For
ιcoustic Simulation

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While these processes do give some insight into the acoustical behavior of the real hall, they are laborious, costly, and time consuming endeavors. It is more effective to use computer simulations combined with computer graphics visualization to test and evaluate the acoustical behavior in performance halls.

There are numerous advantages inherent in using computer simulation and visualization over the traditional approach of using scale modeling for acoustical analysis. With the increasing use of computers in the modeling and design of buildings, the geometric models needed to conduct the acoustical analysis will already exist, making additional simulations using the same database very convenient. Furthermore, the same computing environment used to design geometric spaces can be used to run acoustical analyses. Computer simulation of acoustical behavior would also be more flexible than physical scale modeling, since it would allow for changes to be easily made and then analyzed in a design. Lastly, computer simulation and visualization would make the acoustical nature of a space more easily and more thoroughly understood since the visualization allows for a global evaluation of many unique locations simultaneously through time.

The primary objective of this paper is to investigate techniques of displaying multi-dimensional data which are both comprehendible and useful to the user. The techniques will be specifically used to visualize acoustical measurements derived from the simulation data. Three model halls will be evaluated and compared.

Geometric Approximation of Sound Propagation

The relationship between Computer Graphics and acoustical design is more than the use of computers to model the physical environments and to display the results of the acoustic simulation. Sound propagation can be simulated with many techniques that are similar to those used to model illumination. These methods, in particular geometric ray tracing and reflection modeling, have been highly refined. By modifying these methods to take into account a few basic differences between light and sound, they can be well suited to simplify the problem. Wallace Sabine [17], considered the pioneer of modern acoustics, used ray theory around the turn of the 20th century in the formulation of his well known equation for the calculation of room reverberation time. In the late 1950's, Allred and Newhouse [1] first applied Monte Carlo Methods to calculate the mean-free paths of spaces by tracing rays on a computer. About a decade later, Krokstad, Strøm and Sørsdal [13] made the first attempt to use a computer to trace rays based on a simple geometric model to get an idea of the acoustical response of a hypothetical room. This was followed by Schroeder's digital simulation of simple reverberant spaces [19]. Haviland and Thanedar then extended earlier work with Monte Carlo methods in an attempt to obtain time histories of the pressure at a given point in a field [8]. Wayman and Vanyo used these and similar techniques applied to more complex environments [22]. Walsh [21] conducted similar research in the development of the Godot System.

Others have attempted to use another method similar to ray casting known as the image method to study the acoustical response of imaginary rooms. Interesting work has been done in this field, by Borish [3] and Edwards [6]. More recently, Sekiguchi, Kimura, Sugiyama have also been working on extending ray methods, using what is known as finite ray integration [18].

The ray method assumes that wave surfaces can be treated as rays normal to these surfaces and traveling in the direction of propagation in the medium. The behavior attributed to sound rays is similar to that of light rays in geometric optics, except for a few crucial differences. These differences stem from the sound ray's slower propagation speed, longer wavelength and higher rate of energy transfer to the surrounding environment. The most obvious distinction is the comparatively limited propagation speed of sound waves. Light propagates away from a source so quickly that the eye is unable to sense its temporal nature. The ear, on the other hand, is able to detect minute variations in sound pressure due to the longer time delays in a sound wave's propagation. Humans have the ability to perceive these variations even within small time scales of observation, on the order of 50 milliseconds.

Another important difference of sound waves when compared to those of light results from the relatively long wavelengths of sound. When the wavelengths of the sound rays are comparable to the boundary and irregularity dimensions of an environment, the behavior of sound rays is not easily compared to simple reflections or refractions in geometric optics. While the acoustical data generated for the visualization did not include the effects of diffraction, the simulation process could be modified to do so using a geometric theory of diffraction [11].

The last major difference between light and sound rays results from the tendency of sound to easily transfer its energy to matter with which it interacts. Little energy is lost by a light ray when it passes through unobstructed air. The theoretical sound ray on the other hand will see considerable attenuation, especially at high frequencies, since a ray's energy vibrates air molecules which in turn dissipates energy in the form of thermal exchange. A surface's acoustical reflectivity is also strongly affected by variations in air pressure caused by rays incident on its surface. For this reason the sound absorption characteristics of a surface depend on the the ray's angle of incidence in ways which are unlike those of light. All of these characteristics combine to make the behavior of sound more difficult to predict and comprehend than the behavior of light, and new visualization methods are required to represent its appropriate measurements.

The authors have used a modified specular and diffuse ray tracing algorithm combined with Monte Carlo techniques to simulate the time varying spatial distribution of sound. Unfortunately, within the space limitations of this paper, it is not possible to provide the details of this simulation procedure. This material is currently being submitted for publication. The interested reader is referred to Stettner's thesis [20] and to the general acoustic's literature [5] and [12].

Characterization of Sound

Reverberation Time

For a long time, reverberation time and other early sound energy decay measurements were considered the primary objective parameters in the acoustical design of sound spaces.

Trying to characterize a hall's sound by using simple criteria, however, can be problematic. Recently, the inadequacy of using the reverberation quantity alone to predict the acoustics of a space has become widely realized [4] [10]. In response, a wide variety of relatively new acoustical measurements have been introduced. Three types of acoustical measurement now used characterize the clarity and definition, the spatial impression, and the overall strength of sound.

Clarity and Definition

The importance of early reflected sound energy to the intelligibility of speech sounds and to the clarity and definition of musical sounds is widely recognized [4]. If there is too much early reflected sound energy, the sounds of either music or speech will blend and lack definition. On the other hand if there is too little, the sound will be overwhelmed by the latter sound and clarity will be lost.

One of the most popular measurements of early to late sound energy was proposed by Reichhardt. [16] Reichhart's measure of clarity incorporated an early energy time of 80 msec, which he believed to be appropriate for music. He defined this measurement, C_{80}, as the log of the early arriving sound (from 0 msec to 80 msec after the direct sound) divided by the late sound energy arriving 80 msec and after the direct sound.

$$C_{80} = 10 \log \left(\int_0^{0.08} p^2(t)dt \Big/ \int_{0.08}^{\infty} p^2(t)dt \right)$$

where p2(t) represents the medial value of sound pressure varying through time. C_{80} is expressed in decibels (dBs).

Spatial Impression

The measurement of spatial impression quantifies to what extent the listener senses being immersed in the sound as opposed to just receiving it and relates to the listener's sense of envelopment in the sound field and perceived broadening of the sound source. The subjective degree of spatial impression has been found to correlate with the ratio of lateral to frontal energy at a listener's position [15]. One useful measurement, found to be linear with the degree of spatial impression, is the lateral energy fraction, Lf, defined as the ratio of early lateral reflected energy (over the first 80msec) to the total early energy including the direct energy [2]. Expressed in the following equation:

$$L_f = \left(\sum_{t=5\,ms}^{80\,ms} r\cos\phi \Big/ \sum_{t=0\,ms}^{80\,ms} r \right)$$

where ϕ is the angle between the reflection path and the axis through the listener's ears, r is the reflection energy, which is dependent on time, and t = 0 milliseconds is the time of the arrival of the direct sound energy. The numerator in the equation of lateral fraction includes only reflected energy and the denominator includes both the direct and reflected sound energy. The closer the incident energy direction approaches this normal direction, the greater its contribution to the lateral fraction, and therefore toward a sense of spatial impression. (Figure 1)

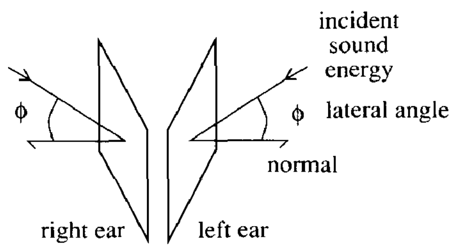

Figure 1: Definition of Lateralization

Overall Sound Strength

A third type of measurement characterizes the overall strength of sound. Unfortunately, the sensation of the strength of sound is based on a number of psychoacoustic factors. Not only is the perception of loudness not linear with the amount of sound energy received, the temporal nature of incident sound also affects its perception. However, as a simple approximation, a measurement of the overall energy at positions through time is useful in detecting possible sound strength problems.

Areas where there are anomalies in sound strength can be caused by a number of different situations. In a hall there may be positions in which the sound field is significantly weaker, either at a particular time or on average, than the desired normal level. These deficient spots can result from an inability to receive direct or reflected sound energy due to room geometry, or from surface or air absorption of sound energy during propagation. Within the normal design process these problems can be very difficult to predict on a global level (at all points in an environment).

In contrast to energy deficient areas, are those room positions of abnormally high energy on average or at particular instances of time. These acoustic phenomena result primarily from room geometry which directs energy toward specific areas. Most often these concentrations can be explained as the result of specular surface reflection. Some extreme examples of specular geometric concentration are whispering galleries, and dome focusing. In both of these situations, the walls in the rooms are shaped in manners which produce extremely consistent reflection from many positions all directed toward a singular area. Geometric situations in which specular focusing occurs can be very difficult to predict using contemporary design techniques, especially if the complexity of a room's shape is great.

A third defect which relates to the measurement of the overall strength of sound through time is acoustic echo. Echos are simply reflections that come after the direct sound and are strong enough to be heard as distinct. A common example of distant echo in a hall is the reflected sound heard by musicians on stage, coming from a highly specularly reflective back wall.

Visualization Techniques

The evaluation of the acoustical properties of a concert hall or auditorium is a difficult problem. But perhaps more difficult is the simultaneous assimilation of all of the information necessary to evaluate its acoustical nature. In addition to the three spatial parameters describing unique locations in space, one needs to be aware of the relative magnitudes and directions of the sound energy as well as its corresponding acoustical characteristics at different positions through time. Furthermore, this information needs to be viewed in its relationship to the reflection properties of the enclosed space, and its dependence on both time and wavelength.

Efficient methods for representing these types of acoustical parameters in terms easily comprehended by the engineer/architect/designer have not yet been developed. Although analytical techniques for the simulation or measurement of the propagation of sound are available, the resulting information is lost using the crude measurements traditional in the practice today.

Computer graphics visualization methods offer some potential opportunities for the display and understanding of this multi-dimensional information. Standard three-dimensional perspective image generation methods with diffuse shading can portray the physical space. Color can be effectively utilized to provide relative scalar values of engineering parameters, but care must be taken to maintain the correct perception of the physical space. The display speed of current graphics workstations allows images to be dynamically updated fast enough to animate time-dependent phenomena. Lastly, abstract symbols and representations can be utilized to depict a wide variety of additional parameters. These icons can be sized large enough to be seen within the global context of the simulation, but small enough as to not affect one's perception of the global behavior.

Just displaying multi-dimensional information, however, is not necessarily going to give useful insight into a physical problem. The data presented must not overload the user's mind with overly specific and possibly insignificant information. It also must be displayed in ways which can be intuitively identified and easily understood.

The visualization techniques presented for displaying acoustical measurements serve as new examples of computer graphics visualization techniques. Their capability for simultaneously displaying multi-dimensional information can help in the understanding of the acoustics of a concert hall.

For comparison purposes, the acoustics of three particular hall designs are evaluated and compared. One model of a real hall was modeled and its design was varied to generate the data for the other two designs. The surfaces common between the models were assigned identical acoustical characteristics. Each test environment contained the same source description and relative position, and each contained a number of detailed listening devices known as "dummy-heads", positioned and oriented in identical positions with reference to the source. The acoustical characteristics of clarity and definition, spatial impression, and overall strength are depicted using icons and color. Although the simulation can be conducted using any particular wavelength of sound, the display of the frequency dependence of the simulation results is not addressed in the visualization examples following.

The primary model used in the simulation was a simplified version of Boston Symphony Hall. (Figure 2a) The environment consisted of approximately 400 surfaces which when meshed amounted to approximately 6000 polygons. The other two environments were based roughly on this model, with variations on the wall angles to produce a fan shaped and reverse fan shaped room when viewed in plan. (Figure 2b) The models remained identical in terms of ceiling and floor angles, but the stage size changed in accordance with the walls. The balconies in each of these rooms also conformed to its wall shape. The angle of slope of the balconies encircling the rooms was in each case equal to that shown in the hall section.

The acoustical attributes of the surfaces within each model were varied to approximate the different reflectance characteristics of different parts of the room. [14][9] The single source used in the tests of the simulation was chosen to emit at a frequency of 1 kHz. Since a geometric approximation for diffraction was not implemented, only the absorption characteristics of surfaces and the air would be affected by a change in the frequency of the source.

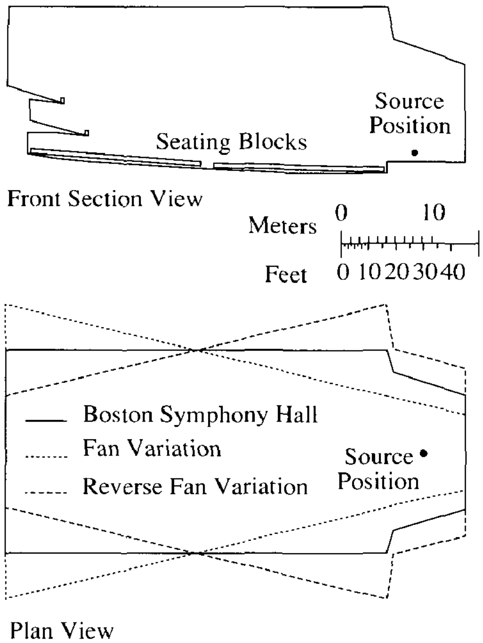

Figure 2a (top): Boston Symphony Hall in Section
Figure 2b (bottom) Variations on Hall Design in Plan

The source was positioned along the center axis of each hall, exactly 10 feet from the front of the stage and 4 feet above the stage floor. The center direction of the source was directed at the center of the back wall of the first balcony. The source emission was weighted 65% in an isotropic spherical emission and 35% in a cosine weighted emission in the center direction. This distribution was chosen to simulate a semi-directional sound source.

Visualization of Clarity and Definition

The measure of early to late sound energy as expressed by the scalar measurement C_{80} serves as a good indicator of the clarity and definition of sound. This scalar measurement could be calculated for all receiver surfaces in an environment and displayed globally using a simple color scale. Then, each of the sample halls could be judged in terms of the absolute C_{80} levels at listener positions and by the variation in the C_{80} levels over many listener positions. If, however, one wants to easily see meaningful variations of the clarity level, and assimilate other acoustical information as well, an abstract icon can be cleverly used.

One way of producing such an icon would be to split an abstract receiver surface horizontally into a upper and lower section. The lower section would represent the energy level reaching the surface within the first 80 msec after the direct sound. The upper section would represent the energy level reaching the surface in the later time interval, spanning from 80 msec after the direct sound to infinity. Any energy level value could be chosen to be represented by the lower section of constant width. The upper section's width could then be sized as a fraction of that hypothetical level, so that the difference between the lower section in dBs and the upper section in dBs would equal the C_{80} value.

In the test environments, each of the ear-like surfaces on the dummy-heads serve as icons for the visualization. The lower section of each icon represents an early energy level of approximately 20 dB. (Figures 3 and 7)

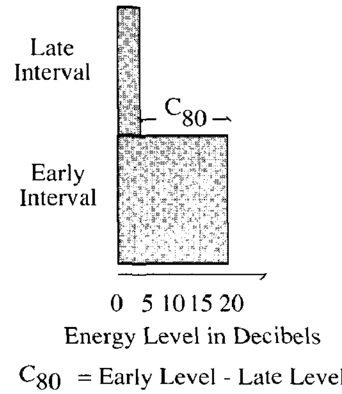

Figure 3: Early-to-Late Ratio Icon - For the desired minimum C_{80} of 0 dB , the icon would have a top portion equal in size to the bottom section. The maximum value of 8 dB would correspond to a top portion equal to 3/5 of the bottom. Icons with top sections larger than the bottom sections or smaller that 3/5 of the bottom's width fall outside the preferred range of values.

Visualization of Spatial Impression

Similarly, lateral fraction, L_f, serves as a good scalar measurement of spatial impression which can be calculated for any number of surfaces in an environment and displayed globally using a simple color scale. The lateral fraction is the ratio of the early lateral reflected energy (over the first 80msec) to the total early energy including the direct energy. By the term lateral, it is meant to the degree it is received along the direction of the normal to the ear. The closer the early incident energy directions approach this normal direction, the greater the lateral fraction, and therefore, the greater the sense of spatial impression. In this case an icon can be generated to portray a relative amount of spatial impression at each receiver surface. A cone originating on the surface of each receiver and whose wide side is directed out in the normal direction can be used to represent the relative degree of spatial impression. To coincide with the intuition of the user, the icon can be manipulated so that the wider the cone angle, α, the greater the degree of perceived spatial impression. (Figures 4 and 8)

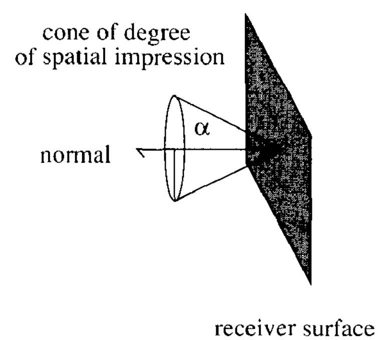

Figure 4: Spatial Impression Icon - The wider the cone angle, α, the greater the degree of perceived spatial impression.

Unfortunately, the cause of poor lateralization and thus deficient sound is not evident from the scalar value of lateral fraction. Lateralization depends on the complex reflective properties of the room, a combination of both geometry and surface attributes. Ray diagrams can allow the user to see the incident energy's relationship with the reflective properties of the room. There are two basic types of ray diagrams which are often used in the spatial design of a concert hall. Ray path diagrams show the paths followed by rays from the source to a given listener position. Ray source diagrams show the positions of real and virtual sources which would be apparent at a receiver position at a given time interval. A virtual source is an image of a real source whose position has shifted from the real source's position because its sound arrived through indirection.

Ray path diagrams can be investigated and used for comparison with other positions in a hall or similar positions in another design. From examining the lateralization of the ray paths of the sound incident at two receiving surfaces representing ears during the critical first 50 milliseconds or so after the direct sound, one is able to see what room features contribute to that incident sound energy. (Figure 5a and 9)

Ray source diagrams give a graphic representation of the envelopment and lateralization of the sound reaching a listener through time. For each ray which hits the surface or surfaces under scrutiny, a line is drawn in the direction opposite to the ray's incident direction, and is given a length equal to the total distance traveled by the ray on its journey from the source to the surface. (Figure 5b and 9)

While a ray diagram for a surface or receiver position may give directional incident energy information, it may not give an accurate description of the energy reaching a surface through a particular direction. Since many rays, each of which deposit their bundle of energy to a surface, may be traveling over the same or nearly the same path as seen in the visualization, the ray diagram will not accurately indicate the magnitude of the sound incident through particular directions, and thus may give an incorrect indication of lateralization. Furthermore, only the energy incident at one listener position can be analyzed at a time.

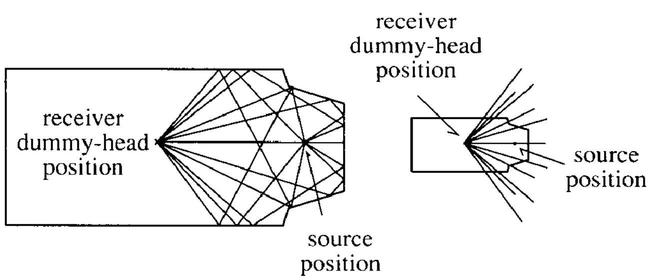

Figure 5a (left): Sample Ray Path Diagram:
Figure 5b (right): Sample Ray Source Diagram:

As an alternative to these diagrams, the rays incident within a chosen time interval can be sorted through subtended solid angles of equal size of the hemisphere over a receiver position, and representative rays can be drawn from the center of the hemisphere out through the center of each chunk of solid angle. (Figure 6) The length of each ray indicates the strength of the incident energy within each solid angle and its direction indicates from which approximate direction that energy arrived. Furthermore, the color of each ray indicates its approximate sound strength in decibels referenced into a color scale. Known as a soundrose diagram, this three-dimensional incident energy distribution can show the time interval incident energy where direction is displayed using rays to indicate both the lateralization at the surface and the area of the room last responsible for its final reception. (Figure 10) The use of ray and soundrose diagrams in acoustical research is not new [7], yet their application within the context of computer graphics visualization techniques warrants their inclusion in this work.

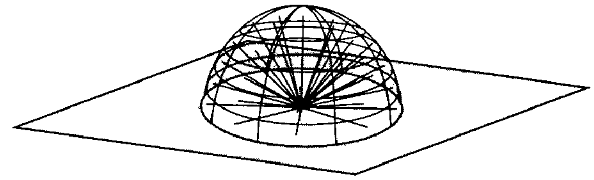

Figure 6: Sample Soundrose Construction

Visualization of the Overall Strength of Sound

The analysis of the overall strength of sound in a room can be approached in several ways. A certain amount of information can be determined simply using the geometric model of the space. More effectively, however, time interval flux or sound pressure levels, displayed at each surface in the environment using color can show global energy hot or cold spots. By displaying global sound pressure levels, global relative loudness levels can be estimated, and improper energy distributions can be recognized (Figure 11). Distinct acoustical aberrations which occur after the direct sound, such as low energy areas, echos or geometric concentrations, can be identified by visualizing the energy reaching the environment during short time intervals. Figures 12 to 23 are 12 frames each of 10 msec time interval, selected from an animation of the dynamic simulation of a sound energy impulse in the model hall. Unfortunately, the dynamic range with which the simulation began was so great that the low level resolution of the late acoustical energy is lost when the same color scale is used late in the simulation. For this reason, Figures 18 to 23 are displayed using a re-scaled color gradient.

Using the global methods described, areas of interest can then be investigated in detail. Echograms, which are plots of the energy (flux) or sound level versus time incident at a position, can be generated for chosen surfaces. From these graphs acoustic spikes or holes can be seen. The echograms can then be analyzed to help identify different types of echos or geometric focusing. Energy levels at particular time intervals can be chosen and the paths between the source and surfaces of the rays contributing to those levels can be shown. This process can not only identify the existence of a problem but also its probable geometric cause. (Figures 24 and 25)

Combined Visualization

Many of the visualization tools described can be simultaneously displayed. In this way, general trends in a room's distribution of clarity, spatial impression, and sound energy strength, in relation to both the reflective nature of the space and the time of propagation can be visualized. The combined visualization can take place on any number of dummy-heads made up of two surfaces which serve as abstractions of oversized ears. These ears can be sectioned to display their early to late ratio measurement of clarity in decibels. They can each have a protruding cone whose spread conveys a relative amount of lateral fraction and therefore the degree of perceived spatial impression. The relationship of the lateralization of received sound energy to the room's reflective properties can be visualized using soundrose diagrams superimposed on each ear surface. The length of a ray indicates its strength relative to other rays. A ray's color indicates its approximate sound strength in flux or decibels referenced into a color scale, and its direction indicates from which approximate direction that energy arrived. Overall sound strength received at each ear as well as at each surface in the environment if desired can be conveyed using the same color scale used to indicate the ray energy level in the soundrose diagrams.

One is able to evaluate and compare some of the important acoustical characteristics of each of the three environments by comparing only the combined visualizations of their acoustical measurements. Figure 26 shows one such combined visualization. The combined visualization is important in a generic sense since it is capable of communicating many parameters simultaneously. Dummy-heads can be placed at any position specifying an x,y,z coordinate. Two ears representing a particular listening orientation specify two more dimensions. Upon each of the ear-like surfaces, the parameters of clarity, spatial impression (lateral fraction), and the direction and magnitudes of the cause of the resultant spatial impression can be conveyed. The overall strength of the sound energy reaching each ear is also shown. By also choosing to show the dynamic propagation of the energy through the environment over time, a dozen or more parameters can be simultaneously imparted to the viewer.

In addition, although not shown, a two-dimensional echogram for any particular receiver position could be concurrently displayed in a separate window to show the time dependence of the energy received there. One could then choose time intervals within the echogram to simultaneously visualize the ray paths responsible for the energy level displayed. This would allow for further analysis into the relationship between the room's reflective characteristics and the sound at a particular position.

Conclusions

A visualization of acoustical measurements allows for the simultaneous assimilation of much of the information necessary to evaluate the acoustical nature of a space. The acoustical analysis of the three performance halls serves as a good example of the visualization of multi-dimensional information in a generic sense. The intuitive use of three-dimensional images, color, animation and abstract representation allows for the comprehension of the complex results of a scientific simulation. Specifically, the simultaneous display of particular icons familiar to the discipline enabled the simultaneous presentation of up to twelve parameters. From a more general point of view, the procedures demonstrate how computer graphics can be utilized for the portrayal of multi-dimensional time dependent data. Thus, the visualization techniques are potentially useful for the display of three-dimensional vector fields in many scientific and design applications.

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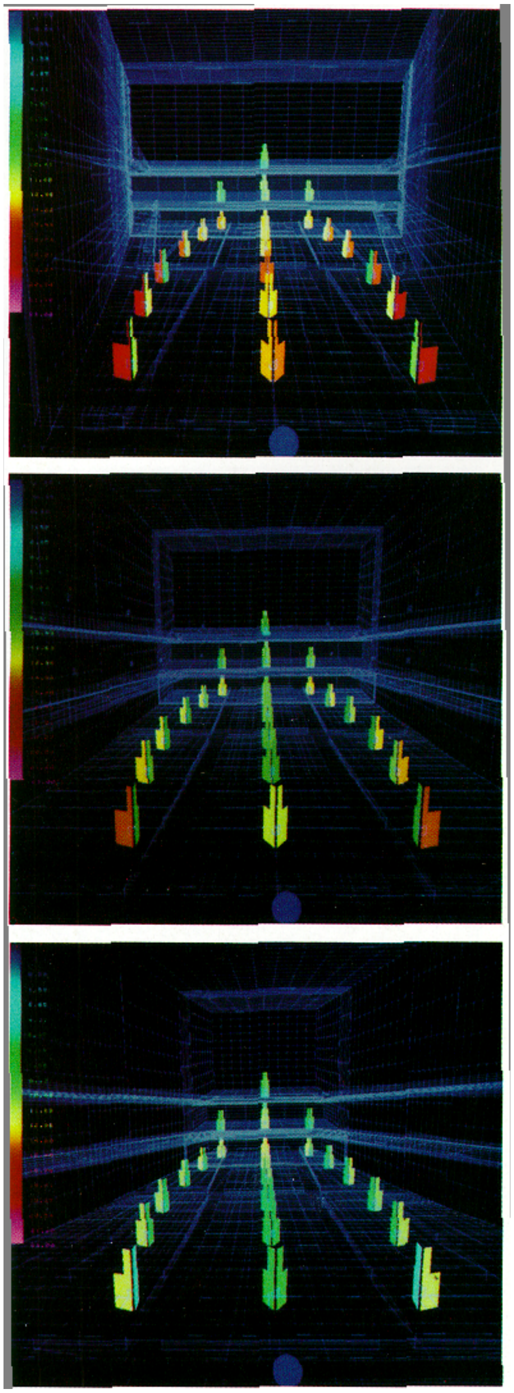


Figure 7: Dummy-head Icon and Color C_{80} in SPL for Fan, Box and Reverse Fan Designs - The fan shaped hall (top left) has improper C_{80} values since the top sections of the icon are so small, and the variation of the values on the dummy-heads is high. The box shape (center left) has both better C_{80} values and less variation between heads. The reverse fan shape (bottom left) clearly has both the best C_{80} values and the least within-hall variation. As a cross-reference, each surface has been assigned a color to represent its C_{80} energy level. Proper values of C_{80} correspond to colors on the gradient starting with a minimum of light blue to a maximum of yellowish green. An analysis of the colors on the listening surfaces of each hall confirms the results shown by the icons.

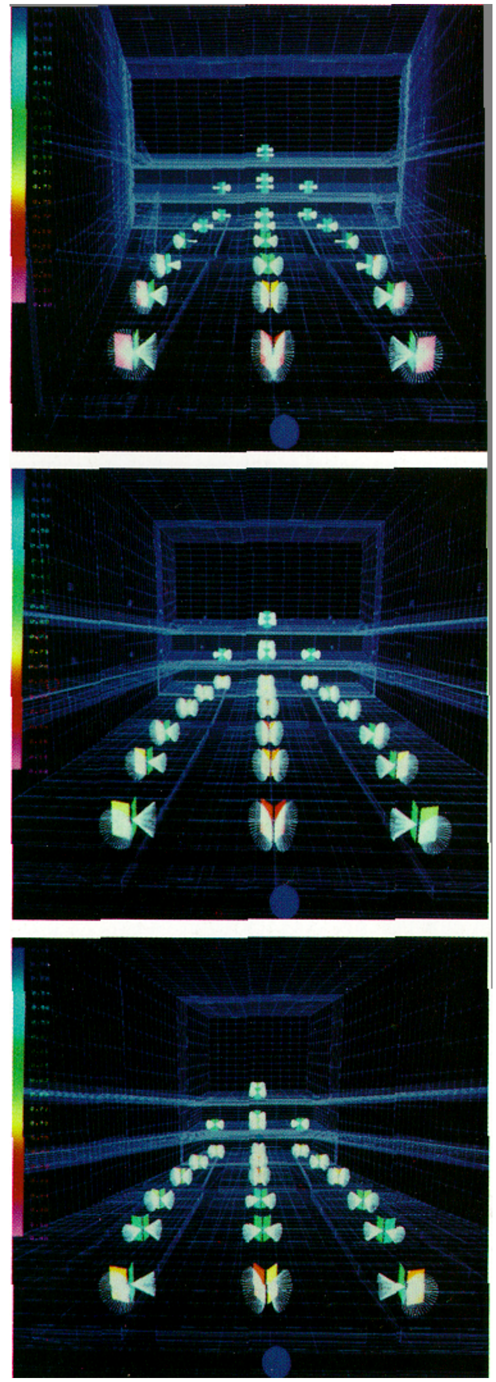
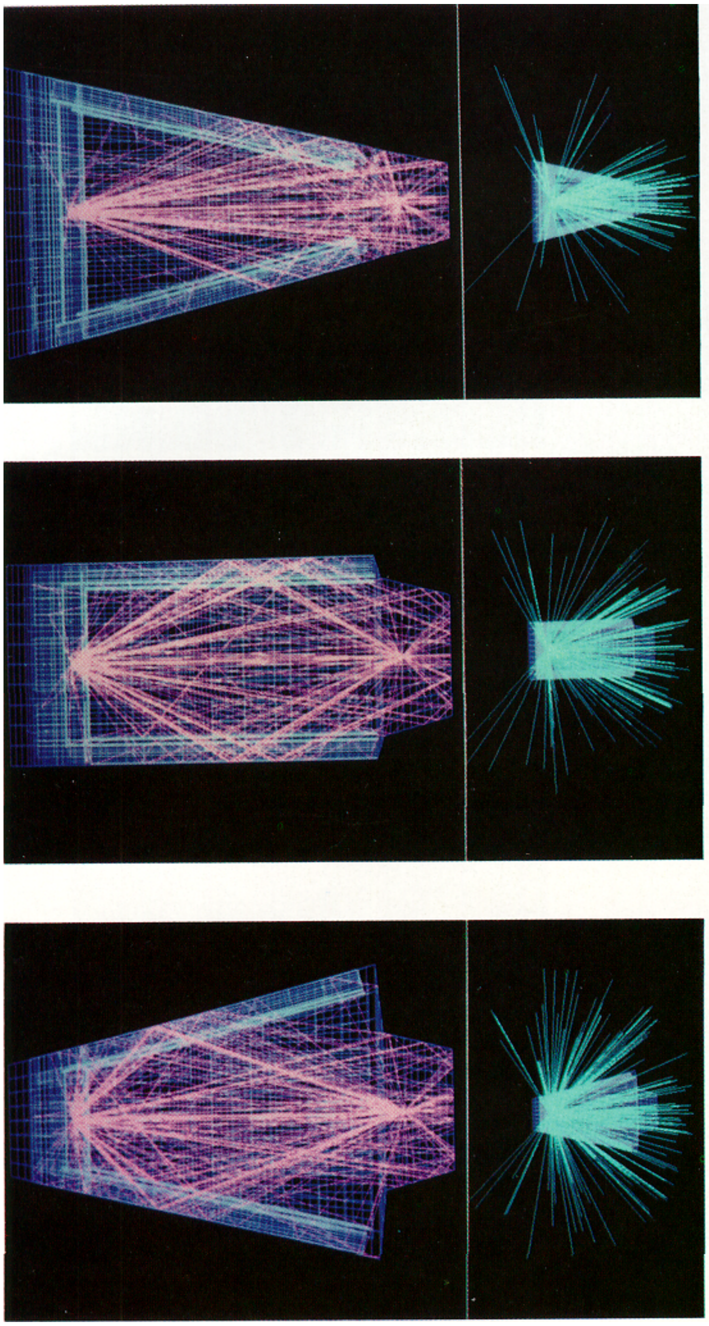


Figure 8: Dummy-head Icon and Color Lateral Fractions for Fan, Box and Reverse Fan Designs - From the cone angles, one is clearly able to see that the fan shaped hall (top right) has much poorer lateralism at listener positions than the other halls, especially as one moves from the middle to the rear of the hall. The box shape (center right) improves on the lateralism as does the reverse fan shape (bottom right). The reverse fan has better lateralization at the rear of the hall and the box has superior lateralization in the middle of the hall.

Images on this page represent views of the concert hall as seen from the source position looking towards the back wall.



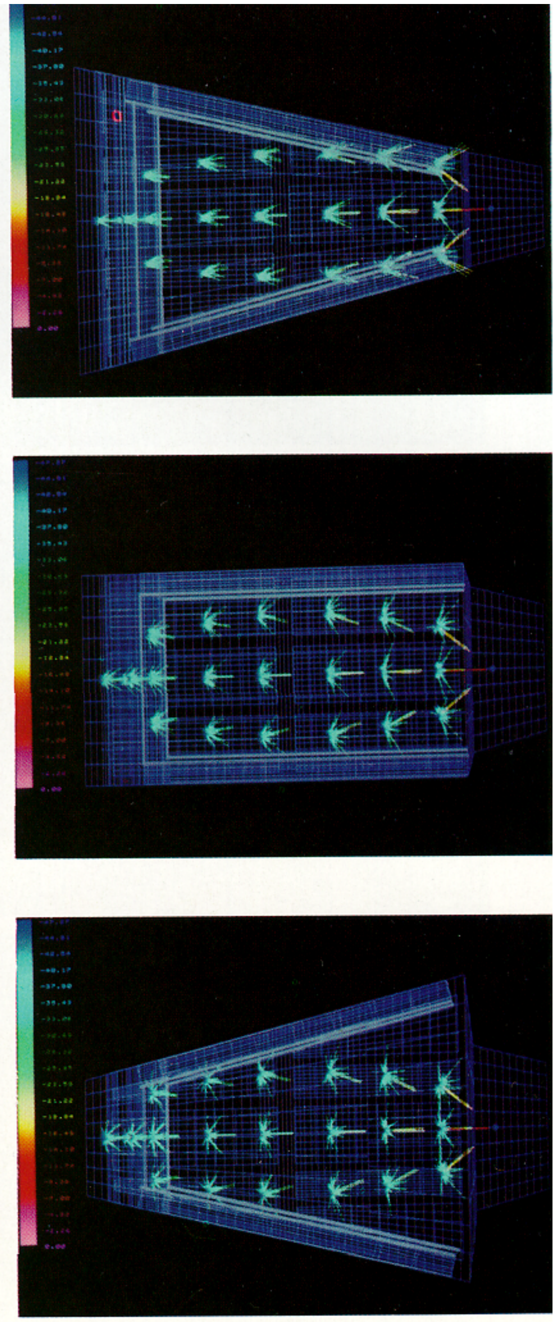


Figure 9: Dummy-head Ray Diagrams in Planar Projection for Fan, Box and Reverse Fan Designs - One is able to see from both the ray path and the ray source diagrams on the left column that the early reflected sound (within the first 50 milliseconds after the direct sound) is least lateral in the fan shaped hall (top), and gets increasingly more lateralized from the box (center) to the reverse fan configuration (bottom). In the fan shaped hall and to some extent in the box shaped hall, sound which can reflect specularly from the side walls and reach the observer at the position shown, must reflect very near the source, thus limiting the possible lateralization. The increased lateralization of the reverse fan shape results from the existence of surfaces on the sides of the hall away from the stage, positioned to specularly reflect sound to the listener.

Figure 10: Dummy-head Soundrose Diagrams in Planar Projection for Fan (top right), Box (center right) and Reverse Fan (bottom right) designs - The relative magnitudes of the rays making up the soundrose icons are displayed using length and color. One is able to see the improved lateralization at numerous positions in the box and reverse fan shaped halls verses the fan shaped one. One is also able to see the general directional characteristics of the lateralized sound which indicates its geometric genesis. Note, the superior lateralization of the box and reverse fan designs for positions in the rear of the hall are consistent with the visualization results of Figure 8 and Figure 9.

Fan Shape

Box Shape

Reverse Fan

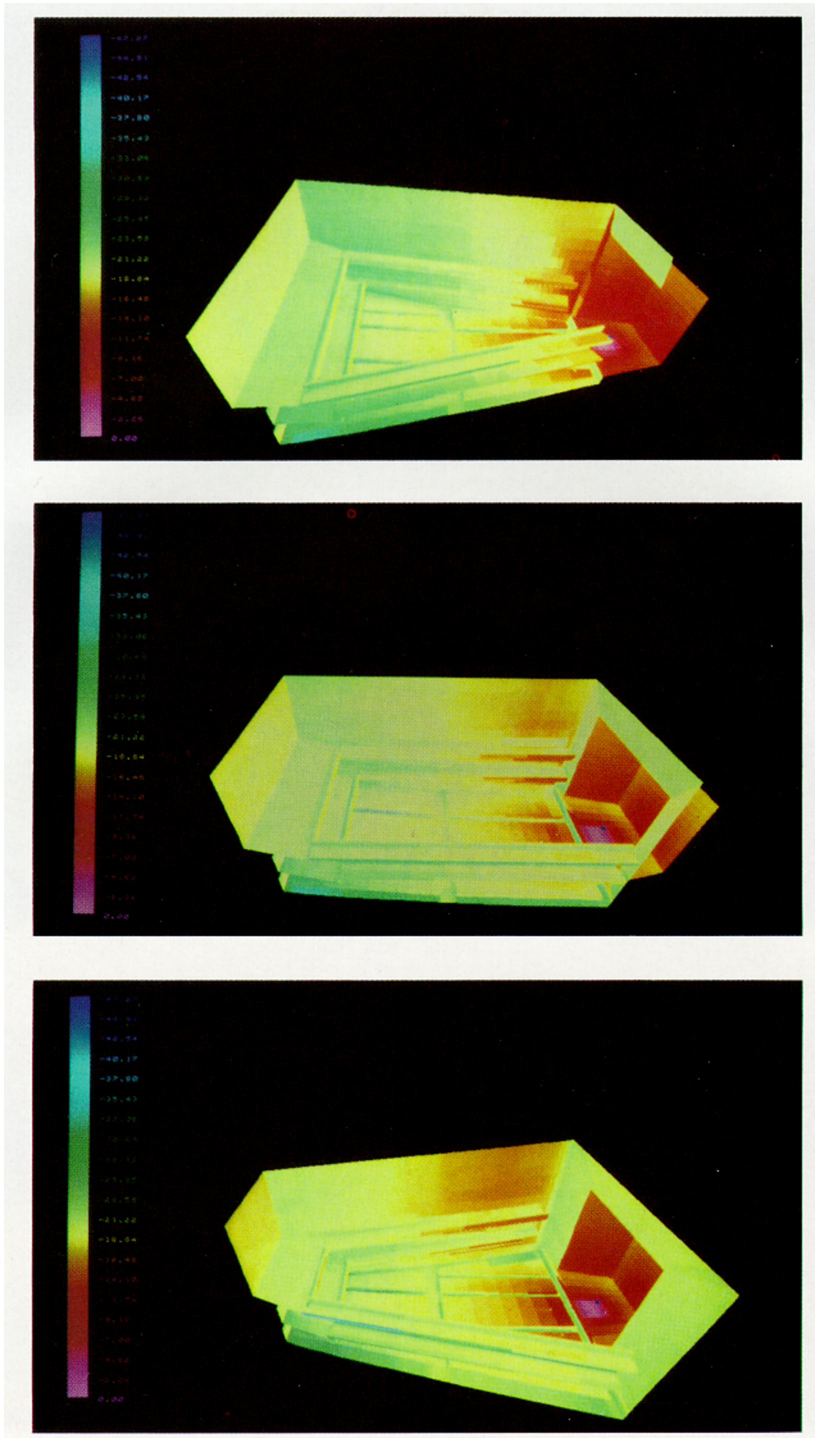


Figure 11: Time Summed Global SPL Over Entire Simulation - In the visualizations of the energy received by surfaces, the bottom color on the color scale represents the maximum incident sound pressure level and the colors as they approach blue are attenuations from this maximum level. A change between two adjacent basic hues, pink, red, yellow, green, aqua and dark blue, corresponds to a change of approximately 10 dB, which is an approximate change in perceived loudness of 2. The sound pressure levels corresponding to each surface energy summed over a time interval can be displayed as a color at each surface. When the energy incident on each surface in the environment is summed over the entire simulation, the fan design clearly has less energy reaching the back portions of the theater, producing a less uniform distribution of energy than the other designs.

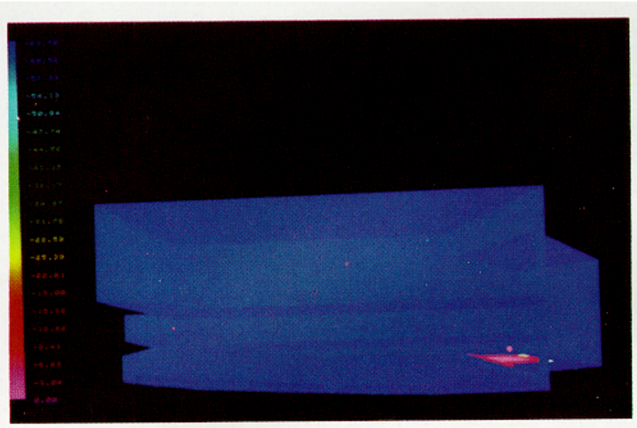


Figure 12: t = 0 - 10 msec

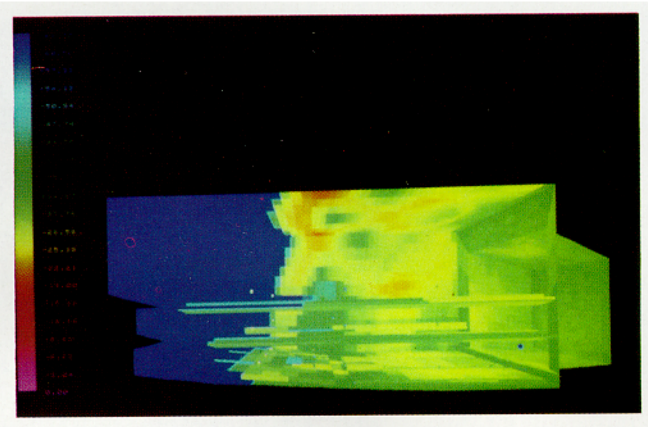


Figure 15: t = 90 - 100 msec

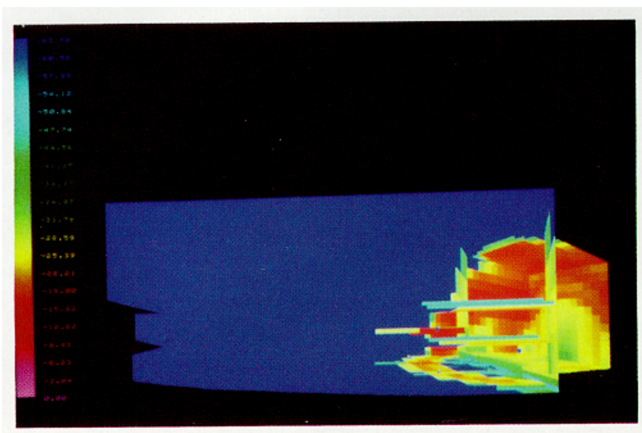


Figure 13: t = 30 - 40 msec

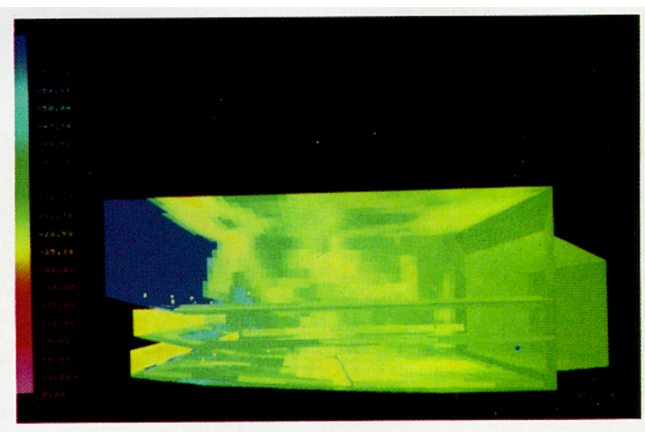


Figure 16: t = 120 - 130 msec

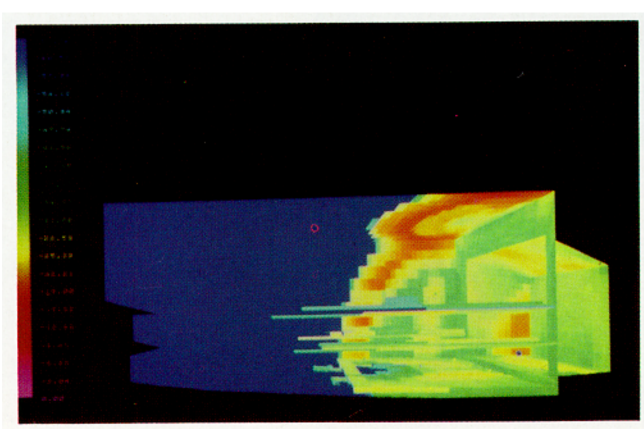


Figure 14: t = 60 - 70 msec

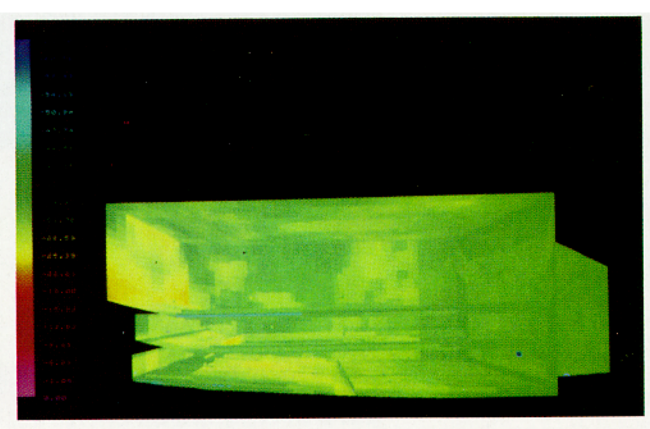


Figure 17: t = 150 - 160 msec

Figures 12 - 17 : Global Early Surface Sound Pressure Levels During Selected Time Intervals - Figure 12 is a side perspective view of the sound pressure levels on the surfaces of the box shaped model during the first 10 millisecond period after the beginning of the simulated impulse of energy. A diffuse lighting model is applied in Figure 12 to enable the viewer to see the environment. Figures 13 through 17 show a sequence of 10 millisecond time interval frames spaced 30 milliseconds apart, which demonstrate the propagation of the sound energy from the source to the surfaces of the environment. One can see the acoustical wave surface as an expanding sphere, then as many superimposed expanding spheres. There is also a distinct secondary wave approximately 20 milliseconds behind the primary wave due to the first reflection of sound from the stage. From these patterns, the distribution of the flux at the surfaces of the environment is discernable.

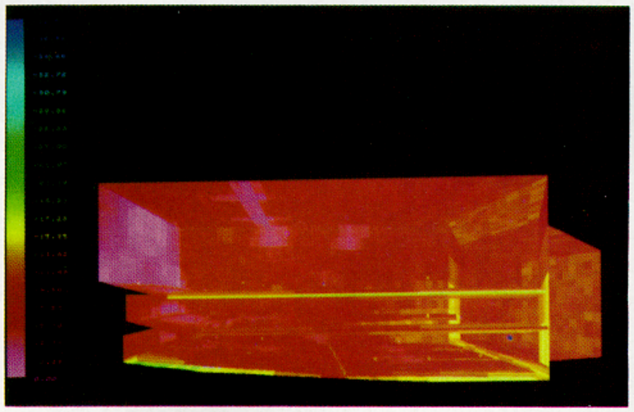


Figure 18: t = 180 - 190 msec

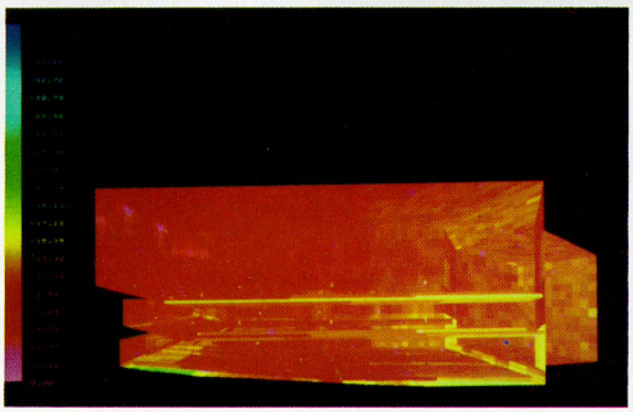


Figure 19: t = 200 - 210 msec

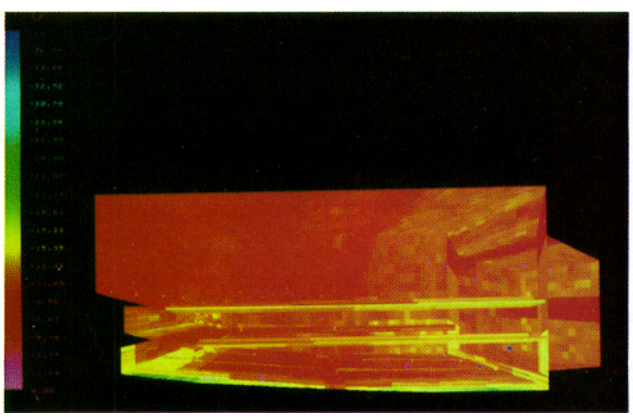


Figure 20: t = 220 - 230 msec

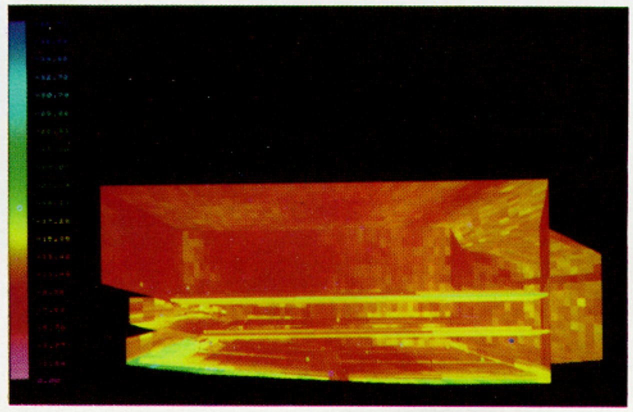


Figure 21: t = 240 - 250 msec

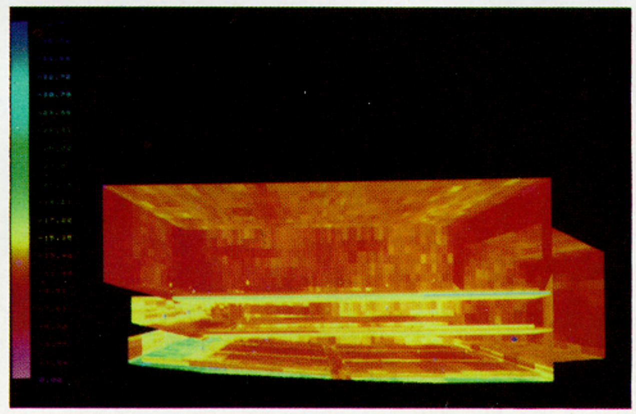


Figure 22: t = 260 - 270 msec

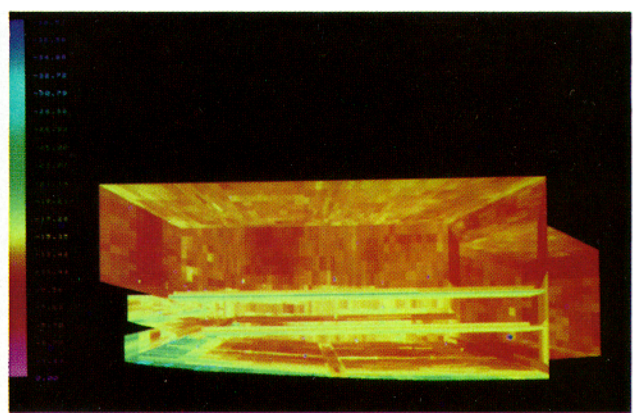
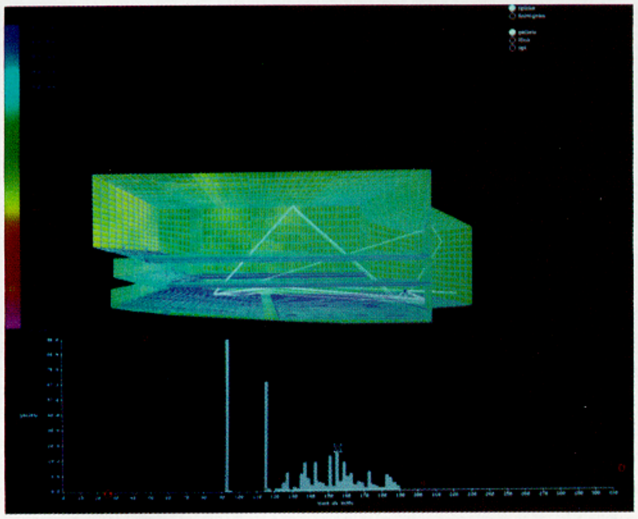
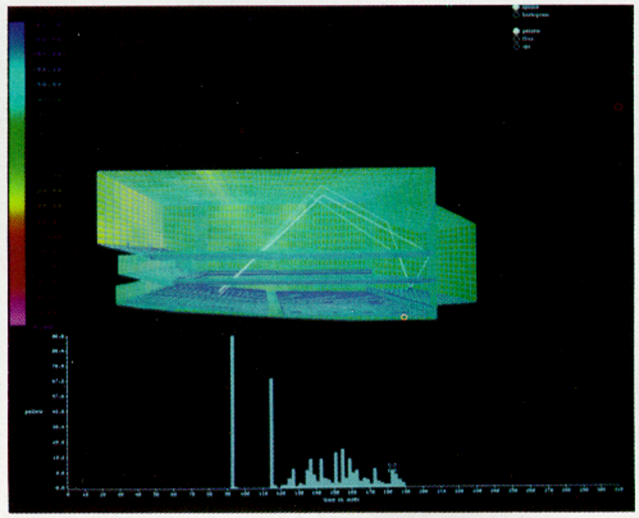


Figure 23: t = 280 - 290 msec

Figures 18 - 23: Global Late Surface Sound Pressure Levels During Selected Time Intervals - These figures are a continuation of 10 millisecond time interval frames in the simulated impulse propagation. Note that they are displayed using a re-scaled color gradient and a change in basic hue now corresponds to a change of approximately 7.5 dB or a 68 percent change in loudness. A number of possible acoustical problems are evident in this sequence. From an approximate time interval starting at 200 msec (Figure 19), to the end of the simulated impulse, there is a clearly little energy in the seating area below the first balcony. In this same area, there appears to be a geometric concentration of sound occurring in the time interval from 280 to 290 milliseconds as shown in figure 23. Another area of concern is the high energy areas on the front wall. Judging from the bright areas in figure 22 on the front wall of the stage, it appears that there might be some degree of echo disturbance on stage 260 to 270 milliseconds into the simulation.





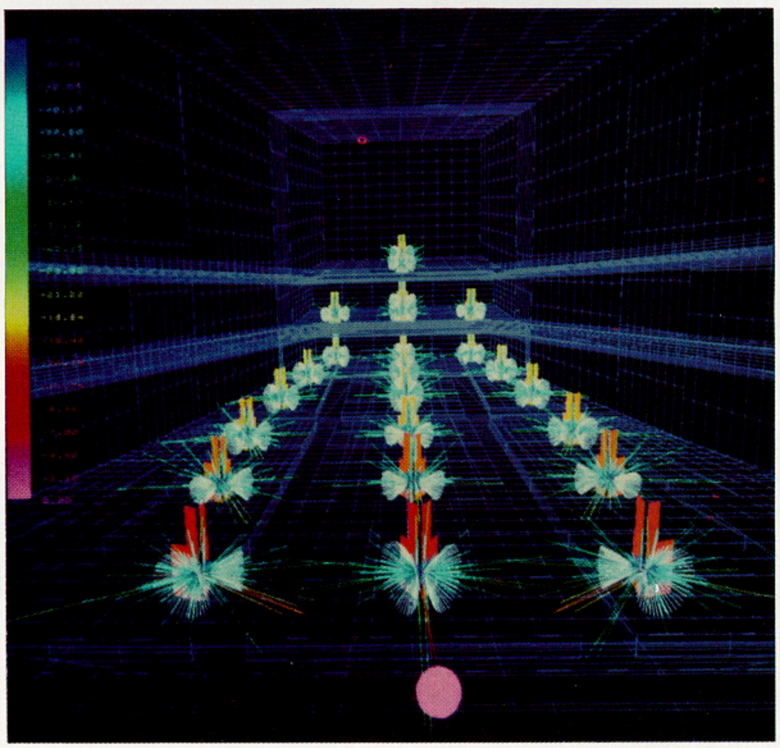


Figure 24 - 25 (top right and top left): Echograms of Receiver Surface and Contributing Ray Paths - These two figures show the 180 - 190 msec time interval surface sound pressure levels, as well as a two-dimensional time verse energy plot or echogram of a particular surface on a dummy-head in the model room. By choosing a spike of energy at any desired time interval or sub-interval, the ray paths responsible for that energy level can be displayed. The X-shaped cursor can be seen over a chosen time interval on each of the two figures, and the ray paths responsible for the energy level at that time interval are displayed in pink.

Figure 26 (bottom center): Combined C_{80} and L_f Icons, Soundrose and Sound Strength in Perspective Projection Summed Through Time - By combining the visualization methods discussed, one can comprehend nearly a dozen parameters important in acoustical evaluation, thus giving one the tools to simultaneously compare and evaluate the acoustical characteristics of each of the three environments.