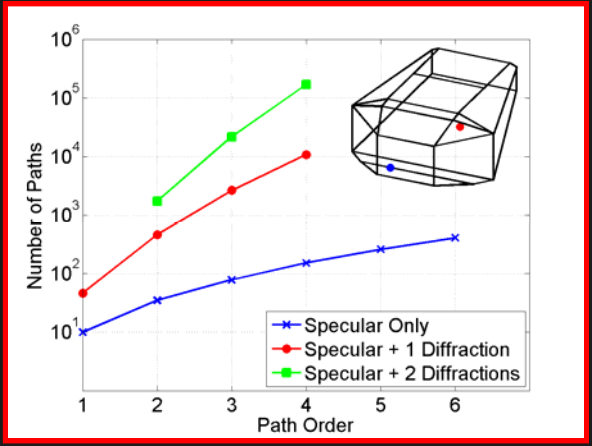
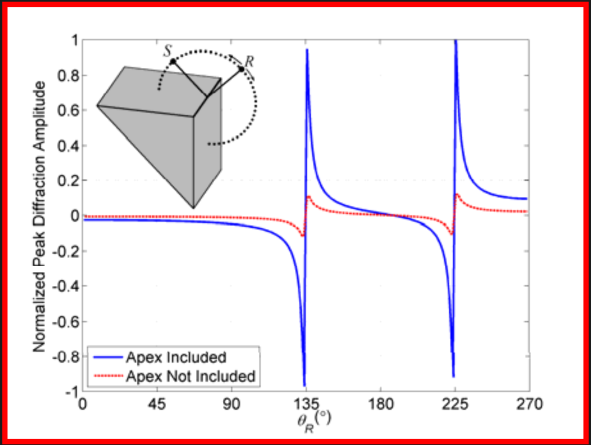
19th International Congress on Acoustics, 2-7 September 2007, Madrid, Spain, Paper RBA-11-003

Culling Insignificant Diffraction Components for Interactive Acoustic Simulations





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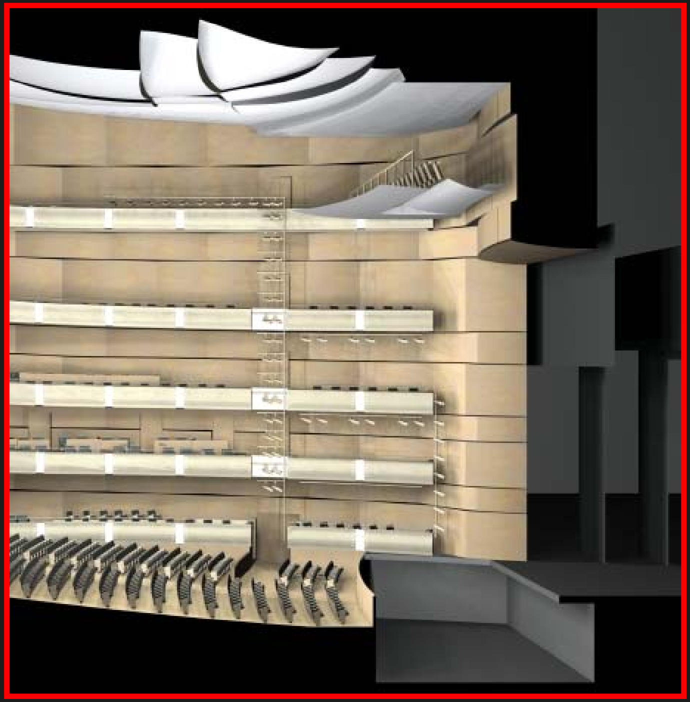
Overview

- Introduction and Motivation
- Terminology and Related Work
- Diffraction Formulations
- Culling Diffraction Components
- Results
- Conclusions and Future Directions

Introduction and Motivation

- Diffraction is necessary to achieve perceptual realism and physical accuracy in acoustic simulations of complex environments
  - Occluded line of sight (e.g. musicians in opera pits)
  - Exposed edges (e.g. reflector arrays or proscenia)

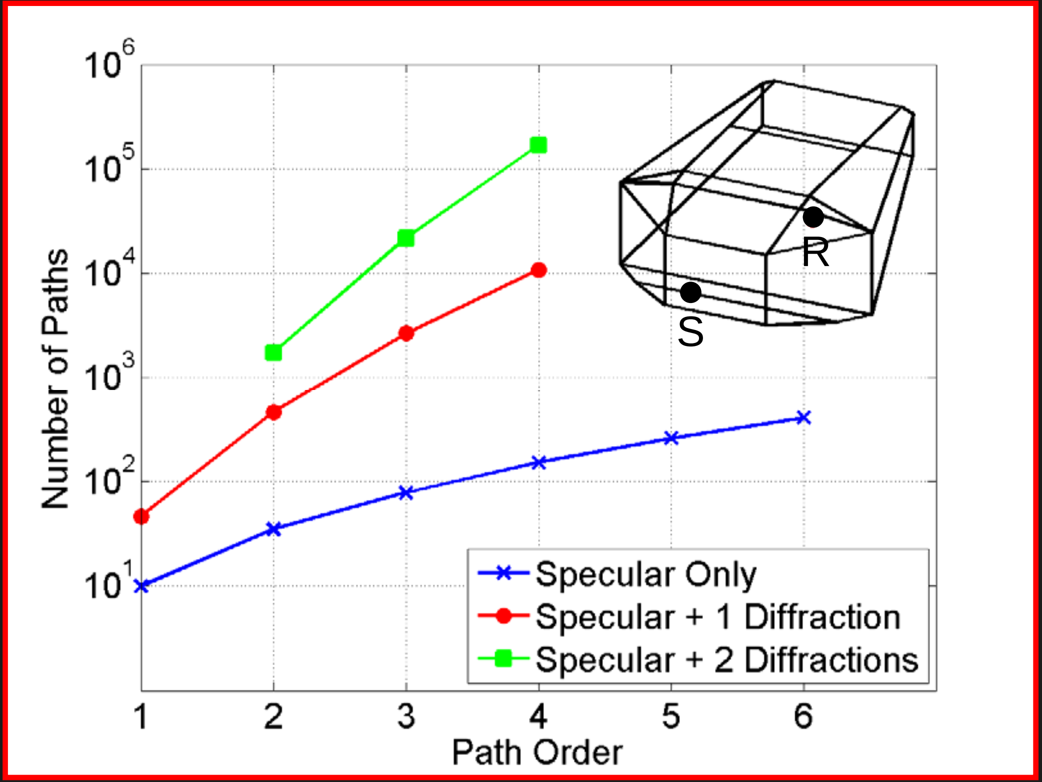


http://www.lancetteer.com/images/Interior_Cut-away.jpg

Central Michigan University Recital Hall
http://www.audiosystemsgroup.com/cmu.htm

Introduction and Motivation

- Diffraction calculations add significant computational load
  - Each diffraction IR can be hard/slow to compute
  - Diffracted paths drastically increase the total number of propagation paths from source to receiver



Introduction and Motivation

- Diffraction calculations add significant computational load
  - Each diffraction IR can be hard/slow to compute
  - Diffracted paths drastically increase the total number of propagation paths from source to receiver
- Computational load makes interactive simulations difficult
- We describe a method to reduce diffraction-related computations by culling insignificant diffracted paths *before* their IRs are calculated

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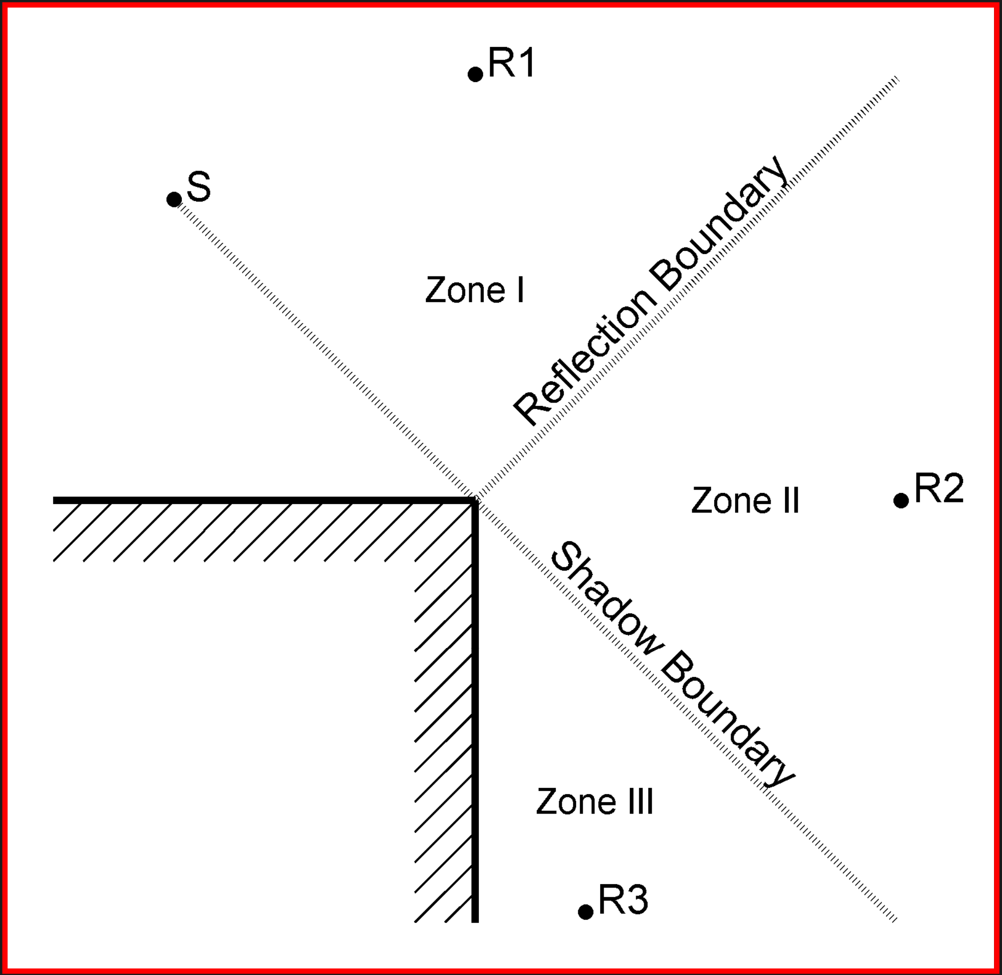
Terminology: Zone Boundary



- Zone I
  - Direct sound
  - Specular reflection
  - Diffraction
- Zone II
  - Direct sound
  - Diffraction
- Zone III (Shadow Zone)
  - Diffraction
- Zone boundary
  - Geometrical acoustics components are discontinuous
  - Reflection boundary: Boundary between Zones I and II
  - Shadow boundary: Boundary between Zones II and III

Previous Culling Work

- Tsingos *et al*. (SIGGRAPH '01)
  - UTD diffraction within a beam-tracing framework
  - Optionally cull all diffracted paths for which the receiver is not in the shadow zone (*i.e.* compute diffraction only in the shadow zone)
- Antonacci *et al*. (EUSIPCO '04)
  - UTD diffraction within a beam-tracing framework
  - Similar shadow-zone culling approach
  - No diffraction calculations for wedges with exterior angle < 180°
- Plenty of other related work on diffraction in room acoustics

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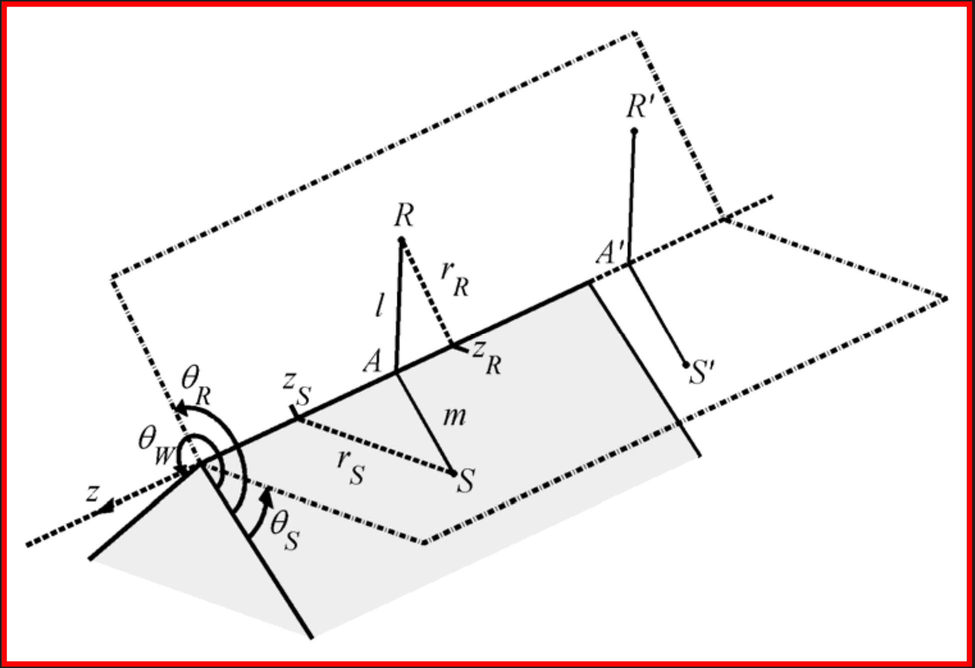
Wedge Geometry

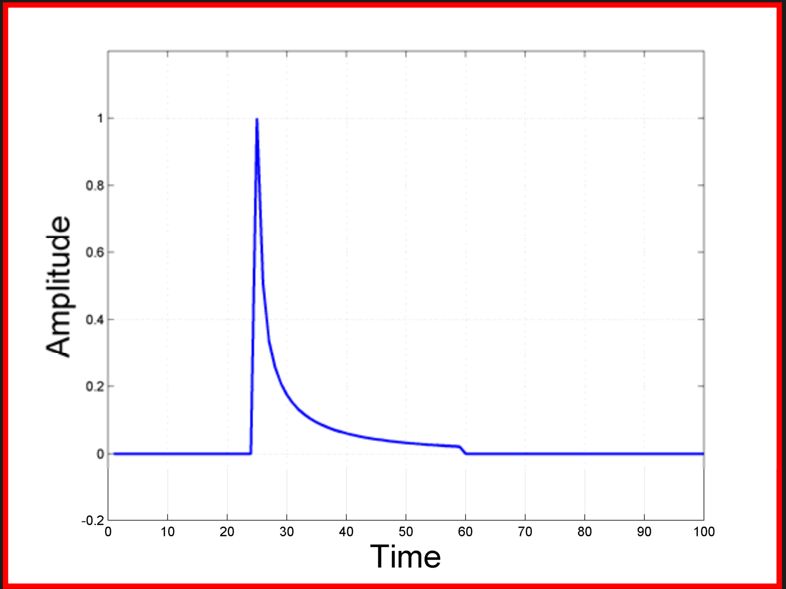


- Wedge
  - θ_w = exterior wedge angle
  - v = $\pi/\theta w$ is the wedge index
- Source and Receiver: Edge-Aligned Cylindrical Coordinates (r, θ, z)
  - r = radial distance from the edge
  - θ = angle measured from a face
  - z = distance along the edge
- Other
  - m = distance from source to edge point
  - l = distance from receiver to edge point
  - A = apex point for S/R
  - A' = apex point for S'/R'

BTM Diffraction Formulation

$$h(n) = -\frac{\nu}{4\pi}\sum_{i=1}^{4}\int_{z_{n,1}}^{z_{n,2}} \frac{\sin(\nu\varphi_i)}{\cosh[\nu\eta(z) - \cos(\nu\varphi_i)]}\cdot\frac{1}{ml}\,dz$$

$$\varphi_i = \pi \pm \theta_S \pm \theta_R \qquad \eta(z) = \cosh^{-1}\left\{\frac{ml + (z - z_S)(z - z_R)}{r_S r_R}\right\}$$

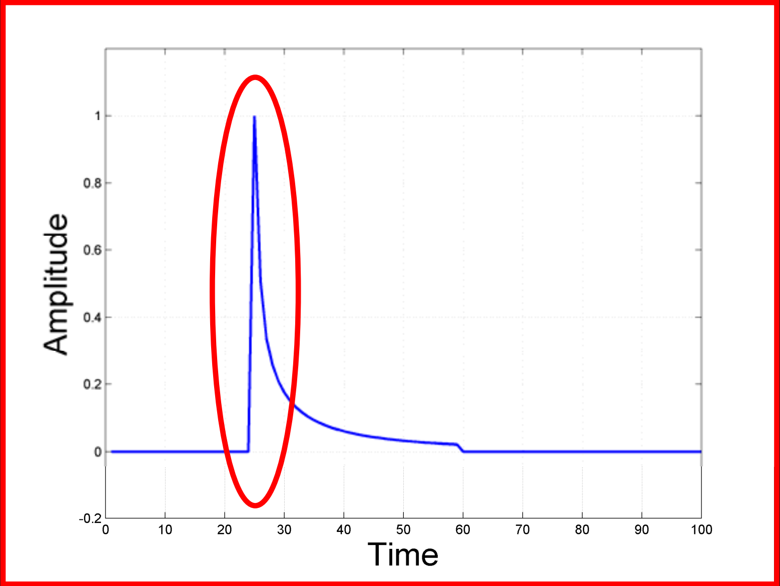


- Various Amplitude Factors
  - S/R Distance
  - Wedge angle
  - Edge length
  - Angular distance to zone boundary
  - Apex included

BTM Diffraction Formulation

$$h(n) = -\frac{\nu}{4\pi}\sum_{i=1}^{4}\int_{z_{n,1}}^{z_{n,2}} \frac{\sin(\nu\varphi_i)}{\cosh[\nu\eta(z) - \cos(\nu\varphi_i)]}\frac{1}{ml}dz$$

$$\varphi_i = \pi \pm \theta_S \pm \theta_R$$



- Various Amplitude Factors
  - S/R Distance
  - Wedge angle
  - Edge length
  - Angular distance to zone boundary
  - Apex included

BTM Diffraction Formulation

- At the zone boundaries cos($\nu\varphi_i$) = 1 for one or two of the four terms
- For the path from *S* to *R* through the apex point cosh($\nu\eta$) = 1
- Combination of the two results in a singularity for the IR onset:

$$\frac{\sin(\nu\varphi_i)}{\cosh[\nu\eta(z)]-\cos(\nu\varphi_i)} \rightarrow \frac{0}{1-1}$$

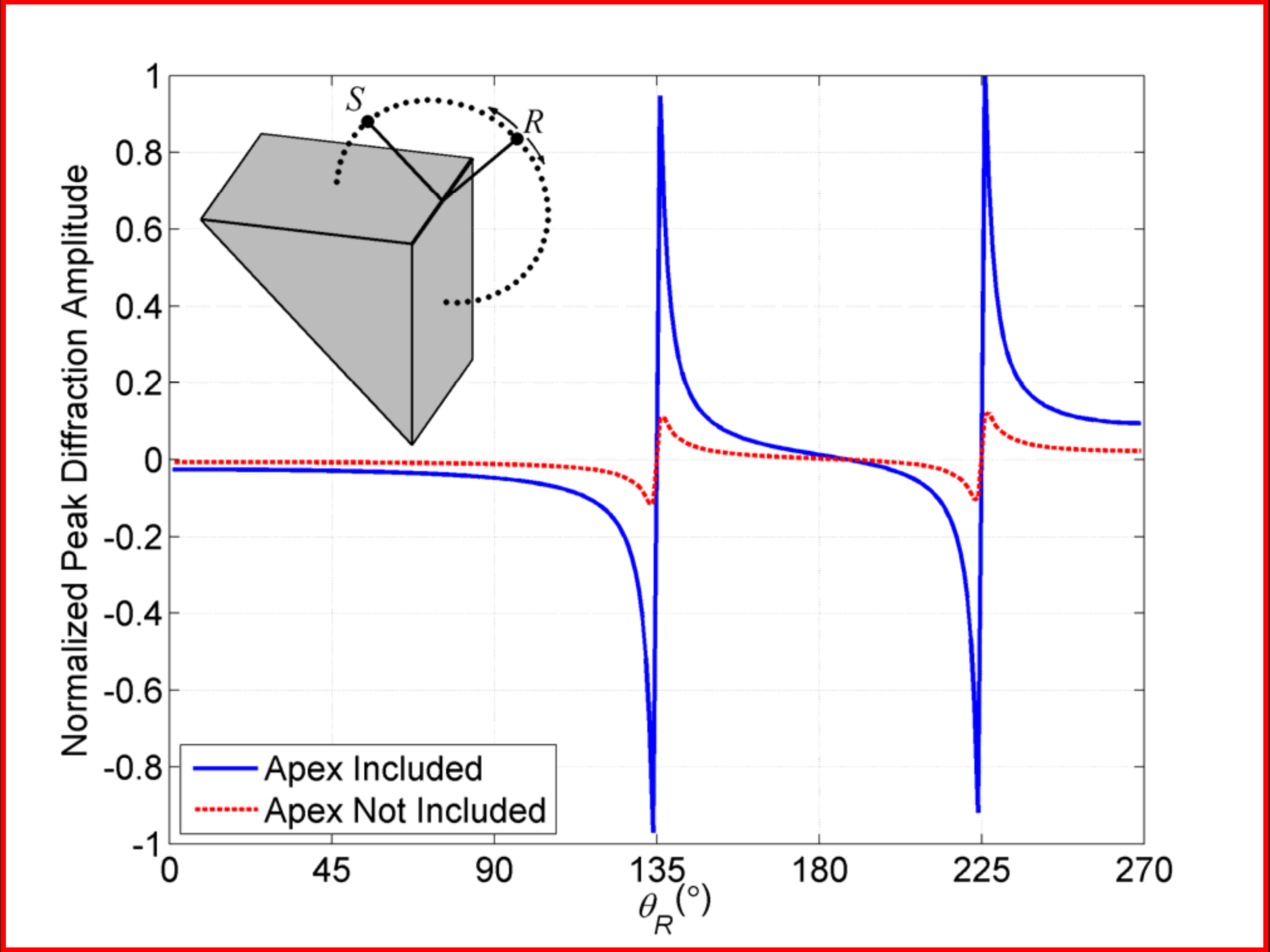
UTD Diffraction

- Zone-boundary singularity also occurs in other diffraction formulations, e.g. UTD:

$$D = C \cdot \sum_{i=1}^{4} \left\{ \boxed{\cot\left(\frac{\nu\varphi_i}{2}\right)} \cdot F_i(\;) \right\}$$

  - D is the diffraction coefficient
  - C is a frequency-dependent constant
  - $F()$ is a ‘transition function’
- No apex-point term since UTD assumes an infinite edge (*i.e.* apex is always included)

Diffraction IR Peak vs. θ_R



Reflection Boundary

Shadow Boundary

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Culling Approach

- Assume perceptually significant diffraction IRs are those with highest amplitude and/or energy
- Find them with limited computation
  - Use proximity to the nearest zone boundary AND apex-point status as first guess
  - Further refine with moving onset threshold, culling IRs with small peaks (relative to the biggest computed so far)
- Fully compute significant diffraction IRs, ignore all others

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Culling Approach

- Proximity to the nearest zone boundary
  - $\min\{\min_i(|\nu\varphi_i|), \min_i(|2\pi - \nu\varphi_i|)\}$
- The apex point is included in the edge
  - $z_1 \cdot z_2 < 0$ ($z = 0$ at the apex point)
- Onset magnitude based on the onset sample of the discrete-time diffraction IR
  - $h(n) = -\frac{\nu}{4\pi}\sum_{i=1}^{4}\int_{z_{n,1}}^{z_{n,2}}\frac{\beta_i}{ml}dz, n = 0$

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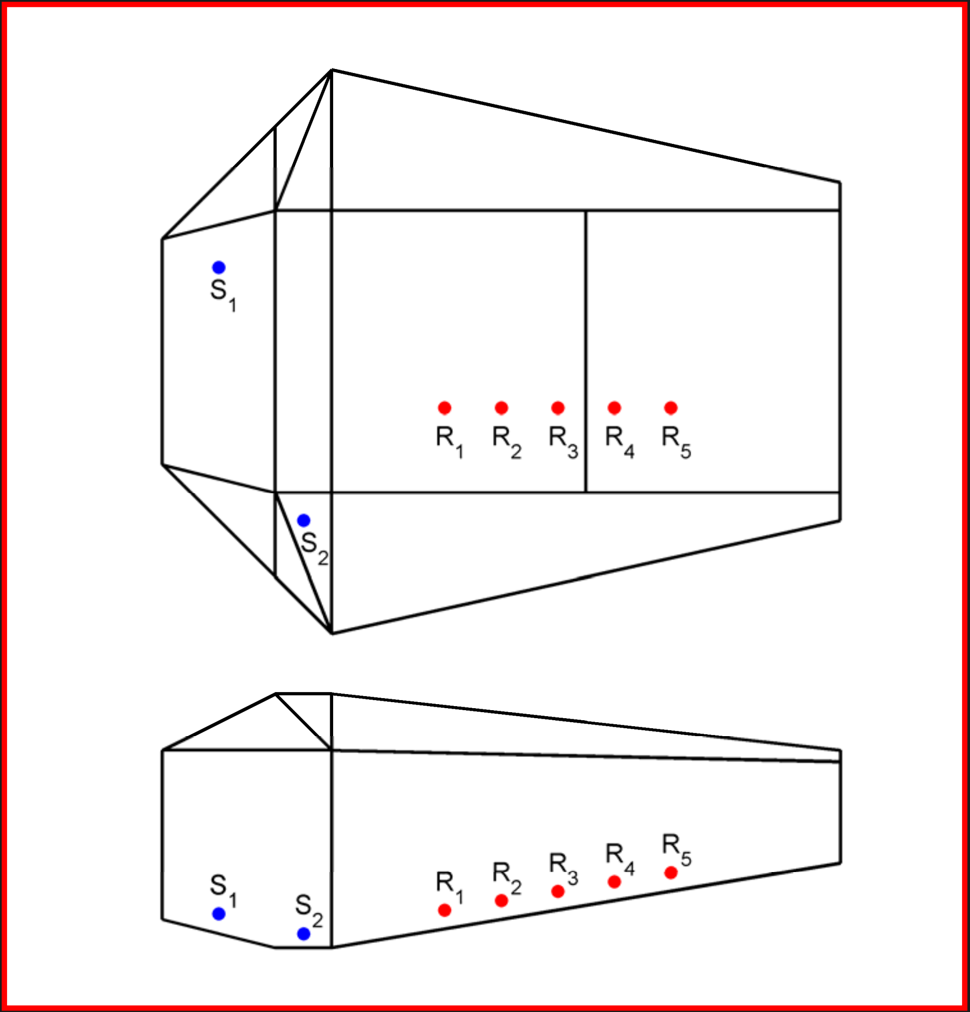
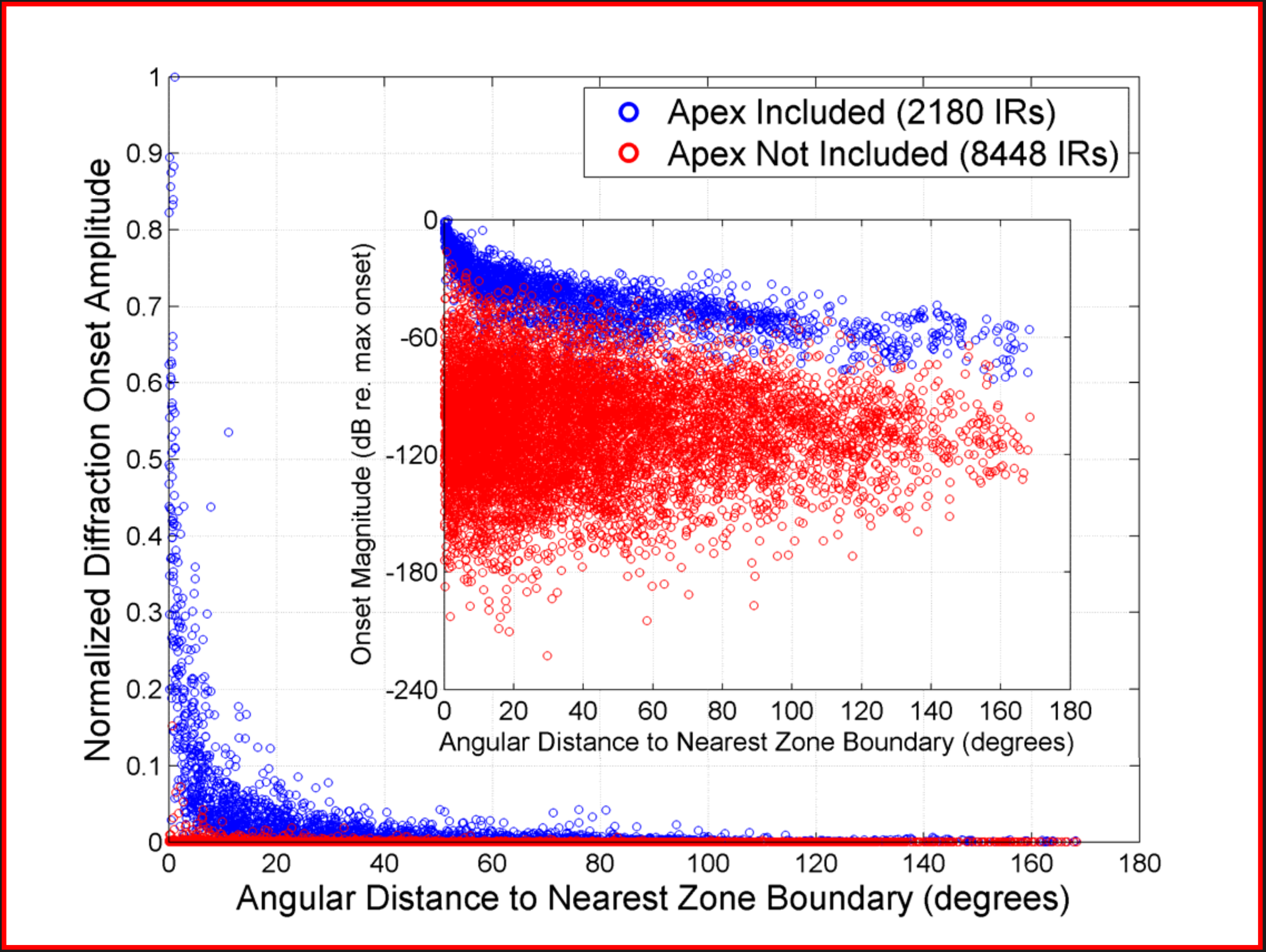
Test Scenario



Model from: F. P. Mechel, "Improved mirror source method in room acoustics," J. Sound. Vib., vol. 256, pp. 873–940, 2002.

- Simple Concert-Hall Model
  - 19 Faces
  - 36 Diffracting Edges
- 2 Source Positions
- 5 Receiver Positions
- 4th-order IRs computed with and w/o culling using the Edge Diffraction Toolbox for Matlab
- Evaluation of processing-time reduction and error due to culling

Diffraction IR Distribution



Data for S1/R3 Impulse Response

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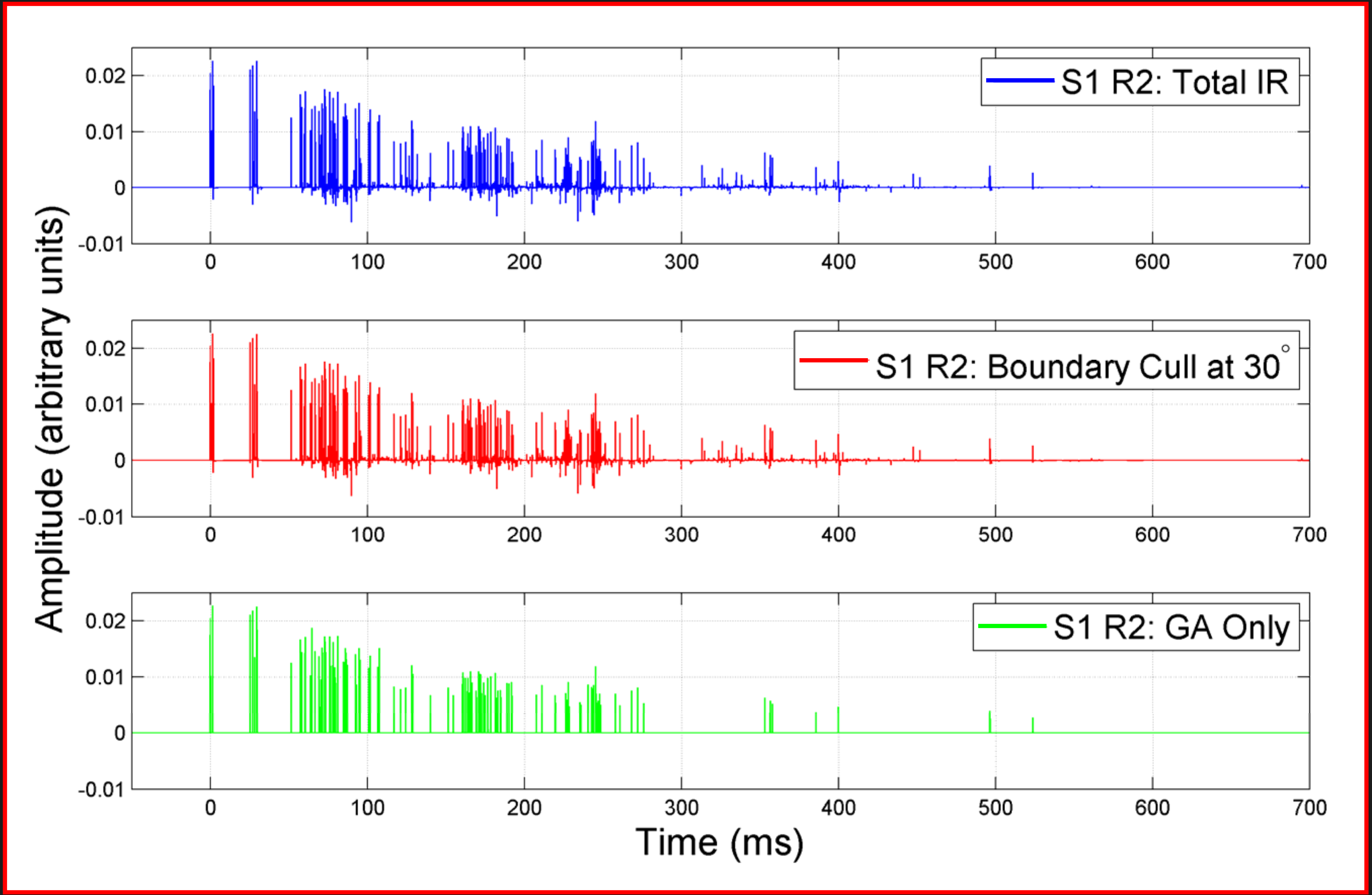
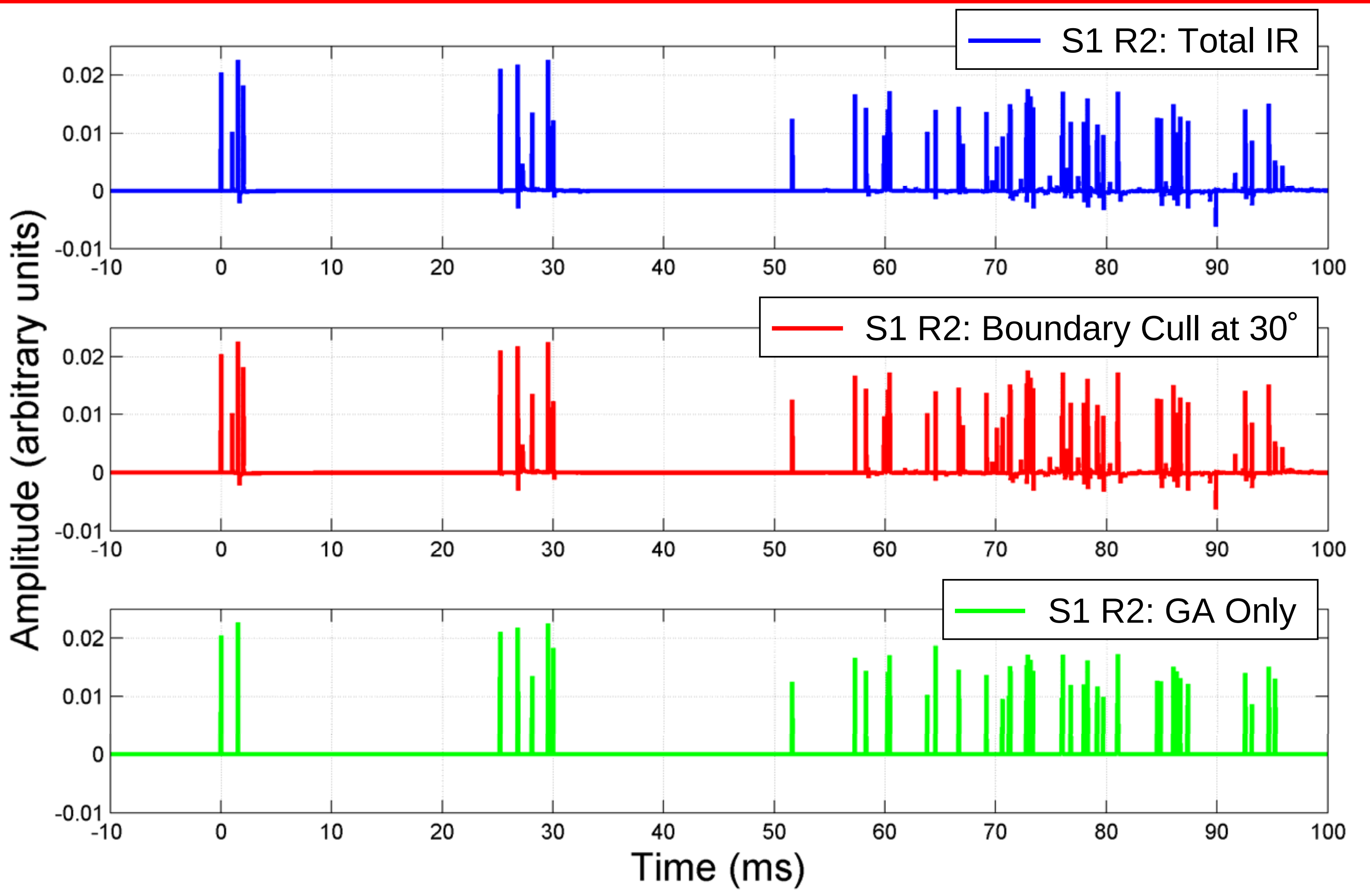
Culling Parameters

- Angular Threshold
  - Receiver within 30° of the nearest zone boundary and apex included
- Magnitude Threshold
  - Diffraction onset within 20, 30, or 40 dB of the largest computed thus far

Time-Domain Comparison



Time-Domain Comparison



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Timing Data

S/R Pair	Total Diff. IRs	30° Only		30° and -40 dB		30° and -30 dB		30° and -20 dB	
		Ret. Diff. IRs	Diff. Proc. Time	Ret. Diff. IRs	Diff. Proc. Time	Ret. Diff IRs	Diff. Proc. Time	Ret. Diff. IRs	Diff. Proc. Time
1/1	11024	974	4.7%	550	3.2%	226	2.0%	87	1.1%
1/2	10994	1009	4.9%	674	3.6%	296	2.1%	111	1.2%
1/3	10628	1092	5.8%	920	4.9%	578	3.5%	238	1.8%
1/4	10184	1177	6.9%	1001	6.1%	661	4.5%	298	2.4%
1/5	10302	1229	7.0%	947	5.7%	528	3.7%	216	1.9%
2/1	11252	847	4.6%	569	3.5%	301	2.3%	133	1.2%
2/2	11041	877	4.7%	694	3.9%	408	2.7%	171	1.5%
2/3	10773	900	4.8%	780	4.3%	524	3.2%	246	2.1%
2/4	10402	926	5.5%	767	4.9%	451	3.3%	180	1.9%
2/5	10595	987	5.6%	786	4.8%	463	3.3%	185	1.8%
Mean:	10720	1002	5.4%	769	4.5%	444	3.1%	187	1.7%

Diffraction-processing time with culling relative to diffraction-processing time without culling

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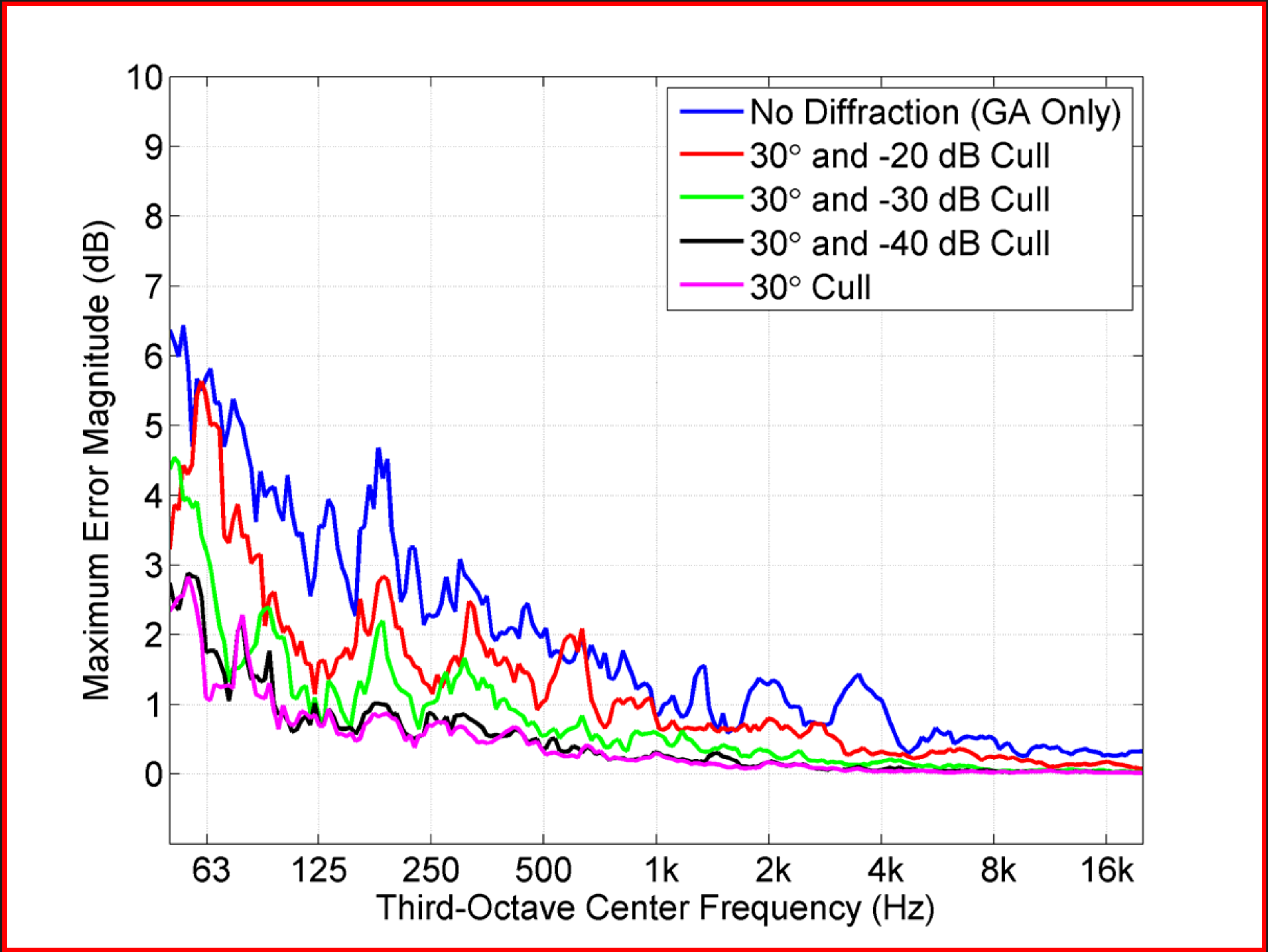
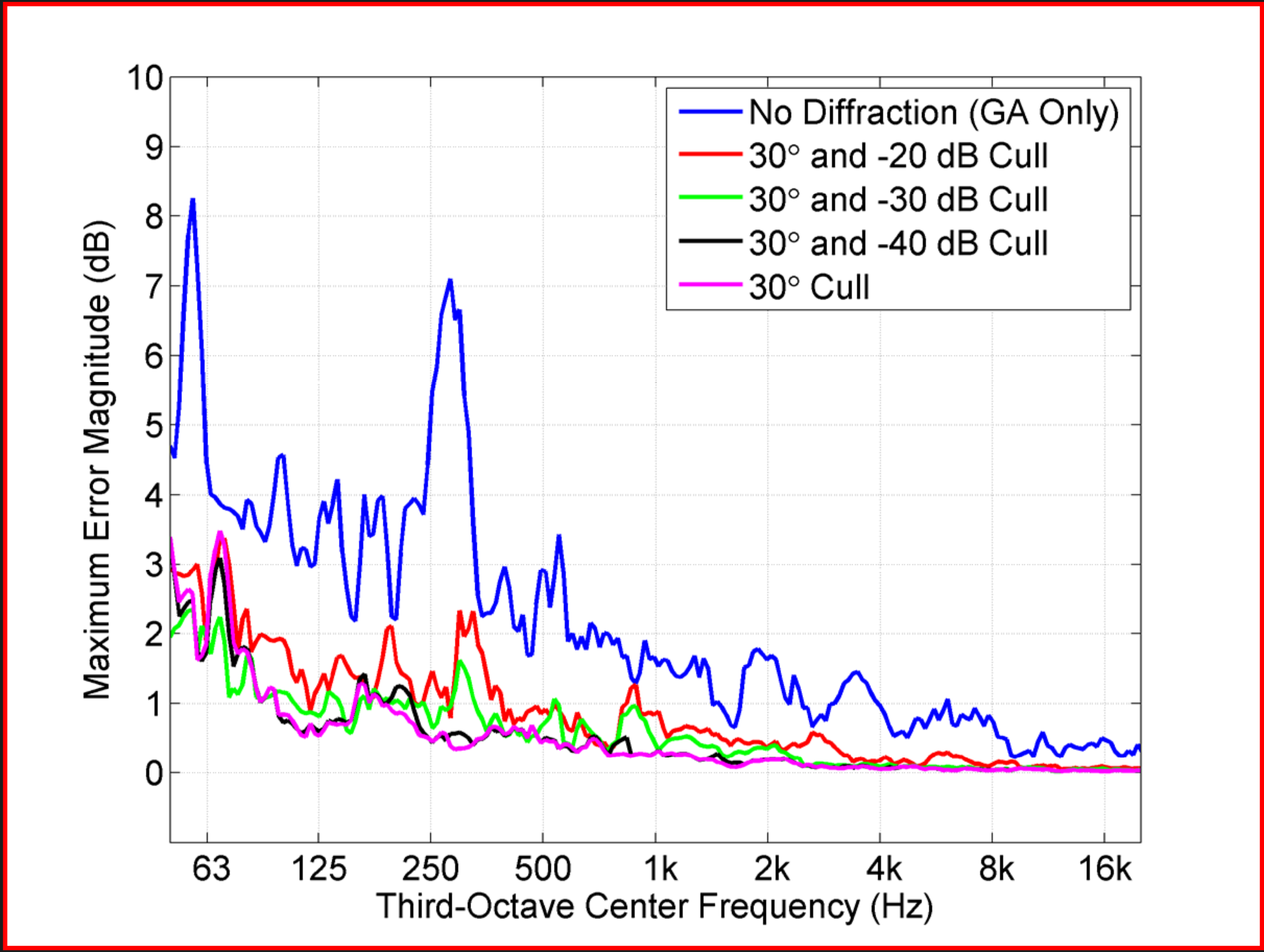
Timing Data: Mean Values

Culling	Num. Diff. IRs	Diff. Proc. Time
None	10720	100%
30° Only	1002	5.4%
30° and -40 dB	769	4.5%
30° and -30 dB	444	3.1%
30° and -20 dB	187	1.7%

Maximum Spectral Error: Full IR



Maximum Spectral Error: First 80 ms



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Conclusions

- Significant diffraction components can be identified by considering S/R geometry with respect to
  - Proximity to zone boundaries
  - The least time path through the edge (i.e. the inclusion of the apex point)
- Culling insignificant components can reduce computation time with limited spectral error in the overall response

Future Work

- Further tests with more complex models
- Listening tests for perceptual evaluation of culling
- Culling with a priority queue rather than a threshold, with priority based on:
  - Zone-boundary proximity and apex-point status
  - Arrival time (early = high priority, late = low priority)
  - Arrival direction (front = high priority, rear = low priority)
- Analysis for interactive scenarios
  - Receiver moving across a zone boundary

The End

Questions?

Thank you for your attention.

Related Work

- Edge diffraction in room acoustics simulations
  - Ouis, “Scattering by a barrier in a room”
  - Torres *et al*., “Computation of edge diffraction for more accurate room acoustics auralization”
  - Pulkki and Lokki, “Visualization of edge diffraction”
  - Løvstad and Svensson, “Diffracted sound field from an orchestra pit”
- Speed and efficiency of diffraction calculations
  - Tsingos and Gascuel, “Fast rendering of sound occlusion and diffraction effects for virtual acoustic environments”
  - Lokki *et al*., “An efficient auralization of edge diffraction”
  - deRycker, “Theoretical and numerical study of sound diffraction: Application to room acoustics auralization”
  - Calamia and Svensson, “Fast time-domain edge-diffraction calculations for interactive acoustic simulations”
  - Kapralos *et al*., “Acoustical diffraction modeling for interactive virtual environments”
- Acoustic modeling with diffraction culling
  - Tsingos *et al*., “Modeling acoustics in virtual environments using the Uniform Theory of Diffraction”
  - Antonacci *et al*., “Fast modelling of acoustic reflections and diffraction in complex environments using visibility diagrams”

Related Work

- Edge diffraction in room acoustics simulations
  - Ouis, *Applied Acoustics* 1999
  - Torres *et al*., *JASA* 2001
  - Pulkki and Lokki, *ARLO* 2003
  - Løvstad and Svensson, *Acoust. Sci. Tech* 2005
- Speed and efficiency of diffraction calculations
  - Tsingos and Gascuel, *Proc. AES* 1998
  - Lokki *et al*., *Proc. AES* 2002
  - deRycker, *École Polytechnique* 2002
  - Calamia and Svensson, *EURASIP JASP* 2007
  - Kapralos *et al*., *GRAPP* 2007
- Acoustic modeling with diffraction culling
  - Tsingos *et al*., *Proc. SIGGRAPH* 2001
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