THE ACOUSTIC SCIENCE OF

# OPERA HOUSES

## A look at why traditional opera houses work so well by Nicholas Edwards

ROYAL OPERA HOUSE MUSCAT OMAN

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# Why do traditional opera houses work so well for opera?

In most computer models of room acoustics sound is simulated as if reflected and absorbed like light. This so-called geometric acoustics assumption is adopted because of the relative ease of computation. The method provides good results where the room surfaces are large – such as the side walls of a concert hall. However, the assumption is not valid for small surfaces such as the balcony fronts, columns and box dividers that comprise most of the surfaces in an opera house.

If the traditional opera house is modelled using geometric acoustics, serious focussing of the early sound is indicated – but this does not occur in reality. The magic of opera house acoustics cannot be simulated correctly using conventional geometric acoustics computation.

One of the acoustical attributes ignored by the geometric model is edge-diffraction of sound. Our research has shown that edge-diffraction must be modelled when studying the acoustics of the traditional opera house.

In the 1920's modelling techniques for room acoustics included the analogue Methode Schlieren that Sabine used to study the propagation of wave fronts. This technique, in a model of a sectional slice of a room, employs a spark source, polarized light and (still) photography to show the propagation of actual wavefronts in air, including the edge-diffracted sound.

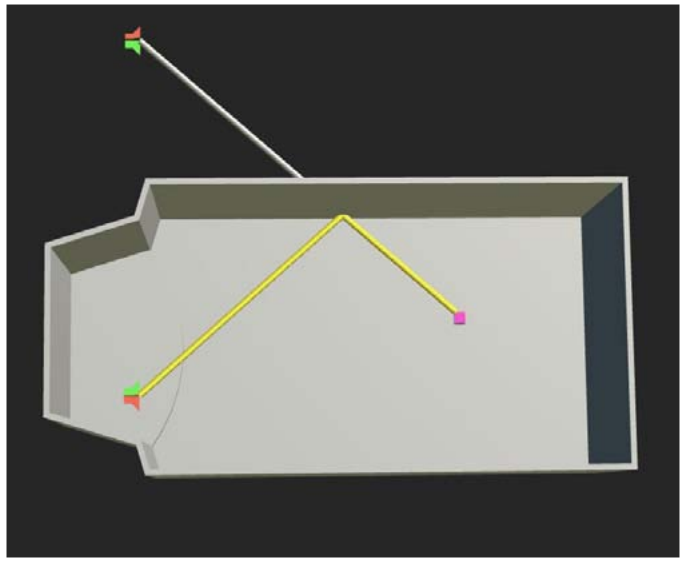
We have replicated Sabine's work using a digital wave-equation method, and this allows us to view wavefront propagation as a movie. As with Sabine's work, this method allows us to analyse a two-dimensional slice of the building.

Idibri's current research in room acoustics simulation includes full 3D methods of modelling edge diffraction, and we have demonstrated prototypes of these methods using a model of a traditional opera house.

While geometric acoustics can be used to predict both early and late sound in shoebox-shaped concert halls, a different approach that includes edge-diffraction is essential for understanding the magic of opera house acoustics.

## Geometric Acoustics

The same way as you see an image of yourself in a mirror, with geometric acoustics we compute the locations of all the images of the sound source in all the room surfaces. Some images will not be "visible" to the listener within the extents of the reflecting surface, this has to be computed for each source-receiver pair. The first-order reflection from the side wall of a concert hall looks like this:



*Interact with this image: https://p3d.in/ZNTAc*



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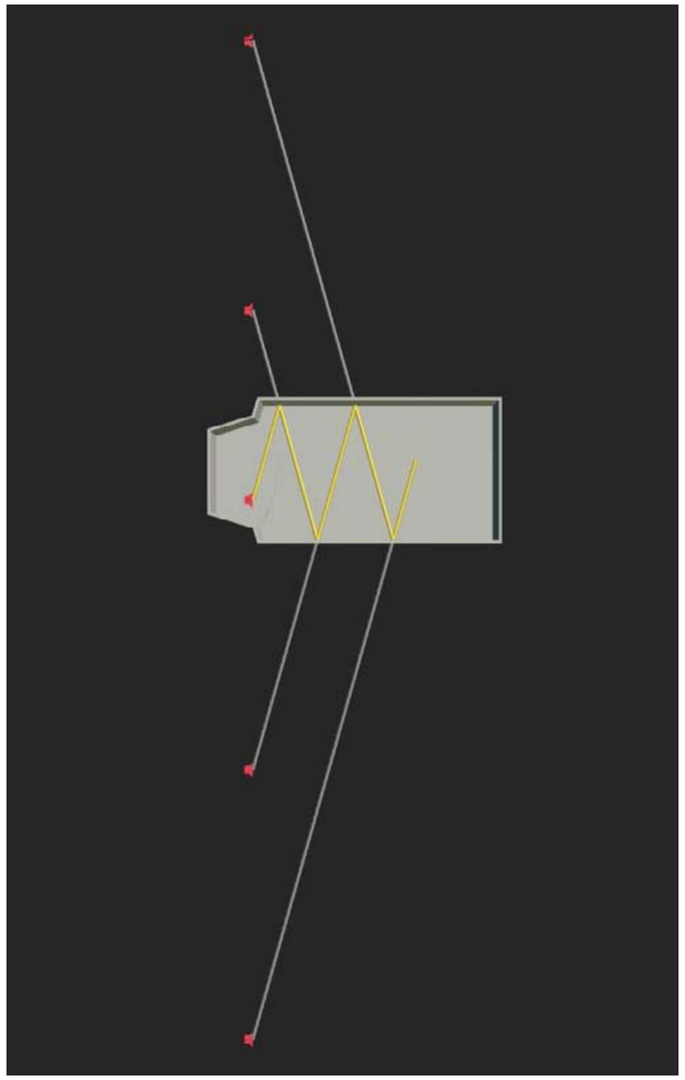
Geometric acoustics can be used to model multiple inter-reflections between room surfaces such as between the side walls of a typical concert hall:



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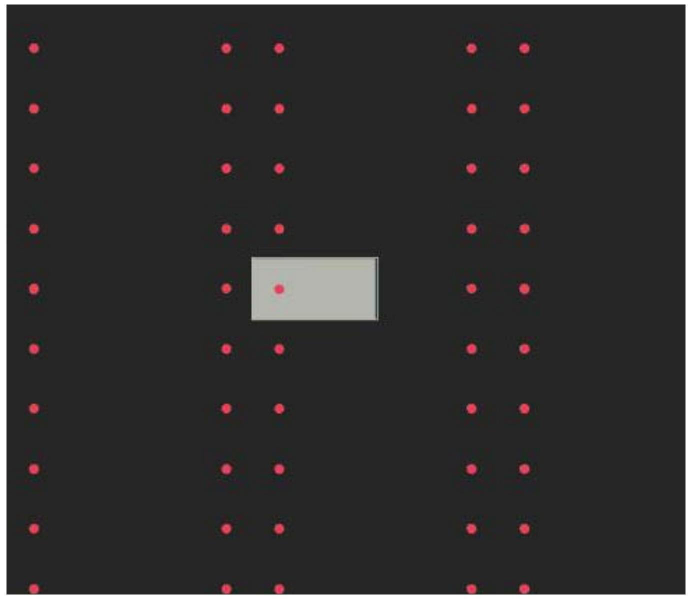
Geometric acoustics modelling can be used to predict not only the early sound reflections but also the late ones that in physical reality are "diffuse" (i.e. arriving from all directions). Both Kuttruff and Cremer have used geometric acoustics models to demonstrate that "the basis for a diffuse sound field is established with specular reflections."[1]

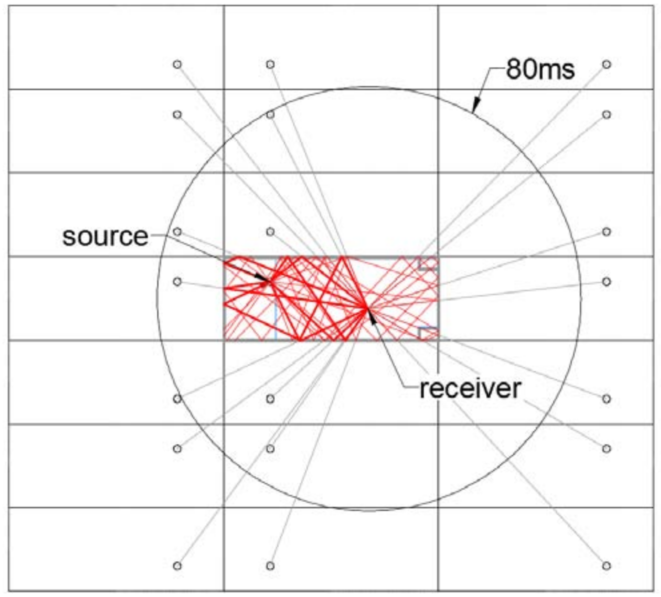
[1]Room Acoustics, Fifth Edition, Heinrich Kuttruff, page 107; Principles and Applications of Room Acoustics, Cremer Chapter 1.1 Sound Waves and Sound Rays, Cremer page 33

Each sound ray has its own "image source" location, and through modelling these locations we can more readily understand the directional qualities of the sound field:



*Interact with this image: https://p3d.in/eYFUQ*

Locating the image sources allows the reflections paths within the room to be determined




The objective acoustical characteristics of a concert hall (such as lateral, early, mid and late sound energy levels) can be modelled adequately with geometric acoustics studies because the side walls generally form large unbroken surfaces.

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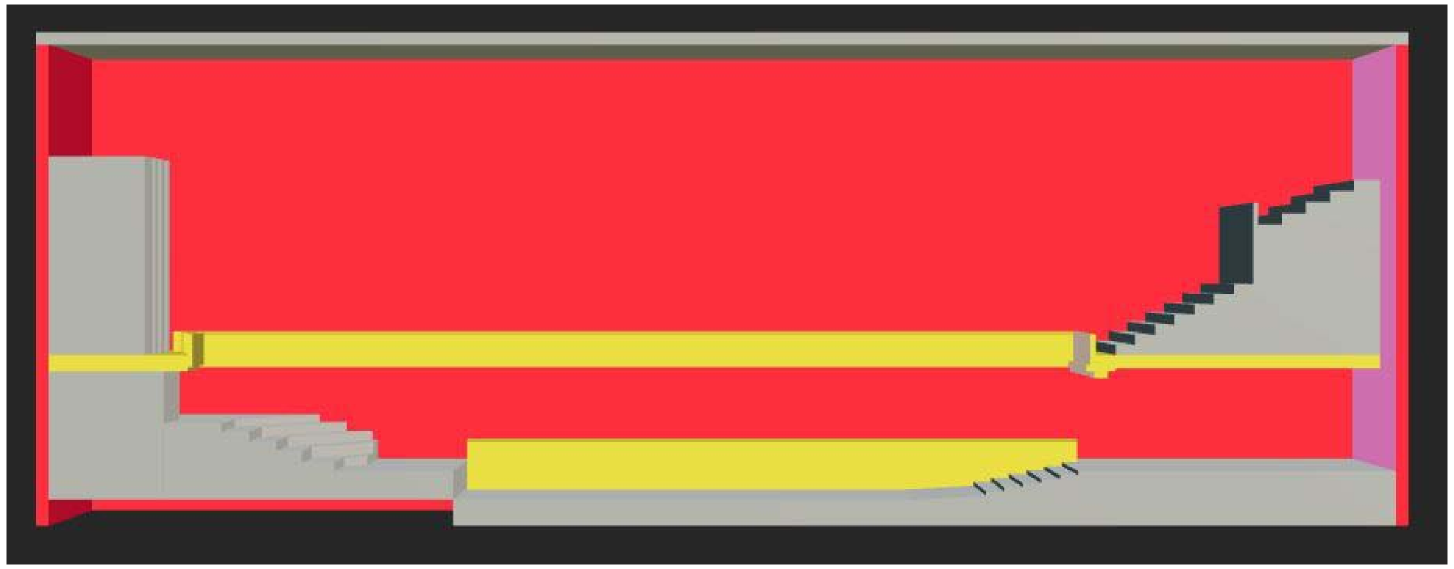
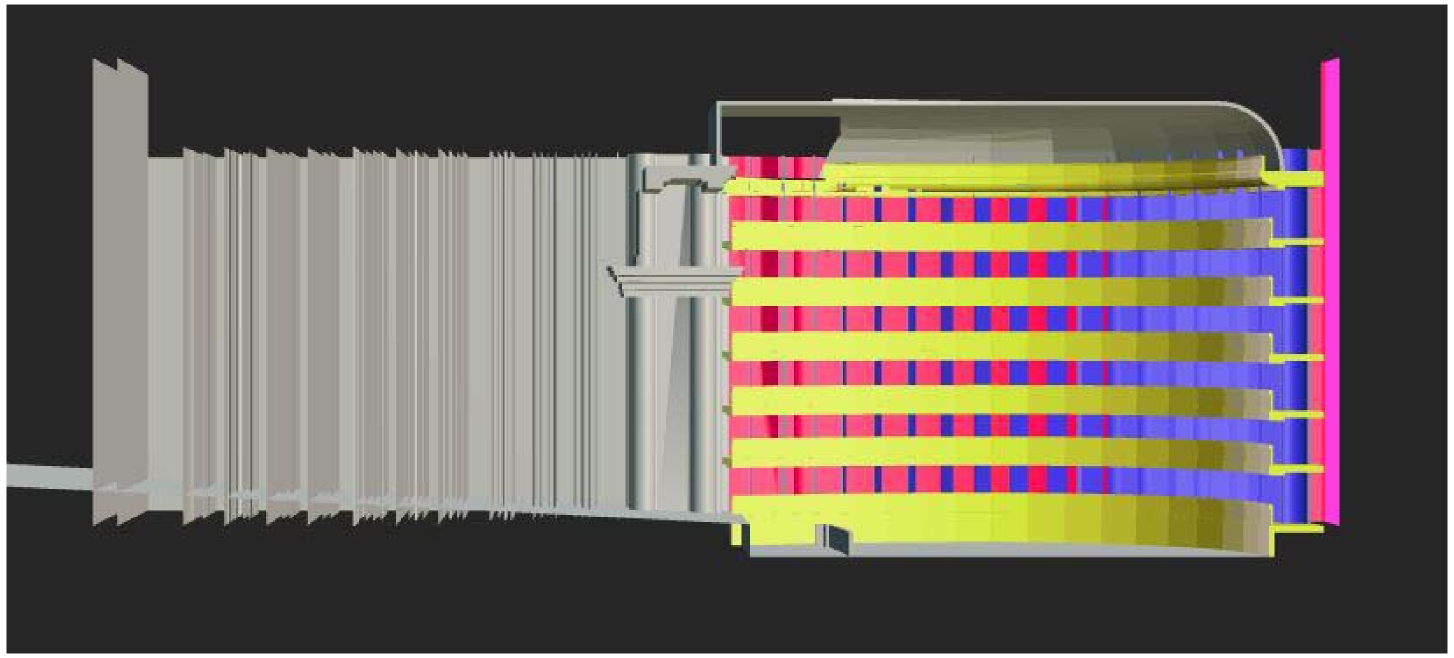
## The Geometric Model Fails in Complex Geometry

The geometric acoustics model does not provide a vaild model for the study of the traditional European opera houses. The captures below are from the IMAGES computer program we conceived in the 1980's to study acoustics. Opera houses have a more complex geometry and to study them we are developing IMAGES2 which builds on GPU processing and multithreading as we work towards real-time acoustics modeling.



The objective acoustical characteristics of a concert hall (such as lateral, early, mid and late sound energy levels) can be modelled adequately with geometric acoustics studies because the side walls generally form large unbroken surfaces. , shown in red in the model: *Interact with this image: https://p3d.in/fD7Dj*



In contrast, the geometric acoustics model of the opera house – in this case La Scala - shows that the side walls (red) are largely screened from sound by the multiple balcony tiers, box dividers, and columns that form relatively small surfaces compared to the sound wavelengths of interest: *Interact with this image: https://p3d.in/MnzQf*



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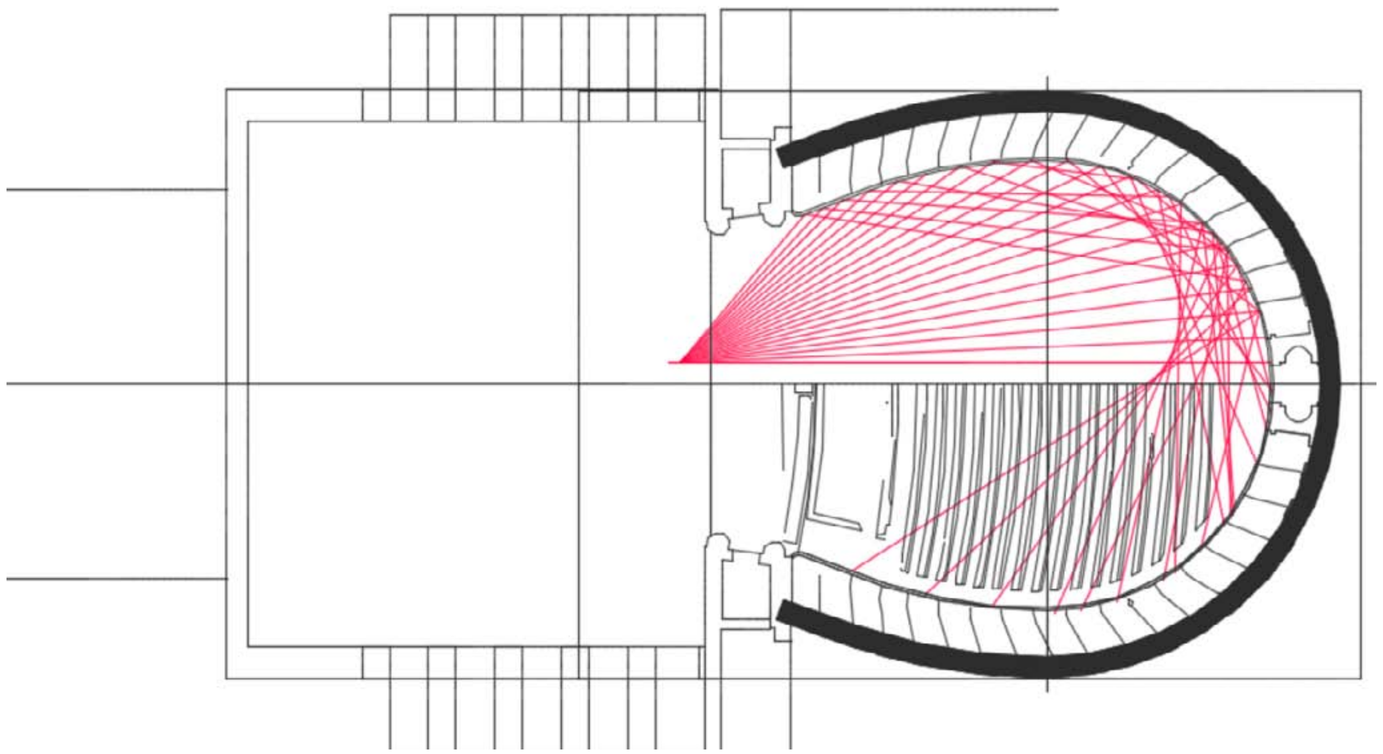
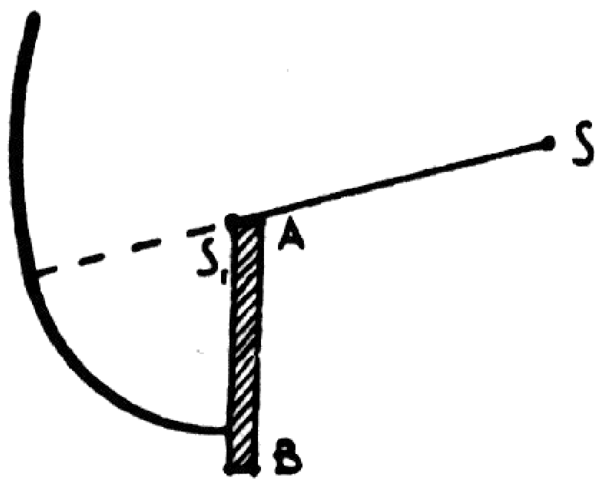


*Geometric acoustics study of an opera house falsely showing sound focusing.*

A geometric acoustics model may apparently show that the traditional European opera house room shape cannot work, either because of focussing of the early sound or because of a lack of late reflected sound.

Clearly, these rooms do work acoustically, and it is the geometrical model that is not valid for these rooms because geometric acoustics does not account for edge diffraction from the balcony fronts and box dividers.




*Diffracted sound wave propagating from an edge (from Bagenal 3, p9)*

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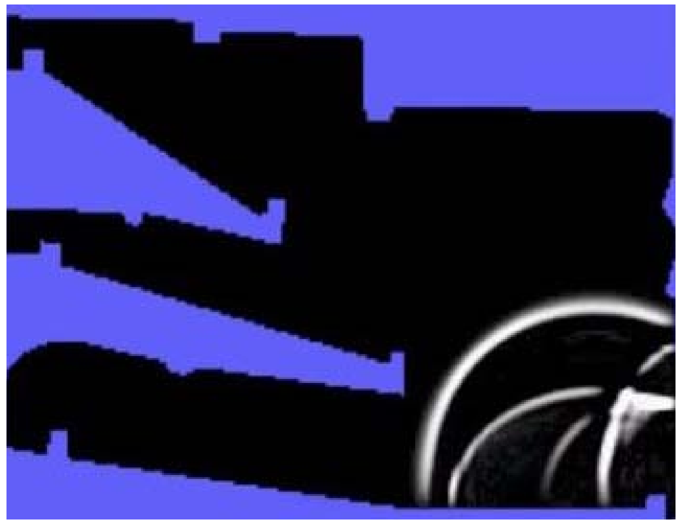
## The phenomenon of edge-diffraction has been known about almost as long as all other aspect of acoustics.

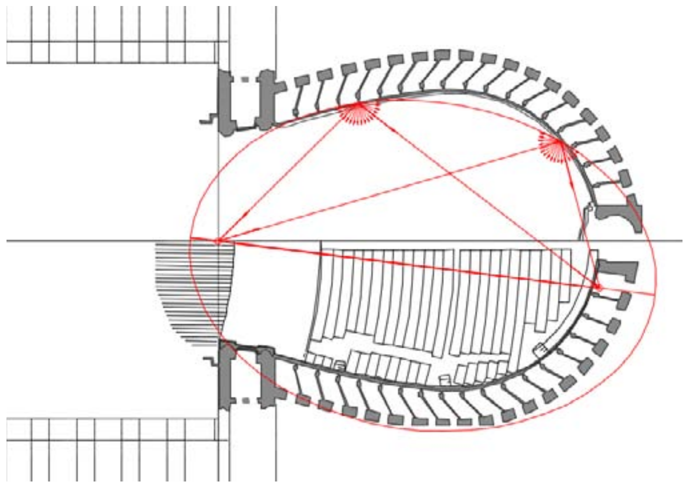
In the 1920's modelling techniques for room acoustics included the analogue Methode Schlieren that Sabine used to study the propagation of wave fronts. This technique employs a spark source, polarized light and (still) photography to show the propagation of actual wavefronts in air, including the edge-diffracted sound in a model of a sectional slice of a room.

*From Collected Papers on Acoustics, Sabine, p191.*

We have replicated Sabine's work using a digital wave-equation method, and this allows us to view wavefront propagation as a movie. As with Sabine's work, this method allows us to analyse a two-dimensional slice of the building.

*View the video: https://www.youtube.com/watch?v=iXYz4lgog1U*





Ellipse representing the locus of an equal-delay-time contour. The foci of the ellipse are located at the source and the receiver. In 3D, this becomes an ellipsoid.

However, this "universal" view of the acoustic process does not represent when the diffracted sound arrives at a particular listener. If we consider sound propagation between a source-receiver pair in a two dimensional representation, the locus would be an ellipse.

The envelope of an equal-delay-time solid will thus be an ellipsoid rather than a sphere.



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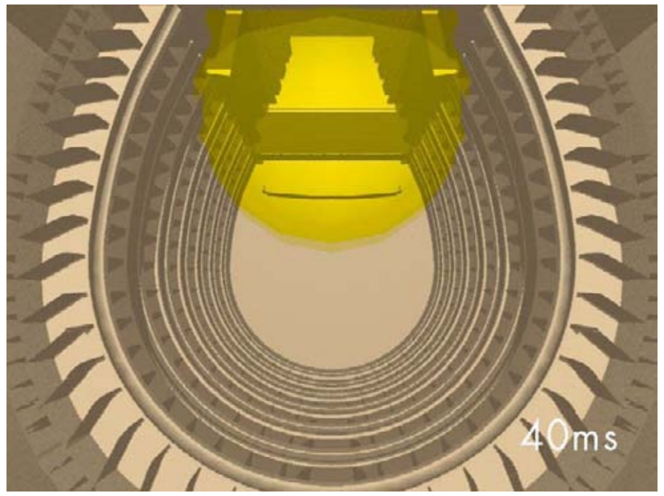
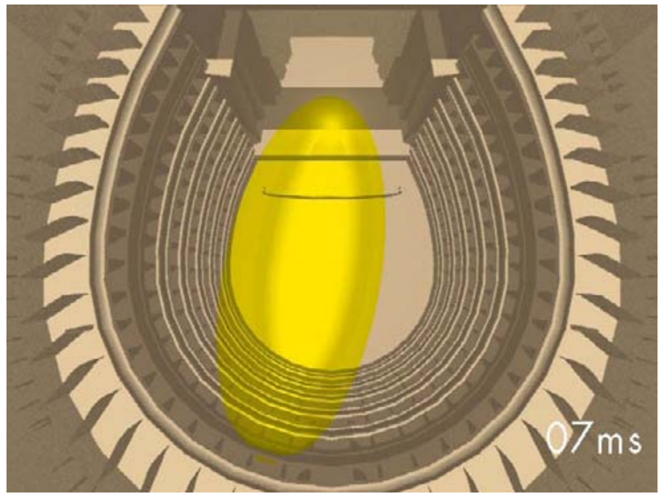
Idibri's current research in room acoustics simulation includes full 3D methods of modelling edge diffraction, and we have demonstrated prototypes of these methods using a model of a traditional opera house.

When a wave front impinges on the balcony fronts, each point on each balcony edge becomes a secondary sound source. So one of our prime interests is to track these locations in 3d space. The wavefront is spherical, and where the spherical wavefront intersects the balcony fronts, the diffracted sound will be generated.

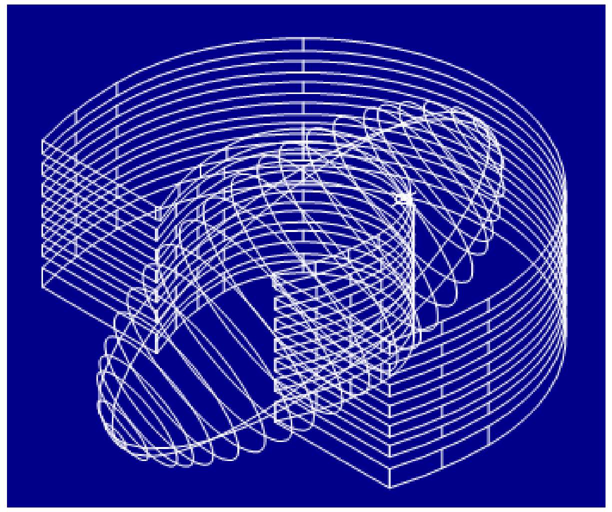



The direct sound propagating from the source, represented by a solid sphere. Diffracted sound will be generated where the surface of the sphere intersects the balcony fronts.

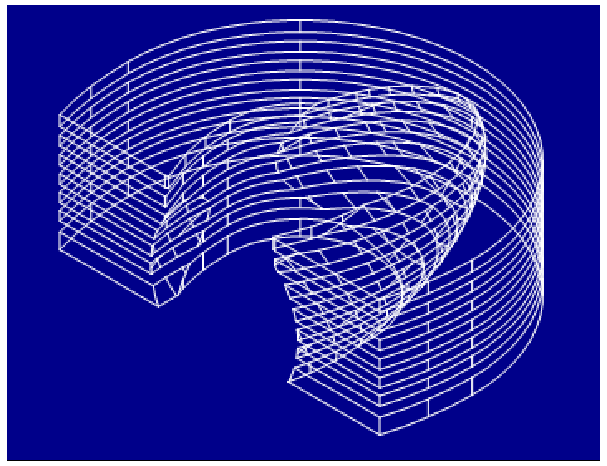



*The ellipsoids expand from the source-receiver line, with increasing detla T. Watch the video.*

By studying where this ellipsoidal volume intersects with the balcony fronts, we can locate where, at any given time, the edge-diffracted sound is coming from.



*Intersection of ellipsoid at balcony fronts identifies the source locations of diffracted sound*



*The solids subtracted to determine the locations of the Intersection of ellipsoid at balcony fronts*

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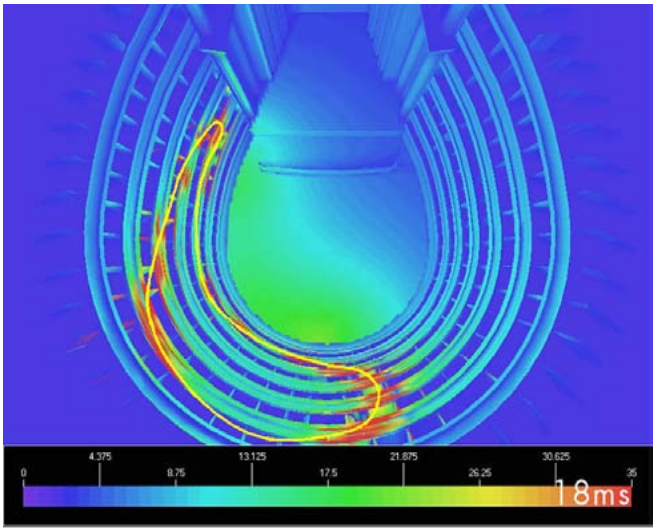


*The acoustic model is illuminated by light sources located at the intersection points (sketched here with a heavy line). This frame shows location of diffracted sound sources with 18ms delay. Watch the video.*

By illuminating a rendered model using light sources located at these intersections, we can produce a visualization of edge-diffracted sources as brighter areas in a rendering (Figure 12). By repeating this process with a constantly-enlarging ellipsoid and compiling the renderings into a moving image, we can visualize the acoustical process.

We have applied this model to La Scala, and a produced an animation showing how the balcony front edges contribute to the sound that is heard over the first 40ms.

We have developed an acoustics model based on edge diffraction. For the typical source-receiver pair shown here in a virtual La Scala opera house, the sound diffracted via the balcony fronts arrives at the listener over a 40ms period.

Our model is just a beginning step in the process of understanding the acoustics of these specialized building types. We hope that the development of this new model will allow us to correlate the acoustical parameters of great opera house acoustics with the architectural features and basic shaping of these rooms much like the geometric models have helped gain an understanding of concert hall acoustics.

## REFERENCES

1. Edwards, N, Considering concert acoustics and the shape of rooms, Architectural Record, Aug 1984, pp133-137.

2. Cremer, L, and Müller, H, Principles and Applications of Room Acoustics, Volume 2, Applied Science Publishers Ltd, 1982 ch IV.2 pp22-26

3. Bagenal, H and Wood, A, Planning for Good Acoustics, Methuen & Co Ltd, 1931