needed for the strength parameter, $G$</td>
<td>Perfect per definition</td>
</tr>
<tr>
<td>Background Noise</td>
<td>Limits the dynamic range, compensation necessary</td>
<td>Not present</td>
</tr>
<tr>
<td>Microphone directivity</td>
<td>Omnidirectional microphone. Some parameters require figure-of-eight pattern or a dummy head</td>
<td>All directivities available</td>
</tr>
<tr>
<td>Results in octave-bands</td>
<td>Filtering is required, which alters the original signal</td>
<td>Results are derived directly in different bands - no alteration due to filtering</td>
</tr>
<tr>
<td>Onset time of impulse response</td>
<td>Critical, especially at low frequencies</td>
<td>Perfect per definition</td>
</tr>
<tr>
<td>Reproducibility</td>
<td>Not perfect: Depends heavily on the source</td>
<td>Can be perfect, depending on the algorithm</td>
</tr>
<tr>
<td>Influence of operator</td>
<td>Knowledge and experience important</td>
<td>Knowledge and experience very important</td>
</tr>
</tbody>
</table>

Models - Just Build 'em, what Could Be Simpler?

- MODELS

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- Level of Detail
Modeling - Diffusion

Modeling - Diffusion

Reflection models
(asymptotic models for short wavelengths)

Snell’s law: $\theta_r = \theta_i$

Lambert’s law:
Probability of diffuse reflection is $\sim \cos \theta_r$

Modeling - Diffusion

Scattering as a weighted vector addition of specular and diffuse reflection

Small scattering, \( s = 0.2 \)

High scattering, \( s = 0.8 \)

Sound scattering coefficient, $s$

- defined as the ratio between the acoustic energy reflected in non-specular directions and the totally reflected acoustic energy
- A sound scattering surface is defined as a surface with $s \geq 0.5$

Modeling - Diffusion

Types of diffusers

- **Geometric diffusers**
  - Simple curved surfaces
  - Irregular geometric structures
  - Periodic geometric structures
  - Mixture of absorbing and reflecting materials

- **Mathematical diffusers**
  - MLS (Maximum Length Sequence) diffusers
  - QRD (Quadratic Residue Diffusers)
  - PRD (Primitive Root Diffusers)
  - Fractal diffusers
  - Curved diffusers

Modeling - Diffusion

![Scattering Coefficients](image)

Table III. Collection of the scattering coefficients (in ODEON) used in the acoustical models.

<table>
<thead>
<tr>
<th>Scattering coefficient</th>
<th>Description of the surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1, ..., 0.19</td>
<td>large, plain surfaces</td>
</tr>
<tr>
<td>0.2, ..., 0.39</td>
<td>large partially fitted surfaces</td>
</tr>
<tr>
<td>0.4, ..., 0.59</td>
<td>small or fitted surfaces</td>
</tr>
<tr>
<td>0.6, ..., 0.89</td>
<td>large densely fitted surfaces</td>
</tr>
<tr>
<td>0.9, ..., 1.00</td>
<td>small densely fitted surfaces</td>
</tr>
</tbody>
</table>

Figure 1: Example on combined scattering coefficients at 1000 Hz used in the Elmia hall, data was provided to participants in the 2nd Round Robin.

Modeling - Diffusion

Guide to scattering coefficients

The scattering coefficient $s$ should be chosen from depth of the structure and from the width of the surface.

The suggested graphs may be used as a rough guide.

The higher of the two values should be used for $s$.

Models - Just Build 'em, what Could Be Simpler?

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Modeling - Diffraction

Screen-based formulas:
- Geometric Theory of Diffraction (GTD)
- Uniform Theory of Diffraction (UTD)

“As all GA models, assumes edges to be large compared to the wavelength”

Good model for environmental noise, where barriers approach infinite relative to $\lambda$

Poor approximation of most room acoustics conditions, like:
- Reflectors
- Office partitions
- Orchestra Pits

“Whitepaper regarding diffraction (v5) for prediction using CATT-Acoustic v9.0c and higher”, BI Dalenback
Modeling - Diffraction

- Secondary Edge Sources – CATT
  - Biot-Tolstoy Medwin/Huygens/Svensson

Frequency, time and directivity of diffracted component encoded in secondary edge IR (screen-based models assume a frequency-dependent pulse)
- Diffracted component included in receivers on local side of edge (which is true!)
- No practical limitation of edge length, S/R angle/location, panel size
- As a bonus, CATT adds source directivity + absorption profile to the mix

“Whitepaper regarding diffraction (v5) for prediction using CATT-Acoustic v9.0c and higher”, BI Dalenback
“With the 5° approximation the correct behavior is in this example achieved up to about 1 kHz while for higher frequencies the approximation is not sufficient and sectors will be seen (but no gaps like with specular-only - just weaker reflections). However, unlike the purely specular GA case, with the SES method it in this case helps to use a better approximation and using 2.5° will roughly double the frequency to 2 kHz where a more correct smooth reflection will be achieved.”

“Whitepaper regarding diffraction (v5) for prediction using CATT-Acoustic v9.0c and higher”, BI Dalenback
Modeling - Diffraction

BUT...is the difference significant enough to justify the increased time?

- 40k rays
- 1s IR Time
- 2nd algorithm
- 2nd order diffraction
- 9 sources
- 4 receivers
- 40 Hours

- 40k rays
- 1s IR Time
- 2nd algorithm
- 2nd order diffraction
- 5 sources
- 4 receivers
- 12 Hours

- 40k rays
- 1s IR Time
- 2nd algorithm
- No diffraction
- 5 sources
- 4 receivers
- 12 Hours

- 80k rays
- 1s IR Time
- 1st algorithm
- 2nd order diffraction
- 5 sources
- 4 receivers
- 2 Hours
Auralisation

Phrase coined by Mendel Kleiner of Chalmers University:

• “Auralization is the process of rendering audible, by physical or mathematical modeling, the sound field of a source in a space, in such a way as to simulate the binaural listening experience at a given position in the modeled space.”

Auralization - What Could Be Simpler?

- Room Model Accuracy
- Playback Topology?
- Anechoic Sources?
- Loudspeaker Accuracy
- Acoustics of Rendering Room
- Model vs Measured
- IR Spectrum
- Diffraction/Diffusion
- Ambisonic
- Ambiophonic
- 5.1-7.1
- <100 Hz?
- WFS
- Headphones
- Binaural
- Transaural
- AURALIZATION
Auralisation - Arup SoundLab
Auralisation - Methodology

Impulse

Real Room or Computer Model

Impulse Response

Auralisation

Anechoic Music

Impulse Response

Listen in SoundLab

54
Auralisation - Arup SoundLab

Site Acoustic Measurements

Convolve with Anechoic Recording

Listen

Data from 3D Acoustic Model

Convolve with Anechoic Recording

Listen
Auralisation - Monaural
Auralisation – Stereo / Transaural
Auralisation - 5.1/7.1 Surround
Auralisation - Ambisonic
Arup SoundLab SF- Loudspeaker Layout

3.25m

45°

8
SoundLab SF - Hardware

- Soundfield mic
- B&K SLM
- MOTU Audio I/O
- (12) JBL 4326P + 4 subs
- London BSS DSP
SoundLab - Software

call

REAPER

MATLAB

MAX6

SysTune
Auralisation - Ambisonic
Auralisation - B-Format to Ambisonic
Time Information - 4 channel
Spatial Information - Very Frontal
Spatial Information - Better Hall
Northrop - Model at Close of DD
3D Audio Data Vis

DD – Position 3
3D Audio Data Vis

DD – Position 5
3D Audio Data Vis

DD – Position 7
3D Audio Data Vis

DD – Position 9
VANCOUVER CONVENTION CENTRE

BALLROOM THEATRE • SOUNDLAB
AURALIZATION
ADD THEATRE “SET” WITHIN ACOUSTICS OF EXISTING BALLROOM: ACOUSTICAL IMPACTS?
NEW STAGE/SEATING "SET" INSIDE BALLROOM
COVERAGE FOR ALL SEATING FROM MAIN ARRAY
SITE ACOUSTIC TESTING

TEST SIGNALS
- DODECAHEDRON + SUBWOOFER

RECORDING + ANALYSIS
- REFERENCE MICROPHONE
- SOUND LEVEL METER
- SOUNDFIELD MICROPHONE
CALIBRATE MODEL TO SITE MEASUREMENTS

1. ONE INCH ACOUSTIC PANEL (BEHIND SLATTED WOOD)

2. DRAPERY

3. SOLID LOWER WALL AREA

4. CARPET

5. OPERABLE WALL PANELS
CALIBRATE BALLROOM ACOUSTIC MODEL TO SITE MEASUREMENTS

1. ONE INCH ACOUSTIC PANEL (BEHIND SLATTED WOOD)

2. DRAPERY

3. SOLID LOWER WALL AREA

4. CARPET

5. OPERABLE WALL PANELS
CALIBRATE BALLROOM ACOUSTIC MODEL TO SITE MEASUREMENTS

![Graph showing reverberation time vs. frequency comparing site measured and 3D acoustic model results.](image-url)
ADD THEATRE TO BALLROOM ACOUSTIC MODEL
COMPLETED ROOM ACOUSTIC MODEL
CALIBRATE BALLROOM ACOUSTIC MODEL TO SITE MEASUREMENTS
LISTENING POSITIONS
<table>
<thead>
<tr>
<th>Seat Location</th>
<th>VIP Seats (Position #1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room</td>
<td>Current Design</td>
</tr>
<tr>
<td>Sound System</td>
<td>Option #1 – Line Arrays</td>
</tr>
</tbody>
</table>
Seat Location: VIP Seats (Position #1)
Room: Bass Absorption Added
Sound System: Option #1 – Line Arrays
THE END.... THANK YOU....