ACOUSTIC DIMENSIONS

Developing the Design of Large Assembly Spaces

The relationship between size, shape, and sound

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Program Outline

The most important factor in determining a room's acoustical qualities is the room size. Room size relates to both the plan dimensions of the room (the footprint) and the ceiling height. Next to room size, room shape is most important. Contrary to popular belief, finishes, while they can affect the resulting acoustical environment, are of much less importance to the sound of a room than size or shape.

In this one-hour lecture, participants will learn how the acoustician functions as an integral part of the architectural design team early in the design process to assist in developing a room’s volume, plan, size, and shape to achieve the required acoustical quality of a space.

Participants will also hear for themselves, through audible simulation, the how the schematic architectural design of large acoustically-critical rooms (e.g. auditoriums, concert halls, theaters, worship spaces) must be developed initially with the acoustical requirements in mind to ensure the completed facility meets the acoustical design requirements of the client (i.e. it sounds the way it is supposed to).

This lecture, geared at an intermediate to advanced level towards those who design theaters, concert halls, performance, rehearsal, religious and assembly spaces, will present visual and audio examples created using computer-generated “auralization” techniques developed by Acoustic Dimensions, which illustrate the acoustical design concepts.

Case studies of projects will be described, and the relationship between the sound quality and architectural features of the rooms will be explained. Examples from our work and others will be used to explain:

- The relationship between sound quality and architectural features
- Why “reverberation time” is generally meaningless in assessing the quality of the listening environment.
- The bridge between Theaters and Concert Halls that makes some multi-purpose rooms work, while others fail.

Questions from the audience will be encouraged.

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David Kahn is an acoustics consultant specializing in the field of architectural acoustics with an emphasis in musical performance space design. His experience includes all three broad areas of architectural acoustics consulting: room acoustics design, building noise and vibration control, and mechanical and electrical systems noise and vibration control.

During his 15 years in the field, he has worked on a broad range of architectural acoustics projects, including performing arts facilities, religious facilities, hotel/convention centers, office buildings, and many residential and environmental noise projects. Recent projects include: Ted Mann Concert Hall, University of Minnesota, MN; Southern Theatre, Columbus, OH; Zaragosa Theatre - Fiesta Texas, San Antonio, TX; and Jarvis Conservatory, Napa, CA.

In 1991, he joined with others to form Acoustic Dimensions. He holds a Master of Science in Acoustics from Pennsylvania State University and a BS Eng. from Columbia University. He is a member of the Acoustical Society of America, The Audio Engineering Society, and the Institute of Noise Control Engineers.

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Presenter: David Kahn, Acoustic Dimensions, Larchmont, NY

Architectural design typically emphasizes the visual sense of space in people's experience of buildings. But three-dimensional structures have other physical attributes. For example the acoustics of a building designed for music performance is at least equal in importance to the visual impact the building makes.

This paper will describe the relationship between architecture and acoustics, and illustrate a few of the advanced techniques we are using in the acoustical design of performance spaces.

A. Do not judge a hall by its reverberation time

Many architects, and others, have long held the belief that reverberation time is a good measure of the quality of a concert hall or theater. For example, Vienna's Musikvereinssaal (Figure 1), a universally renowned hall for music performance, has a reverberation time of about 2.0 seconds. Should we expect other halls with a reverberation time of about 2 seconds to be good as well?

The short answer is no. For example, the Gasteig Philharmonic Hall in Munich (Figure 2) has a reverberation time of 2 seconds, but has a sound not at all similar to that of Musikvereinssaal, and is considered by many to have poor acoustics for music performance.

To further illustrate this point, we have created three audible simulations of three different rooms, all with the same reverberation time of 1.8 seconds. While each musical example has the same reverberation time, each simulation sounds very different. [Musical Examples 1, 2, 3]

But if reverberation time is not a good way identify a hall's acoustic quality, what is? This question is not unlike the question of what single quantitative measure makes great architecture. Not surprisingly, no single quantitative measure that correlates well with good acoustics has yet been found.

In the last 20 - 30 years, however, significant research has been done which assists us in correlating objective measures with good acoustics. The most important acoustical attributes of a space are its size and shape. In other words, **acoustics is architecture**. The consequence of this relationship is that the only real way to ensure a concert hall, theater, or other performance-oriented space achieves its acoustical functions is to consider acoustics as an integral part of the design of a hall from its earliest conception.

B. Geometric Acoustics and Computer Modeling

In order to demonstrate how architecture and acoustics interact, we should review a few basics:

Sound travels from a performer to a listener directly, and may be reflected off one or more room surfaces. The direct sound, which travels in a straight line from the source to the receiver, takes a certain amount of time to reach the listener, depending on distance (Figure 3).

The three-dimensional image in Figure 3 shows how direct sound travels from a performer to a listener in a simple room. This figure also displays a graph showing the arrival time and level of the direct sound ray reaching the listener's ear. We call this graph an echogram. Since there is only direct sound and no reflections, there is only one line on this graph. The third graphic in Figure 3 is called a sound rose. It demonstrates the direction of arrival and strength of the direct sound.

We can also listen to how music sounds in this room. Notice how dry, and without reverberance, this example sounds. [Musical Example 4].

That example was created by an orchestra playing in an anechoic room, a room in which all the surfaces (walls, floor, and ceiling), are completely sound absorptive.

In a real room, though, some sound is reflected off the room surfaces. Figure 4 shows a ray of direct sound, one sound reflection from a wall, and the "image" of that reflection behind the wall. In analyzing the acoustics of a room, we utilize this geometric raytracing and the attributes of images and superposition of sound rays. This gives us the ability to create a computer model based on geometric acoustical theory.

Figure 5 is similar to Figure 3, except that it shows the combination of direct sound plus sound reaching the listener after one reflection. We call these reflections 1st order reflections because the sound bounces off one only one surface to get from the sound source to the listener. The echogram graph now shows the level and time of arrival of the direct sound as well as each of the 1st order reflections. By measuring the length of each ray, we can determine the time of arrival of sound at the listener position. The sound rose now shows the direction of arrival and strength of the 1st order reflections, as well the direct sound.

Figure 6 shows the 2nd order reflections. These are the rays which bounce off two surfaces in their path from sound source to sound receiver (listener). Note that some of the 2nd order reflections arrive before some of the 1st order reflections. The order of the reflections does not necessarily correlate with how long after the direct sound the reflection arrives, or from what direction.

Figure 7 shows this process taken out to a sufficient number of orders of reflections to determine all of the sound reflections which arrive within the first 500 msec (1/2 second) after the arrival of the direct sound. Clearly, in this room, there are a great many ways for sound from this simple source on the stage to reach the listener within the first 500 msec.

This geometric model of the room acoustics can be manipulated mathematically, and a computer-generated simulation of music played in the room can be generated through a process called “convolution”. When the anechoic music of the previous example is convolved with the room shown in Figure 7, it sounds like this [Musical Example 5]. You can easily hear the effect adding reflected sound energy has. All of these reflected sound rays is what actually makes up the reverberant sound in the room.

C. The Relationship Between the Echogram and What We Hear

Some of the subjective terms which can be used to describe a room’s acoustics qualities are clarity (intimacy) and reverberance (spaciousness, envelopment). We have heard in our first series of musical examples that reverberation time does not seem to correlate well with these subjective terms. In those three simulations, we heard the amount of clarity reduced, and the level of reverberance increased, with no change in reverberation time. For convenience, we repeat the first three musical examples [Musical Examples 1,2,3]. We now listen to three more musical examples with three different reverberation times [Musical Examples 6,7,8]. Interestingly (with the exception of what you hear at the end of each example) when the music is playing, the three examples sound essentially the same.

We would like to explain the difference between these six musical examples in terms of the echogram (Figure 8). This echogram is labeled to define three areas: the early sound, the middle sound and the late sound. Let’s talk about these, and how they relate to what we hear.

If we can correlate what we hear with certain characteristics of the echogram, and we use our knowledge of how the size and shape of a room can be used to determine the echogram, we can then correlate what we hear with architectural attributes of a room.

D. Early Sound and Clarity

Clarity is generally synonymous with acoustical intimacy. The early reflections, which arrive within 50 to 80 msec after the direct sound, are the acoustical characteristic that provides clarity. In that time, the reflected sound will have traveled 60 – 90 feet farther than the direct sound. Therefore, it is easier to achieve greater clarity in a smaller room than in a larger one where the room boundaries are further away from more listeners.

However making a room small enough so that most seating areas are sufficiently close to one or more room boundaries is only part of the challenge of achieving good clarity. A similarly important issue relates to the **level** of the “early” reflections in the echogram compared to the later-arriving reflections. We will come back to this issue after introducing the middle sound, late sound, and their respective subjective attributes.

E. Middle Sound and Reverberance

Another acoustical attribute is what we will call reverberance, as opposed to reverberation time. Music consists of both moving segments, which we call “running music” and end notes, which

The question we would like to ask, with respect to reverberance, is “When you are listening to running music, how reverberant does it sound?” Reverberance is provided by sound reflections arriving within the range of 150 msec -–500 msec. We define middle sound (Figure 8) as the sound reflections arriving within the range of 150 msec -–500 msec. The more middle sound there is, the more reverberant it will sound.

But as you can imagine, like the issue of clarity, achieving strong reverberance requires not only lots of sound reflections arriving 150 msec to 500 msec; the **level** of the middle sound reflections must be sufficiently high compared to the other sound reflections.

In Musical Examples 1,2 and 3, the level of middle sound, compared to the level of the early sound progressively increased. This is why each example sounded progressively more reverberant, even through the reverberation time did not change. (Figure 9).

F. Late Sound and Reverberation Time

The only time we can hear the late sound is at terminal chords, such as at the end of piece, or at a significant pauses in the sound. One good musical example is the opening of Beethoven’s Consecration of the House. [Musical Example 9].

Musical Examples 6,7 and 8, where the reverberation time was increased in each successive example, sounded the same except for the end when the music cut off.

In order to hear a long decay (long reverberation time~~)~~), there must be a sufficient number of sound reflections arriving after 500 msec, and the **level** of these reflections must be sufficiently high compared to the sound reflections arriving earlier.

G. The Relationship Between Architecture and Early, Middle and Late Sound

In general, smaller rooms sound smaller than larger rooms. As a room's boundaries expand, it takes that much longer for the sound to reflect off the boundaries and into the listening areas. One might conclude that as rooms get larger, there is less clarity (early sound), and more reverberance (middle sound). Experience tells us that this is not necessarily true. We can see this by examining the **level** of the sound reflections in the echogram.

Let's now go back and reconsider the two halls we discussed at the outset. When we examine the Musikvereinssaal with geometric acoustics modeling, we learn that the room supports the creation of strong early and middle sound energy, with lots of reflections arriving at listeners in the 150 to 500 msec time frame. Listening in the hall, one can hear both the clarity or immediacy, and strong reverberance during running music, which certainly contributes to the room's high reputation among musicians and listeners.

While the Gasteig is clearly a much larger hall in plan (compare Figures 1,2), and sounds larger, it is not particularly lacking in clarity. It is lacking in reverberance. A geometric acoustics computer model of Gasteig shows much less early and middle sound than Musikvereinssaal. Interestingly, the **level** of early sound compared to the level of middle sound in Gasteig is somewhat higher than at Musikvereinssaal. This is why the hall is not considered lacking in clarity.

Another helpful exercise is to take a simple shoebox room with the same dimensions as Musikvereinssaal (Figure 10). This room has a similar echogram to that of the Musikvereinssaal, but there are fewer early sound reflections. The significant difference between the shoebox and Musikvereinssaal is the lack of the balcony level which wraps around the Musikvereinssaal. This balcony ledge is a critical architectural feature which adds early sound reflections to a majority of the seating areas, creating greater clarity. For interest, we took our simple model of Musikvereinssaal and added two balcony ledges (Figure 11). By comparing the echograms of Figures 10 and 11, it becomes clear that the balconies provide a great deal of additional early sound. This is why traditional Italian-style opera houses, with five tiers of balconies which wrap around the main floor seating, generally have great clarity.

H. Spaciousness and Envelopment (lateral reflections)

We now understand that there is a direct relationship between the architecture of a room and acoustics qualities such as clarity and reverberance. But there is much more to acoustical quality than controlling early, middle, and late sound reflections.

Among the most important findings of the psychoacoustic studies in the last 20 to 30 years is that sound reflections should arrive laterally (from the sides as opposed to overhead) in order to develop a greater sense of spaciousness and envelopment. It should not be a surprising that the direction of sound reflections arriving at a listener should be significant, as our ears are located not at the top and bottom of our heads, but at the sides.

Sound reflections arriving laterally arrive at different times at each of our two ears. The difference in the signal arriving at each ear is what allows us to create a three-dimensional representation of the sound, and is what creates the sense of spaciousness and envelopment. If a sound reflection arrives from above your head, the signal reaching the two ears is essentially the same. There is a very good analogy between stereo vision, and stereo listening. Listening in a room where the sound reflections do not arrive laterally is like looking at something with one eye instead of two. Using our geometric acoustics computer modeling tool, we can examine the difference in the direction of sound reflections in rooms by examining the sound rose.

Figure 12 illustrates sound reflections in the middle of a fan-shaped room. Figure 13 shows sound reflections in the same size room, except that the plan shaping is rectangular.

We see that in the fan-shaped room, there is less lateral sound. The more fan-shaped the room, the less lateral sound there is. Not surprisingly, fan-shaped rooms are known for sounding monophonic.

Figure 14 shows a study of the same room as shown in Figure 13, except that the listener is placed towards the rear. From looking at the sound rose, we see that rectangular rooms are lacking in lateral sound at the rear. In fact, in rectangular rooms such as Symphony Hall in Boston, the sound is more enveloping in the middle of the main floor; the sound quality diminishes, and can be described as “frontal”, as you move towards the back of the hall.

Figure 15 shows the same size room as the previous figures except that the plan shaping at the rear is what we call reverse fan-shaped. The sound rose shows that the reverse-fan shaping in the rear increases the amount of lateral sound energy.

The new concert hall in Dallas is shaped in plan essentially as the room model shown in Figure 15. In fact, one of the fabulous characteristics of the hall in Dallas is that the sound is enveloping in all of the seating areas of the hall; the sound is equally enveloping in the rear and middle of the hall. Figure 16 shows the development of the plan shaping of the hall in Dallas, based on the concept of maximizing lateral sound energy.

This discussion should help to assist in understanding why so many fan-shaped halls, including the Gasteig, are not successful as music performance spaces.

H. Multi-Use Assembly Spaces

What if a room has to serve many functions, each with unique acoustical requirements? This brings us to the issue of multi-use halls, which often must serve a wide variety of functions, from drama to opera to symphonic music.

We would now like to illustrate one interesting acoustical concept that has been used successfully to allow a hall to function well for both opera and symphonic music. We know from previous discussions that a room with many balcony ledges will generate a great deal of early sound, which we know from experience is important for operatic performance (hence the success of the traditional Italian-style multi-tier opera house). How can we add more middle and late sound, which is not required for opera, but is considered an important ingredient for symphonic music?

Suppose we could tack on a large empty room with no sound absorbing materials in it. Such a tacked-on room would have a strong middle and late sound, like the simple rectangular room with no balconies we looked at earlier. Sound generated in the main room will decay quickly, but then the sound from the large tacked-on empty room will feed back into the main room, creating a better environment for music performance.

Figure 17 shows how this is being achieved at the Southern Theatre in Columbus, Ohio. This theatre has an intimate audience chamber with small plan dimensions. The room shaping provides for a great deal of early sound, and a considerably lower level of middle sound. When used for music performance, the orchestra pit is raised to stage level, allowing the musicians play out in front of the proscenium. A ceiling is flown in the stagehouse just below where all of the sound absorbing draperies are stored, creating a large empty box.

I. Conclusion

We have seen that reverberation time is misleading as a descriptor of the acoustical performance of a concert hall, opera house, or multipurpose room. We have also shown a way to model a room, and how the results of the model can be used to help us hear what that room might sound like.

By looking at a variety of acoustical parameters and their interrelationship using computer aided analysis tools, we are able to identify the architectural attributes of a space during design which will support or detract from the acoustical design goals that should be achieved to create magical performance spaces.

It is not coincidental that we have not discussed the issue of finishes at all. We are not suggesting that the room finishes have no impact at all on the resulting acoustical quality. But we are saying that the overall impact on the acoustical quality is determined far more by the size and shape than by the room finishes. This is why it is so important for the acoustics consultant to be involved at the earliest stages of the design where basic room shape and size are set.

There is clearly a great deal more research, as well as applied acoustical design, that should be incorporated at the earliest stages in the schematic design of performance spaces. It is only through collaborative work effort between the architect and acoustics consultant that the world's greatest performance halls can yet be built.

List of Figures

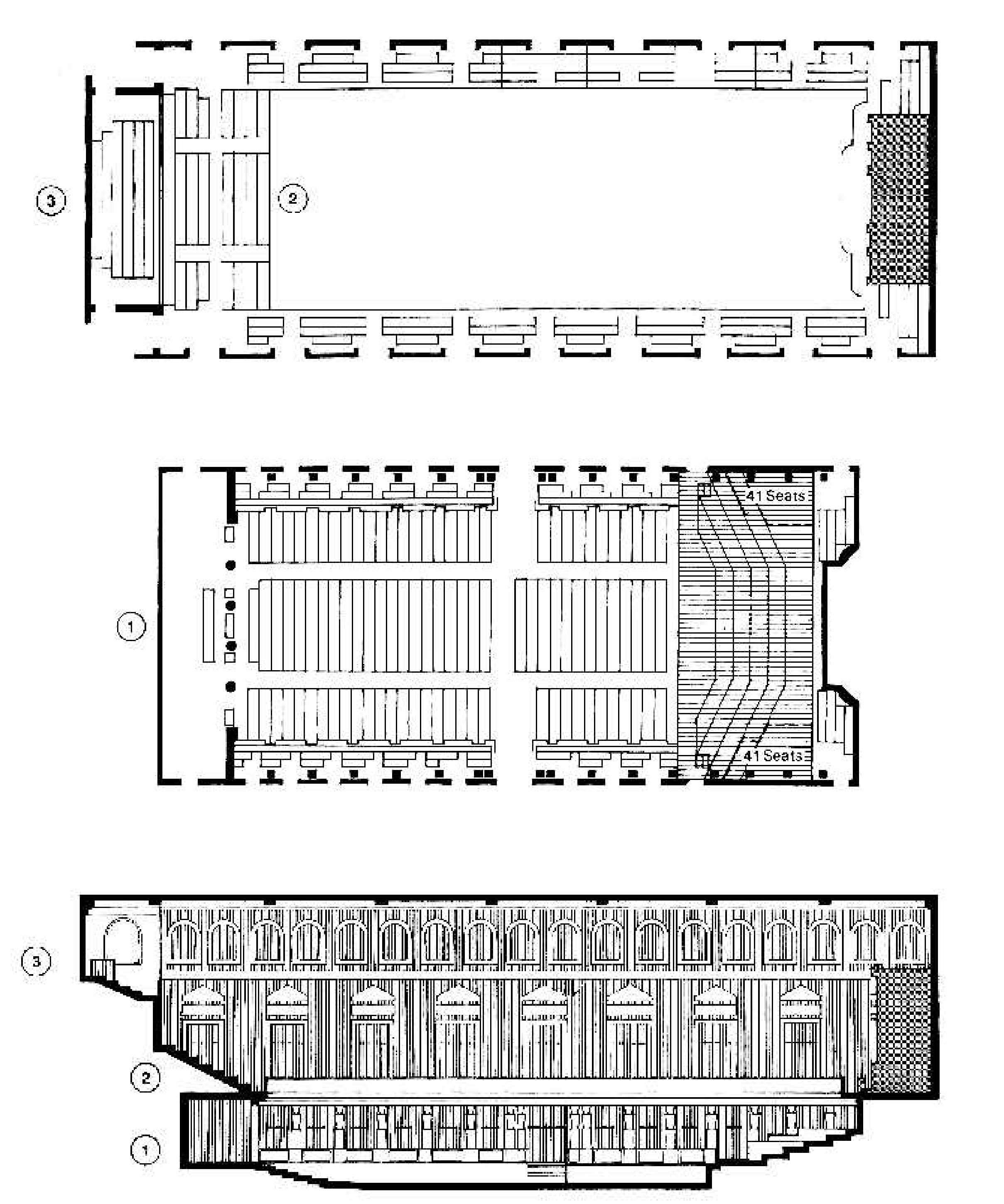

FIGURE 1 **Grosser Musikvereinssaal, Vienna**

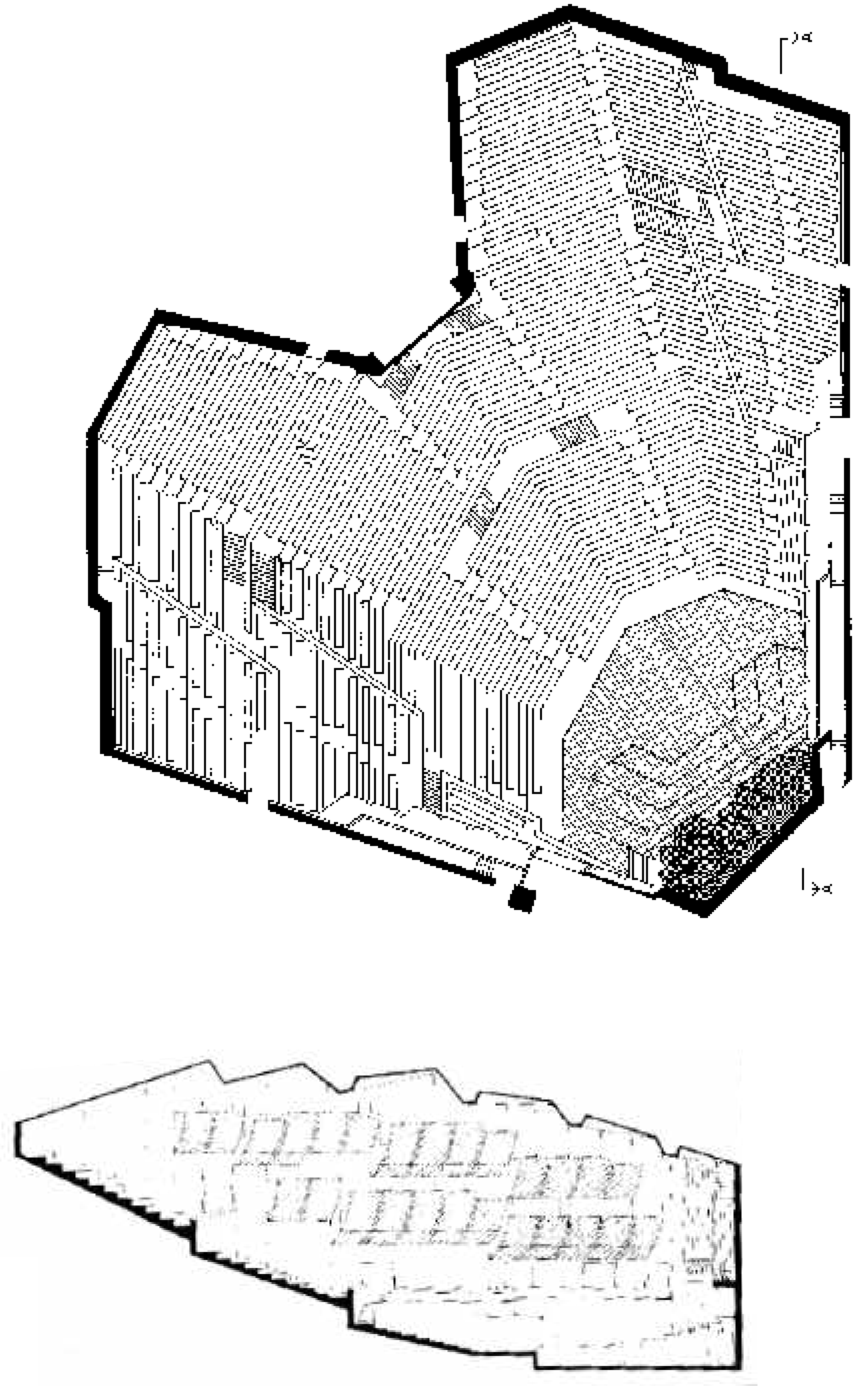

FIGURE 2 **Philharmonie am Gasteig, Munich**

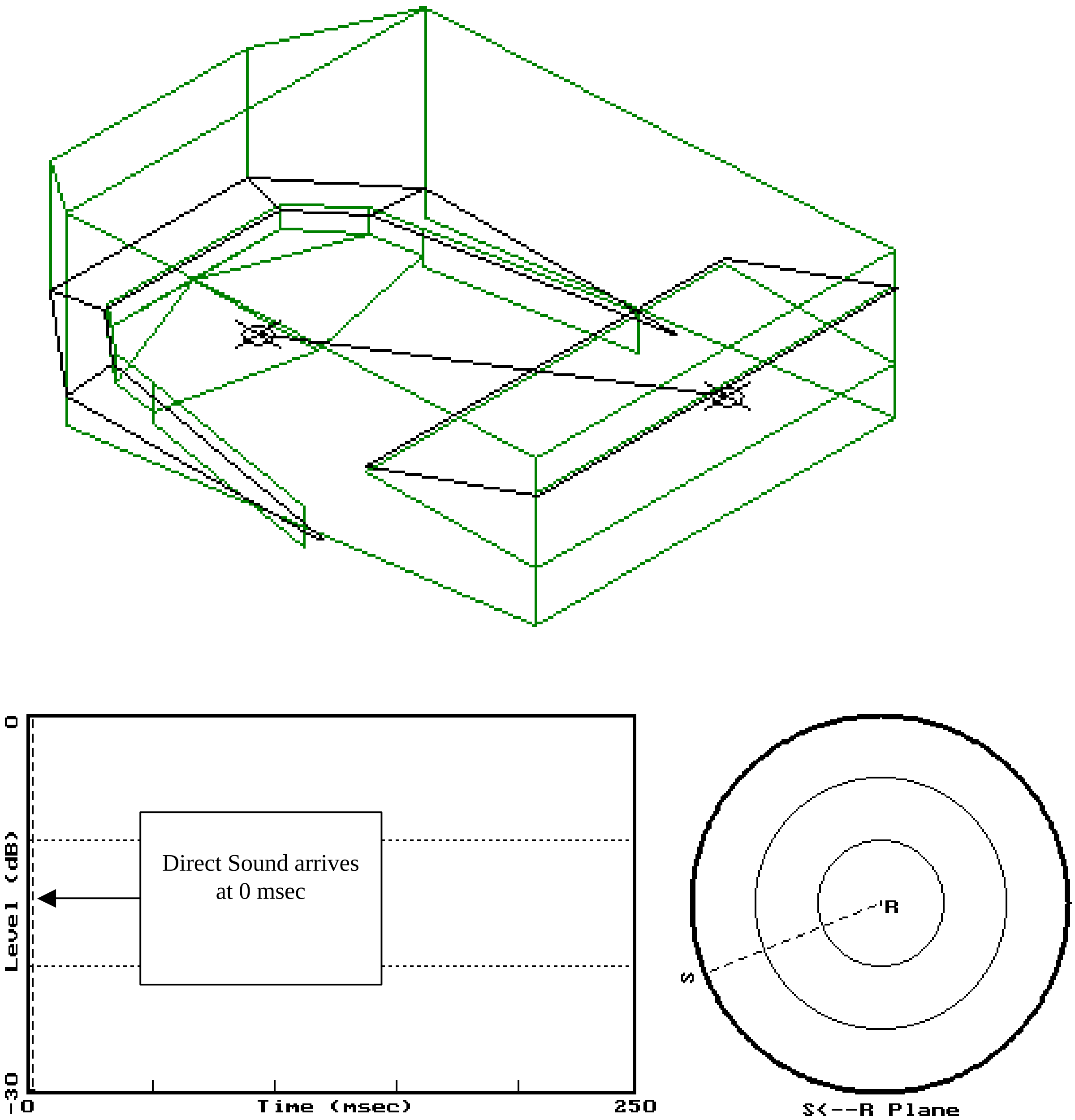

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FIGURE 3 Direct Sound: Ray, Echogram, Rose

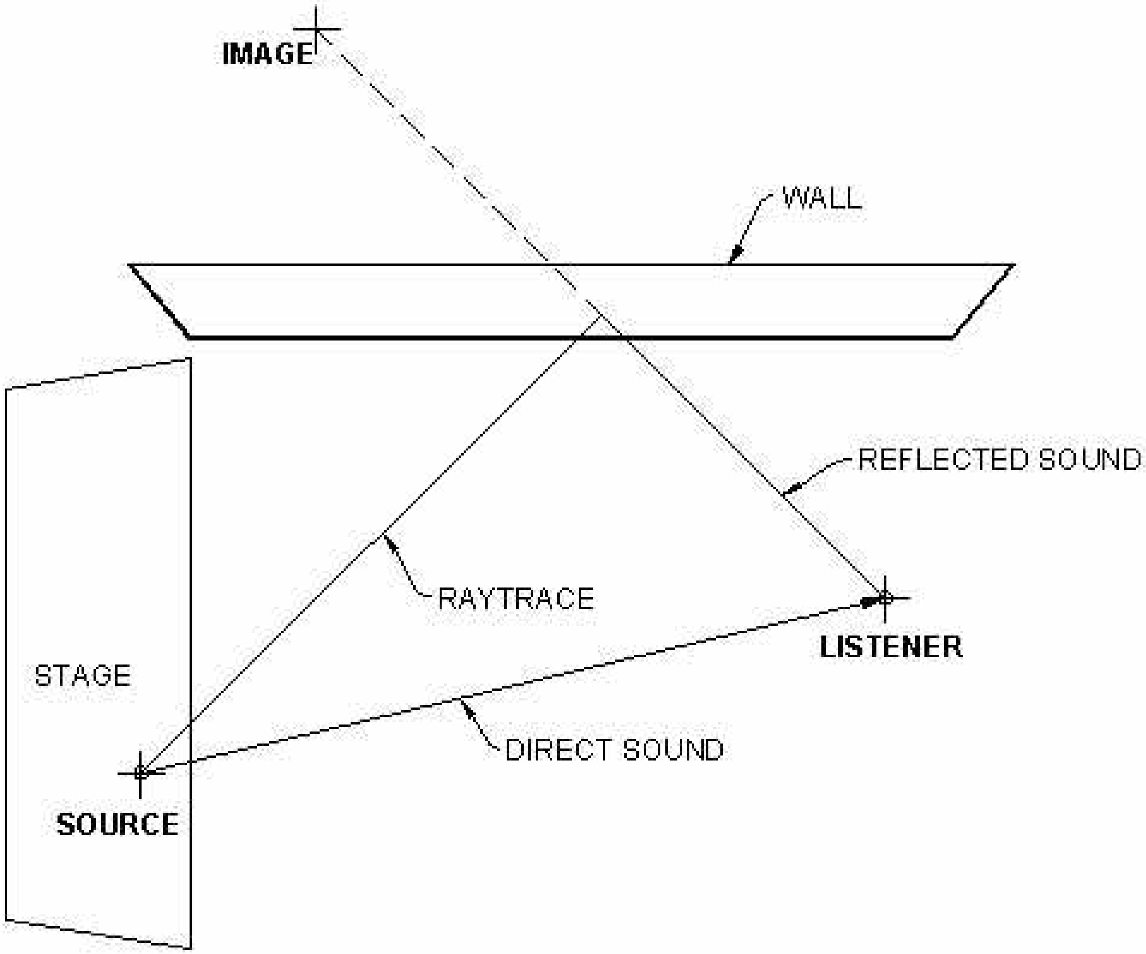

FIGURE 4 **Direct and Reflected Sound Rays**

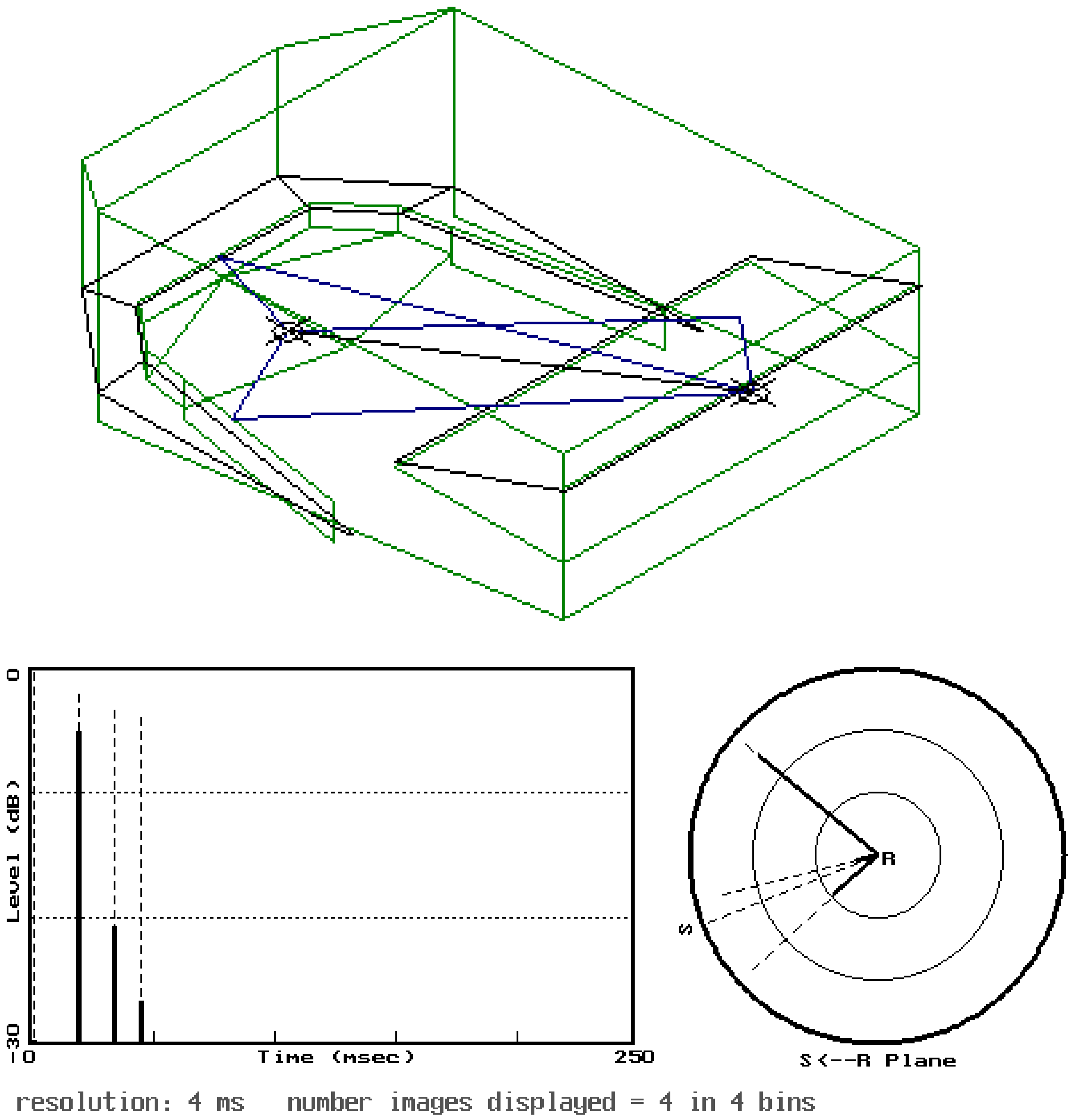

FIGURE 5

Direct Sound plus 1st Order Reflections:
Rays, Echogram, Rose

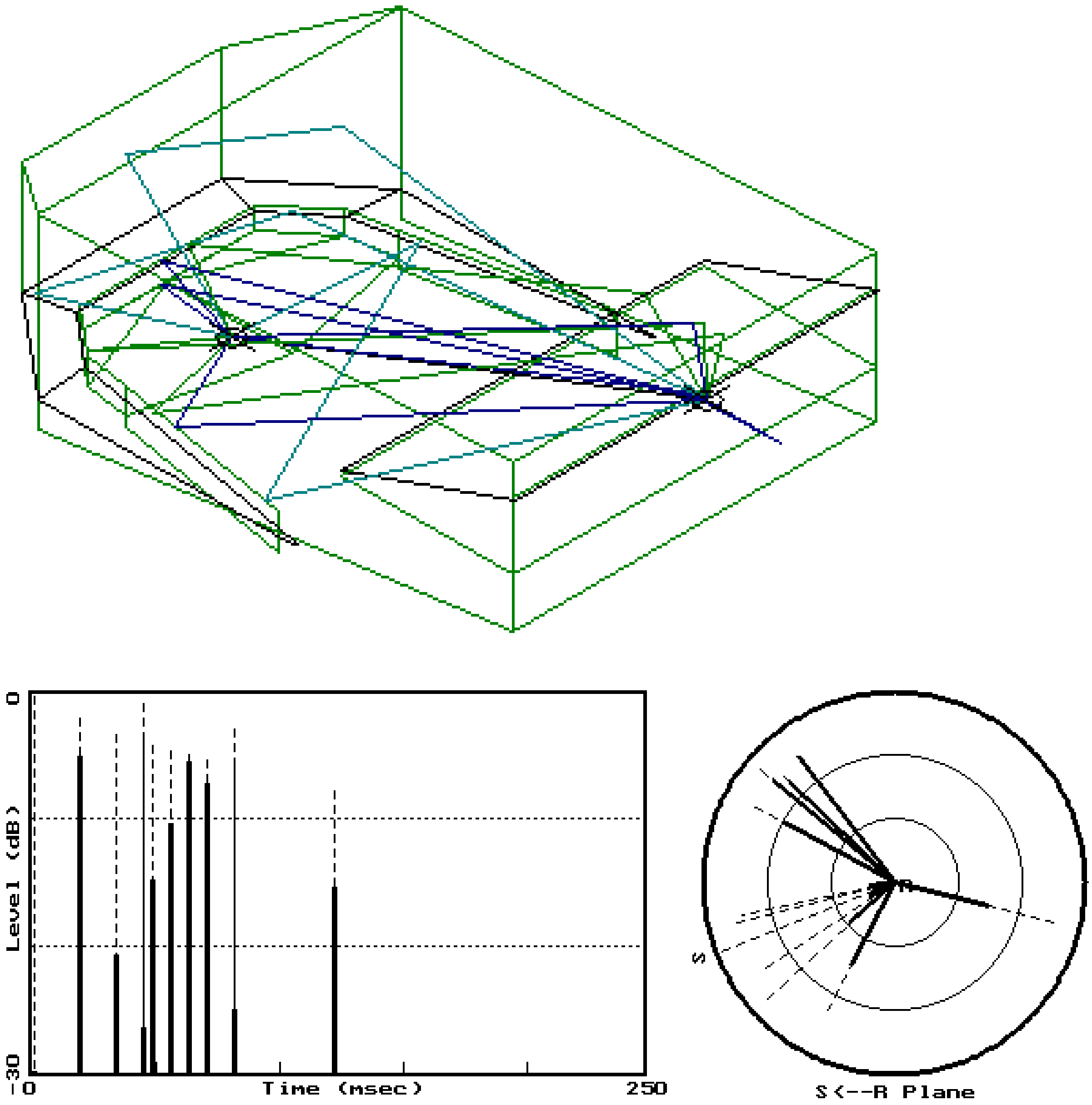

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FIGURE 6

Direct Sound plus 1st and 2nd Order Reflections:
Rays, Echogram, Rose

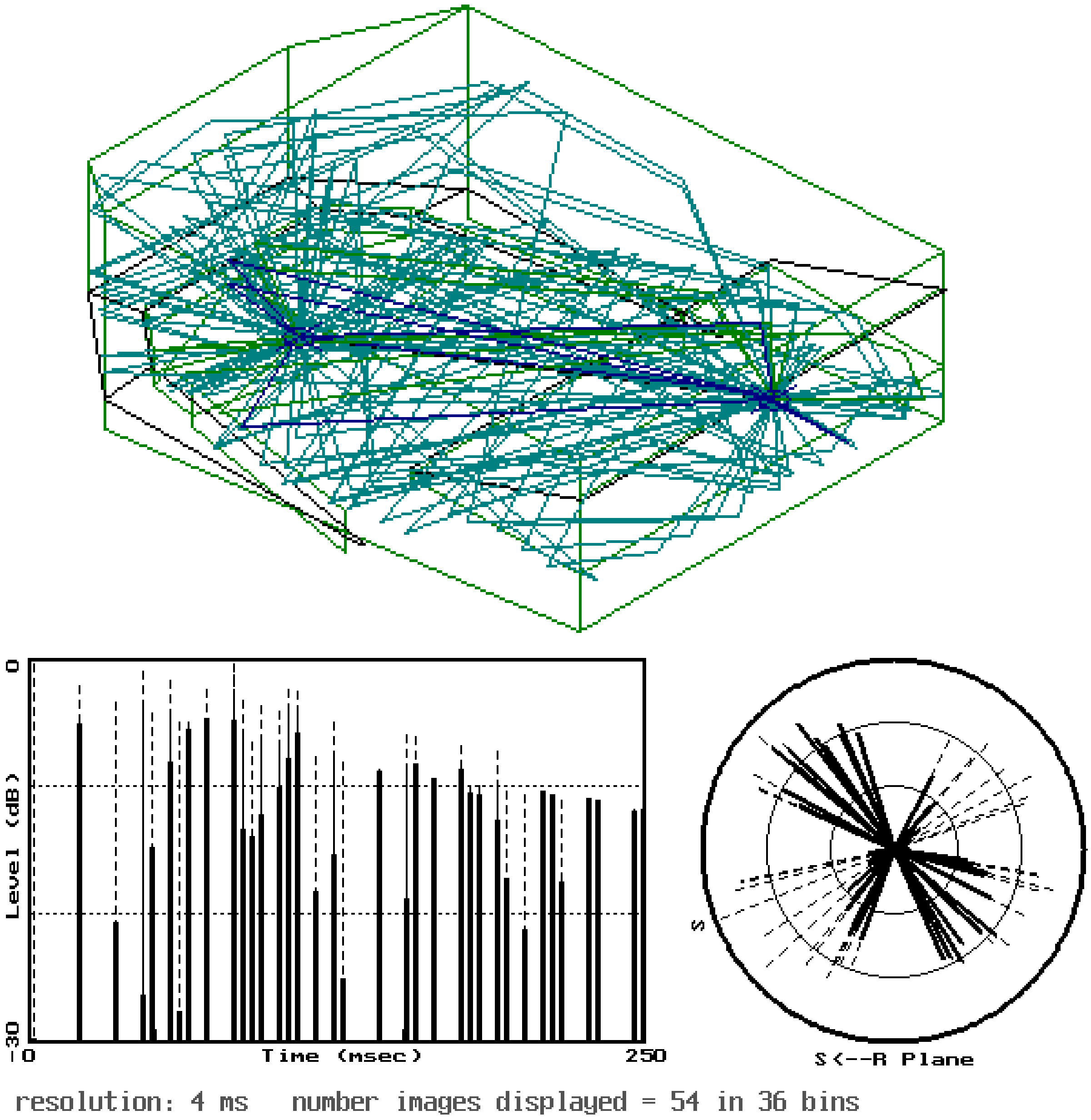


FIGURE 7

**Direct Sound plus Reflections to 500 msec:
Rays, Echogram, Rose**

Sound Level vs. Time Graph for Auditorium

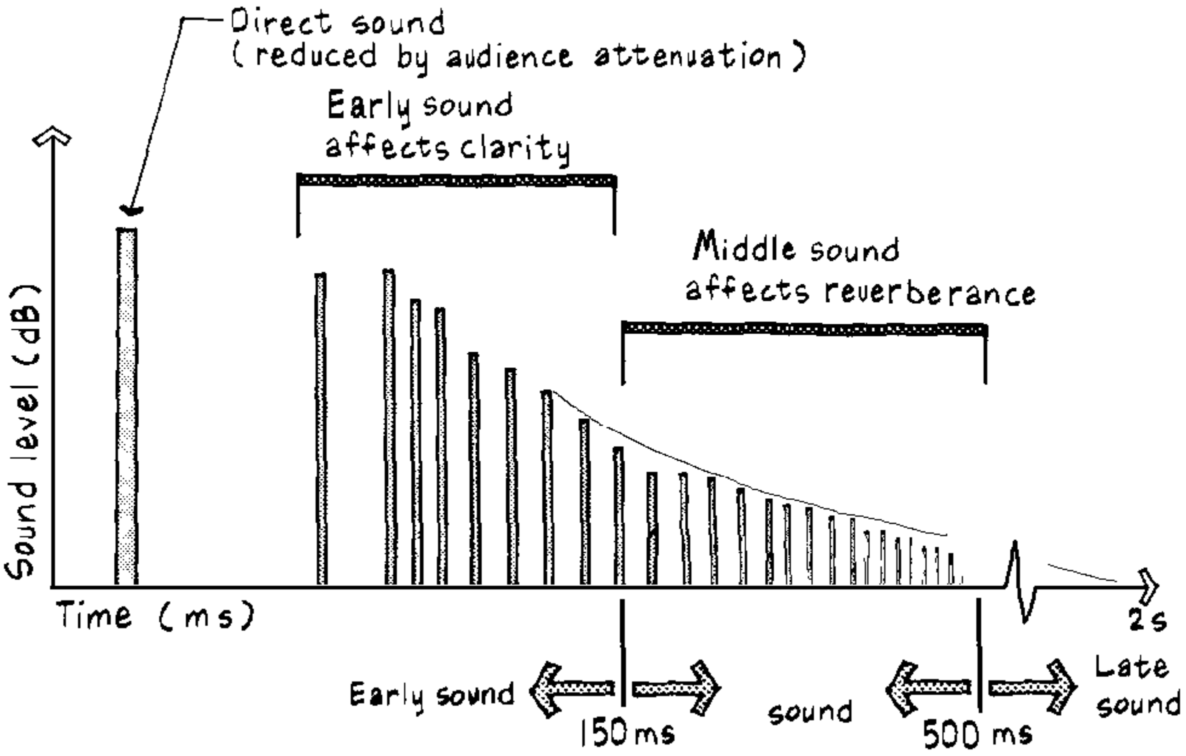


FIGURE 8 **Echogram: Early, Middle and Late Sound**

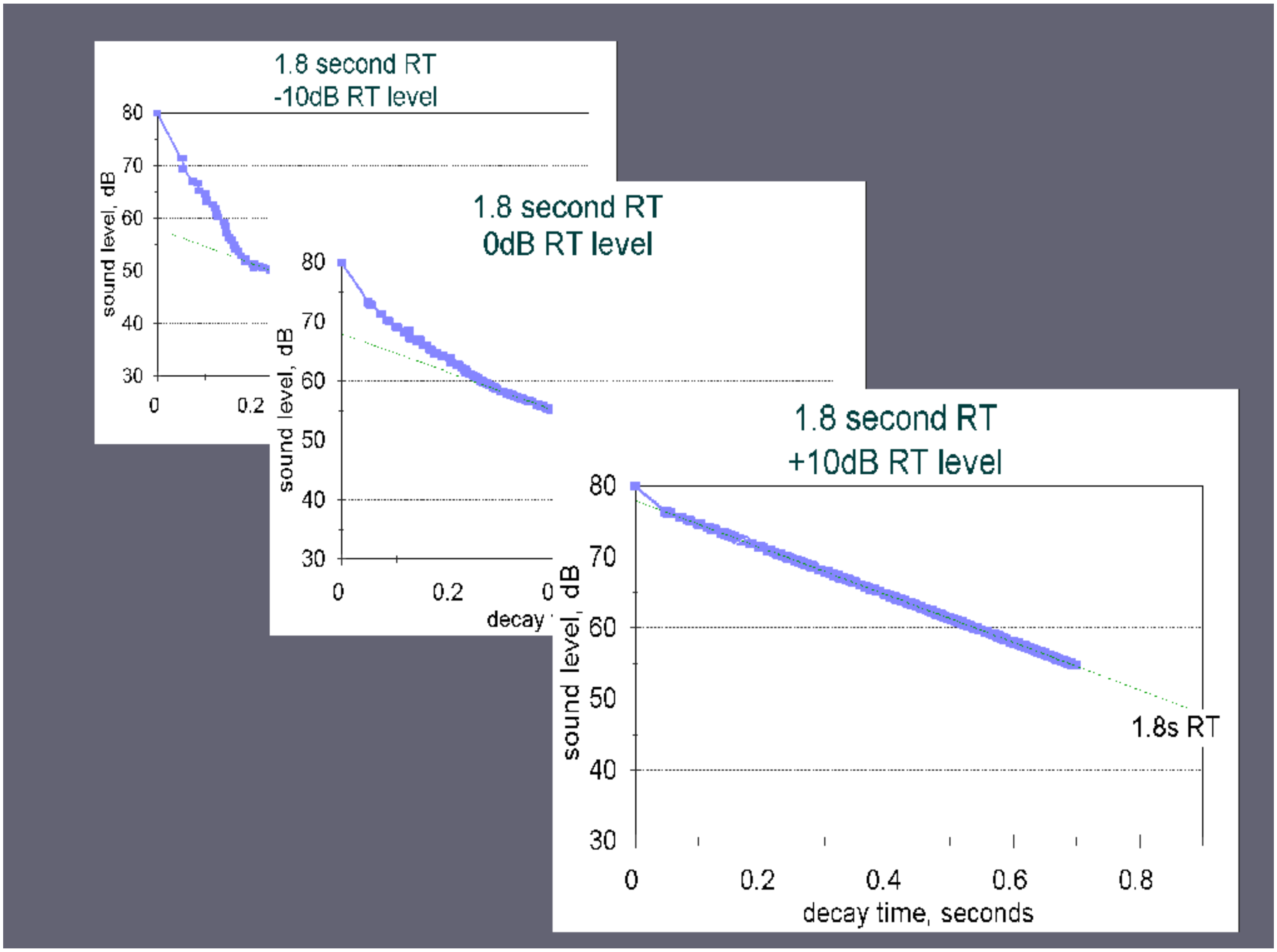
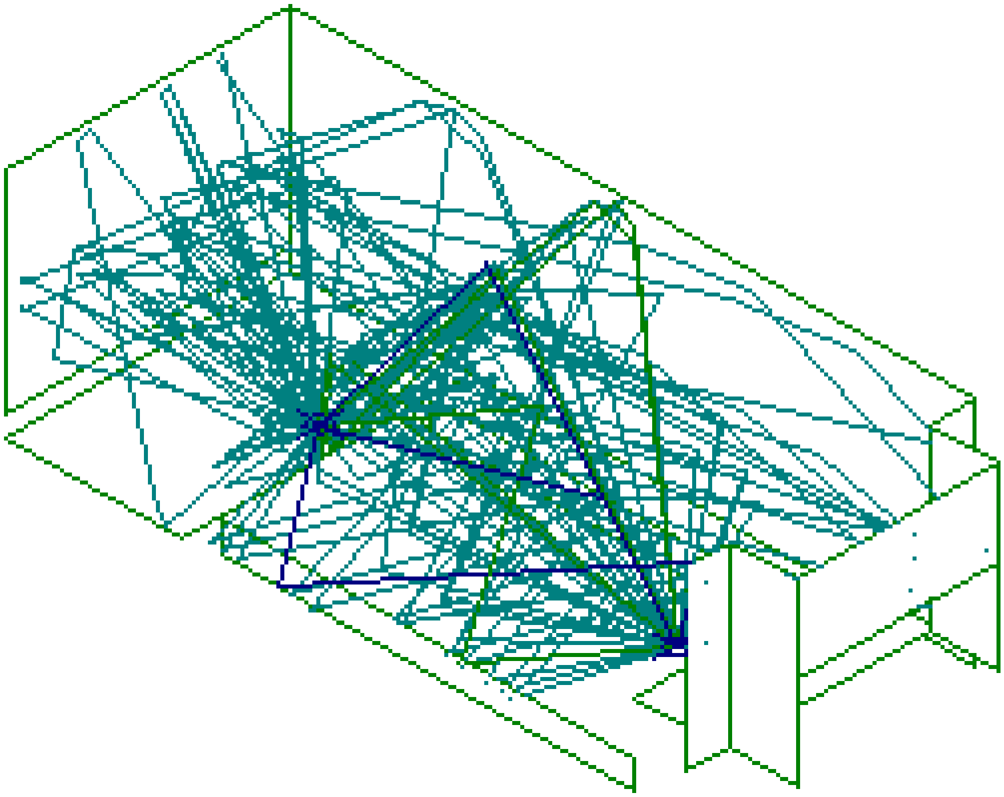


FIGURE 9 **Reverberance**



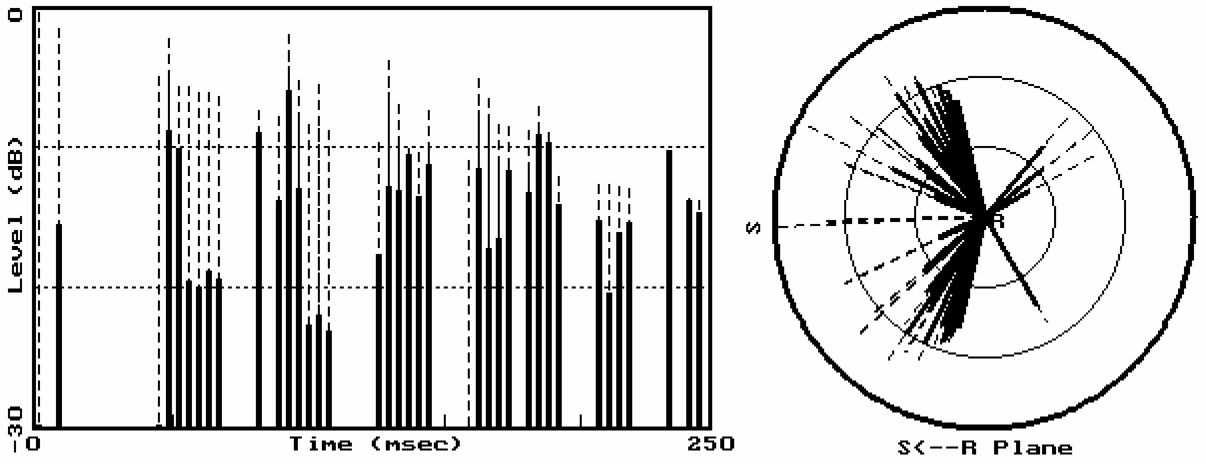


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FIGURE 10

Shoebox Hall, no balcony:
Rays, Echogram, Rose

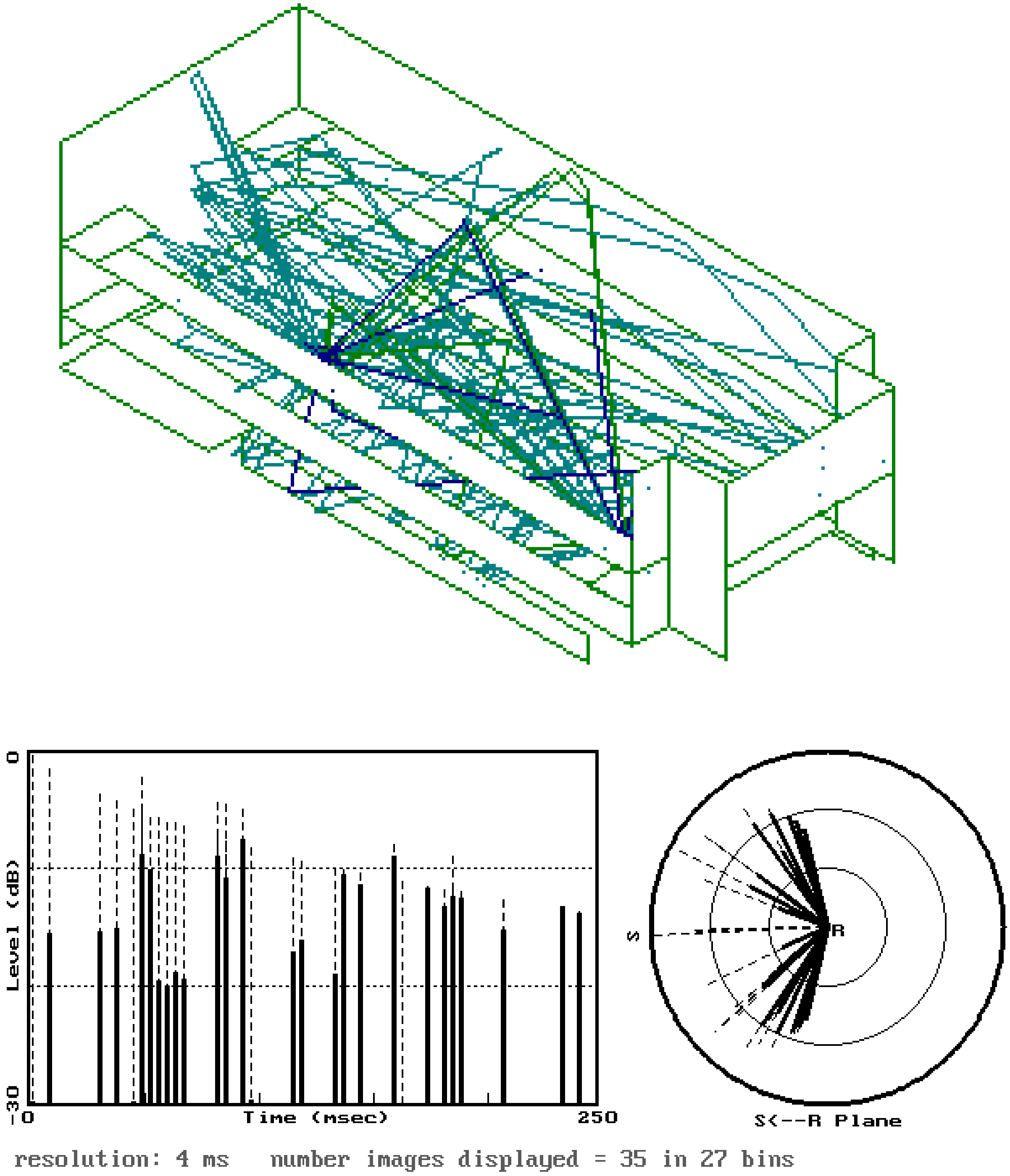

FIGURE 11

Shoebox Hall, 2 balconies:
Rays, Echogram, Rose

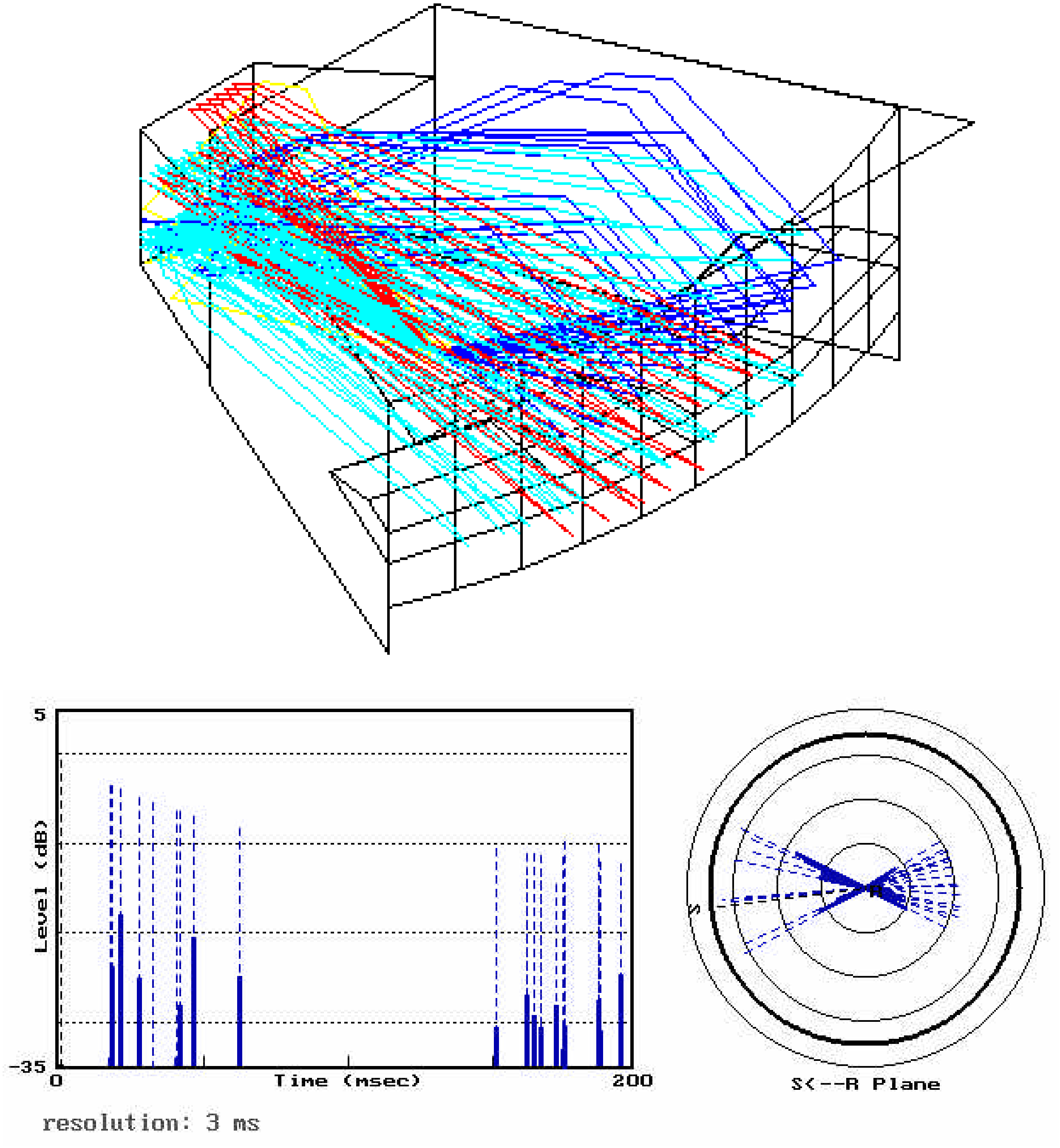

FIGURE 12 Fan-shaped Room: Rays, Echogram, Rose

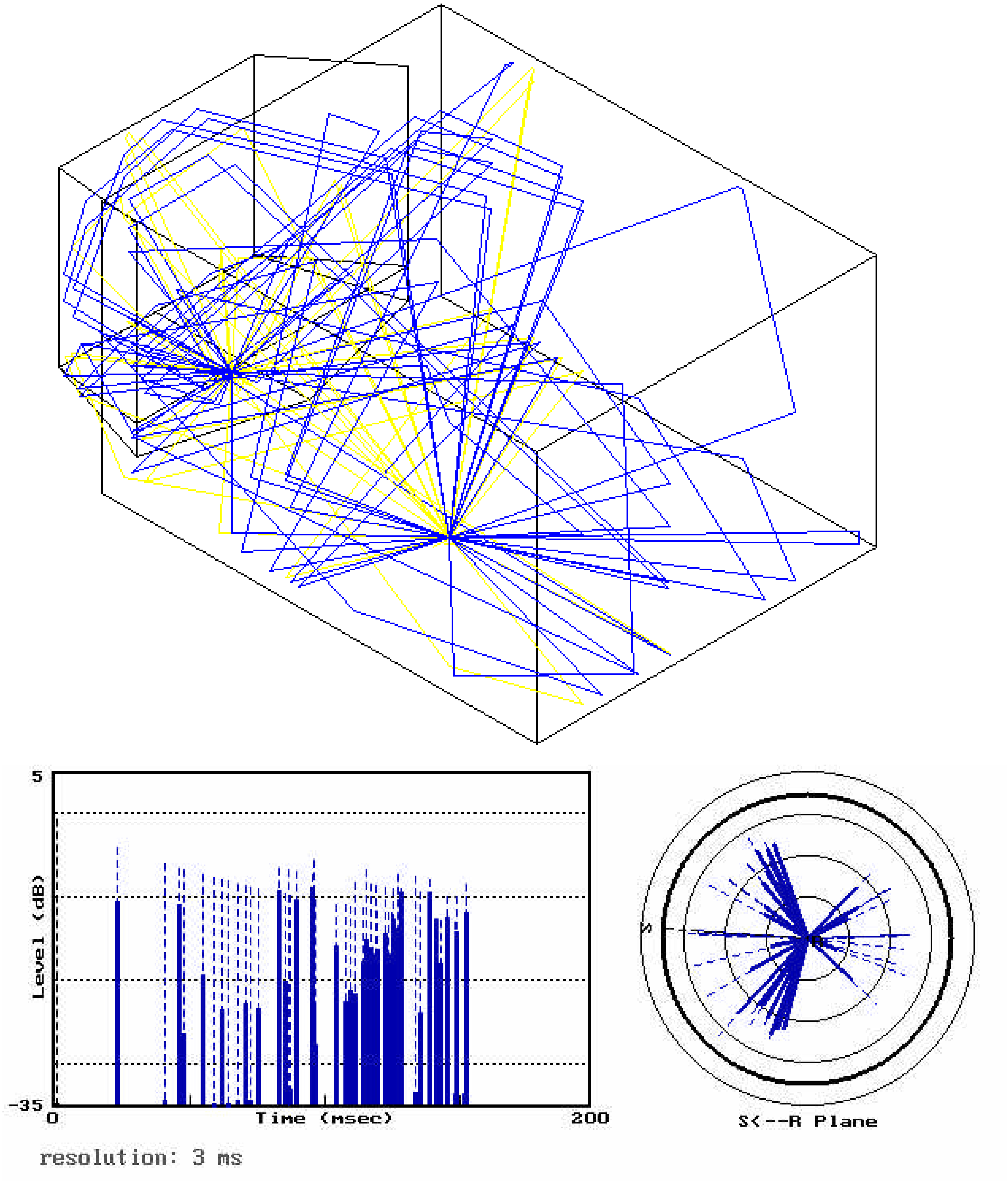

FIGURE 13

Rectangular Room, seat in center
Rays, Echogram, Rose

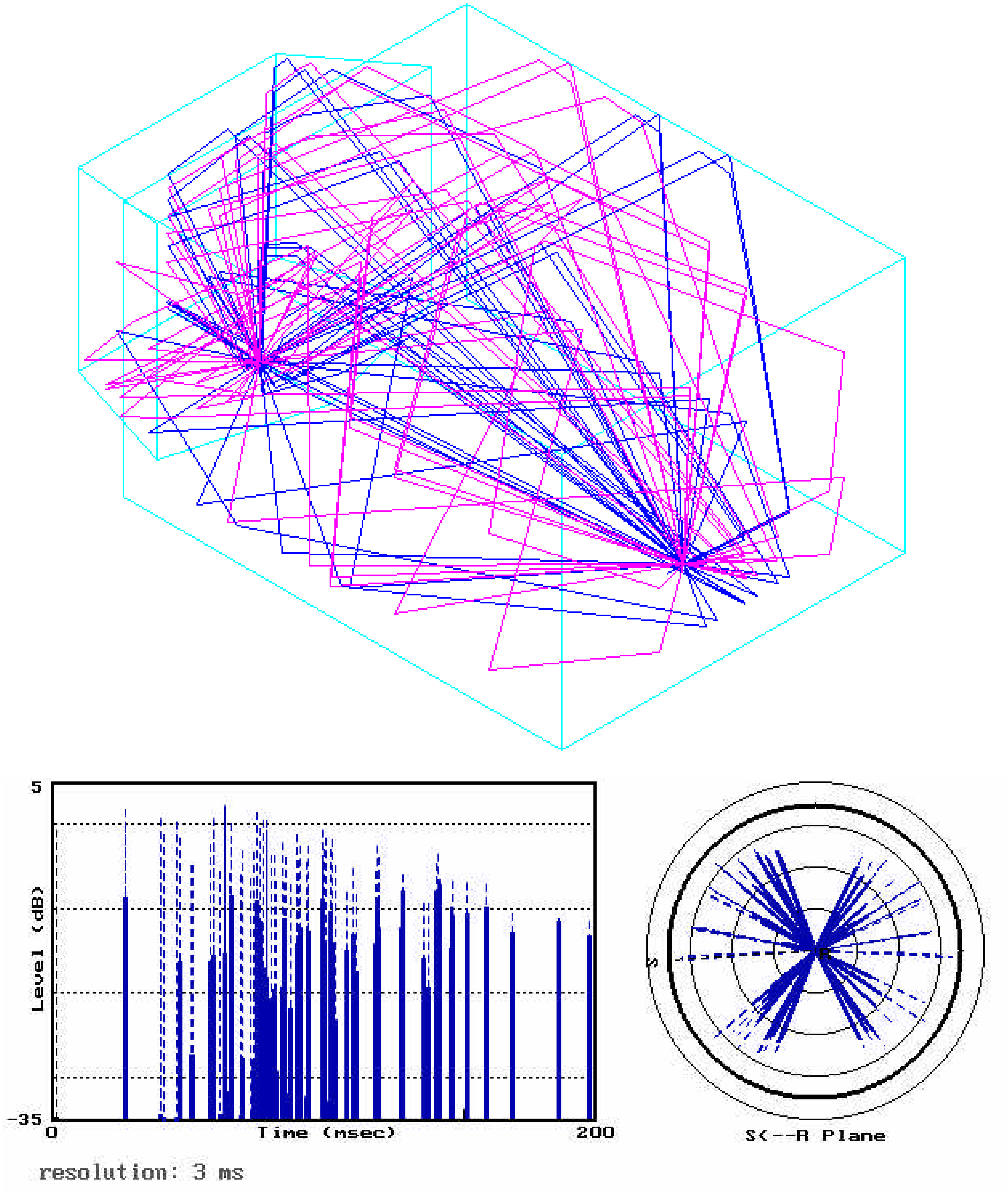

FIGURE 14 Rectangular Room, seat in rear
Rays, Echogram, Rose