Proceedings of the Institute of Acoustics

THE USE OF BINAURAL TECHNIQUES IN THE EVALUATION OF CONCERT HALL ACOUSTICS

P. H. Scarbrough

Jaffe Holden Scarbrough Acoustics, Norwalk, Connecticut USA

1. INTRODUCTION

Binaural recording, measurement and analysis techniques have been significantly improved over the past decade. The coupling of modern binaural recording heads with advanced computer-based signal analysis and processing equipment offers acoustical designers a valuable tool for use in both objective and subjective evaluation of concert hall acoustics. The author will review recent experiences in the use of binaural technology for such evaluations, focusing on specific examples of how the technology can be used to improve our understanding of the acoustical environment of these spaces. The specific halls which are studied include a 2300-seat multiple-use auditorium built in the late 1960's, and a 2700-seat symphony concert hall reconstructed in the mid-1970's.

2. THE BINAURAL SYSTEM

2.1 The Origin and Composition of the Present System.
The binaural technology employed in the case studies described below was developed by Dr. Klaus Genuit through the sponsorship of Daimler-Benz. It consists of several components:

2.1.1 A dummy head – the characteristics of which are based upon detailed studies of the response of the human head and ear, i.e. the hearing mechanism.

2.1.2 A record sub-system which implements a free field equalization of the dummy head signals to remove the influence of the outer ear transfer function for sources directly in front of the head. This provides compatibility with standard single microphone measurement techniques and also imparts loudspeaker compatibility to the recordings.

2.1.3 A digital audio tape recorder or similar low noise/wide dynamic range recording unit.

2.1.4 A playback sub-system with headphones, headphone amplifiers and equalisers to restore the binaural characteristics of signals presented to the listener.

2.1.5 A sophisticated two-channel digital signal analyser and processor which allows comprehensive time and frequency domain analysis of dummy head signals enables us to give non-directionalised signals full binaural imaging.

2.2 The Development of Binaural Testing in Concert Halls
The binaural system developed by Klaus Genuit and HEAD acoustics were initially conceived to study noise in automobiles. Five years ago, our firm began to experiment with the use of the system to evaluate concert hall acoustics. The positive results of these early efforts convinced us to integrate binaural testing into many of our projects. The advantages of this approach are as follows:

2.2.1 The system concept is fully compatible with single microphone measurement techniques. Traditional acoustical measurement and analysis practices are not compromised in the least.

2.2.2 The results obtained are often more insightful because the signals being analysed fully account for the subtle binaural response characteristics which distinguish the human hearing mechanism from single measurement microphones.

2.2.3 The system allows signal analysis which integrates sophisticated time/frequency domain study with the substantial analysis capabilities of the human ear-brain mechanism. For example, an impulse response can be examined to discover the location from which a particular reflection originates. This is accomplished by excising the reflection from the impulse response, inserting the reflection into a recording of room tone and presenting the results to one or more listeners. When the reflection is presented in isolation, the inter-aural time and frequency differences in the signals presented to both ears enable good listeners to determine the source location for many signals.

2.3 Applications for Binaural Testing
As a result of our work, we have found that the system has broad application in at least three areas of interest to acoustical and audio designers:

2.3.1 The objective measurement of acoustical characteristics in auditoria.

2.3.2 The subjective evaluation of acoustical characteristics in auditoria and the subjective impact of changes made to a particular environment.

2.3.3 The balancing, tuning and evaluation of electro-acoustic systems, especially electronic architecture systems.

2.3.4 The first two of these are discussed at greater length in the sections which follow.

3. APPLICATIONS AND RESULTS IN OBJECTIVE MEASUREMENTS

In 1990, our firm was engaged to evaluate the audience chamber and orchestra shell of a 2,300 seat multiple-use performance hall which was completed in 1969. Measurements were taken in the house and on-stage using both known acoustic test signals (pink noise and impulses) and music signals produced by the orchestra.

3.1 Conditions Tested
Several different conditions were studied:

3.1.1 The characteristics of the existing shell.

3.1.2 The characteristics of the shell after the hall's large pipe organ was lifted into its performance position at the rear of the shell

3.1.3 The impact of introducing absorptive and/or diffusive treatments in the shell.

3.2 Results
An analysis of the various tests produced many interesting and useful results:

3.2.1 The basic shell does not incorporate a sufficient amount of diffusion. This tends to blur the sound image received by musicians, making ensemble playing more difficult. Figures 1 and 2 illustrate this condition.

3.2.2 The construction of the shell panels apparently results in these units acting as low frequency absorbers of sound energy. This is thought to make a significant contribution to the perception of poor bass presence in the hall. The presence of the organ on-stage and the introduction of acoustic treatments significantly improves the acoustical environment by increasing the diffusiveness of the enclosure and decreasing the exposed area of the (low frequency) absorptive rear wall. Figure3 and 4 show the improvement in bass response.

3.2.3 The background noise in the hall exhibits audible amplitude modulations in the band below 100 Hz. This is the result of complex beating of several closely spaced and strong spectral components in the noise produced by the mechanical systems in the hall. Figure 5 illustrates this.

3.2.4 As a result of these measurements, we recommended that the orchestra shell be extensively modified or replaced. In addition, mechanical engineers have been instructed to examine the mechanical systems to reduce overall noise levels and to discover and attenuate the sources of the spectral components in the band below 100 Hz.

4. APPLICATIONS AND RESULTS IN SUBJECTIVE EVALUATIONS

In 1991, our firm was engaged to undertake a comprehensive evaluation of the stage acoustics of a major 2,700-seat concert hall in the Northeastern United States. This facility was built in the early 1960's and was substantially reconstructed in the mid-1970's.

4.1 Objectives of the Testing
The purpose of these tests was to evaluate both objectively and subjectively two significant changes to the stage area:

4.1.1 The introduction of new acoustical reflector panels suspended approximately 10 feet below the existing ceiling.

4.1.2 The introduction of more diffusion into the walls surrounding the orchestra.

4.2 Specifics of the Testing Process
The testing process was developed to allow ready comparisons between the results of the objective measurements and the preferential tests with a jury musicians from the orchestra. The test process is summarised below:

4.2.1 A series of measurements were taken with known acoustic test signals (pink noise and impulses) with the existing stage configuration.

4.2.2 Additional measurements were taken after the placing quadratic residue diffuser panels (QRD) around the perimeter of the stage enclosure.

4.2.3 Additional measurements were taken after the ceiling reflector panels were hung in place. The QRD panels were removed for this test.

4.2.4 A final set of measurements was taken with both the ceiling reflector panels and QRD panels in place.

4.2.5 The following day, the orchestra conducted two special test rehearsals, playing short segments of several works in each of the above described configurations.

4.2.6 A total of four dummy heads were used. Three of these were located on-stage while the fourth was placed in the center of the orchestra seating level in the house.

4.3 Objective Analysis Results
After all of the tests were completed, we analysed the objective measurements to discover the sources of musicians' complaints about problems with on-stage hearing and orchestral balances. The objective measurements of the existing stage revealed a number of conditions which we believed contributed to the on-stage hearing and orchestral balance problems:

4.3.1 There are strong, long delayed reflections from the rear wall of the hall which arrive back to the stage nearly 300 milliseconds after a sound is produced on-stage. Figures 6 and 7 shows this characteristic along with the improvement which results from the addition of the ceiling and QRD panels on-stage.

4.3.2 The design of the enclosure does not incorporate an adequate amount of diffusion. This is illustrated in Figure 6. The improvement achieved with the ceiling and QRD panels is shown in Figure 8.

4.3.3 The hall has a serious deficiency in bass frequency reverberation. This contributes to musician hearing problems by making the bass content of a musical passage extremely difficult to perceive on-stage [and in the house as well]. A comparison of Figures 9 and 10 will illustrate the magnitude of this deficiency.

4.3.4 The design of the rear wall of the stage emphasizes certain frequencies in the region of 6,500 Hz. Figure 11 shows this effect and the impact of introducing either the ceiling or QRD panels or both together.

4.4 Subjective Evaluation Method
Upon completion of the objective analysis, we used the editing capability of the analyser to prepare a series of jury tests in which samples of music from the different stage configurations could be presented to the musicians for quick comparison. In each of these tests, the musicians were presented with signals recorded from the same location (on-stage or in the house) using the same musical material (precisely the same measures of music were used in a particular comparison). Specific comparisons were tested more than once and configurations were presented in different order to ensure that results would not be biased by the order of presentation. All test were blind, i.e. musicians were not informed which configurations they were listening to in a comparison. Two sets of jury tests were conducted. In the first, 32 musicians participated, while in the second only 16 participated. A control group of 5 musicians who were familiar with the hall but who had not participated in the rehearsals was also tested.

4.5 Subjective Results and their Correlation with Objective Measures

We were pleased that the results of the jury test conformed with our expectations. The objective analysis led us to predict that the introduction of the ceiling reflector panels and the QRD panels together would produce the greatest subjective improvement in the quality of the sound on-stage. This was in fact the case, with musicians expressing a strong preference for the configuration with both the ceiling and QRD panels in place. When all of the recording positions were averaged, the margin of preference was rarely less than two-to-one in favor of the altered stage and at times the margin approached three-to-one. The results for the control group closely followed the preferences expressed by the orchestra musicians who had participated in the tests.

5. OTHER APPLICATIONS

In addition to the studies which we have undertaken with respect to architectural acoustics, we have also found the binaural system to be extremely valuable in the commissioning and documentation of new audio systems, particularly electronic architecture systems, i.e. those which are used to enhance a deficient architectural acoustical environment.

5.1 Tasks in Electro-acoustic Applications

The tasks for which we have employed these techniques include:

5.1.1 Equalization of loudspeaker elements to ensure that an overall system has a flat response.

5.1.2 Analysis of changes in system level and equalization adjustments to assess the success of a particular tuning approach.

5.1.3 Documentation of the final system results so that comparisons can be made during future inspections to ensure that a system is still performing to its original standards.

5.2 Potential Future Applications

We also see important new applications in the area of acoustics research. For example, numerous studies have recently been undertaken (many by members of this Institute) to understand better the issues related to speech intelligibility. We believe it would be insightful to repeat some of the practical experiments using binaural techniques to see what differences, if any, are produced. Should significantly different findings result, we may be forced to re-examine measurement techniques and establish new standards centered around the use of binaural measurements and analysis.

6. CONCLUSIONS

The latest generation of binaural technology does indeed offer significant advantages in the evaluation of acoustical phenomena. Chief among these advantages are the ability to correlate objective analysis with subjective evaluations, to conduct more reliable subjective testing and to study acoustical characteristics in a fashion which more closely mimics the way in which humans hear. We believe that the use of binaural testing will increasingly be seen as an essential part of any acoustical analysis.

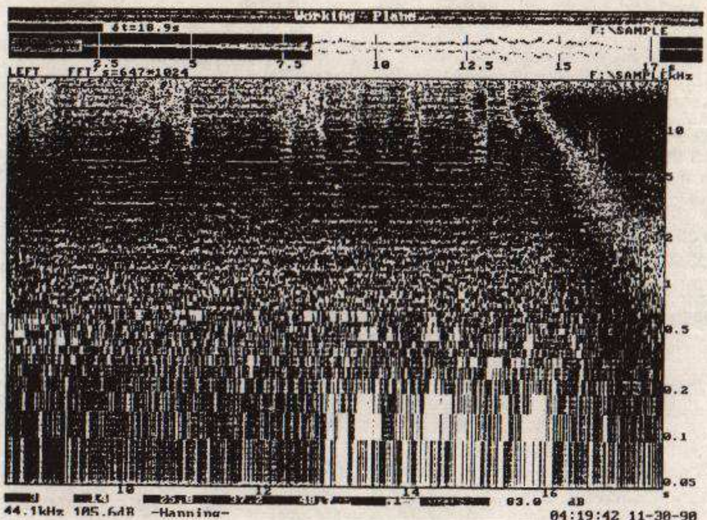


Figure 1

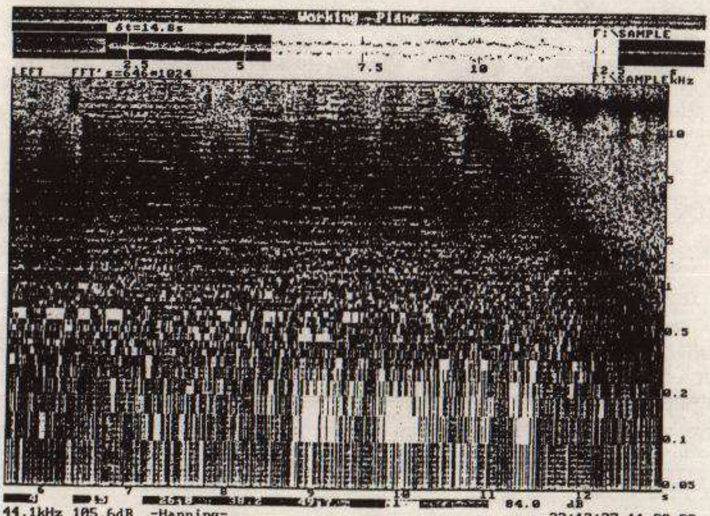


Figure 2

When one compares Figures 1 and 2, one will note less smearing at mid and high frequencies, indicative of greater musical clarity. The graph is a color spectrograph which shows time a the bottom axis, frequency in kHz along the vertical axis and amplitude in color. The source was orchestral music.

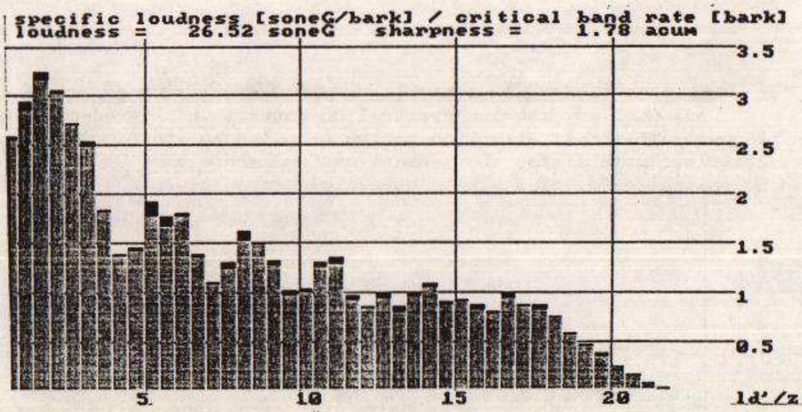


Figure 3
A graph of specific loudness of an impulse. In this measurement, the organ and absorptive treatments had been removed from the shell. The fall in loudness in the first two critical bands (far left side of the graph) can be readily seen.

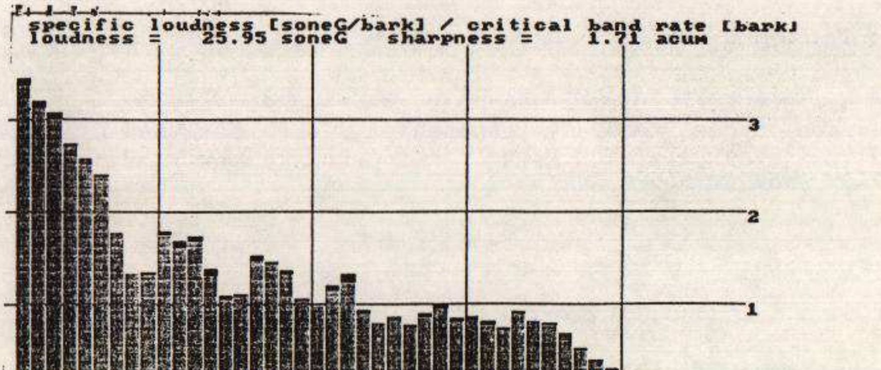


Figure 4
The impact of adding the pipe organ and absorptive treatments. Note the sharp improvement in loudness in the first two critical bands.

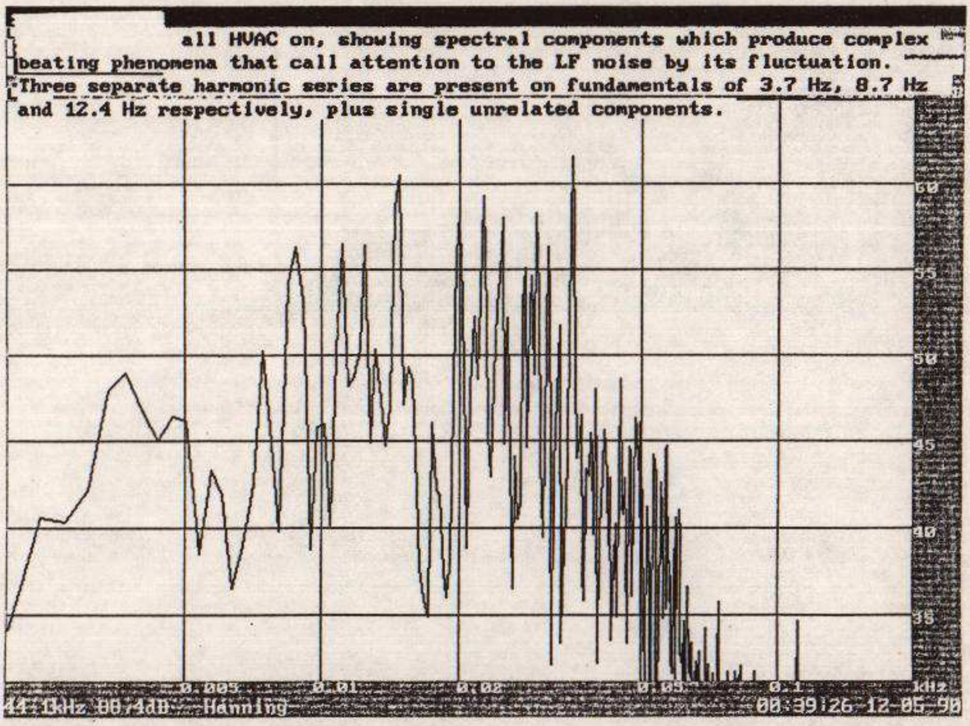
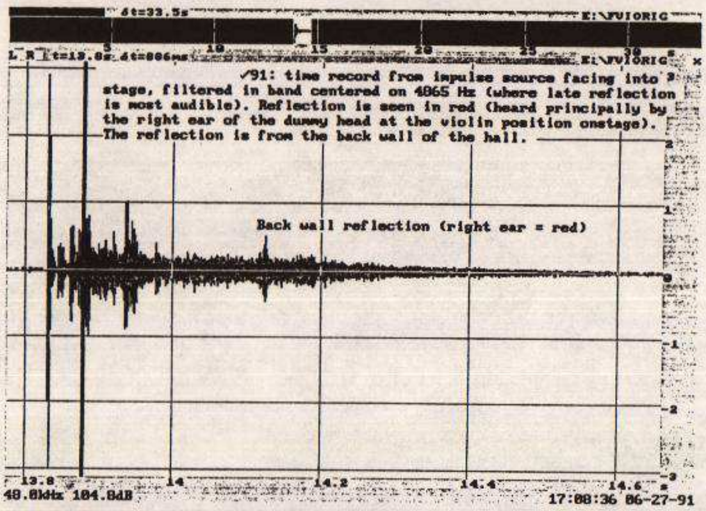


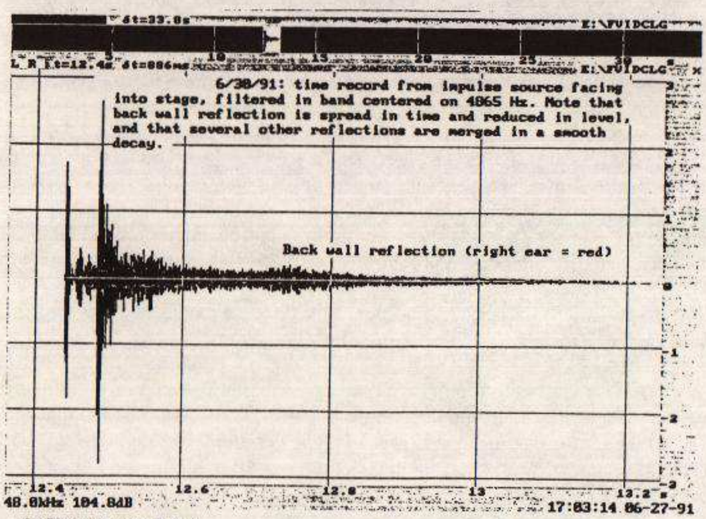
Figure 5
A graph of the frequency response of a sample of background noise in the hall. The range of frequencies illustrated are from below 5 Hz to above 100 Hz.



RELATING THE CHANGES TO ON-STAGE HEARING

The response of the stage and hall as heard at the violin position. Green spikes indicate sound energy which is heard by the left ear, red represents energy reaching the right ear, while yellow shows energy received at both ears. The first tall green pulse is the direct sound; the second tall pulse is a reflection from the rear wall of the stage; the third pulse is a reflection from the ceiling. The arrival time of this ceiling reflection is quite late with respect to the direct sound (approximately 109 milliseconds after the direct sound). There is also a discrete reflection or echo from the rear wall of the house (bright red spike) This arrives at about 292 milliseconds after the sound direct sound. Both of these conditions will denigrate on-stage hearing conditions.

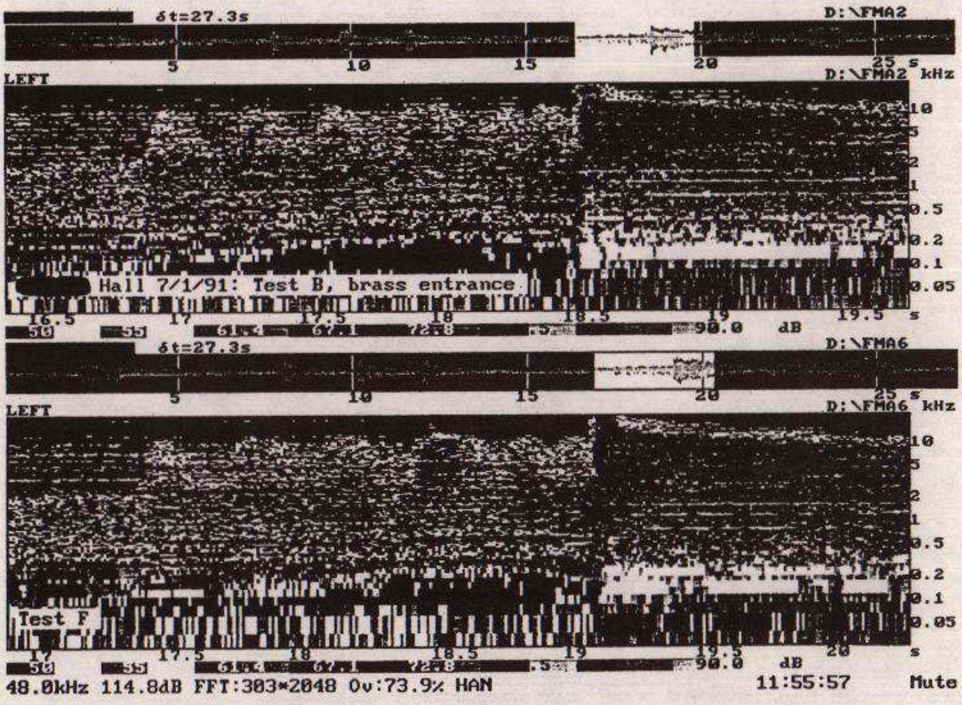
Figure 6



ON-STAGE HEARING–PART 4...

The impulse response after the introduction of the diffuser panels and lowered ceilings. The ceiling reflection is now smoothly blended with the other stage reflections and the total room decay. The strength of the echo from the rear wall of the house is reduced.

Figure 7



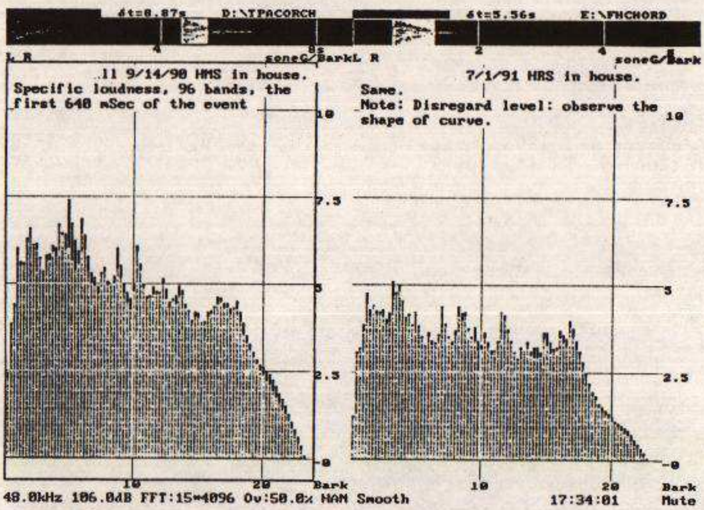
THE IMPACT ON MUSIC

The illustrations above, called spectrographs, illustrate time (along the bottom axis), frequency (along the vertical axis) and amplitude or volume (in color, according to the scale at the bottom). These particular graphs show a passage from the fourth movement of Mahler's *Symphony No. 1*, as recorded during two different stage set-ups. The specific passage illustrates a major entrance by the brass section. In the upper spectrograph, definition in the band around 5000 Hz. is significantly improved over that illustrated in the lower graph. Notice how one can easily see black between each attack in the upper graph. In the lower graph, the frequencies around 5000 Hz. are smeared. The area between each attack does not show much black, indicating reduced definition.

The upper spectrograph was from Test B, the stage with diffuser panels and lowered ceilings added. The lower graph was from Test F, the original stage condition.

Another interesting effect is also noticed in the comparison of these two samples. Even though the two graphs have the same time scale (time interval between divisions) and the first attacks are in line, one can see that the tempo is somewhat slower in the lower graph. Perhaps during Test F the conductor adjusted the tempo to compensate for the poorer listening conditions on the stage.

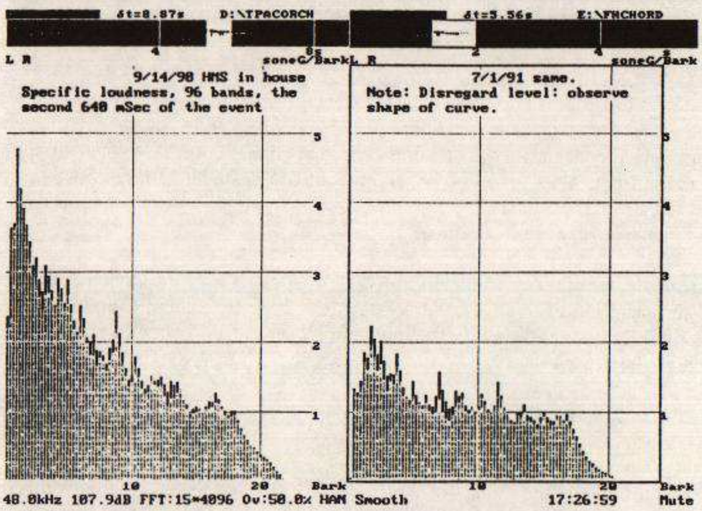
Figure 8



ANOTHER QUANTITATIVE VIEW OF THE LOW FREQUENCY DEFICIENCY

The graphs above are a measurement of the loudness of the two stop chords over a particular time interval. The test Hall is the right side. These graphs show the first 640 milliseconds of the stop chord decay (a little more than 1/2 of a second). In both halls the balance between low (left side of each graph), mid and high frequencies (right side of each graph) are comparable. This is illustrated by the fact that the shape of the two curves are nearly the same.

Figure 9

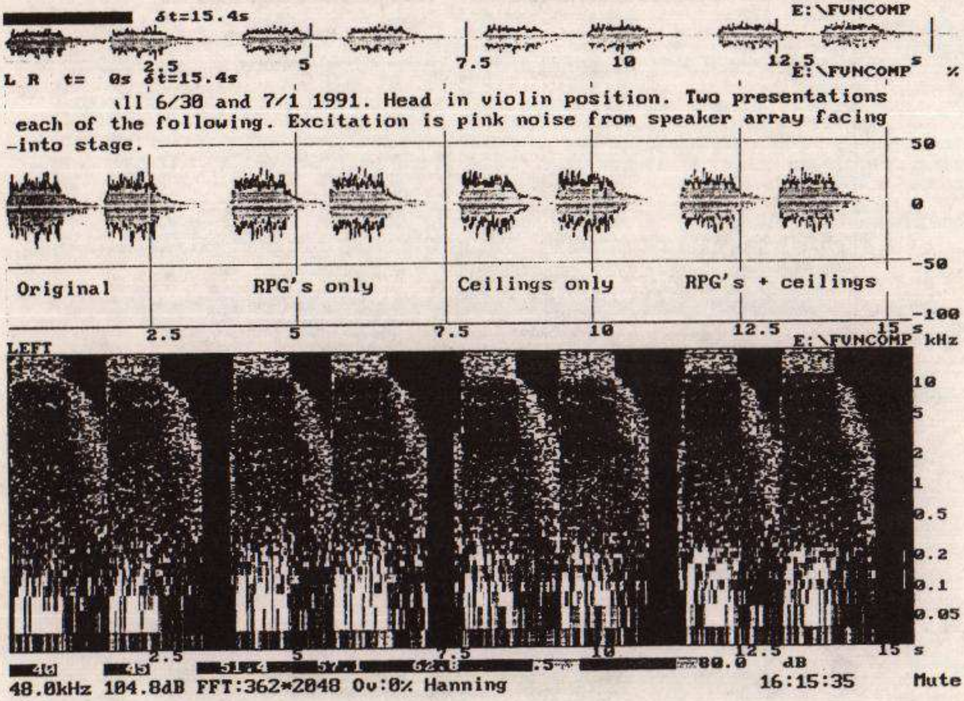


THE LOW FREQUENCY DEFICIENCY...

These graphs show the second 640 milliseconds of the stop chord decay. In these graphs, one can see how the lower frequencies are favored over the mid and high frequencies in the sample hall. This is distinctly different from the results in The test Hall where there is very little change in the balance between low, mid and high frequencies.

This emphasis in the low frequencies is one of the major characteristics which distinguish great concert halls from mediocre or poor halls.

Figure 10



A COMPARISON OF THE IMPACT OF CHANGES TO THE STAGE ENVELOPE

These spectrographs illustrate a comparison of the effect of each change to the stage. Two pink noise bursts are shown for each stage condition. At far left is the original stage condition. With a pink noise source on the stage, there is an emphasis (the pinkish red band near the top of the spectrograph) in the frequencies around 6500 Hz. (about G# in the 5th octave above middle C). This is perceived as a sharpness in the sound quality and contributes to the perceived overwhelming loudness of the brass section of the orchestra.

In the second example, the addition of the diffuser panels alone reduces the emphasis at 6500 Hz., but also increases energy in the octave bands centered on 2000 Hz. (about C at 3 octaves above middle C) and 4000 Hz. (about C at 4 octaves above middle C). Consequently, the perception of sharpness is actually increased.

The third example illustrates the impact of the lowered ceilings alone. The addition of the ceilings actually increases the emphasis of the frequencies at 6500 Hz.

At right is the graph showing the impact of the diffuser panels and lowered ceilings together. In this condition, the energy at 6500 Hz. is reduced while producing only a marginal increase in the energy at the 2000 and 4000 Hz. octave bands. These factors in combination actually result in a reduction of the perception of sharpness on stage.

Figure 11