Project Number: 41-1001

DESIGNING A PERFORMANCE ROOM

An Interactive Qualifying Project Report
submitted to the Faculty of
WORCESTER POLYTECHNIC INSTITUTE
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Degree of Bachelor of Science
by

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Abstract

This project involves finding and treating acoustical problems in a small studio space (WICN Radio) to improve its acoustic environment. The approach adopted was to consult professionals and literature in acoustics, set up a computer model of the acoustic problems, and run acoustical tests. The project concludes the presence of modal problems and an irregularly distributed reverberation time, which need to be addressed. Recommendations and analysis suggests the implementation of RPG Inc.'s Modex solutions complimented by a constructed performance stage.

Acknowledgements

It is impossible to complete a project such as this without an obvious indebtedness to Prof. Bianchi and Prof Campbell for their guidance. Our gratitude is also due to Prof. Falco for having introduced us all, to Kyle T. Warren and WICN Radio for the opportunity, to Joseph Chilorio and Mechanics Hall for the invaluable information, and to the EE MQP lab and workshop for the use of their facilities and equipment.

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1 INTRODUCTION

The studio space available at WICN Radio currently functions as a conference room and occasionally accommodates talk shows and interviews. WICN Radio intends to redesign the space to serve various functions such as recording and live broadcast. The current space lacks acoustical treatment for these purposes and requires attention to accommodate WICN's objectives. This project involves finding and treating acoustical problems in a small studio space (WICN Radio) to improve its acoustic environment.

We intend to provide WICN with a number of feasible and practical solutions along with projected costs and respective evaluations. With this project we anticipate to gain a good understanding and feel for the study of acoustics; in particular, that in relation to small listening/performance/recording studio spaces and various ways to enhance their acoustical appeal. The results of this project may be applied to home studios due to the similarities of the environment.

Familiarity with the study of acoustics in small listening/recording studios was accomplished by reviewing literature – books and articles written by audio engineers as well as acoustic software manuals, different types of acoustical analysis, architecture, acoustic materials, and theory.

Understanding that modal problems are most evident in smaller rooms which may also lead to uneven frequency responses and extended sound decays helped direct our investigation on certain acoustical properties (i.e. modal analysis, impulse response and reverberation)

The project starts by discussing previous studies in the field of acoustics. Then, an acoustical modeling program, CATT-Acoustic is utilized to simulate various solutions and theoretical results based on room specifications. Several practical experiments were conducted at the WICN performance room/studio space in order to confirm and acknowledge suspected acoustical problems.

Results obtained from simulated observations and theoretical conclusions are then outlined. Recommendations based on analysis and conclusions are then proposed to WICN Radio.

2 BACKGROUND

2.1 Acoustic Architecture

A room full of air behaves as a complex acoustical vibrating system. Understanding the room's resonance problems and behavior becomes critical.

What is a good studio space? There is only one criterion: the acceptability of the sound recorded in it by its intended audience. Sound within a studio space is composed both of direct and indirect sound. Direct sound denotes sound waves perceived by the receiver directly from its source. What follows immediately after the direct sound as a result from various "nonfree-field effects of an enclosed space"[i] is indirect sound. Indirect sound is also referred to as "studio response" or reflected sound.

Sound clarity within the enclosed studio space would be the optimal objective based on the behavior of the indirect sound. Sound waves are generated from a source and travel at a constant speed with frequency variations and different wavelength compositions. These wavelength compositions may pose as a problem depending on room dimensions. These compositions also known as modes or standing waves resonate with the room's natural frequency.

The spacing of these resonances becomes critical; avoiding signal energy boosts within a certain frequency range (usually low frequencies) is a requirement when during design. Room size determines the treatment of low frequencies. Larger rooms would result in support for lower frequency components, and smaller rooms would result in great spacing of room modes. The latter implies an abnormal boost in sound energy of the particular frequency.

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[i] Everest, F. Alton, *Master Handbook of Acoustics*

Studio proportions are decided based on modal distributions (further discussed in 3.1). Although extensive studies have been made on the subject, initial studio dimension design becomes a primary concern of acoustical architects and is decided during the actual physical construction of the space. Different dimensional ratios result in different modal distributions (over a frequency range).

This project is interested in introducing acoustical solutions respective to present problems in an existing studio space. The general discussion on room dimensions and its relevance to modal distributions establishes an introduction to the primary cause of modal problems faced evidently in WICN's performance room.

2.2 Acoustic Materials and Relevant Fire Codes

Acoustical treatment materials generally fall into three different categories. They are absorbers, diffusers, and resonators.

A material that allows air to pass through it will act as an absorber. This can consist of many different types of materials like open cell foam, fiberglass, mineral fiberwool, or acoustic ceiling tiles. Various characteristics like material used and thickness will determine how much sound energy it will absorb and at what frequencies.

Diffusers essentially work against absorbers. They generally reflect sound instead of absorbing it, and are used to change the direction and quality of sound that is reflected.

Resonators are effective low frequency absorbers made of semi-porous or rigid panels with an enclosed airspace behind it, which contain an absorptive material like fiberglass. Resonators are made out of diaphragmatic panels, for example plywood, and are usually designed and made during the construction of a listening or recording studio.

The fire codes for the materials used for acoustical treatment in an enclosed space are defined by the Massachusetts Fire Codes, 780 CMR, 6th Edition.[7]

The fire codes for thermal and sound insulating materials are defined in 780 CMR 722.0. Exposed installations should have a flame spread rating of less than 25 and a smoke developed rating of less than 450. Concealed installations, such as insulating materials, should have a flame spread rating less than 75, and a smoke developed rating less than 450.

The interior finish and trim codes of an enclosed space are defined in section 803.0 of the 780 CMR. Carpet and carpet-like wall coverings that have napped, tufted, looped, woven, or a similar type surface, must have a class I flame spread classification, and be installed only in rooms that have automatic sprinkler systems. The materials should also undergo fire exposure tests to show that it will not spread fire to the edge of the item or cause flashover. The next section of 780 CMR, 804.0, states that class II and class III interior finish materials that are thinner than .25 inch should be directly applied to a non combustible backing that provides a complete surface behind the finish.

Interior Hangings and Decorations, as explained in 780 CMR 807.0, should be noncombustible and or made to be flame resistant in accordance to the guidelines specified in section 807.2. The amount of noncombustible hangings is not limited; however flame resistant hangings should not exceed more than ten percent of the total surface area of the enclosed space.

For more specific and detailed fire codes, please refer to relevant sections of 780 CMR 6th Edition.

2.3 Modeling/Analysis Software

Acoustical modeling software allows engineers to initially design studio or room and have it analyzed and simulated before actual construction. These software packages generally require a 3-dimension CAD model used to represent the studio space intended for analysis. Other acoustical properties such as surface material absorption, diffusion, source and receiver variables are later assigned within the software itself. Auralization capabilities are dependent on the software package – the ability to sonify the room's properties to simulate actual experience before construction.

Acoustic modeling programs come in a wide array supported on a variety of platforms with varying costs. AcoustaCADD[ii] and CADP2[iii] are both MS-DOS based and expensive, (over $1000) and are distributed by Altec-Lansing and JBL respectively. Another DOS based acoustical simulation program is ODEON[iv] developed by the Department of Acoustic Technology (former Acoustics Laboratory) of the Technical University of Denmark along with six other Danish consulting companies in 1984. The program caters to a wide range of analysis capabilities and currently provides desktop auralization of predicted results. These programs were not used subject to availability.

CATT-Acoustic by Bengt-Inge Dalenback is a Windows based acoustic modeling program that features reliable predictions and a wide array of control. CATT-Acoustic features an AutoCAD™ type interface and allows the creation of room geometry in both CAD and CATT form. Several graphical examinations are provided such as the 3D geometry projection and reverberation decays. The program allows for a wide array of simulated acoustic measurements and predictions (except our most favored in this case – modal analysis) and also features desktop auralization functionality. The software

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[ii] Software package by Altec-Lansing, http://www.altec-lansing.com/

[iii] Distributed by JBL Professional, http://www.jblpro.com/

[iv] Danish based, Department of Acoustic Technology (former Acoustics Laboratory), Technical University of Denmark and six Danish consulting companies in 1984. http://www.dat.dtu.dk/~odeon/about.html/

package however is costly – well over $2000 per license. Prof. Campbell made the software available through the WPI's Electrical Engineering (EE) department and its labs, although usage was restricted.

JBL's SIA Smart[iii] and RPG Inc.'s RoomSizer were other acoustical analysis programs used by our team and made available to us by Prof. Campbell through the EE labs. These programs did not allow room modeling, but concentrated on impulse response and modal analysis respectively.

Other modeling programs available on the market include Bose Corporation's Modeller[v] for the Apple Macintosh and EASE by Renkus-Heinz, Inc. The MLSAA program was also considered for analyzing modal properties of a room and its reverberation times. However these, programs were ruled out subject to its availability.

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[v] Bose Corporation, http://www.bose.com/

3 Room Acoustics

3.1 Modal Frequencies

Any enclosed space contains a natural reverberation time. On the same level, all rooms have natural frequencies, or modal frequencies. When an input frequency matches a specific mode for an enclosed space, this input will be strongly reinforced, and a relatively loud sound will be heard. When this happens, a standing wave is created. When only considering two opposite walls, this happens when:

$$f_0 = 1{,}130 / 2L$$

where

1,130 = the speed of sound

L = the distance in feet between the two walls.

f_0 = the natural frequency

This natural reaction also occurs at multiples of the natural frequency. To the musician this type of response is not beneficiary, and usually requires modification to the room to aid the problem.

Modal frequencies are completely dependent on the dimensions of a space. Modes can exist not only between parallel walls, but also can include up to 6 different surfaces. Axial modes involve opposite walls. Tangential modes include four different surfaces. And finally Oblique modes include all six walls in the enclosed space. Modal frequencies can be predicted using the following mathematical equation developed by Raleigh:

$$Frequency = (c / 2) * sqrt((p^2/L^2) + (q^2/W^2) + (r^2/H^2))$$

where:

c = speed of sound = 1130 ft/sec

L,W,H = room length, width, and height

p, q, r = integers 0,1,2,3…

There are three different types of modal frequencies, axial, tangential, and oblique. An axial mode will include two walls. A tangential mode will include four walls, and an oblique mode, all six walls of a room. To determine if a calculated frequency is either axial, tangential, or oblique, the values of p, q, and r need to be analyzed. If two of the pqr values are zero, then the mode is axial. If one is zero, then it is tangential, and if all of them are nonzero, then it is an oblique mode. There is one constraint to the modal frequency equation. It can only deal with perfectly rectangular rooms. If two walls are parallel then the modal frequencies can be calculated accurately. However, if two walls are not parallel, then the average distance has to be taken between them, and used as the width or length instead.

The calculated modal frequencies should be evaluated in an experimental setup afterwards. This can be done in many different ways. Two simple methods are an impulse response test, or a sine wave oscillator test. Both will give fairly accurate representations of the various axial, tangential, and oblique modes in any given space. The sine wave test involves sweeping a sine wave generator through multiple frequencies, and physically listening for response peaks. The impulse response test is slightly more complicated.

The impulse response test involves setting up a microphone and a speaker in the space at various locations. Impulses are outputted through the speaker and the reaction of the room is recorded into wave sound files on a computer. The Fourier Transform is performed on the wave files to analyze it in the frequency domain. Spikes in the frequency domain denote modal frequencies. This data can be compared to the calculated modes, and results found in the sine wave generator test. An example of a waveform in the frequency domain is shown in Figure 1.

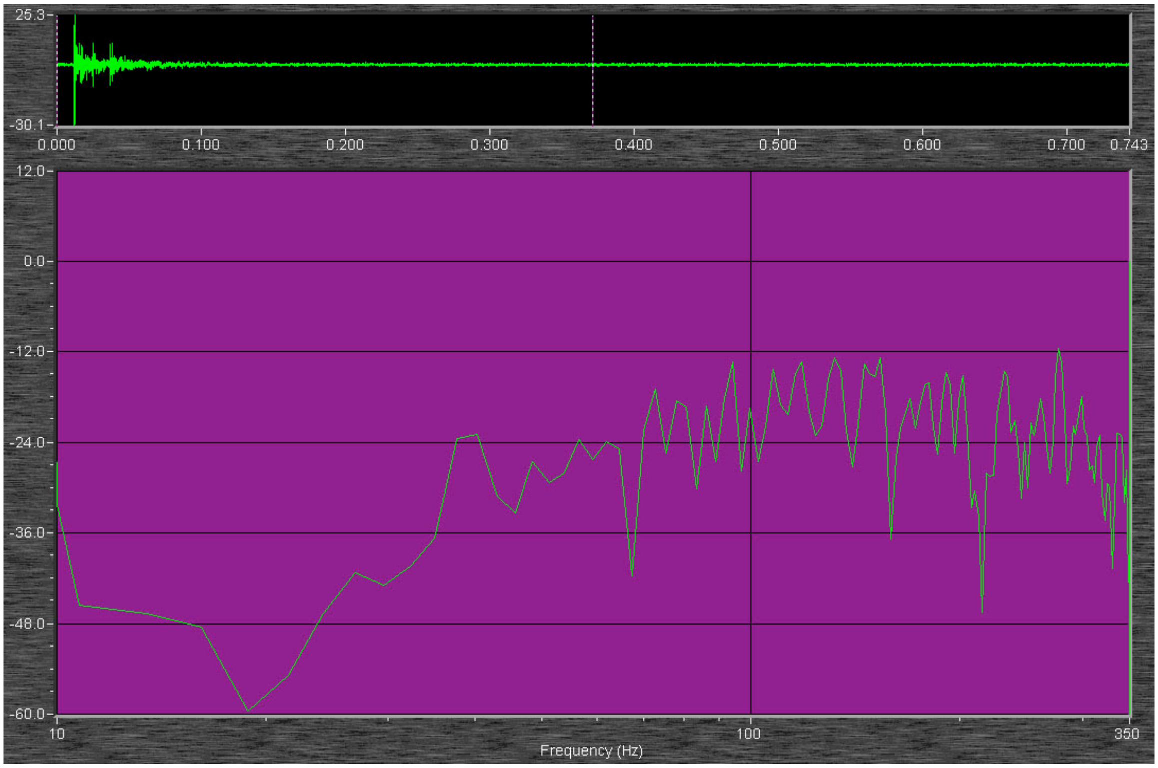


Figure 1 Example of a waveform in the frequency domain shown in SIA Smart.

Once the data are analyzed, problematic frequency ranges can be indicated. These ranges usually contain an abundant number of modes. This will cause unwanted feedback, which consists of a relatively loud reinforced sound when a musician is performing in these ranges. This could cause other sounds to be drawn out, or simply sound unorthodox.

3.2 Absorption

Sound is defined as the vibration energy of air particles. When this sound wave comes in contact with a wall, its energy is dissipated in the form of heat. This heat loss is coupled with the reflected component of the sound wave, which is directed away from the wall. There will also be a certain amount of sound energy that seeps into the wall. The amount of sound energy that is absorbed is determined by the material of the wall. As the sound wave continues to strike various walls, more of its energy is absorbed and the reflected component becomes weaker and weaker.

The magnitude of sound absorption any material has is determined by its absorption coefficient. If, for example, a wall has an absorption coefficient of 0.45, then it absorbs 45 percent of the sound energy. This material has .45 sabins of absorption per square foot. The absorption coefficient of a material will vary according to the frequency and the angle at which the sound wave strikes it. Since the direction of sound is virtually infinite in all directions, the average absorption coefficient relating to all possible angles needs to be taken. There are two different types of absorption coefficients, one based on the arithmetic mean reflection coefficient, and the other on the geometric mean reflection coefficient. Both are two different ways of analyzing the absorption of a material. Their relation can be seen using the following equation:

$$a = -\log_e (1 - \alpha)$$

where:

a = Sabine absorption coefficient (arithmetic mean)

α = energy absorption coefficient (geometric mean)

When a specific absorption coefficient is discussed, it will refer to the Sabine coefficient, otherwise known as the arithmetic mean. Aside from the following relation shown above, there are many other factors that contribute in determining the overall absorption coefficient of a material.

The thickness of a material has varying effect on sound absorption. At low frequencies, generally below 500 Hz, absorption is increased depending on how much thicker the material was made. Absorption increases proportionally to increases in thickness. However, at frequencies greater than 500 Hz, absorption remains relatively unaffected by changes in thickness. Increasing airspace behind an absorbent has similar effects to changing thickness. By widening the gap between the absorbent and the wall, low frequency absorption is raised. Unlike increasing airspace and thickness of a material, changing the density has little effect on the absorption coefficient.

Carpet provides many problems acoustically for enclosed spaces. One main issue is the uneven absorption at a range of frequencies. While it may provide a high absorption coefficient at higher frequencies, it gives weak absorption at lower frequencies. To aid this problem, usually an added low frequency absorber must be placed in the space. Another issue to deal with is the difficulty in determining the absorption coefficient of carpet. Since so many different types and kinds exist, a specific coefficient is hard to find.

Similar to carpet, the sound absorption by people poses many problems. The physical sound absorption by a person is extremely difficult to calculate, and include in absorption coefficient calculations. Knowledge of aspects like the type of people or what clothes they wear are all key to determining how much a person will absorb sound. Only relative estimates can be determined and used.

3.3 Reverberation

Reverberation refers to a room's natural decay. When a musician stops performing in an enclosed space, the time it takes for the sound level in the room to become inaudible is called the reverberation time. This natural resonance is an important factor in determining the acoustical quality in a room. There is a thin line in determining an optimum reverberation time. It is often left to personal opinion; however an extremely short or long reverberation time can contribute to several negative side effects.

A short reverberation time implies there is a high amount of absorption in the room, while a long reverberation time means that there is a low amount of absorption in the room. Too much absorption is often referred to being "too dry" of an atmosphere, and the later "too wet." Again, it is up to the listener to determine if either of the two conditions are true. For speech, a relatively short reverberation time is ideal. High absorption results in speech being more intelligible, allowing separate consonants to be more understandable. If the absorption in a room is decreased, increasing the reverb time, there is the chance that previous consonants will mask the ones that follow it, creating impairment in the intelligibility in speech. However, determining an ideal reverberation time in music depends on many more factors.

The type of music being played is one of the more important characteristics of finding an optimum reverberation time. Also involved is the size of the room being played in. For example, a large church which plays melodic, slow paced music such as organ music would be better suited with a long reverberation time. However a smaller church, which mainly deals with speech sermons, would be better suited to have a shorter reverberation time. In general, the optimum reverberation time will increase on a semi-linear scale as the volume of the room increases. The current reverb time of a space can be estimated using the Sabine equation.

Sabine developed a universal reverberation time equation, RT60, relating to the volume, surface area, and absorption of a space.

$$RT60 = (0.049 * V) / Sa$$

where

RT60 = reverberation time, seconds

V = Volume of room, cubic feet

S = total surface area of room, square feet

a = average absorption coefficient of room surfaces

Sa = total absorption, Sabins

RT60 refers to the time it takes the sound level in the room to decay by 60db. This equation can be used to determine an approximate reverberation time, however to be accurate, physical tests have to be done on the space. This can be done with a simple amplified pink noise generator, and a non-directional microphone, placed at ear height, connected to a tape recorder. An example of a setup is shown in Figure 2

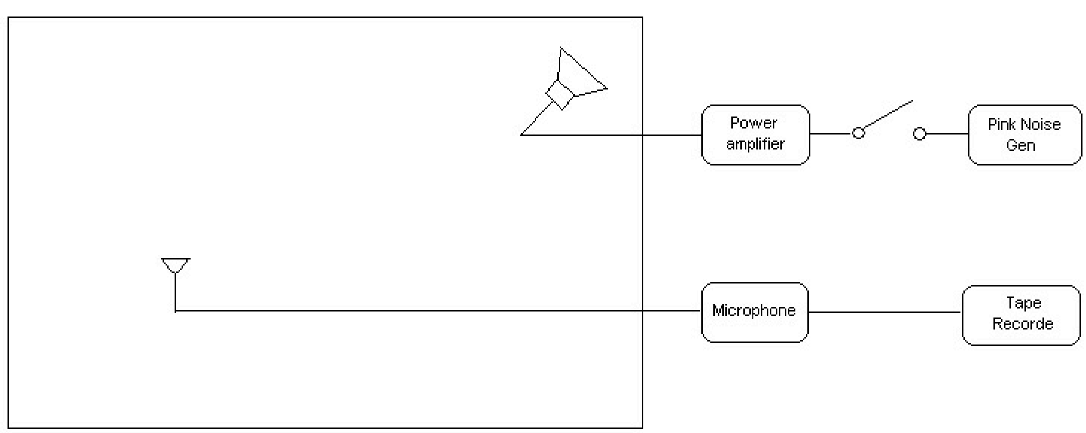


Figure 2 Simple setup to measure RT60 values in a room

When the switch is closed the room is filled with pink noise. When it is opened, the microphone records the sound decay. The tape recorder then picks up this decay and records it to be analyzed. Once a pretty close real reverberation time of a space is computed, it can then be shortened or lengthened according to the type of music being played in many ways. For example if a completely bare room (lined with concrete walls) is used for jazz, the reverberation time will be too short for the performance to sound adequate. The average absorption of the room should be decreased to increase sound quality. Wood has a lower absorption coefficient than concrete. So if a wood stage were built in the space, the average absorption coefficient of the room would fall. And according to Sabine's equation, the overall reverberation time would increase because it is inversely proportional to the average absorption coefficient.

There is no pre-determined ideal reverberation time for every situation. However, through analysis of the current reverb time of a space, an optimum time can be established through the judgment of the individual making the decision.

Table 1 illustrates a sample table with list of absorption coefficients with respect to various acoustic materials.

Material	Thickness, inches	Mounting**	Frequency						Author*
			128	256	512	1,024	2,048	4,096	
			Coefficient						
Corkhoustic B-5	1 ½	2	0.08	0.41	0.70	0.51	0.58	0.65	A.M.A.
Cushiontone A-3	7/8	2	0.17	0.51	0.73	0.95	0.75	0.72	A.M.A.
Sanacoustic pad with metal facing	1 1/8	3	0.25	0.56	0.99	0.99	0.91	0.82	A.M.A.
Fibretex	13/16	2	0.16	0.49	0.56	0.78	0.84	0.78	A.M.A.
Acoustex 40R	¾	2	0.09	0.17	0.59	0.90	0.75	0.73	A.M.A.
Fiberglas tile Type A	1	2	0.17	0.44	0.91	0.99	0.82	0.77	A.M.A.
Acoustone F	13/16	1	0.12	0.31	0.85	0.88	0.75	0.75	A.M.A.
Acousti-Celotex C-4	1¼	2	0.25	0.58	0.99	0.75	0.58	0.50	A.M.A.
Draperies hung straight, in contact with wall, cotton fabric, 10 ounces per square yard	--	--	0.04	0.05	0.11	0.18	0.30	0.44	P.S.
Same as above, but velour, 18 ounces per square yard	--	--	0.05	0.12	0.35	0.45	0.40	0.44	P.S.
Same as above, hung 4 inches from wall	--	--	0.09	0.33	0.45	0.52	0.50	0.44	P.S.
Felt, all hair, contact with wall	--	--	0.13	0.41	0.56	0.69	0.65	0.49	P.S.
Rock wool	1	--	0.35	0.49	0.63	0.80	0.83	--	V.K.
Carpet, on concrete	0.4	--	0.09	0.08	0.21	0.26	0.27	0.37	B.R.
Carpet, on 1/8-inch felt, on concrete	0.4	--	0.11	0.14	0.37	0.43	0.27	0.27	B.R.
Concrete, unpainted	--	--	0.010	0.012	0.016	0.019	0.023	0.035	V.K.
Wood sheeting, pine	0.8	--	0.10	0.11	0.10	0.08	0.08	0.11	W.S.
Brick wall, painted	--	--	0.012	0.013	0.017	0.020	0.023	0.025	W.S.
Plaster, lime on wood lath on wood studs, rough finish	½	--	0.039	0.056	0.061	0.089	0.054	0.070	P.S.
Individual object	**Absorption units, square foot (sabins)**								
Audience, per person, man with coat	--	--	2.3	3.2	4.8	6.2	7.6	7.0	B.S.
Auditorium chairs, solid seat and back	--	--	0.15	0.22	0.25	0.28	0.50	--	P.S.
Auditorium chairs, upholstered	--	--	--	3.1	3.0	3.2	3.4	--	F.W.

Table 1 Sample table of absorption coefficients[vi]

[vi] *Modern Recording Techniques*, David Miles Huber and Robert E. Runstein

3.4 Interview with Joseph Chilorio

[vii]On June 20, we had the opportunity to visit the recording studio in Mechanics Hall with Joseph Chilorio (Facilities Manager at Mechanics Hall). We were given detailed information on the small listening room as well as the monitoring room of the studios used for concert recordings. Mr. Chilorio gave us a few pointers to look out for while conducting our project with WICN.

The most important thing initially is that the studio space should be uncolored or sonically neutral. This means in the basis of what you hear is what you get. Diffusion in the listening room space (which is about the size of our performance room at WICN) is clean and clear. The size of the room in particular is approximately 15 by 21 feet. The listening room has about a 0.25 - 0.30 seconds reverberation time and generally absorbs all frequencies just about evenly; he indicated that this was ideal.

Issues that were taken into consideration during its design stages were (1) over absorption, (2) under absorptions, and (3) a matter of case of absorption vs. frequency. We were also directed to study and take note of the Sabine equation.

He then proceeded to give us explanations on the functionality of the acoustics of the materials present in the room.

The white panels on the front of the studio absorbed frequencies above 4000Hz. half the sound gets reflected back at frequencies below 1000Hz. The panels are composed of sonic acoustical foam. This material basically acted as a high frequency absorber with some reflection on the lower range.

[vii] Studio photograph from Mechanics Hall home page, http://www.mechanicshall.com

The ceiling tiles were made to absorb well at frequencies above 5000Hz but less absorptive at lower/mid frequencies. At really low frequencies (i.e. Less than 30Hz) the ceiling absorb, demonstrating a diaphragm effect resulting in efficient absorption within the low frequency range.

The floor was made of oak parquet on concrete. This was basically a hard floor with no absorption (about less than 1/1000 Sabine). If Mr. Chilorio had had his way, he would have had the floor float on a small carpet of air and springs to absorb building noise. This however would be an expensive solution and might not be viewed to be critical in a project room of this size.

The poly cubes on the wall were used to improve diffusion and scatter sounds in different ways. It also provided low-mid frequency absorption. It has a thin membrane as an effect of the material. Mr. Chilorio stresses here that this acoustic material plays an important role with the acoustics of the human voice/speech.

The slat panels located near the rear corner of the studio was made of wooden panel with an air space about 4" deep. Slits in the wood were about 1/8" apart which meant a sharp absorption at ~190Hz according to Mr. Chilorio. On the other side of the slats was a thick piece of insulation to broaden the frequency range. The reason slat absorbers were usually located in rear corners are that low frequencies tend to collect within this area. (A solution that we are considering for our project)

[viii]Windows in the studio do not have a parallel pane so that sounds do not directly reflect back straight into the room, but instead, goes off in a tangent. The window is located in between the listening room and the control room. Absorbent foam in between the panes serve as insulation to help with some absorption. (This is also evident in WICN).

[viii] Control room photograph from Mechanics Hall home page, http://www.mechanicshall.com

Studio walls were made of sheet rock. Not a lot of coupling and each wall consisted of 3 floating walls inside, between studio and the control room. The door in this case has a frame made of rubber sealing on the sides to prevent leakage of noise from the hallway.

Background noise can be problematic especially when recordings tend to pay attention to the finest detail. The cooling system in Mechanics Hall, was chosen with noise issues taken at hand. Moderate air volume flow was used to decrease noise pollution. Although, small amounts of air with reasonably low temperatures were used to achieve the same cooling effects as conventional vents at a quiet rate.

No fluorescent lights were used because they have buzz or a sing. Softer down lights were in favor, and dimmers were used with a sine wave transformer, in order to reduce the filament sing of the lights.

Mr. Chilorio noted that the WICN performance room was designed with a good dimension ratio and he recalls – 1.0 ceiling, 1.6 width, 2.33 length. Reasons for this are so that the standing waves are evenly spaced and all frequencies are flat. If the walls were to be designed parallel to each other, it would induce problems with standing waves. However, when bent (such in our case), the waves goes off in a tangent, which is generally desirable.

He suggested that since the space would be used for live jazz bands, we might want to consider including a drum booth or a drum shield of some sort. Drum isolation can be very important in a small space, especially if the studio wishes to further use the studio space for recording liver performances.

Modal analysis for small rooms such as these is important, as stressed by everyone in the business. Finally, Mr. Chilorio provided us with some handouts on some of Mechanics Hall's MLSSA tests results and modal analysis as done with Prof. Campbell quite awhile ago which is available in the appendix.

3.5 What's best for Jazz Musicians?

Not many halls have been designed specifically for the needs of jazz music. Acoustical attributes of a certain space are adjusted relative to subjective taste. Jazz music is tight in a sense that its musicians/band members are "locked together in a strong groove" which must be appreciated by members of the audience. For this reason, any space that is intended for use of jazz performances should be designed with clarity of tone (where blending of successive notes must be avoided). It has to be clean, articulate and smooth. Every beat from the bassist must be distinct, every slice of the drummer's high-hat must be audible, a certain minimal sustain of chords should also be realized (different from those sustains intentionally created from the musician himself) [1]. To summarize, jazz music can often be considered a technical music, with a large number of notes reaching the listeners in a short period of time. With this, the indirect sounds of the room (acoustical properties of the space) must not overpower the musicians.

Jazz music appears to be greatly appreciated in an acoustically intimate place - that is a place where clarity is strong but large enough to contain some reverberation. Reverb time lengths may not be as problematic as its decay rate. That is to say that each reverberation is significantly softer than that of the previous, hence drowning or any other sort of interference between notes would not affect its clarity. Ultimately, initial time delay gaps are important in the design of a room of this use. This is the difference in time in arrival of the direct sound and the first indirect sound (reflected). Room size and dimensions will now play an important role contributing to this factor. Jazz musicians would prefer a shorter impulse response as opposed to that of larger concert halls. Clarity within the space is optimum.

4 METHODOLOGY

4.1 CATT Acoustic Simulation & Analysis

To help us understand of the room's problems, we used CATT-Acoustic to help simulate problems and solutions for our studio space. We used CATT-Acoustic to draw a basic plan of the empty studio, being stripped down to the bare minimum to allow us to first analyze and simulate its minimal absorption properties and natural room acoustical responses.

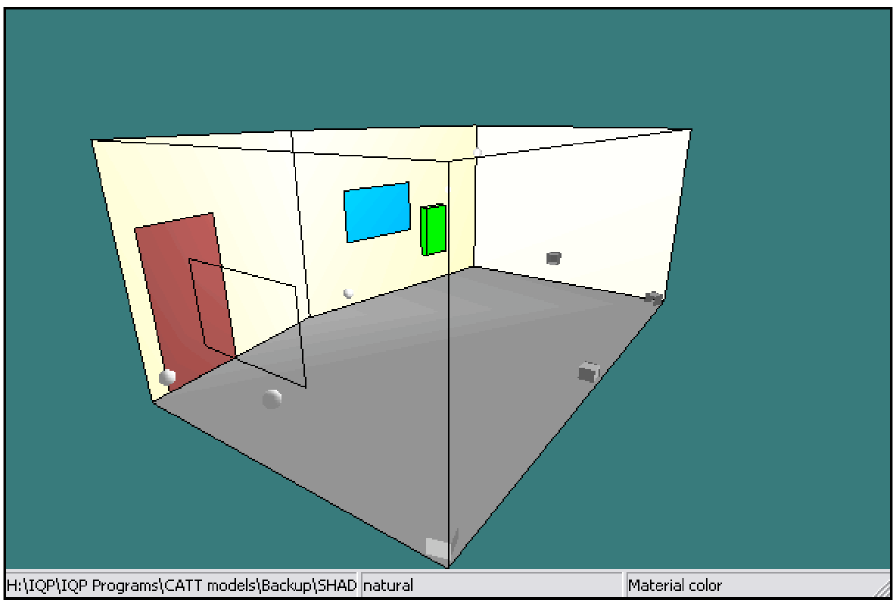


Figure 3: WICN Performance Room Space at its minimum configuration setup

4 separate modules of code were defined to allow flexibility during simulations. For example, we could include the table in the studio into the CATT simulations as a separate module, or an option for the drop-ceiling and intended treatment room adjustments. As a result we were able to analyze different room setups and solutions. Table 2 describes the input values for a defined user prompt for the respective studio space configurations.

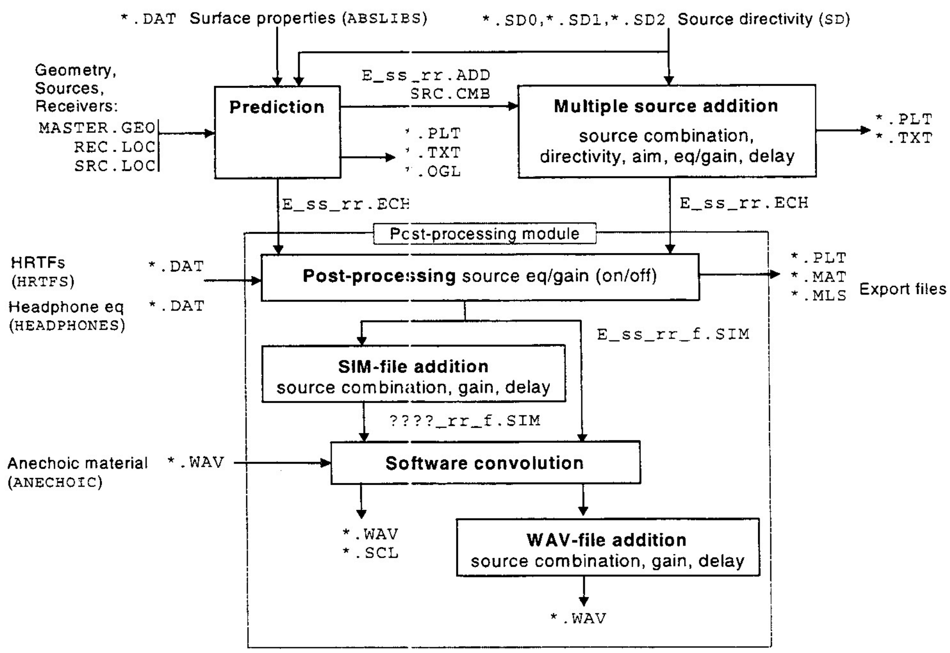


Figure 4 General data flow of CATT-Acoustic. CATT library folders are shown in round brackets.

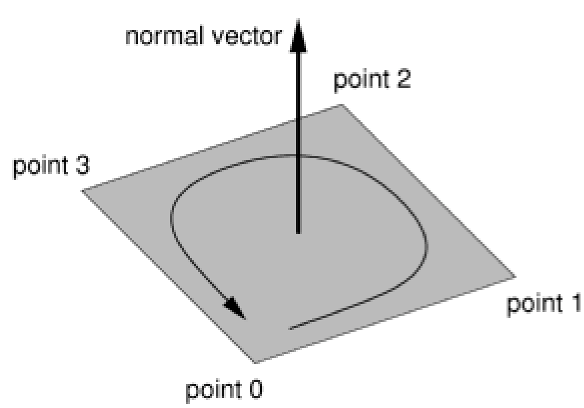
Input Value	Table	Drop Ceiling	Carpet Floor	sLaminated Wooden Floor(Stage)	Notes
0					Bare empty studio
1	x				Empty room with table
2		x			Empty room with drop ceiling
3			x		Empty room with carpet floor
4	x		x		
5		x	x		Studio as it is without table
6	x	x			
7	x	x	x		The studio like it is in WICN, present time
8		x	x	x	Proposed layout

Table 2: CATT-Acoustic model configuration setups

The code for the basic design of the room is defined in “performance.geo” (Geometry File) also included in the appendix. The general overview of input/output and data flow of CATT-Acoustic is illustrated in Figure 4. Further reference of the program’s functionality can be obtained from its user's manual. The first parameters listed define the absorption coefficients of the materials needed to compose the different surface types of the studio space. The percentages of absorption figures for each surface property respectively were defined in the order of 6 octave bands[ix].

The next portion of code lists Global Variables used to define room measurements made by Shukanth and I at the initial start of our project. The definition of walls and other planes of the model must be initialized first with definitions of corner points of each plane in relation to the x, y, z – axes. We defined the room relative to the x-plane, as we did not need to center the room about this axis since we had no use of the mirror function of the program (the only function to require models sitting on the symmetry of the x-plane).

CATT-Acoustic also requires that the corners defined be listed in the order they would be seen, following the rule of thumb, counter clockwise listed points in order to view the plane's reflecting surface in the direction of your thumb as you define the corner points in the direction of your other four fingers.



[x]

Figure 5 Rule of Thumb with the normal vector representing the active surface of a plane

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[ix] Absorption properties and equations are discussed in Section 2 – Room Acoustics, and are usually obtained from absorption coefficient tables published in acoustical papers or journals and references.

[x] Right hand rule, http://www.schorsch.com/kbase/glossary/right_hand_rule.html

Other geometry files used for our simulations were “floor.geo” which defines the module needed to include the suggested wooden laminated floor stage for the studio as part of our solution analysis. The geometry file is structured in a similar manner as the “performance.geo”. The drop-ceiling evident in the actual studio space is defined in “ceiling.geo”. Lastly, “table.geo” defines the geometry for the conference table at WICN.[xi]

Two additional files, rec.loc defines designated receivers which basically represents a microphone, but in our practical case – the 1933 General Radio Precision Sound Meter and Analyzer; src.loc defines source objects suck as a speaker, in our practical case - FOSTEX 6301 Personal Monitor. Both types of objects were given specific definitions as to their position coordinates as well as its directivity.

Analysis done within the CATT-Acoustic model was based on source/receiver configurations that were used in our Impulse-Response experiments. Figure 6 and Figure 7 illustrates the room setup and source/receiver configurations.

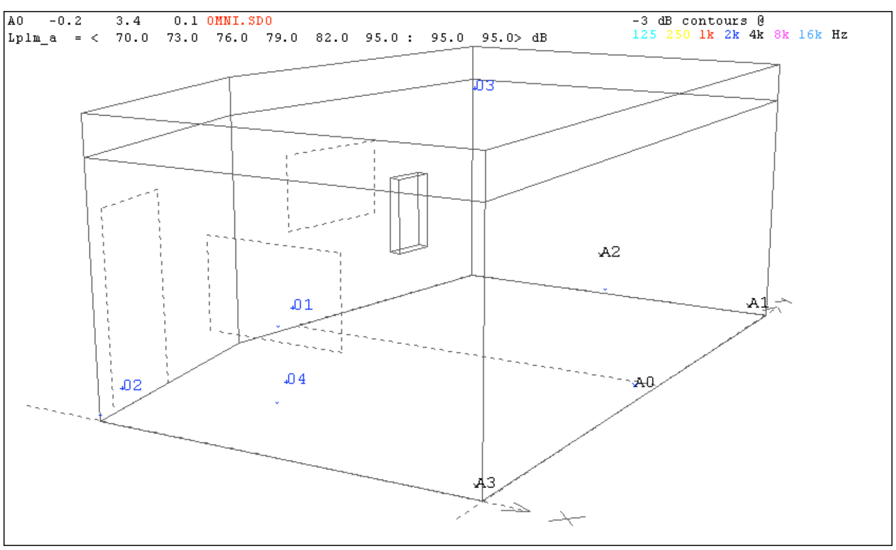


Figure 6 Locations of source and receivers. Source = A0, A1, A2, A3; receivers = 01, 02, 03, 04

[xi] CATT-Acoustic geometry files for this project are included in Appendices.

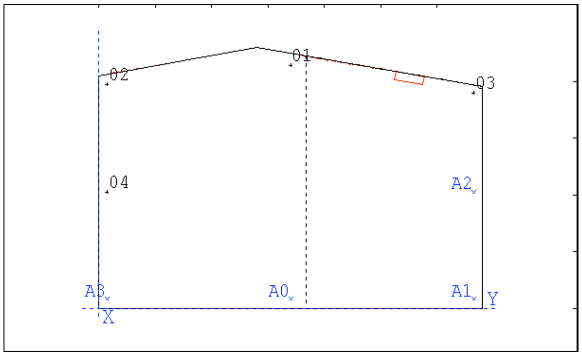


Figure 7 Top view of source/receiver positions

After defining our room space and model, we used CATT-Acoustic to simulate the response of the bare-room CATT model with minimal absorption to see what its baseline Reverberation Time (RT60/30) values were. We then proceeded to run CATT-Acoustic simulations of the actual configuration of the performance room in WICN without including the conference table (Figure 8).

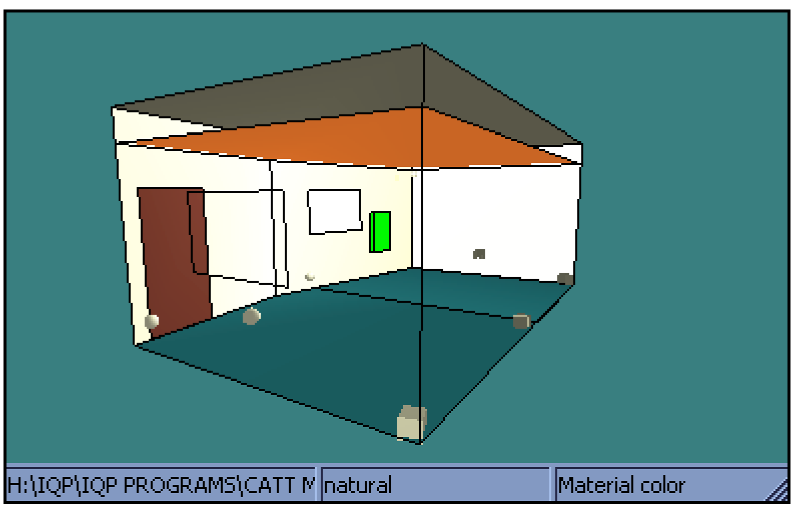


Figure 8 CATT-Acoustic model of the actual room setup in WICN without its conference table

In Figure 10 we can observe a fairly distributed reverberation time well under a second. The plot indicates a decreasing trend as the frequency range increases, noting that frequencies lower than 250Hz have relatively higher reverberation times. Treatment for the higher frequencies should be noted and an overall slight increase in the reverberation time would be optimum for the intended use of the performance space. Reverberation time within 0.6 of a second would be the optimum in this case.

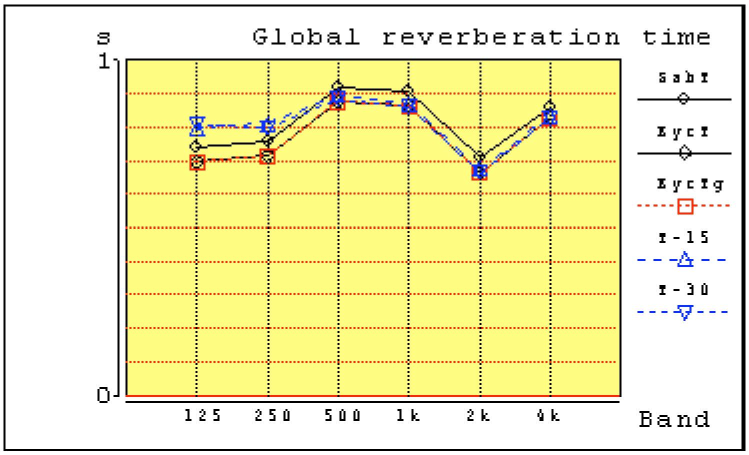


Figure 9 Global reverberation time for a bare room (WICN) – empty configuration.

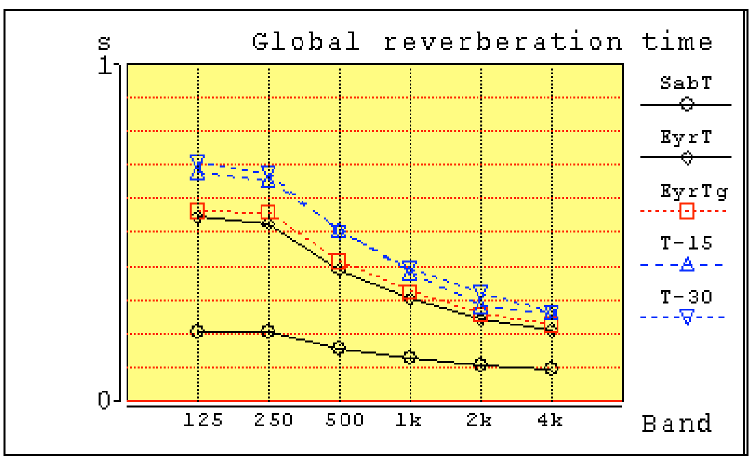


Figure 10 Global reverberation time simulated for WICN' Performance Room in its current state (carpeting and Celotex panels present in space)

Figure 9 illustrates reverberation times for an empty studio space (stripped of all its elements). WICN's space would have global reverberation time distributed 0.7 to 0.93 seconds. The carpeting and Celotex panels (ceiling) currently present in WICN's performance room introduces significant uniform absorption, decreasing the reverberation times to about 0.1 to 0.22seconds as shown in Figure 10.

In relation to the global reverberation times, simulated echograms indicated that the time it took for sound levels of 100dB to decay to 0dB was well within the range of 500 – 700 milliseconds for all axial, tangential and oblique setups.

The distribution of the room's reverberation time directly suggests an inverse relationship with its mean absorption coefficients. As shown in Figure 11, we observe an increasing trend as predicted. The plot hints that absorption for lower frequencies require attention and treatment.

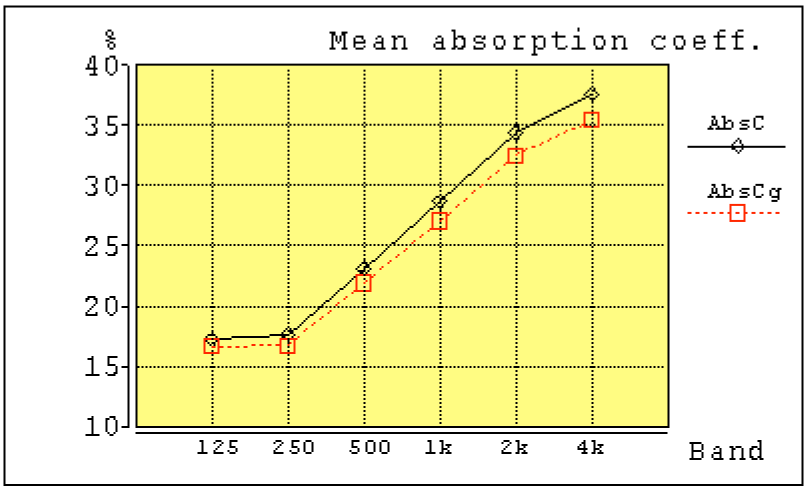


Figure 11 Mean absorption coefficients of WICN's performance room with source in position A

We can make several general conclusive observations based on data obtained from this particular CATT-Acoustic simulation. The carpeted floors provide the room with ample absorption particularly within the higher frequency ranges. Also the drop-ceiling (made from perforated celotex panels) provides absorption and diffusion for entire range.

The CATT-Acoustic simulations did not indicate any serious problems with the percentages of wall hits in the room. 15% of sound reflection within the room was falling on Wall D (the wall plane located directly across the entrance door of the studio). Another noticeable average was hits on the room's floor and ceiling – at 24.5%.

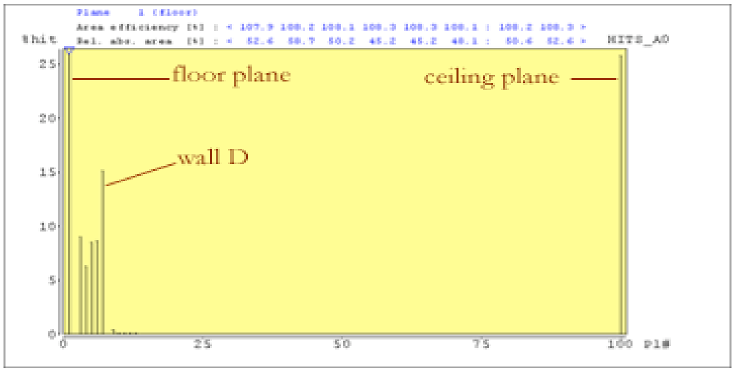


Figure 12 Wall hits (%) vs. Plane

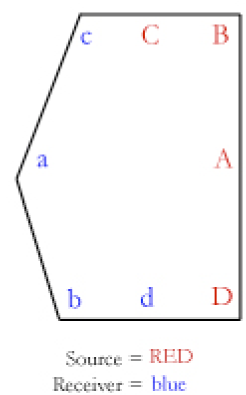
Analysis in CATT-Acoustic indicated that the initial space had a slight uneven distribution in reverberation times across frequencies. The reverberation times of lower frequencies were relatively higher to reverberation times of higher frequencies. This suggests a necessary introduction of low frequency absorption as part of a solution. Otherwise, WICN's room appears to be relatively isolated. Modal problems need to be confirmed and balanced out before the room can be considered ready for WICN's objectives.

4.2 SIA Smart Impulse Response Experiments

SIA Smart was used to analyze the impulse responses generated with the Fostex 6301 Personal Monitor and the 1933 General Radio Precision Sound Meter. Eight impulse response tests were taken in the room at various locations. The data was gathered in 16-bit mono PCM wave files sampled at 44.1 kHz using SIA Smart Live. Actual oblique, tangential, and axial modal frequencies can be observed and compared to calculated modes. SIA Smart imports the wave file in the time domain, and then transforms it to the frequency domain so modes can be observed. SIA Smart uses a Fast Fourier Transform for its calculation. Spikes in the frequency domain values at high dB values are assumed to be modal frequencies.

Source A, Receiver a:

Selected Modes (Hz) – 40.37, 72.67, 94.21, 131.89, 191.11, 231.48



Source A, Receiver b:

Selected Modes (Hz) – 48.45, 75.37, 107.67, 129.20, 193.80

Source A, Receiver c:

Selected Modes (Hz) – 37.68, 61.91, 78.06, 131.89, 148.35, 199.81

Source B, Receiver a:

Selected Modes (Hz) – 24.22, 40.37, 61.91, 75.37, 126.51, 166.88, 228.79

Source B, Receiver b:

Selected Modes (Hz) – 21.53, 37.68, 48.45, 61.91, 83.44, 102.28, 129.20, 169.57

Source B, Receiver c:

Selected Modes (Hz) – 24.22, 40.37, 48.45, 75.37, 107.67, 129.20, 142.66, 164.19, 228.8

Source C, Receiver d:

Selected Modes (Hz) – 24.22, 51.14, 76.06, 83.44, 91.52, 126.51, 164.19, 215.33

Source D, Receiver c:

Selected Modes (Hz) – 24.22, 40.37, 48.45, 61.91, 75.37, 94.21, 104.97, 110.36, 164.19

Most of the modes found through SIA Smart correlated well with the modes calculated using the Raleigh model. The calculated modes will not be exactly the same as the ones gained through SIA Smart due to the limiting constraints of the Raleigh modal. When a room is non-rectangular, average height, width, and length have to be used in the Raleigh modal, because the formula is designed for simple rectangular rooms. The observed modes also agreed with the Raleigh bar graph. There is a higher concentration of modes located between the 111.8 and 223.6 Hz in the calculated[xii] results as shown in Figure 13. This can be easily seen in any of the Fourier transformed wave files in the frequency domain.

In the analysis of the time domain, time of flight, the time it takes an impulse to reach the receiver from the source, can be observed. Nothing out of the ordinary appeared in the various wave files, except for source location B and receiver location C. There is a obvious reflection around 40ms. This however is most likely due to the fact that the receiver was placed on top of a large metal cabinet. It can only be assumed that the metal cabinet created such a large reflection.

[xii] Calculations of modes in third octaves using the Raleigh equations are located in the appendix.

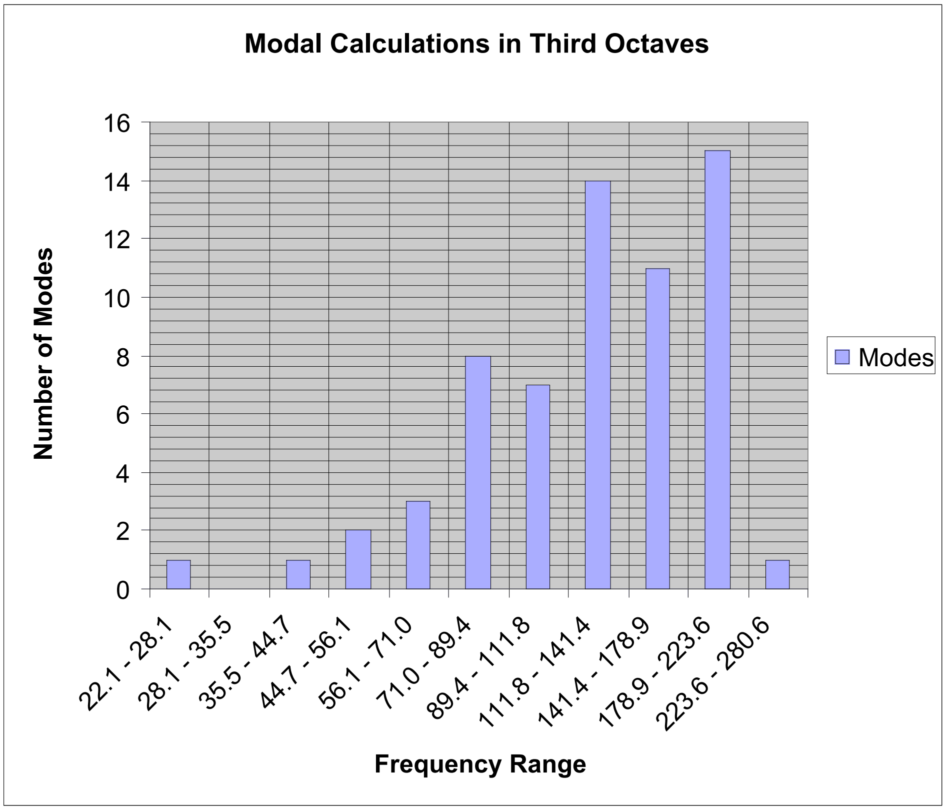
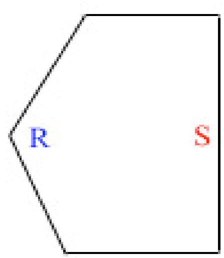


Figure 13: Modal Calculations in Third Octaves, based on the Raleigh Equations

4.3 Sine Wave Modal Test

To go alongside the calculated analysis of modal frequencies in CATT and SIA Smart, a basic sine wave test was done on the performance room in order to physically hear the various modes. A basic sine wave generator was used in the experiment. A Fostex Model 6301 personal speaker was connected to the output of the sine wave generator. The speaker was placed at various points in the room in conjunction with the impulse test performed earlier. A person would then stand at the receiver location and attempt to pick out modes, while the sine wave generator was swept from a range of zero to 300 Hz.

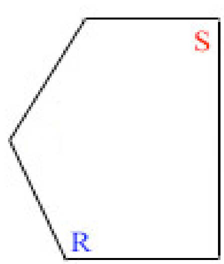
Location AA



Modal Frequencies (Hz)

45
55
72
81-83
95
150 - 200

Location BB



Modal Frequencies (Hz)

50
65
87
180
230

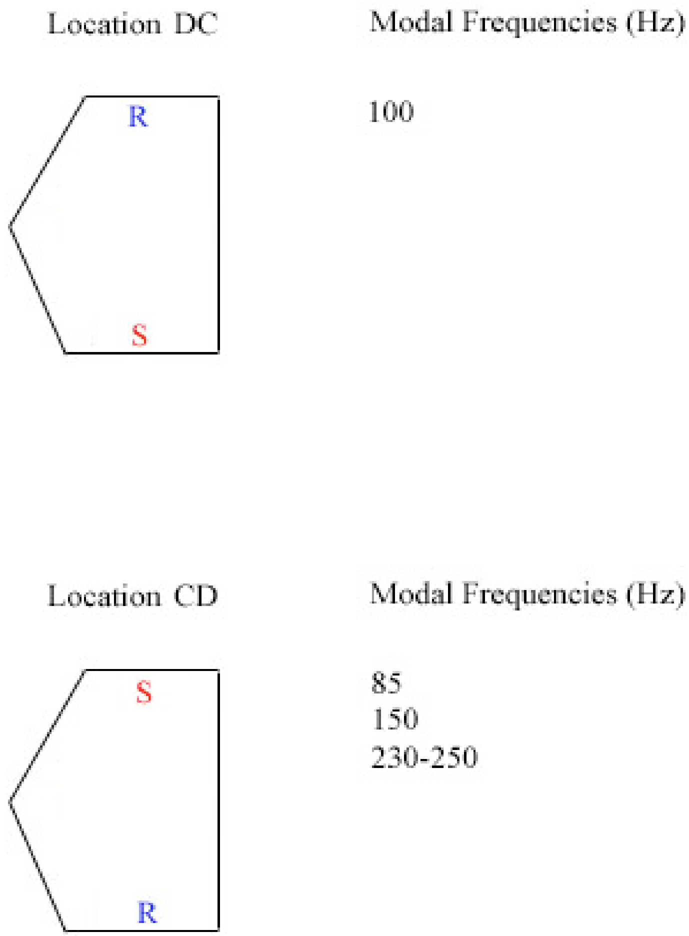


Figure 14: Different setup configurations and its corresponding modal frequencies. S = source, R = receiver as noted in document.

The sine wave results were compared to the data acquired through calculation in SIA smart. SIA Smart revealed that there would be modal problems at 71.0 – 89.4 Hz and 111.8 – 141.4 Hz which corresponds to a range of notes – E (2^{nd} octave) and B (2^{nd} Octave) respectively. A fair number of modal frequencies heard in the test did fall in the E2 range, which follows the SIA Smart calculation. However, there were zero modal frequencies heard in the B2 range. Even though the actual and calculated frequencies do not agree to an extent, the SIA smart data appears to be more valuable. This is due mainly to inexperience by the listener to distinguish between modal and non-modal frequencies. There was a significant amount of human error possible in the sine wave test. Another factor contributing to this disagreement is the limitation of the equipment used. The sine wave generator used was analog, so an exact frequency could not be chosen. There is a far lesser chance of error by using the SIA Smart results than with using the data gained through the sine wave test. Therefore, for our recommendations in handling the modal frequencies in the room, the SIA Smart data will be used.

4.4 LARES-Lexicon System Test[xiii]

The Wenger V-Room Studio environment uses LARES technology to recreate the acoustics of world-class venues as well as custom-programmed acoustical simulations. It removes the boundaries introduced by small sterile spaces such as WICN's performance room.

The LARES technology is a patented system (electronic acoustical enhancements) that generates direct, reflected, and reverberant energy at appropriate timings and levels – which allows optimization of acoustical characteristics in real time. The system is flexible and cost effective when compared to actual architectural acoustical treatments[xiv].

It provides a wide range of control that enables the user to manipulate critical acoustical parameters with great precision even in real time. The system is also visually transparent to the listener (once correctly implemented).

This electronic enhancement method was considered as one of the many acoustical solutions for WICN's performance room. LARES offers demo kits for interested clients for a limited period of time (usually under a week).

It was unfortunate however, that our proposed experiments with the system did not materialize due to the unavailability of the demo system. The system will still be considered and proposed as an alternative solution for WICN.

[xiii] Details on Wenger Corporation's V-Ready Room using the LARES-Lexicon technology is further discussed in 5.3 as part of our proposed solutions.

[xiv] Information from LARES-LEXICON website, http://www.lares-lexicon.com

4.4.1 Live Musician Test

As a follow up to the LARES-Lexicon system test, it was proposed that we would invite a jazz band to perform within WICN's space after the LARES system installations and setups. The live musician test would enable us to experience the advantages and efficiency of the LARES system and its applicability to our problems. However, as previously discussed, we were unable to execute this plan as a result of the systems unavailability.

5 ACOUSTICAL SOLUTIONS

5.1 Performance Stage

The introduction of a performance stage in WICN's performance room would provide musicians with an indirect medium of coordination. The wooden stage constructed on sleepers would demonstrate resonance properties. This ensures that the musicians remain in a tight grove as described important in Section 3.5. The stage also provides an aesthetical improvement to the performance space with functionality. Indirectly, it also contributes to the initial impression (atmosphere) when jazz musicians enter the space. Thus satisfying the "look good, feel good = play good" theory. Figure 15 illustrates the addition to the studio.

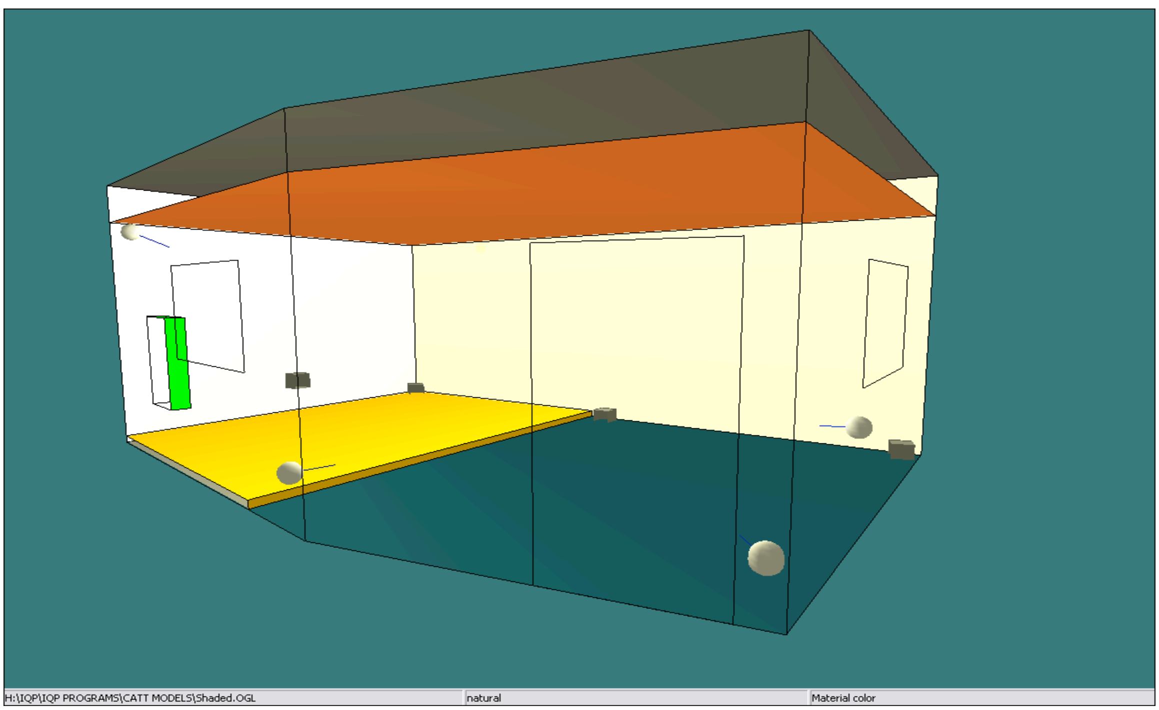


Figure 15 CATT-Acoustic modeled WICN studio space, laminated wooden floor stage with drop ceiling in view

The stage is specifically to be covered with wood parquet. While this is a beautiful solution, the flooring is moderately priced. The stage is a highly reflective floor and is opposed by the highly absorbent drop-ceilings already present in WICN's performance room. Figure 16 indicates an average slight increase (under 1%) in reverberation time an all frequencies and it also contributes to a smoother continuous trend (gradual) in the plot.

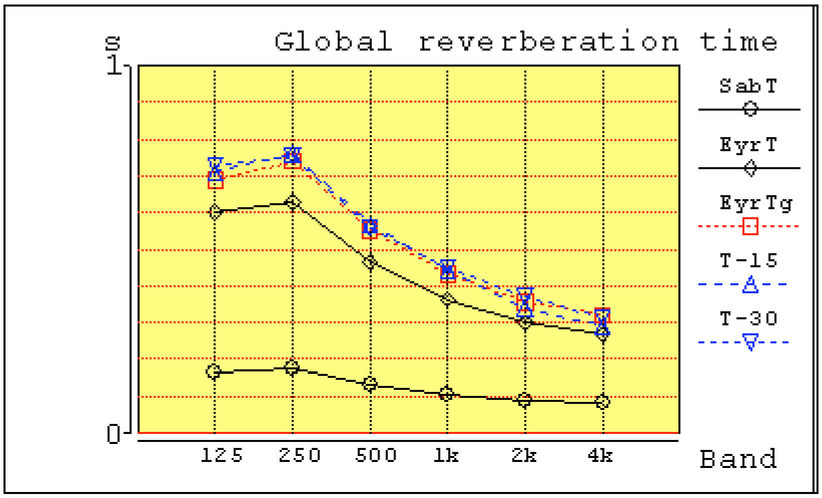


Figure 16 Global reverberation time after implementing the stage

Note that the front portion of the stage is open and not sealed as to allow air flow under the stage (a wire frame/screen may be attached). A construction diagram of the stage and basic instructions are attached in the appendix.

5.2 Low Frequency Absorbers / Modal Treatment

WICN's small performance room space exhibits slightly poor low frequency response with significant emphasis at modal resonances particularly around 71.0 – 89.4 Hz and 111.8 – 141.4 Hz. WICN also has limited available physical space to adjust acoustical characteristics of the room. The following solutions, both available as prefabricated retail solutions and suggested custom-built solutions are discussed.

5.2.1 Diaphragmatic Absorbers

Resonant absorbers (reactive) handle lower audible frequency problems in a room. Glass fiber and acoustical tiles are among the common types of resonant absorbers in which sound energy is dissipated as heat through the interstices of the fibers[xv]. For an efficient absorption, the thickness of the resonant material must be compared to the wavelength of the problem sound. Having this in consideration we note the frequency of resonance of the absorber structure to be calculated[xv] as:

$$f_0 = 170/\sqrt{(m)(d)}$$

where

f_0 = frequency of resonance, Hz

m=surface density of the panel, lb/sq ft of panel surface

d = depth of airspace, inches

For WICN's performance room, a piece of 1/4" plywood (with a surface density of 1.6lbs/sq ft) would be an excellent solution, assuming that the airspace depth gives close to about 2". This would address modes within a rough range of 125Hz to 180Hz with moderate treatment on surround frequencies.

[xv] Everest's Master Handbook of Acoustics

These absorbers are simple to build. The 1/4” plywood panel is fastened to a wooden framework to give the desired airspace depth from the wall. Either a glass or mineral fiber blanket of 3/2” is glued to the wall surface within the framework. The remaining 1/2” of empty space between the blanket and the panel should be maintained.

Suggested two of these panels be constructed on Wall D (wall plane across the entrance door). Plywood may be varnished and decorated to provide aesthetic function.

5.2.2 Slat Absorbers

This is another form of resonant absorber that utilizes closely spaced slats over a cavity. The resonant system here functions on the reaction of the mass of the air within the slats with the springiness of air in the cavity. Fiber glass is usually introduced behind the slots as a resistance to broaden the peak of absorption. Resonance frequency treatment introduced by the slat absorber is deduced from the equation:

$$f_0 = 216 \sqrt{(p/(d)(D))}$$

where

f_0 = resonance frequency, Hz

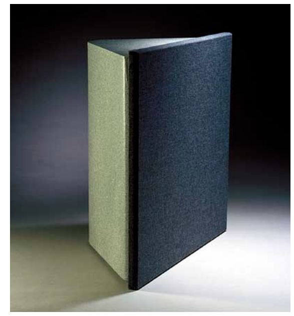
p = percent perforation

D = airspace depth, inches

D = thickness of slat, inches

The slat absorber will address modal problems for frequencies below 100Hz. Suggested resonance frequency treatment, f_0 = 83.2 Hz with airspace depth of 2” and 1/4” slat thickness. The panel should be 4’ x 8’ and placed in the rear corner of the performance stage suggested in WICN. The plywood planks should be varnished prior to assembly to ensure even spread in the slits. The use of temporary shims while nailing the panels in place ensures uniform slits. To avoid optical illusions as eyes are swept across the slats, the slats should be positioned in diagonal fashion with uniform slits and should have a dark finish to add to the effect. Fiberglass will be used as fill some similar in fashion as discussed in the previous section. The amount of material filling can be later fine-tuned to accommodate the desired Q of the absorbent.

5.2.3 Modex Corner by RPG Diffusor Systems



An alternative to the described modal treatments, it is possible to purchase prefabricated acoustical solutions. RPG Diffusor Systems Inc. provides many acoustical solutions for home theaters to studio projects. In our particular problem, the Modex Corner would be suitable due to its small size and pleasant appearance (shown right).

The Modex Corner solution takes advantage of RPG's development of a unique membrane system that converts high sound pressure fluctuations (typically found in room corners) into selective absorption in the modal frequency range. This solution has a better effect over porous surface absorption since air motion near walls and corners are essentially zero for longer wavelengths. Implementation of this solution is also cost effective.

The Modex Corner treats modes within the 80 – 316 Hz range effectively with concentrations at 80Hz and a slight additional span thereof. Hence the Modex Corner would be a suitable solution to use in compliment with other suggested modal solutions as described in this section. The Modex Corner has specific dimensions: 23 5/8" (W) x 23 5/8" (H) x 12 1/4" (D). The Modex Corner is shipped in pairs and each Corner weighs 15lbs and can be mounted in corner walls. Custom colors for the Modex Corner are also available upon request to accommodate aesthetic considerations.

The Modex Corner is priced at $676 for a pair and is made available through Parsen Audio[xvi] located in Wellesly Hills, MA. (Tel: 781 – 431 8708).

[xvi] RPG Project Studio dealer in Massachusetts

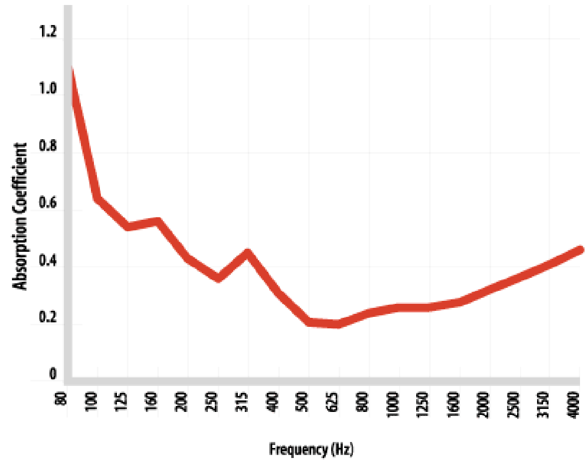


Figure 17 Modex Corner absorption coefficients in effective range[xvii]

In summary, the Modex Corner is highly efficient in converting any available corner into a highly absorptive low frequency absorber through its internally damped membrane. It is also lightweight, portable, modular and aesthetically pleasing.

5.2.4 Modex by RPG Diffusor Systems

The Modex model is an alternative to the Modex Corner and handles a slightly different range of modal problems. Similar in construction with the Modex Corner, the Modex is effective to our applicable modal problems. The light blue line plot in Figure 18 indicates the treatment range for the Modex bass tool with a cavity depth of 8". This particularly addresses our modal problem at ~80Hz with a 20Hz wide span. The green plot in Figure 18 addresses modal problems 40Hz wide at a center 130Hz, with cavity depth of 2" – which falls well within our problem range.

The Modex bass tool (shown right) is relatively small in size, with dimensions 23 5/8" (W) x 23 5/8" (H) x 7" (D) for the regular models that can be placed against the largest wall surface, in WICN's case, suggested placing

[xvii] RPG Diffusor Systems, http://www.rpginc.com/

against Wall D. Two separate models of same sizes can be purchased and fabricated to handle both modal ranges that require treatment as mentioned in section 5.2. Wall modules are available if WICN decides to place these solutions on wall D itself. The Wall modules come with different dimensions: 23 5/8" (H) x 47 1/4" (W) x 7" or 12" (D). Customized colors and dimensions are also available so that aesthetic limitations are not restricted. Modex™ can be applied to walls, ceilings, and corners or mounted free standing; the solution can also be added modularly, stacking as many Modex needed for experimentation and modifications. These flexibilities make utilize unused space in the studio leaving no sacrifice of precious studio space.

The Modex solution only costs $246 per module and is also made available through Parsen Audio.

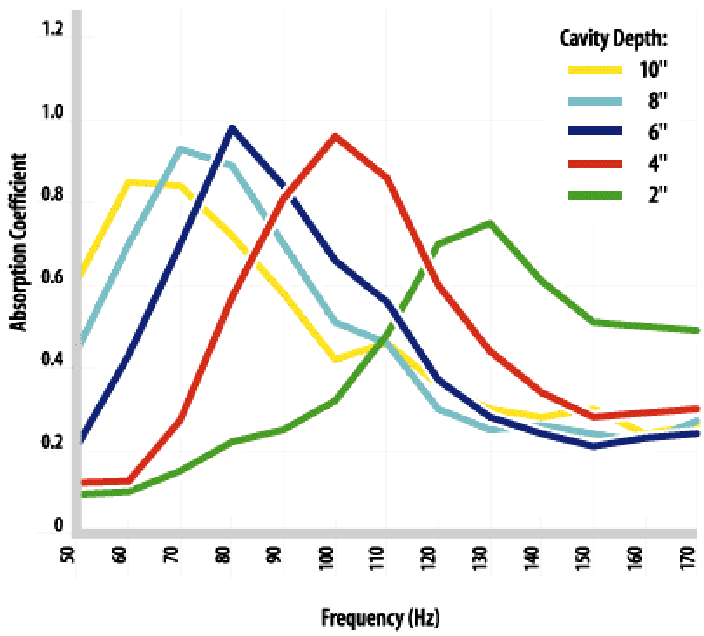
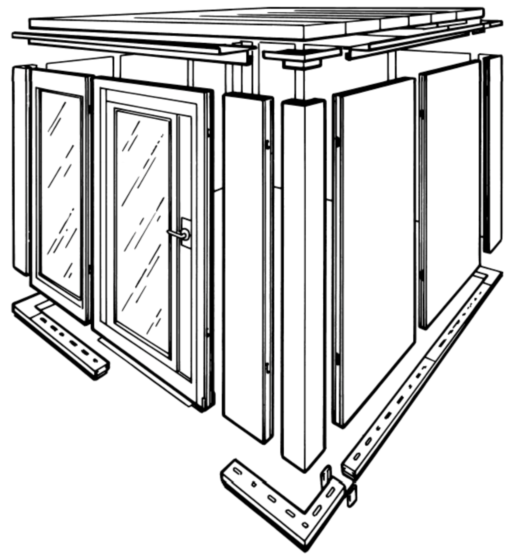


Figure 18 Modex Absorption Coefficients[xvii]

Both these featured products from RPG Diffusor Systems prove to be advantages given its effectiveness, portability, and flexibility.

5.3 Wenger V-Room Broadcast and Recording using LARES-Lexicon Technology



The self-sealing Wenger V-Room (shown right)[xviii] can be installed into WICN's performance room under two hours with no fasteners, caulking or any other form of permanent attachments to the original structure. It can also be relocated as needed or deconstructed. The acoustically dry/neutral environment provides a solid basis for the implementation of LARES technology in creating artificial acoustical properties suited for specific clients needs. This acoustical environment is ideal for broadcasting uninterrupted recordings and performances. Custom sizes are available with minimum dimension specs satisfying WICN's performance room maximum capacity. The room can be upgraded with V-Room technology at any point and is modular.

The room features 16 different environments from Wenger's library of acoustic simulations and also allows 4 distinct user defined configurations. The ambience provided by this technology pays attention to every detail, from wood floorings to open ceilings, lightings, recreating any desired ambience environment.

Window wall panels are also available to accommodate two of WICN's window panels adjacent to its control rooms. The room meets fire safety codes and is self-accommodating, with ventilation systems, lightings, and electrical input and output outlets.

This solution can be considered over several modular acoustical solutions as described in previously, and would act as an infinite substitute to prefabricated solutions. The

[xviii] Illustration from Wenger Corporation, http://www.wengercorp.com/

electronic acoustical solution provides an efficient general solution to all of WICN's performance space's problems as analyzed in one convenient modular solution. It leaves the client free from acoustical technical know-how and satisfies WICN's objectives at the push of a dial. Not only will the V-room accommodate live jazz performances, but also speech related broadcasting as well as future intended recording sessions.

The room allows real-time modification of acoustical environments allowing infinite possibilities and limitless flexibility both for the musicians and WICN. The only setback in the system might by its initial cost, although the solution may be weighed in its long-term effects. Without doubt this system provides optimum quality solutions to WICN's space but with a slight additional cost relative to others. The V-Room is uniform in design which also provides a themed aesthetic look to the studio, advantages over separately custom-built solutions with different design styles in addition to current room interior design.

The V-Room is also relocatable, thus protecting WICN's investments if decided so. The room is also resizable as needs change and its panels are easily disassembled by a turn of a wrench. Detailed architectural specifications are available at Wenger's Corporation's website, http://www.wenger.com/.

However, after recent correspondence with Wenger Corporation, a solution suitable for WICN's space would be the V-Room Broadcast/Recording model which acts as an isolation room. The implementation of this solution would range between $30,000 to $40,000. The isolation room will provide WICN with a uniform RT time of 0.6 to 0.7 seconds although frequencies below 85Hz would still need attention, depending on the sensitivity constraints.

Wenger Corp. only provides V-Room's with LARES Lexicon technology for room's up to size 10' by 12'. For further details on this particular solution, contact John Kimpton at tel: 978-424 4378.

5.4 Aesthetic Solutions

Besides treating acoustical problems within the studio space, aesthetic enhancements should not be ignored. Aesthetics enhances comfort within an enclosed environment – indirectly improving general emotions of the studio's occupants. This proves to be beneficial towards production quality, as suggested by the psychological principles of aesthetics.

Having a certain theme of art present on walls around the studio is generally desired. One suggested way to achieve this would be to coordinate with a local public school and have students produced art pieces that satisfy certain requirements (adjusted to have acoustically friendly features).

Art pieces can be the size of a shoebox (of the general shape) being 1 3/4' wide and 1' tall with a depth of 3". Students are encouraged to work within dimension constraints to produce creative pieces whether from papier-mâché, painted ornaments/sculptures, etc.

Absorption introduced by this overall effect would be insignificant to the room although it would introduce slight scattering and diffusion, which is generally desired.

Indirectly a collaborative project such as this can be beneficial both to the local community and WICN Radio in many ways.

Finally, the large electrical metal box located next to the side control window of the room should be covered with a soft piece of fabric (preferably decorated). This will provide some dampening effect (not very significant) and would hide its unpleasing presence.

6 CONCLUSION

WICN's Performance Studio measures show a number of acoustical problems. Unbalanced reverberation time across the frequency range and modal problems are evident within the structure.

After simulated analysis and practical experiments, we confirmed suspected acoustical issues present within the space. A number of solutions were then derived through various aspects, and were analyzed.

In summary, the reverberation times of lower frequency bands needs to be reduced while maintaining balance relative to the higher frequencies. Modal problems caused by the room's physical structure need to be addressed through low frequency absorbers, ensuring balanced clarity throughout low frequencies.

While solving acoustical aspects of the room, aesthetic solutions may also be implemented without the penalty of cost. Space and cost issues have been acknowledged as a decision variable while realizing the problem model and its solutions.

7 RECOMMENDATIONS

Based on analysis and results, the construction of the performance stage and the Modex solutions are best, weighing cost and usability factors. The use of the stage with the Modex solutions would provide the performance space with a desired global reverberation time suitable for a jazz environment and addresses modal problems within the space.

Realizing a collaborative-project with a local school for the creation of various artistic exhibits serving as aesthetic decorations of the room may prove to be worthwhile.

The construction of the custom built modal and low frequency solutions may prove to be an extensive task, given design, cost and artistic considerations. The RPG solutions present an effective sufficient solution without severing cost and convenience.

The Wenger V-Room solution is evidently too costly and inefficient in terms of unavailability of desired technology (LARES system) for WICN's room dimensions. The implementation of this solution isn't worth its cost given WICN's objectives.

Suggested Solution	**Projected Costs**
Performance Stage	□ $2,000
Modex Modules	= $246
Modex Corners (2 units)	= $676
Total cost:	□ $2,922

8 REFERENCES

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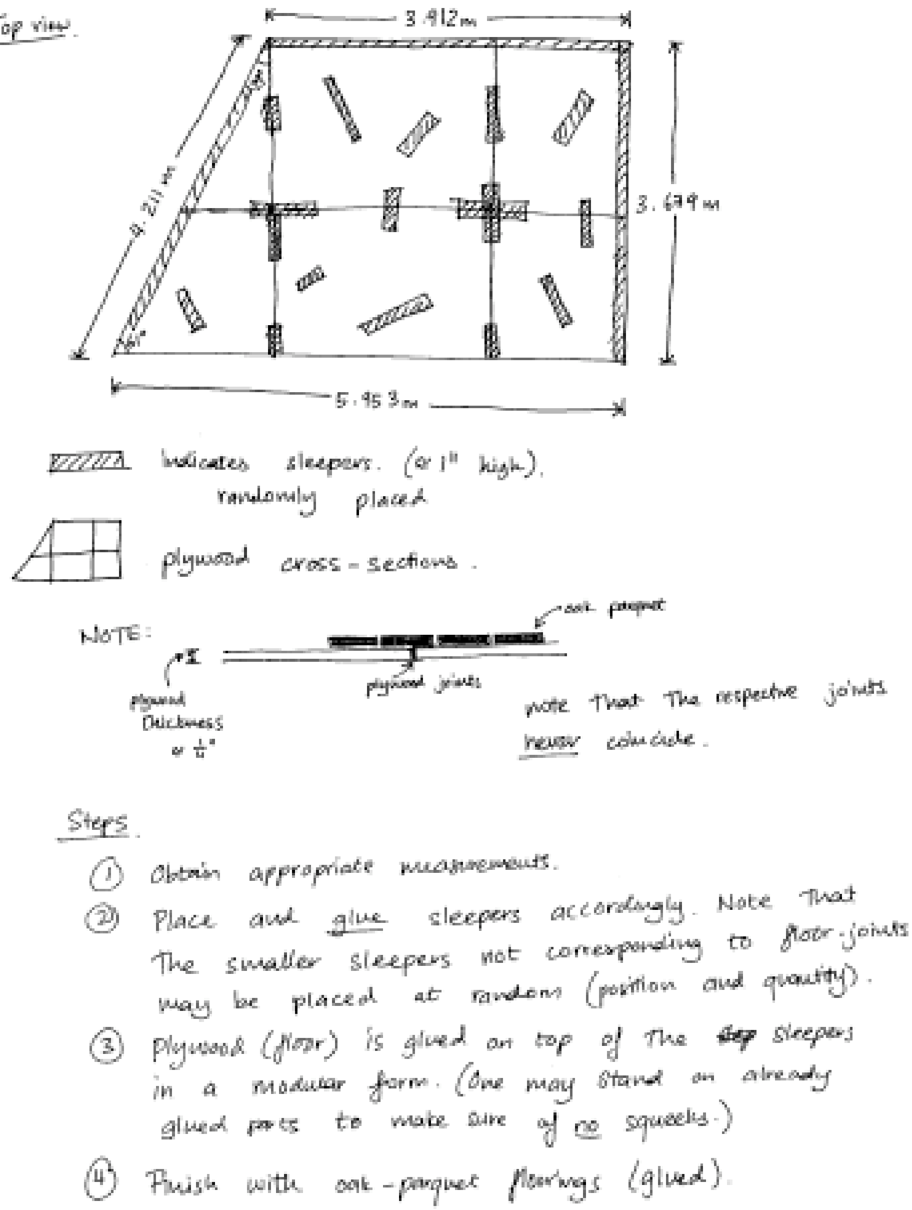
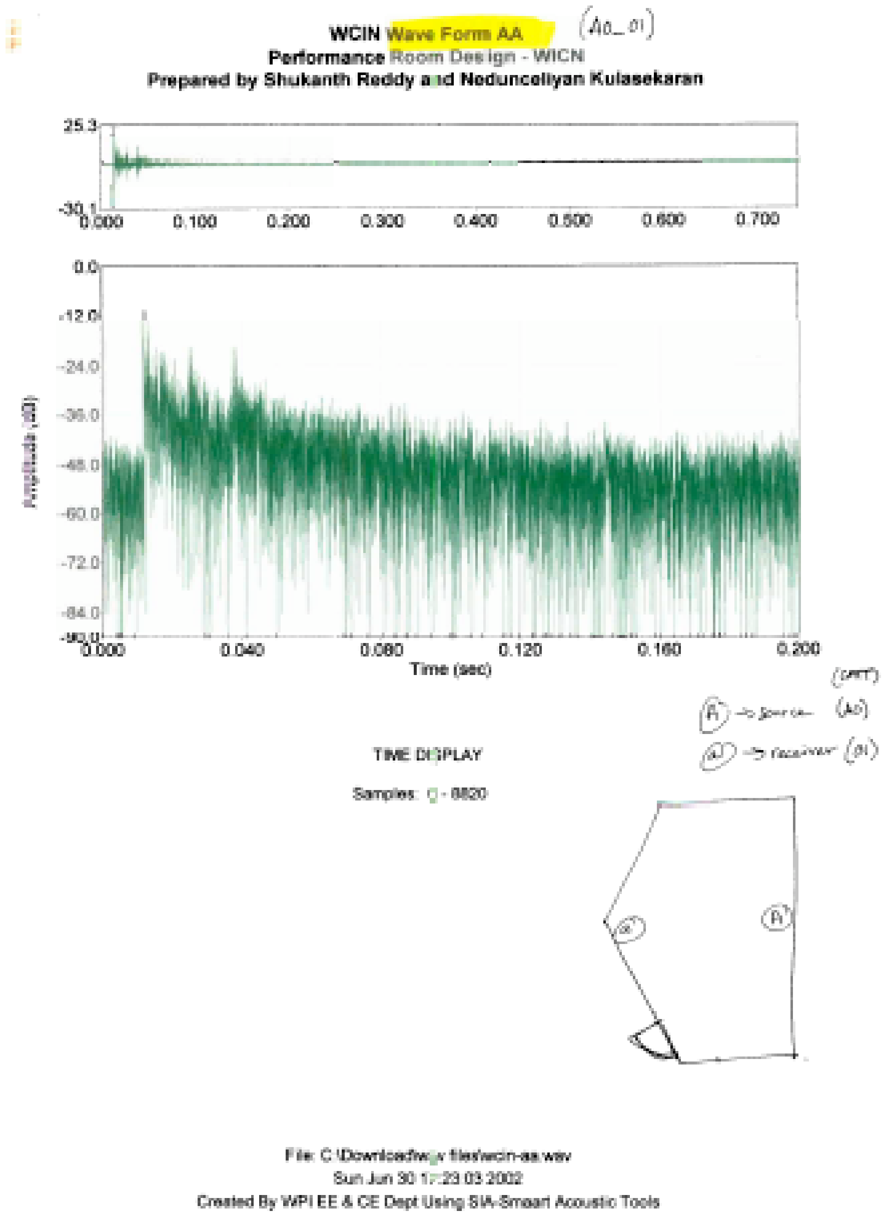
9 APPENDICES

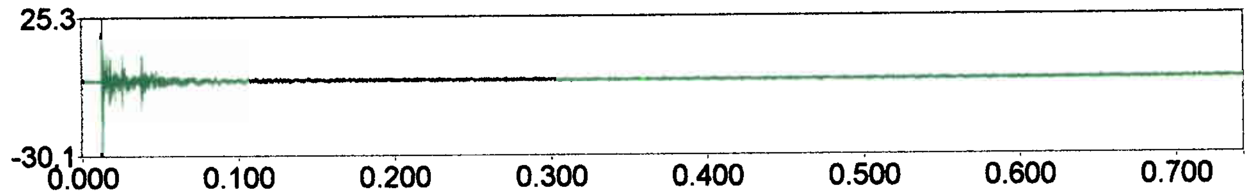
APPENDIX A: Construction Diagram for the Performance Stage

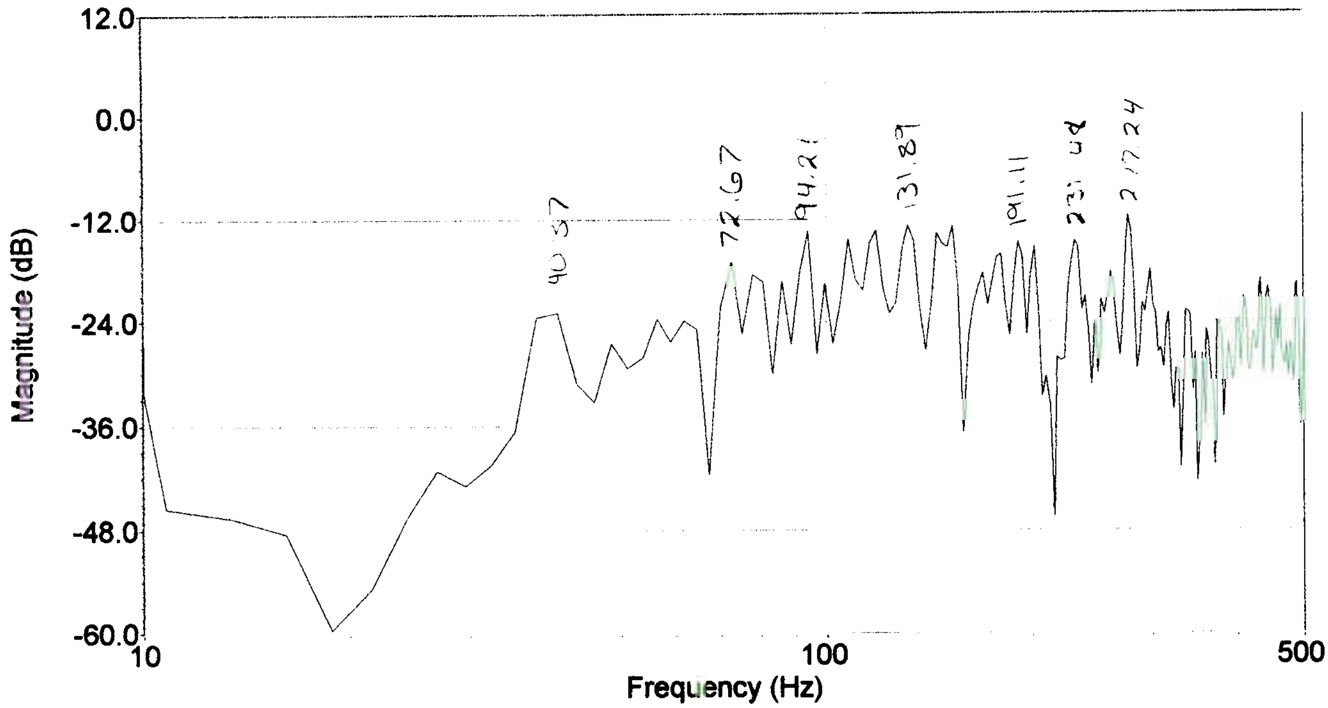


APPENDIX B: SIA Smart Impulse Response results



WCIN Wave Form AA
Performance Room Design - WICN
Prepared by Shukanth Reddy and Nedunceliyan Kulasekaran





FREQUENCY SLICE

Frame: 0 (0.00 sec)
Frames: 0 - 4
Banding: Log (NB)

File: C:\Download\wav files\wcin-aa.wav

Sun Jun 30 17:14:34 2002

Created By WPI EE & CE Dept Using SIA-Smaart Acoustic Tools

WCIN Bands Table AA
Performance Room Design - WICN
Prepared by Shukanth Reddy and Nedunceliyan Kulasekaran

Band	T (R)	EDT (R)	DTR	T (20)	T (30)	EDT	C10	C20	C50	C80
Broadband	0.48	0.07	18	***	***	***	1.98	4.58	11.47	16.39
63 Hz	0.35	0.43	9	***	***	***	-4.80	-3.09	7.19	13.58
125 Hz	0.31	0.53	15	***	***	***	-4.44	1.05	4.04	8.58
250 Hz	0.58	0.63	17	***	***	***	-5.59	-1.61	3.93	7.18
500 Hz	0.56	0.49	14	***	***	***	-3.69	-1.13	5.05	8.37
1 kHz	0.46	0.07	13	***	***	***	2.51	4.46	10.02	14.32
2 kHz	0.41	0.07	10	***	***	***	-0.59	3.24	10.48	17.25
4 kHz	0.34	0.10	14	***	***	***	3.21	5.85	13.94	19.45
8 kHz	0.50	0.10	19	***	***	***	0.31	3.22	11.39	16.15

%Alcons (Short Form): 2.44

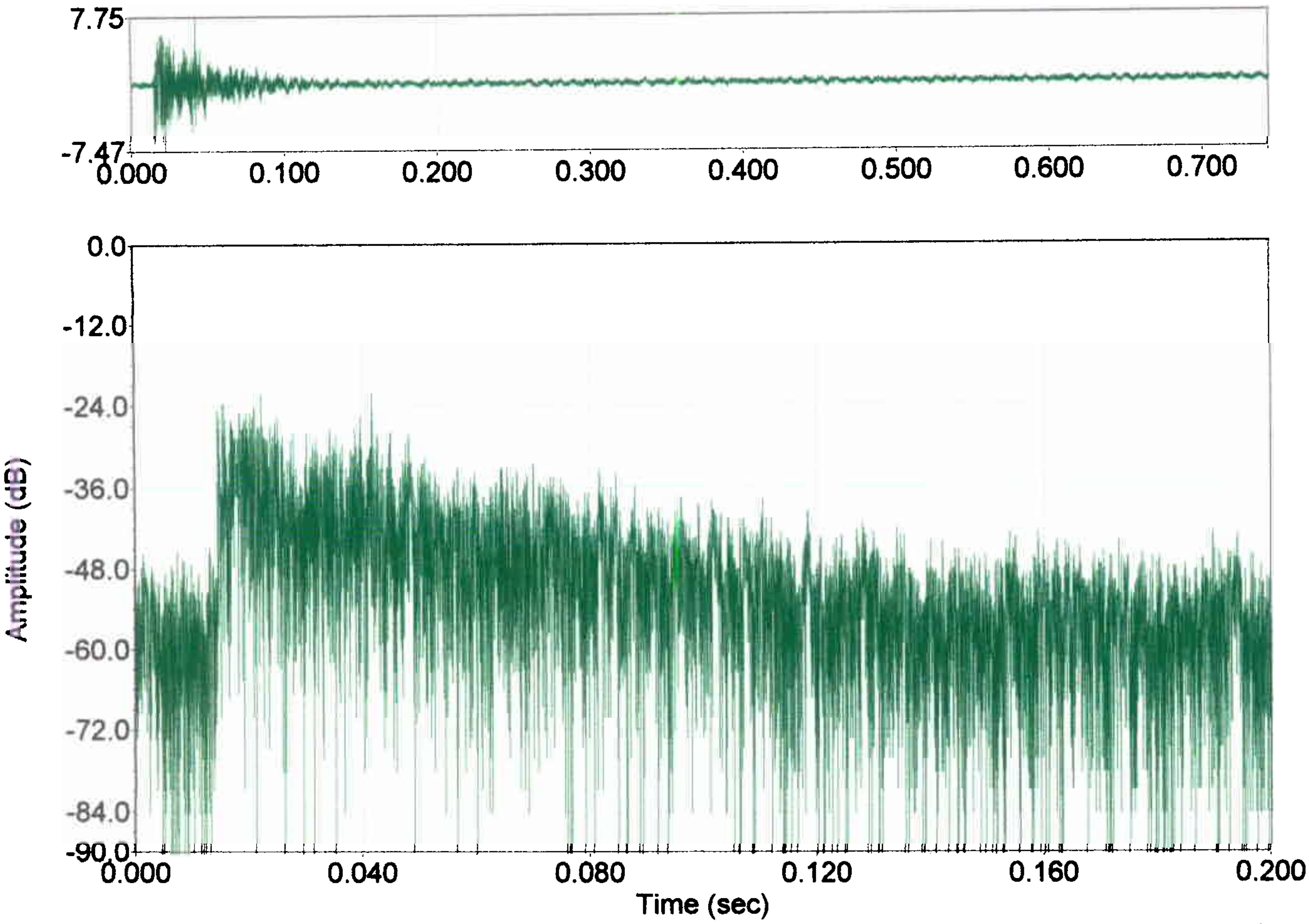
%Alcons (Long Form): 3.38

File: C:\Download\wav files\wcin-aa.wav
Sun Jun 30 17:32:02 2002
Created By WPI EE & CE Dept Using SIA-Smaart Acoustic Tools

WCIN Wave Form AB (A0 – 02)

Performance Room Design - WICN

Prepared by Shukanth Reddy and Nedunceliyan Kulasekaran

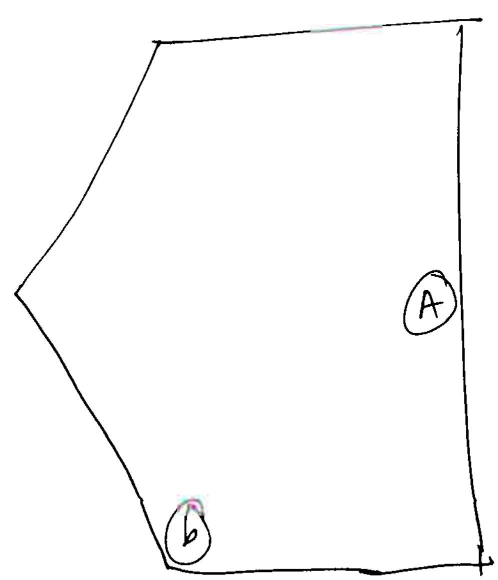


(A) → source (A0)

(b) → receiver (02)

TIME DISPLAY

Samples: 0 - 8820



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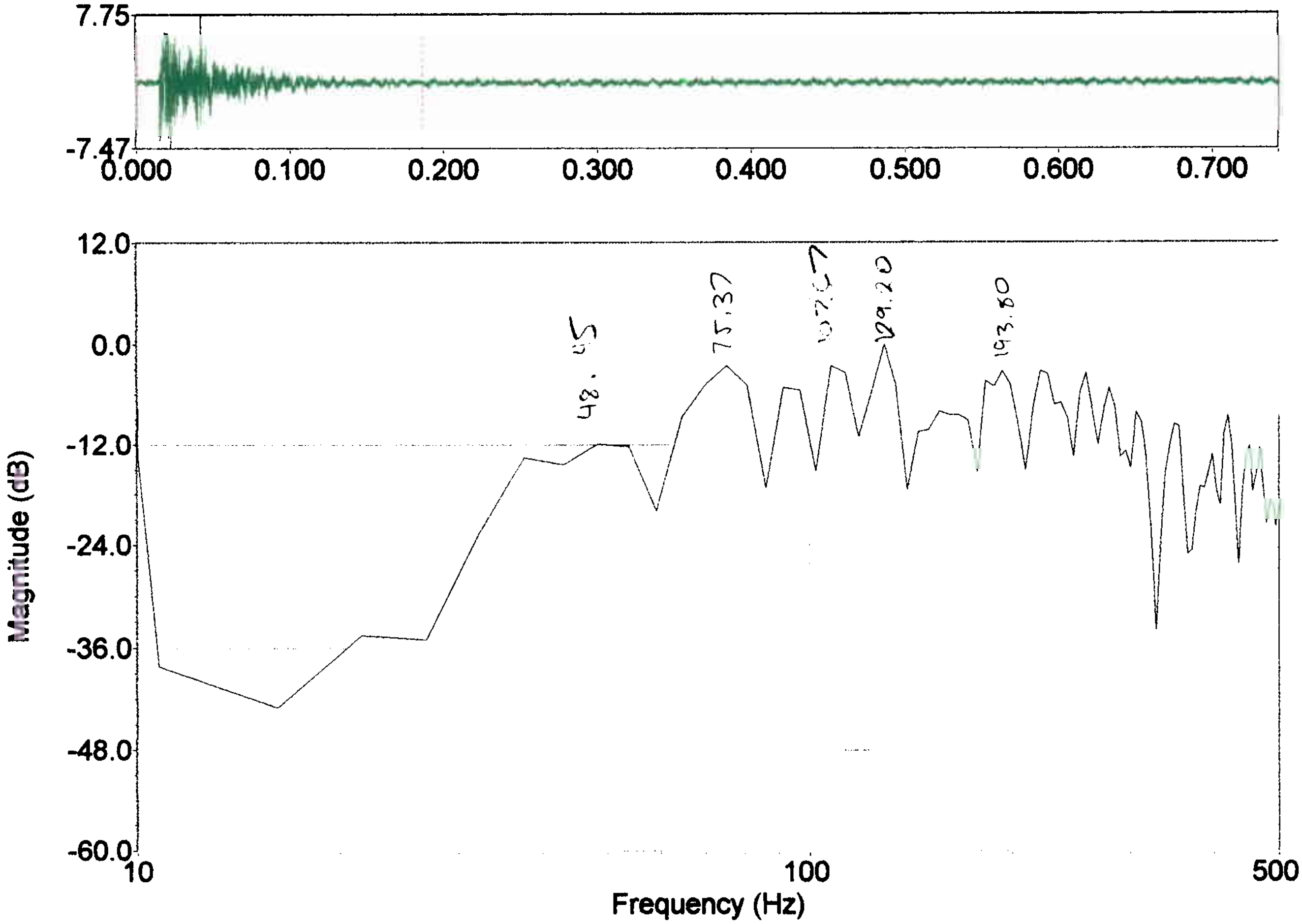
Sun Jun 30 17:35:20 2002

Created By WPI EE & CE Dept Using SIA-Smaart Acoustic Tools

WCIN Wave Form AB
Performance Room Design - WICN
Prepared by Shukanth Reddy and Nedunceliyan Kulasekaran



FREQUENCY SLICE

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Banding: Log (NB)

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Sun Jun 30 17:45:27 2002
Created By WPI EE & CE Dept Using SIA-Smaart Acoustic Tools

WCIN Bands Table AB
Performance Room Design - WICN
Prepared by Shukanth Reddy and Nedunceliyan Kulasekaran

Band	T (R)	EDT (R)	DTR	T (20)	T (30)	EDT	C10	C20	C50	C80
Broadband	***	***	***	***	***	***	***	***	***	***
63 Hz	0.26	0.61	5	***	***	***	-1.26	1.66	7.32	22.39
125 Hz	0.52	0.20	10	***	***	***	-2.82	0.03	5.73	10.91
250 Hz	0.49	0.42	8	***	***	***	-4.49	-3.17	2.64	8.71
500 Hz	0.36	0.52	8	***	***	***	-5.20	-2.91	3.75	11.01
1 kHz	0.42	0.42	11	***	***	***	-4.10	-0.73	5.41	11.20
2 kHz	0.53	0.29	15	***	***	***	-1.45	1.55	7.72	14.72
4 kHz	0.36	0.08	7	***	***	***	-3.06	0.42	8.85	14.49
8 kHz	0.35	0.10	12	***	***	***	-0.66	1.58	9.44	15.96

%Alcons (Short Form): 2.32

%Alcons (Long Form): 3.22

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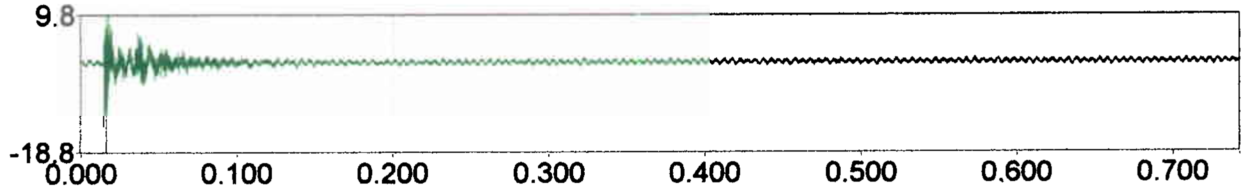
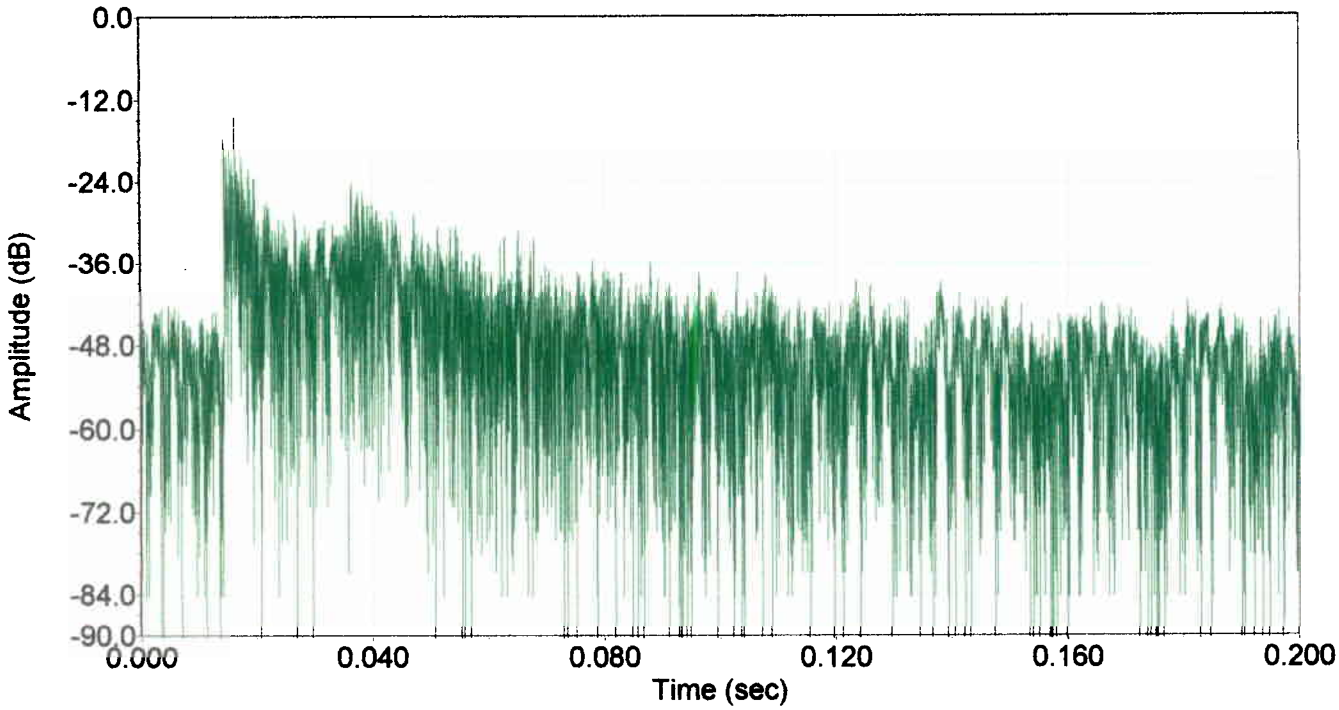
Sun Jun 30 18:19:24 2002

Created By WPI EE & CE Dept Using SIA-Smaart Acoustic Tools

WCIN Wave Form AC (A0 - 03)
Performance Room Design - WICN
Prepared by Shukanth Reddy and Nedunceliyan Kulasekaran





TIME DISPLAY

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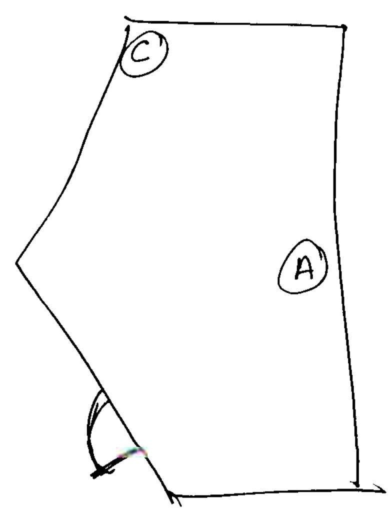

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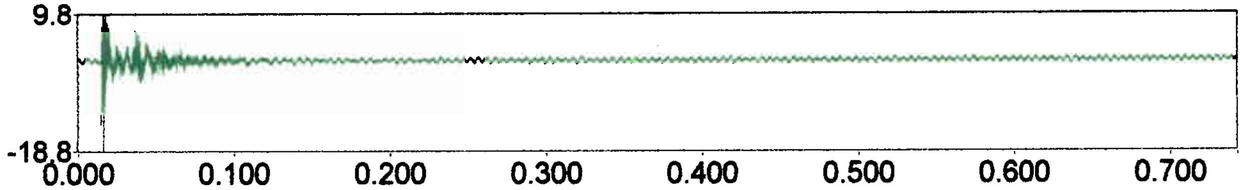
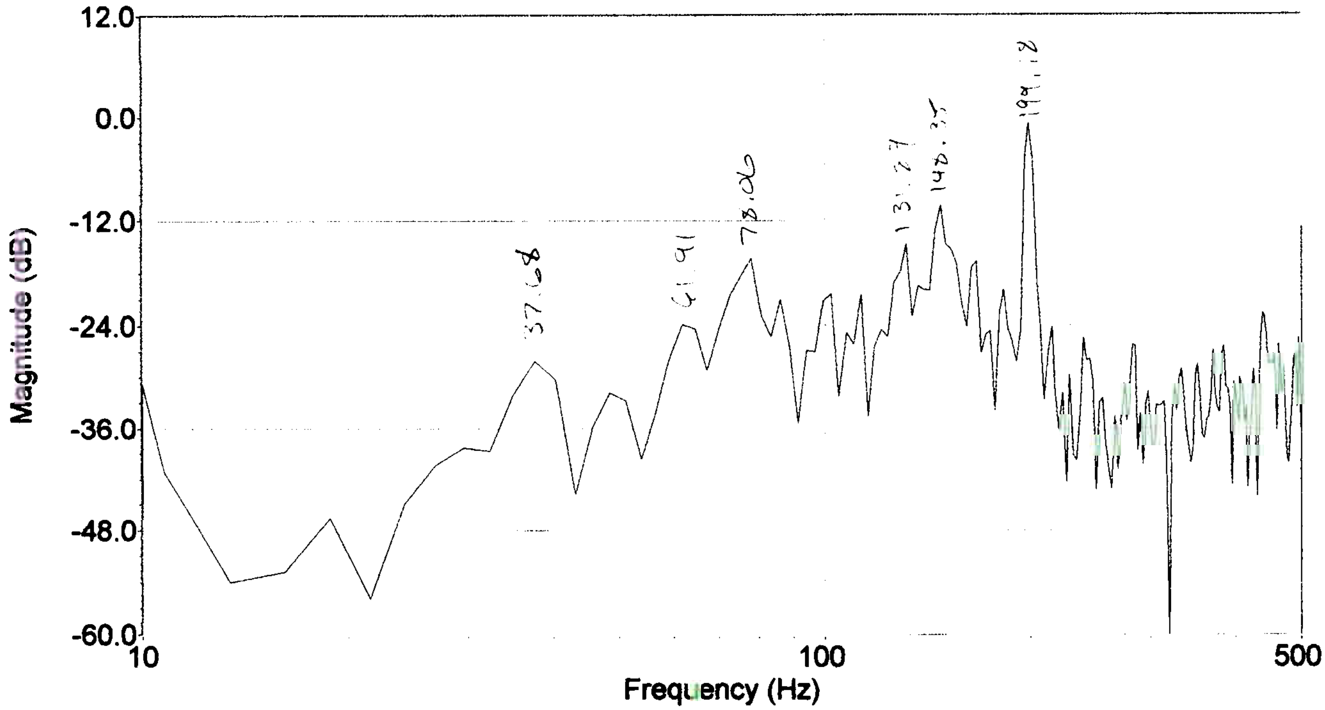
WCIN Wave Form AC
Performance Room Design - WICN
Prepared by Shukanth Reddy and Nedunceliyan Kulasekaran





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Banding: Log (NB)

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Created By WPI EE & CE Dept Using SIA-Smaart Acoustic Tools

WCIN Bands Table AC
Performance Room Design - WICN
Prepared by Shukanth Reddy and Nedunceliyan Kulasekaran

Band	T (R)	EDT (R)	DTR	T (20)	T (30)	EDT	C10	C20	C50	C80
Broadband	0.48	0.07	14	***	***	***	-0.71	1.61	10.08	14.67
63 Hz	0.45	0.20	8	***	***	***	-0.66	0.48	5.75	7.08
125 Hz	0.26	0.20	10	***	***	***	-2.88	1.18	25.00	-9.00
250 Hz	0.33	0.12	11	***	***	***	0.63	7.89	-9.00	-9.00
500 Hz	0.44	0.18	5	***	***	***	-5.69	-1.95	4.72	12.50
1 kHz	0.35	0.25	10	***	***	***	-3.01	-1.65	9.11	15.74
2 kHz	0.41	0.06	13	***	***	***	1.62	2.79	10.38	17.74
4 kHz	0.30	0.21	12	***	***	***	-0.22	1.74	11.83	18.88
8 kHz	0.30	0.10	18	***	***	***	0.54	2.84	11.81	18.34

%Alcons (Short Form): 2.32

%Alcons (Long Form): 3.23

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Sun Jun 30 18:29:44 2002
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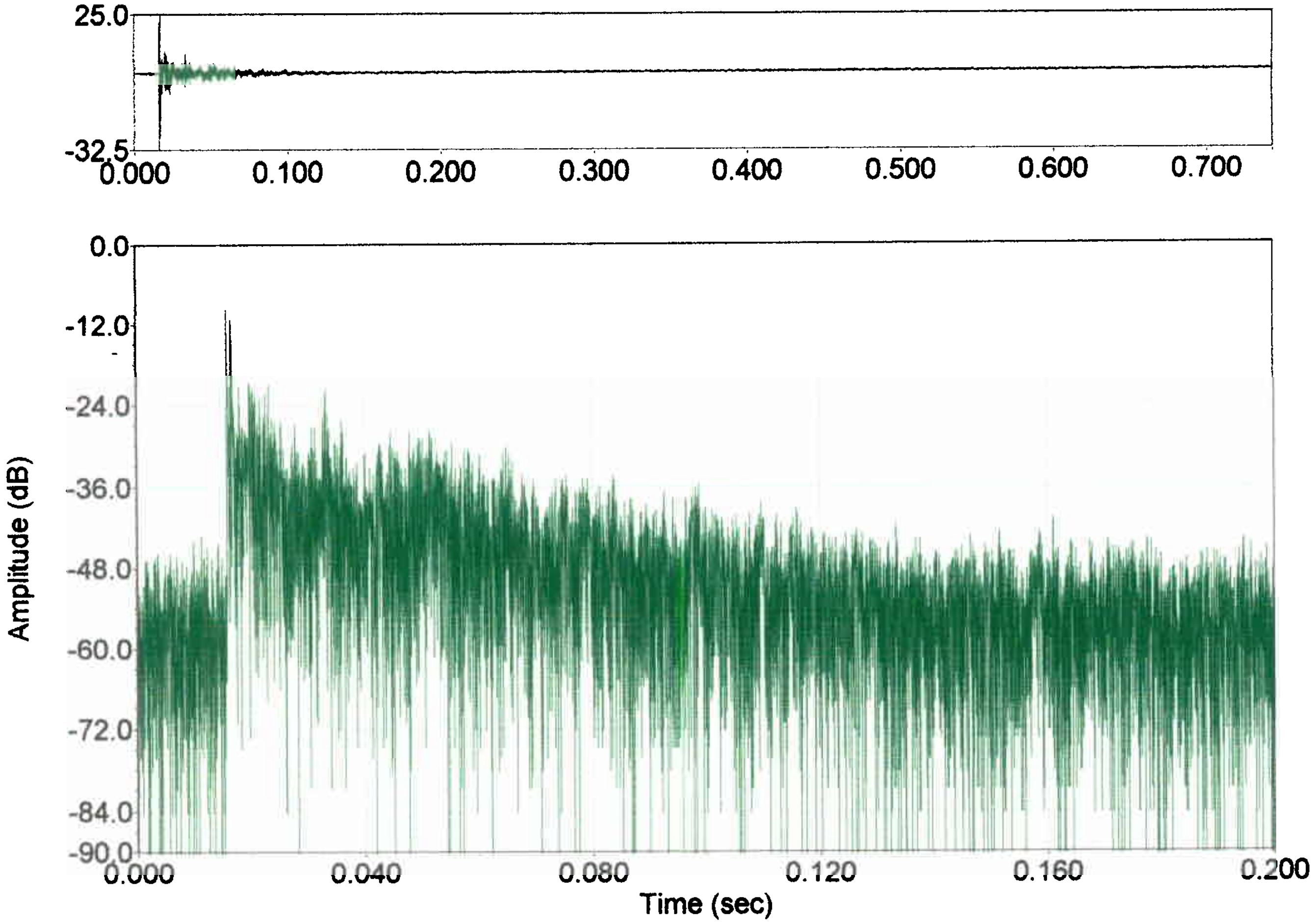
WCIN Wave Form BA (A1- 01)

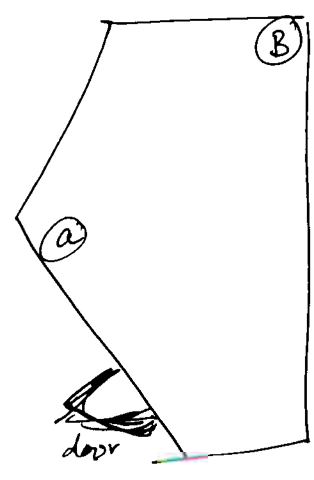
Performance Room Design - WICN

Prepared by Shukanth Reddy and Nedunceliyan Kulasekaran



TIME DISPLAY

Samples: 0 - 8820



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Sun Jun 30 18:32:47 2002

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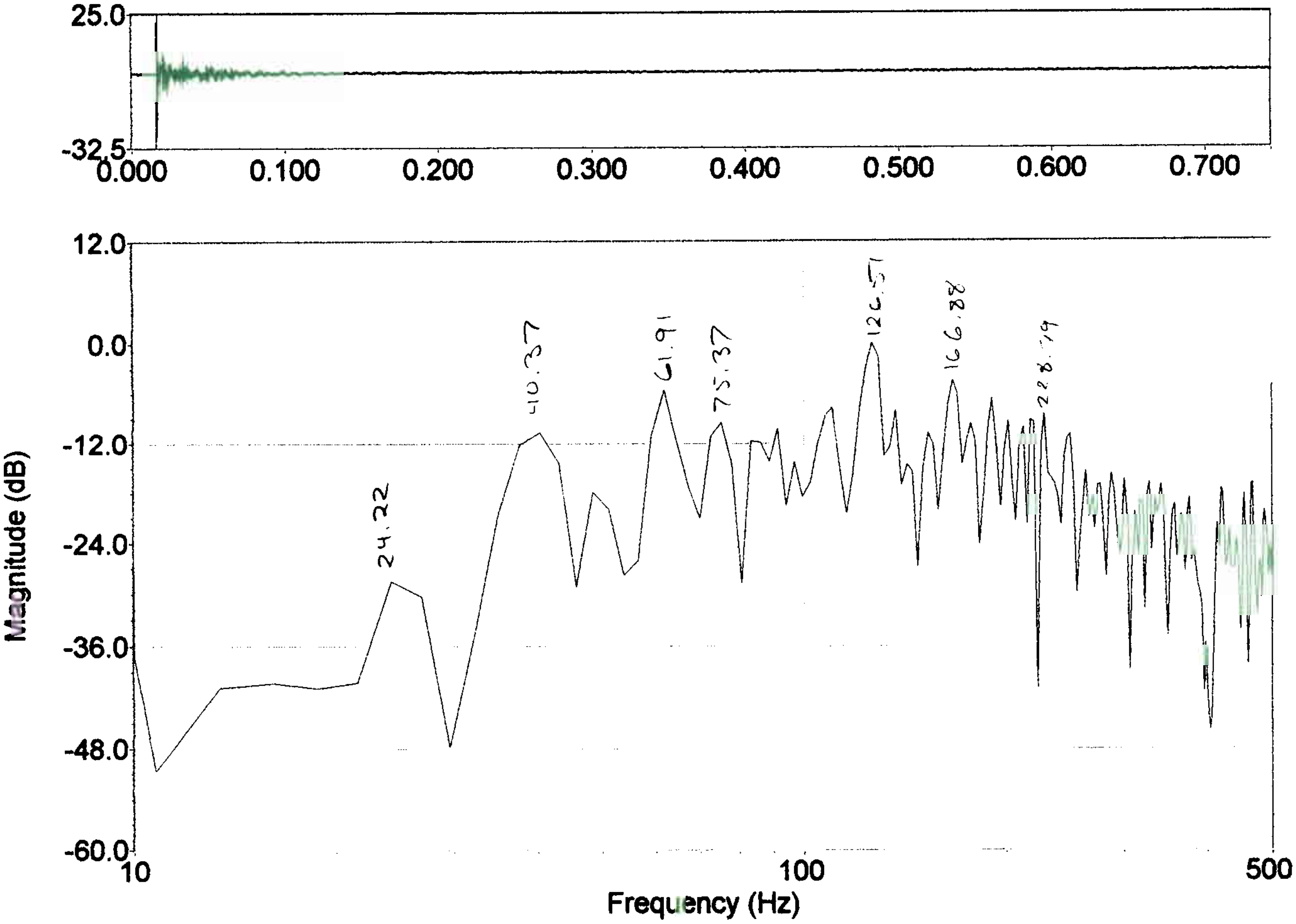
WCIN Wave Form BA
Performance Room Design - WICN
Prepared by Shukanth Reddy and Nedunceliyan Kulasekaran



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Banding: Log (NB)

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Created By WPI EE & CE Dept Using SIA-Smaart Acoustic Tools

WCIN Bands Table BA
Performance Room Design - WICN
Prepared by Shukanth Reddy and Nedunceliyan Kulasekaran

Band	T (R)	EDT (R)	DTR	T (20)	T (30)	EDT	C10	C20	C50	C80
Broadband	0.31	0.06	12	***	***	***	3.45	5.49	11.94	16.64
63 Hz	0.71	0.52	11	***	***	***	-10.25	-7.64	2.07	11.50
125 Hz	0.58	0.12	10	***	***	***	-1.67	-0.85	5.49	11.39
250 Hz	0.56	0.10	10	***	***	***	-0.82	-0.63	7.70	12.79
500 Hz	0.49	0.17	10	***	***	***	-4.45	2.78	8.51	19.55
1 kHz	0.42	0.16	10	***	***	***	-1.79	1.39	9.36	15.06
2 kHz	0.29	0.12	9	***	***	***	-0.14	3.68	11.80	18.79
4 kHz	0.36	0.08	16	***	***	***	2.60	5.83	12.29	19.24
8 kHz	0.36	0.06	18	***	***	***	2.34	5.37	12.71	18.40

%Alcons (Short Form): 2.35

%Alcons (Long Form): 2.96

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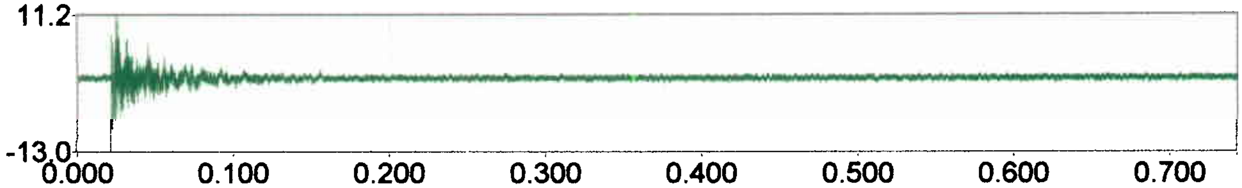
Sun Jun 30 18:39:46 2002

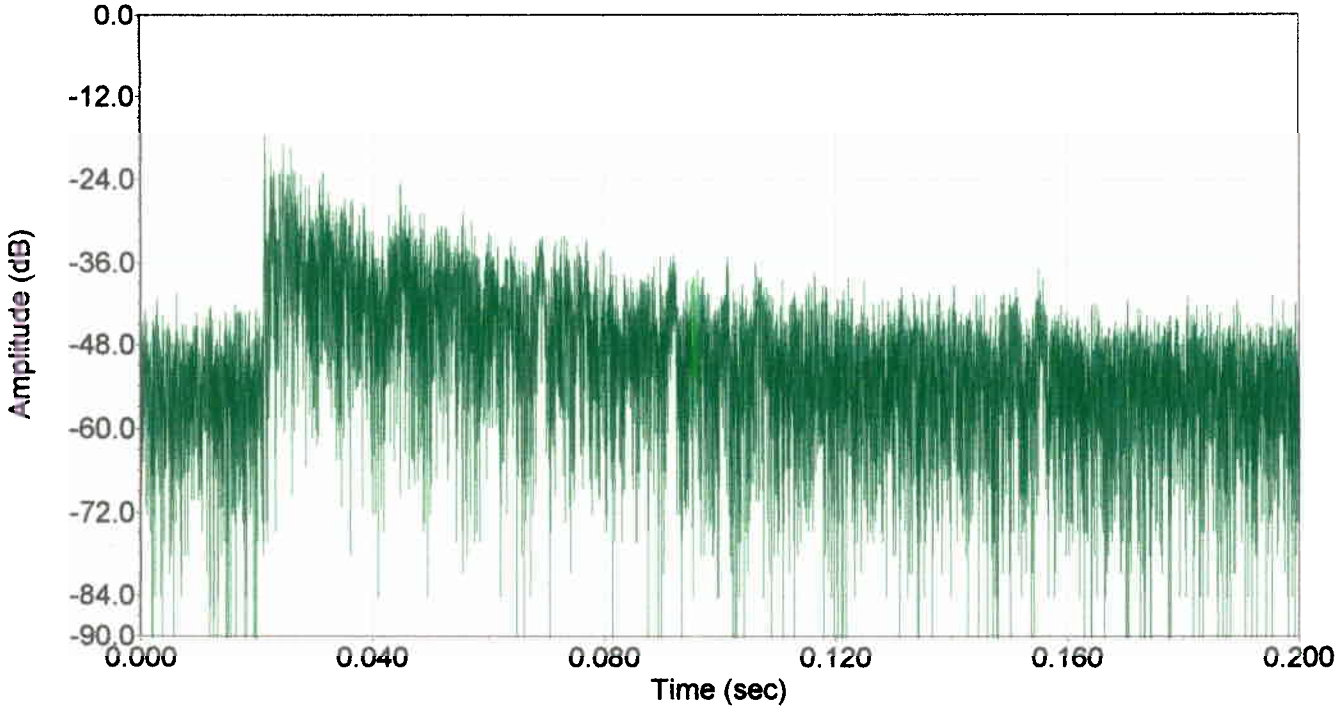
Created By WPI EE & CE Dept Using SIA-Smaart Acoustic Tools

WCIN Wave Form BB (A1_02)

Performance Room Design - WICN

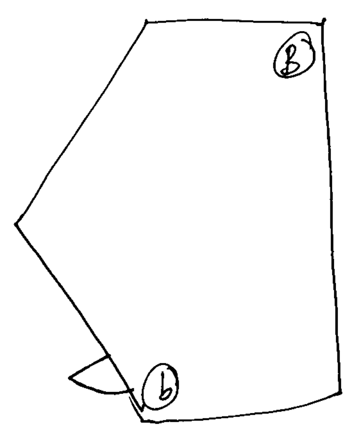
Prepared by Shukanth Reddy and Nedunceliyan Kulasekaran





TIME DISPLAY

Samples: 0 - 8820



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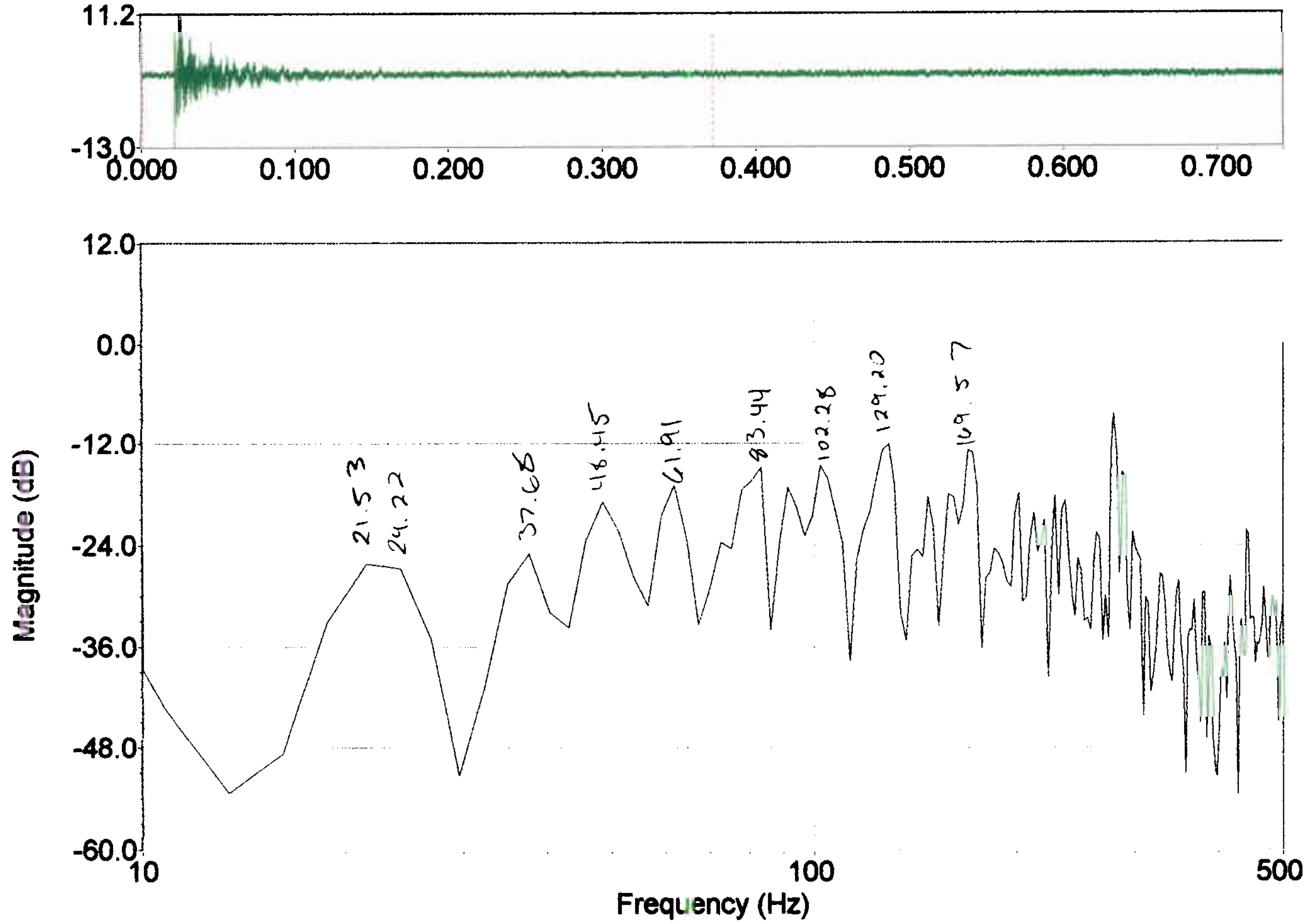
Sun Jun 30 18:42:24 2002

Created By WPI EE & CE Dept Using SIA-Smaart Acoustic Tools

WCIN Wave Form BB
Performance Room Design - WICN
Prepared by Shukanth Reddy and Neduncelíyan Kulasekaran



FREQUENCY SLICE

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Frames: 0 - 4
Banding: Log (NB)

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Sun Jun 30 18:42:42 2002
Created By WPI EE & CE Dept Using SIA-Smaart Acoustic Tools

WCIN Bands Table BB
Performance Room Design - WICN
Prepared by Shukanth Reddy and Nedunceliyan Kulasekaran

Band	T (R)	EDT (R)	DTR	T (20)	T (30)	EDT	C10	C20	C50	C80
Broadband	0.46	0.12	10	***	***	***	-0.13	2.85	8.90	14.01
63 Hz	0.39	0.23	6	***	***	***	-1.84	-0.10	7.06	21.60
125 Hz	0.39	0.26	9	***	***	***	-0.57	1.25	6.74	13.32
250 Hz	0.63	0.37	12	***	***	***	-2.21	-1.38	6.42	10.00
500 Hz	0.61	0.12	9	***	***	***	-2.07	-0.63	5.85	10.34
1 kHz	0.45	0.18	13	***	***	***	1.67	3.87	8.85	14.54
2 kHz	0.45	0.13	9	***	***	***	2.73	5.25	10.90	15.62
4 kHz	0.50	0.07	10	***	***	***	-1.40	1.73	8.46	33.67
8 kHz	0.41	0.06	9	***	***	***	0.44	3.59	10.73	15.56

%Alcons (Short Form): 2.50

%Alcons (Long Form): 3.46

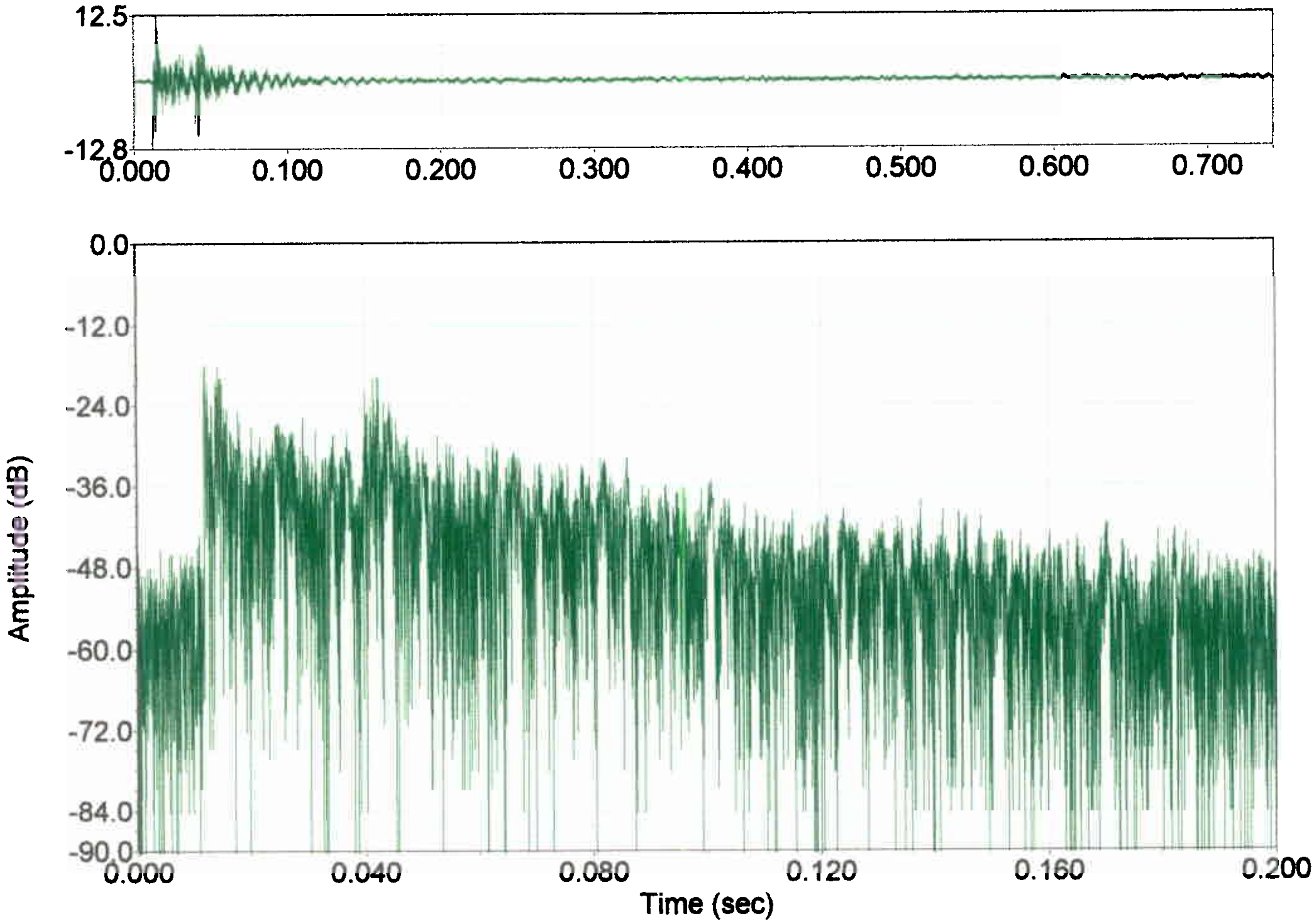
File: C:\Download\wav files\wcin-bb.wav
Sun Jun 30 18:54:32 2002
Created By WPI EE & CE Dept Using SIA-Smaart Acoustic Tools

WCIN Wave Form BC

(A1 – 03)

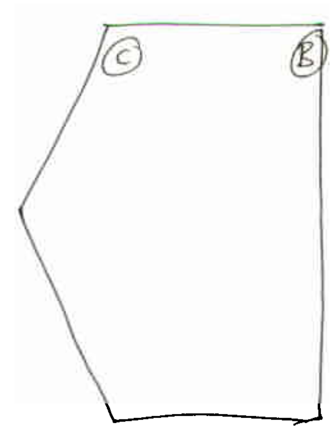
Performance Room Design - WICN

Prepared by Shukanth Reddy and Nedunceliyan Kulasekaran



TIME DISPLAY

Samples: 0 - 8820



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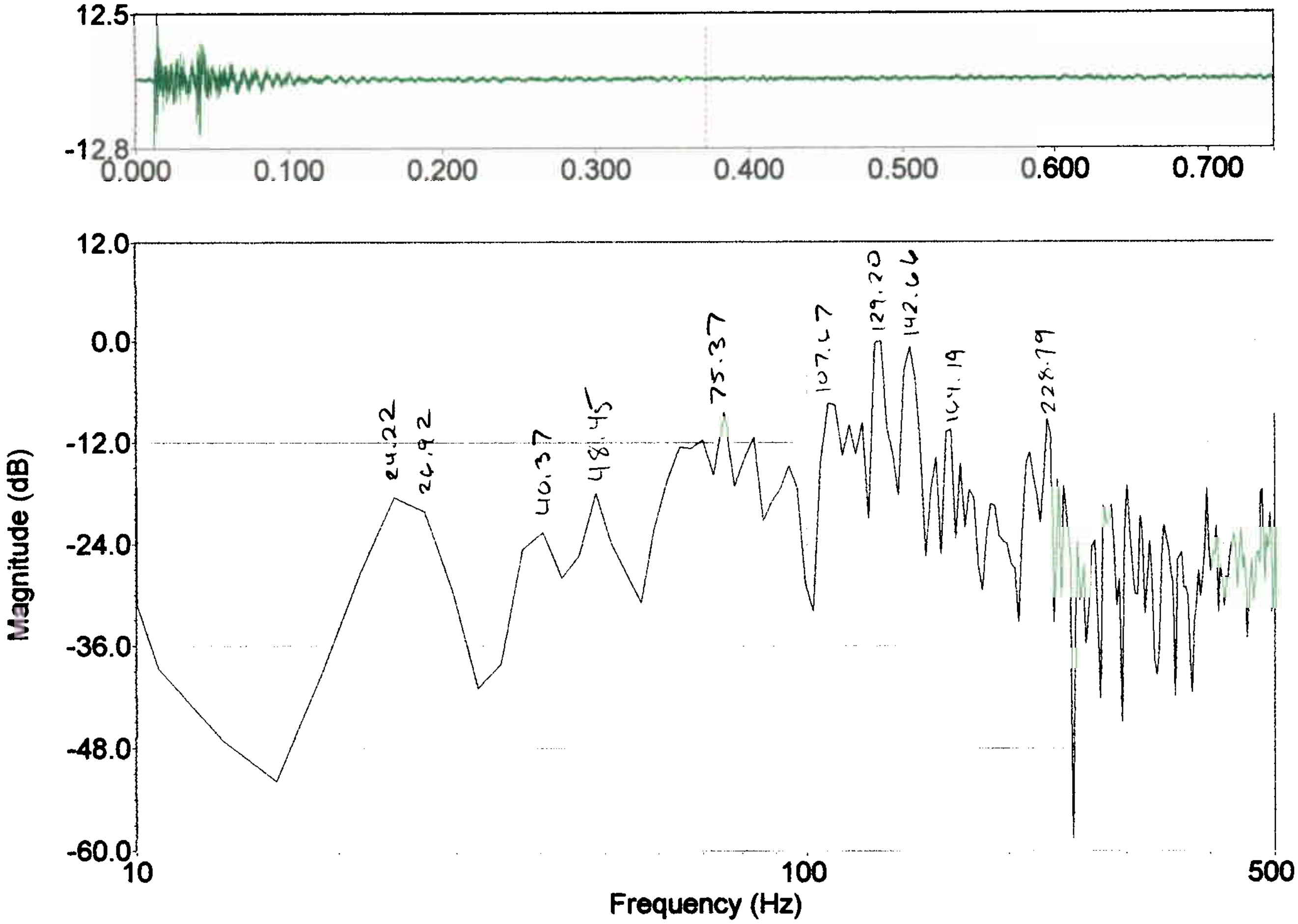
Sun Jun 30 18:55:15 2002

Created By WPI EE & CE Dept Using SIA-Smaart Acoustic Tools

WCIN Wave Form BC
Performance Room Design - WICN
Prepared by Shukanth Reddy and Neduncellyan Kulasekaran



FREQUENCY SLICE

Frame: 0 (0.00 sec)
Frames: 0 - 4
Banding: Log (NB)

File: C:\Download\wav files\wcin-bc.wav
Sun Jun 30 18:55:34 2002
Created By WPI EE & CE Dept Using SIA-Smaart Acoustic Tools

WCIN Bands Table BC
Performance Room Design - WICN
Prepared by Shukanth Reddy and Neduncellyan Kulasekaran

Band	T (R)	EDT (R)	DTR	T (20)	T (30)	EDT	C10	C20	C50	C80
Broadband	0.24	0.83	2	***	***	***	-2.76	-0.63	7.70	15.02
63 Hz	0.33	0.55	6	***	***	***	-1.98	-0.25	5.22	10.47
125 Hz	0.48	0.37	9	***	***	***	-3.95	-2.20	6.83	10.41
250 Hz	0.46	0.27	13	***	***	***	-1.08	0.85	7.43	11.96
500 Hz	0.48	0.22	15	***	***	***	-1.74	1.47	9.13	14.06
1 kHz	0.29	0.38	6	***	***	***	-1.53	0.82	8.18	14.08
2 kHz	0.24	0.26	8	***	***	***	-0.95	0.36	11.05	16.39
4 kHz	0.39	0.08	17	***	***	***	2.46	5.83	12.12	20.92
8 kHz	0.34	0.18	11	***	***	***	-1.43	0.75	10.27	16.57

%Alcons (Short Form): 2.30

%Alcons (Long Form): 2.83

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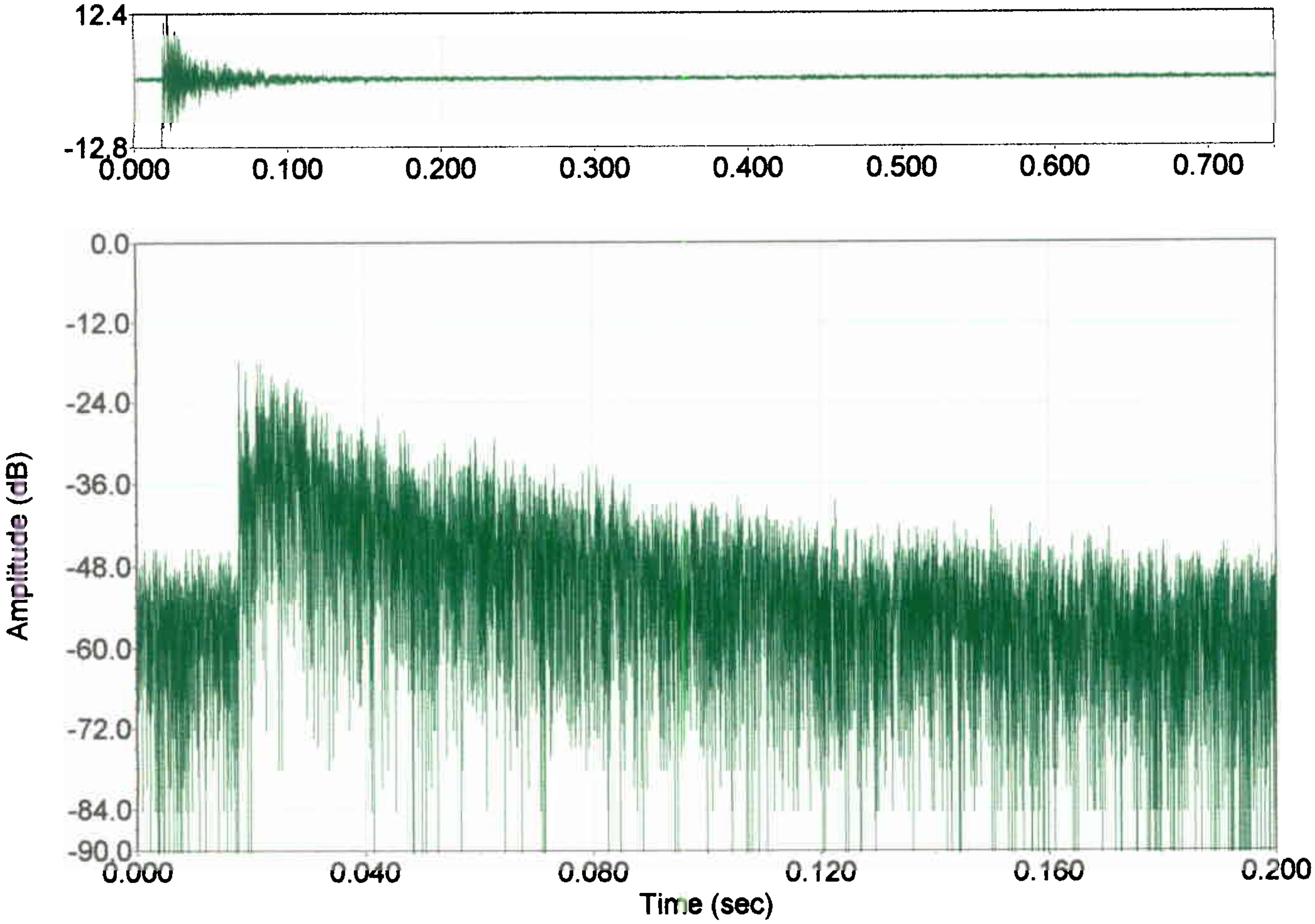
Sun Jun 30 19:03:46 2002
Created By WPI EE & CE Dept Using SIA-Smaart Acoustic Tools

(A2 – 04)

WCIN Wave Form CD
Performance Room Design - WICN
Prepared by Shukanth Reddy and Neduncelіyan Kulasekaran



TIME DISPLAY

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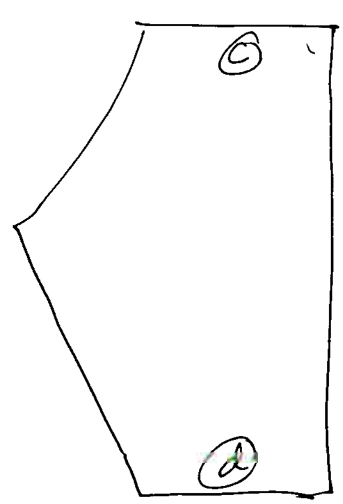

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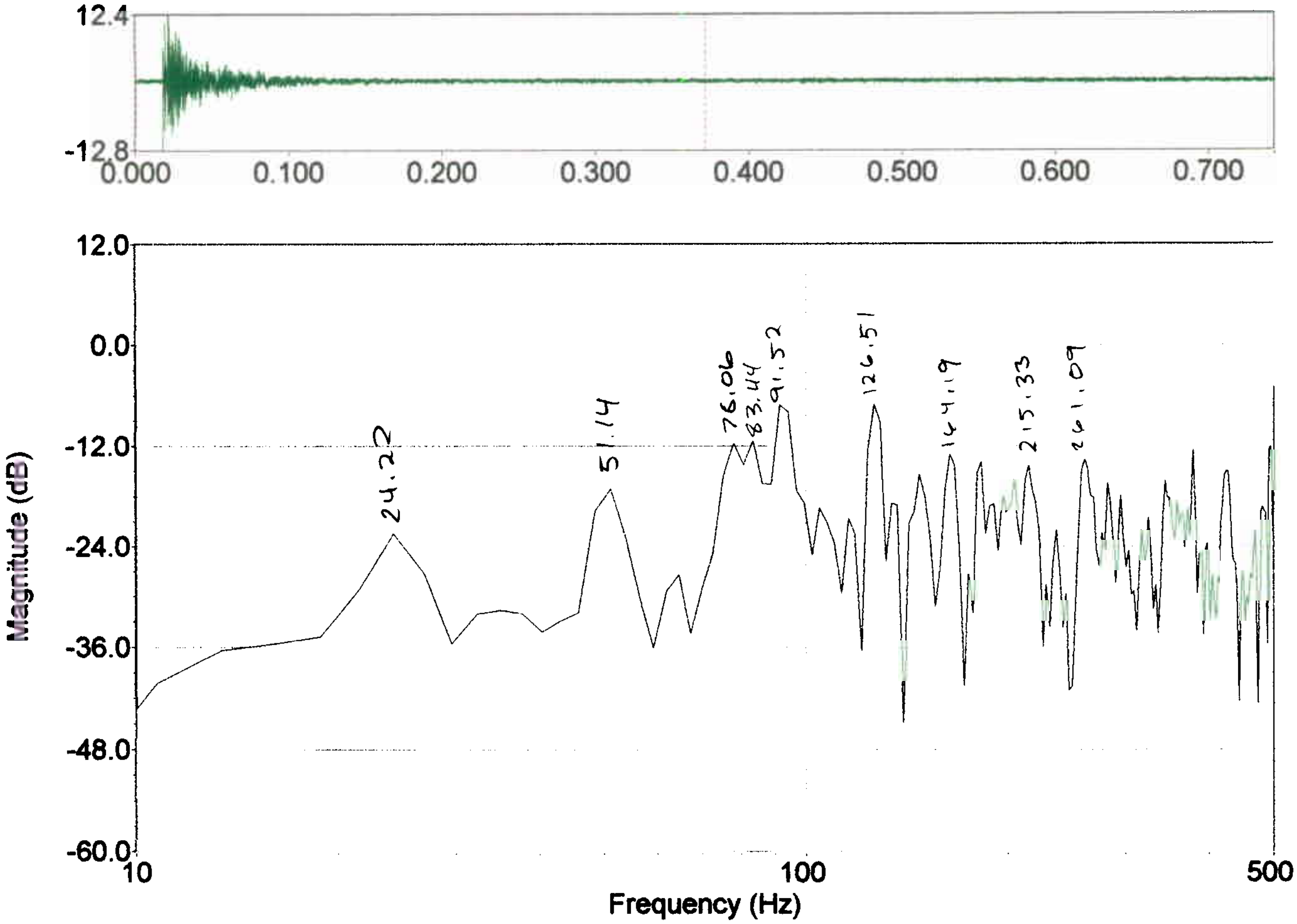
Sun Jun 30 19:04:17 2002
Created By WPI EE & CE Dept Using SIA-Smaart Acoustic Tools

WCIN Wave Form CD
Performance Room Design - WICN
Prepared by Shukanth Reddy and Nedunceliyan Kulasekaran



FREQUENCY SLICE

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Frames: 0 - 4
Banding: Log (NB)

File: C:\Download\wav files\wcin-cd.wav
Sun Jun 30 19:04:38 2002
Created By WPI EE & CE Dept Using SIA-Smaart Acoustic Tools

WCIN Bands Table CD
Performance Room Design - WICN
Prepared by Shukanth Reddy and Nedunceliyan Kulasekaran

Band	T (R)	EDT (R)	DTR	T (20)	T (30)	EDT	C10	C20	C50	C80
Broadband	0.45	0.13	10	***	***	***	0.46	4.77	10.62	15.20
63 Hz	0.57	0.26	11	***	***	***	-3.83	0.70	8.22	11.42
125 Hz	0.63	0.35	8	***	***	***	-6.48	-2.82	6.78	10.57
250 Hz	0.50	0.24	11	***	***	***	-3.21	1.30	5.55	11.15
500 Hz	0.58	0.28	13	***	***	***	-2.91	1.48	7.28	11.78
1 kHz	0.56	0.26	7	***	***	***	-2.63	1.23	7.03	11.97
2 kHz	0.49	0.15	13	***	***	***	2.45	4.90	10.44	14.47
4 kHz	0.47	0.12	12	***	***	***	1.03	4.01	9.96	14.79
8 kHz	0.42	0.17	13	***	***	***	2.33	5.63	12.52	17.59

%Alcons (Short Form): 2.38

%Alcons (Long Form): 3.39

File: C:\Download\wav files\wcin-cd.wav
Sun Jun 30 19:12:44 2002
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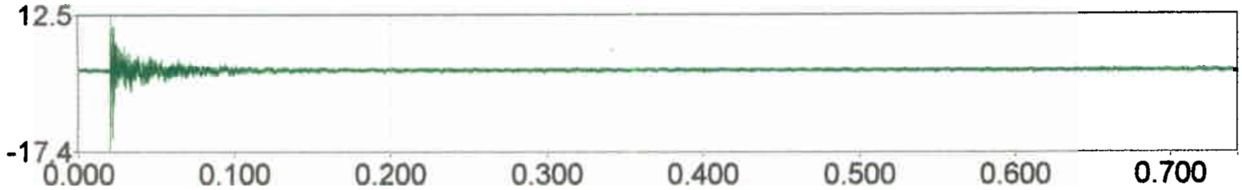
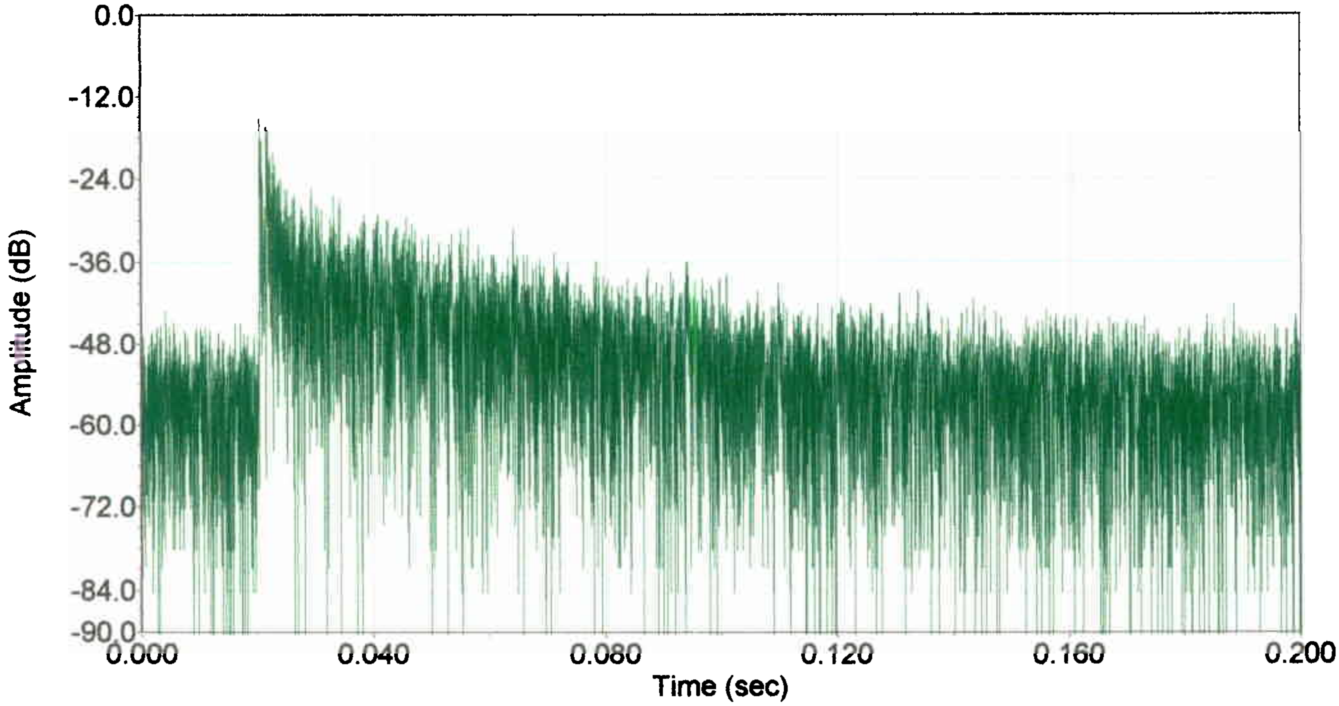
WCIN Wave Form DC (A3 – 03)

Performance Room Design - WICN

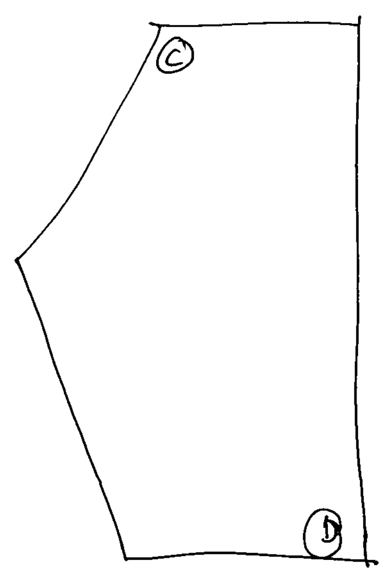
Prepared by Shukanth Reddy and Nedunceliyan Kulasekaran





TIME DISPLAY

Samples: 0 - 8820



File: C:\Download\wav files\wcin-dc.wav

Sun Jun 30 19:13:13 2002

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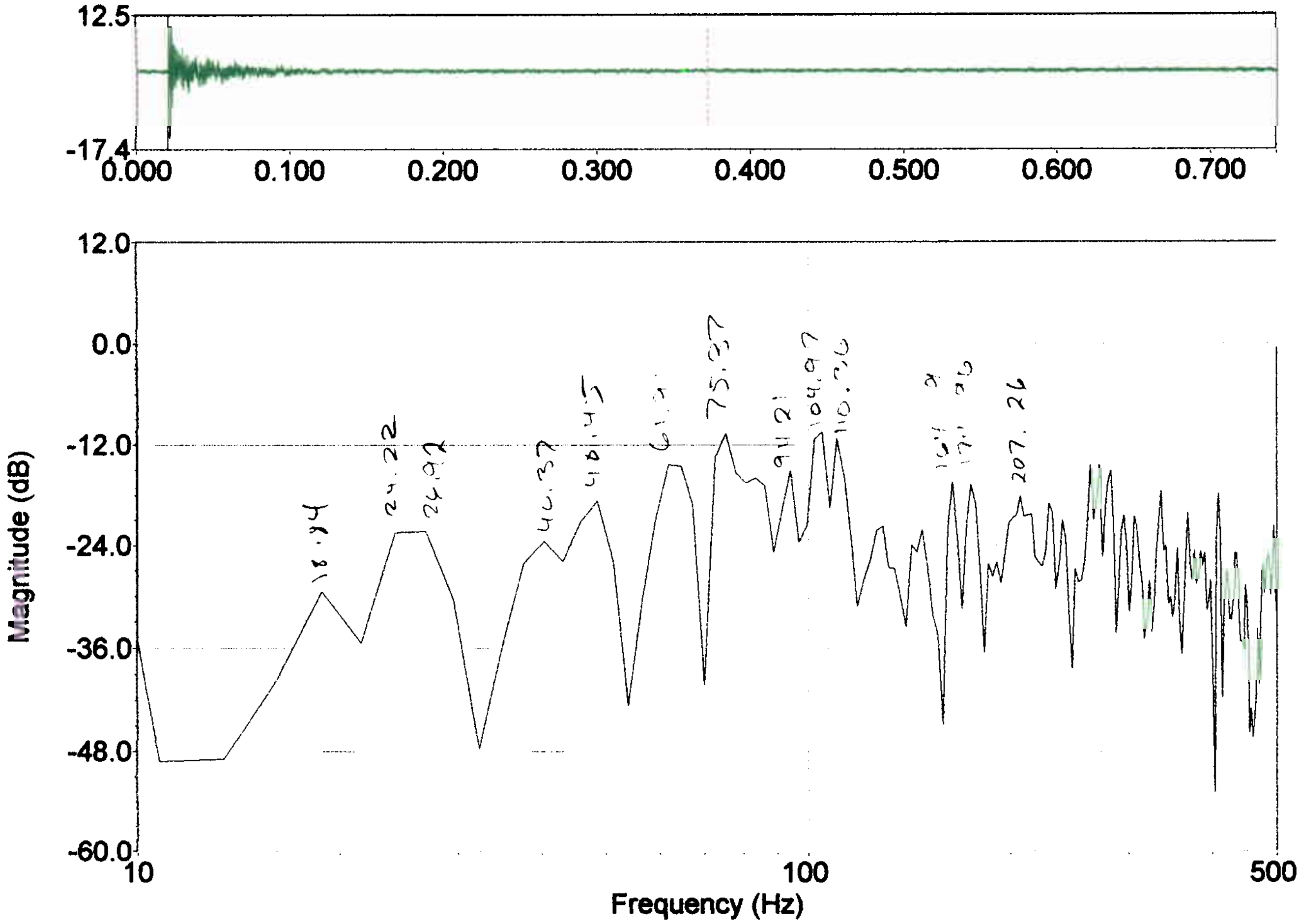
WCIN Wave Form DC
Performance Room Design - WICN
Prepared by Shukanth Reddy and Nedunceliyan Kulasekaran



FREQUENCY SLICE

Frame: 0 (0.00 sec)
Frames: 0 - 4
Banding: Log (NB)

File: C:\Download\wav files\wcin-dc.wav
Sun Jun 30 19:13:37 2002
Created By WPI EE & CE Dept Using SIA-Smaart Acoustic Tools

WCIN Bands Table DC
Performance Room Design - WICN
Prepared by Shukanth Reddy and Nedunceliyan Kulasekaran

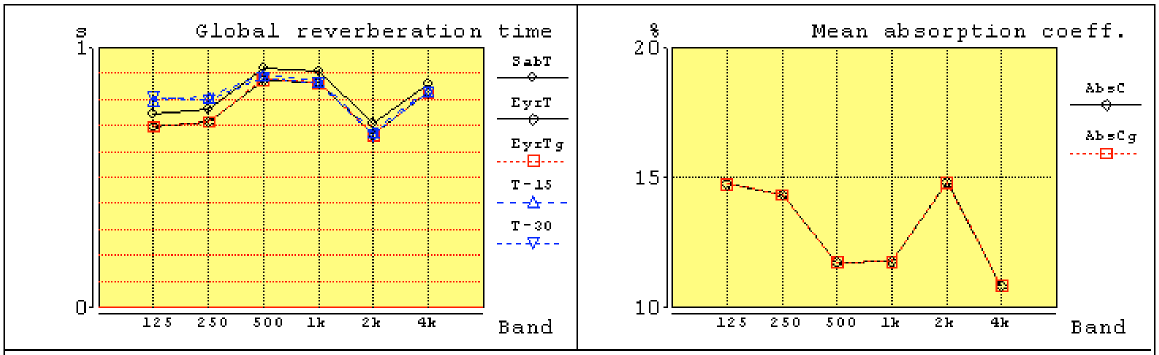
Band	T (R)	EDT (R)	DTR	T (20)	T (30)	EDT	C10	C20	C50	C80
Broadband	0.34	0.07	11	***	***	***	3.13	5.56	11.87	18.36
63 Hz	0.41	0.56	8	***	***	***	-3.72	-0.76	5.46	10.57
125 Hz	0.43	0.43	8	***	***	***	-1.71	0.94	4.68	9.77
250 Hz	0.45	0.45	14	***	***	***	-2.62	1.75	7.32	11.61
500 Hz	0.56	0.27	10	***	***	***	0.06	2.56	7.61	11.74
1 kHz	0.44	0.16	8	***	***	***	-0.26	2.07	8.84	16.20
2 kHz	0.42	0.16	9	***	***	***	0.92	3.29	10.79	15.12
4 kHz	0.40	0.12	12	***	***	***	1.27	3.83	11.03	15.55
8 kHz	0.52	0.08	17	***	***	***	4.15	6.56	12.20	16.62

%Alcons (Short Form): 2.49

%Alcons (Long Form): 3.46

File: C:\Download\wav files\wcin-dc.wav
Sun Jun 30 19:22:41 2002
Created By WPI EE & CE Dept Using SIA-Smaart Acoustic Tools

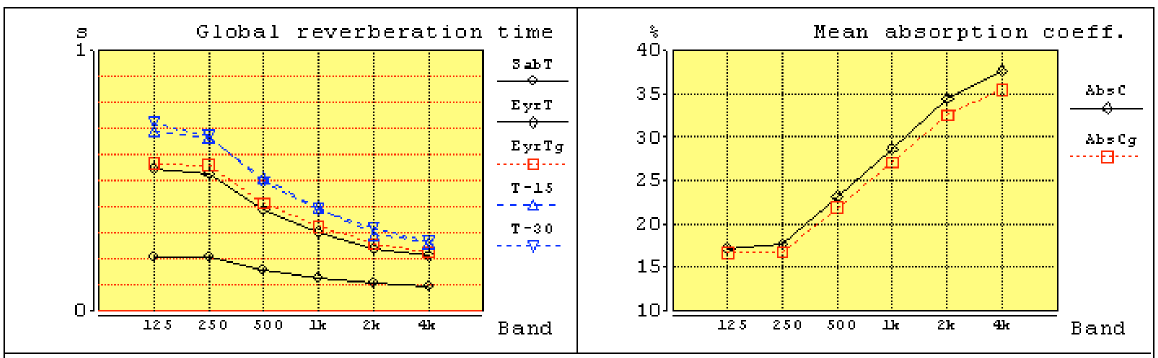
APPENDIX C: CATT-Acoustic Reverberation Analysis



	125	250	500	1k	2k	4k	
EyrT	0.69	0.71	0.87	0.86	0.66	0.83	s
EyrTg	0.69	0.71	0.87	0.86	0.66	0.83	s
SabT	0.74	0.76	0.92	0.91	0.71	0.86	s
T-15	0.80	0.81	0.89	0.87	0.67	0.83	s
T-30	0.81	0.80	0.88	0.86	0.66	0.83	s
AbsC	14.74	14.33	11.73	11.75	14.80	10.83	%
AbsCg	14.74	14.32	11.72	11.75	14.81	10.83	%
MFP	2.78	2.78	2.78	2.78	2.78	2.78	m
Diffs	10.34	19.93	29.36	38.95	48.56	57.84	%

Trunc 1000.0 ms
Rays 12732 (used/oct)
0 (lost/oct)
0 (absorbed/oct)
Angle 1.80 degrees

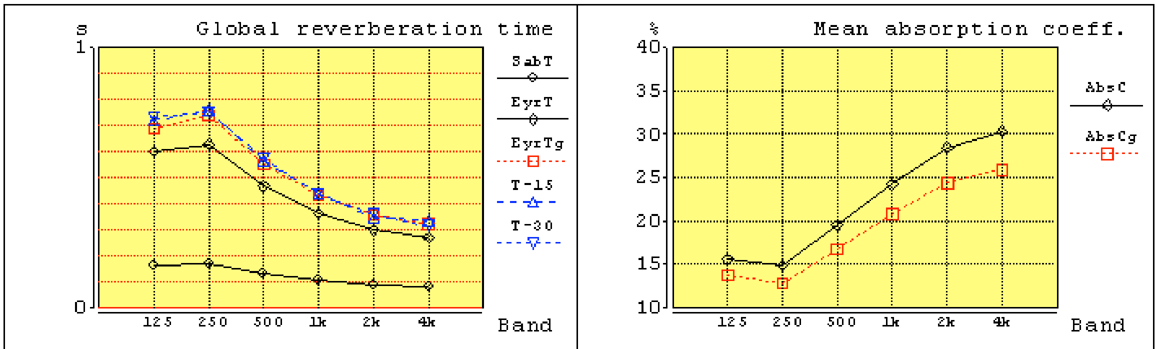
Figure 19 Global reverberation times for WICN's performance room (bare empty state). Note the 2KHx spike in the mean absorption coefficients.



	125	250	500	1k	2k	4k	
EyrT	0.55	0.53	0.39	0.30	0.24	0.21	s
EyrTg	0.56	0.56	0.41	0.32	0.26	0.23	s
SabT	0.21	0.21	0.16	0.13	0.11	0.10	s
T-15	0.69	0.66	0.51	0.40	0.29	0.26	s
T-30	0.72	0.67	0.49	0.39	0.32	0.26	s
AbsC	17.17	17.68	23.18	28.66	34.40	37.67	%
AbsCg	16.65	16.72	21.89	27.06	32.51	35.47	%
MFP	2.58	2.57	2.58	2.58	2.57	2.58	m
Diffs	15.52	24.98	34.57	41.48	48.41	55.40	%

Trunc 1000.0 ms
Rays 12732 (used/oct)
0 (lost/oct)
0 (absorbed/oct)
Angle 1.80 degrees

Figure 20 Global reverberation times for WICN's performance room in current room state



	125	250	500	1k	2k	4k	
EyrT	0.60	0.63	0.47	0.36	0.30	0.27	s
EyrTg	0.69	0.74	0.55	0.43	0.36	0.32	s
SabT	0.16	0.17	0.13	0.11	0.09	0.08	s
T-15	0.72	0.76	0.57	0.44	0.35	0.34	s
T-30	0.73	0.75	0.58	0.44	0.36	0.32	s
AbsC	15.55	14.89	19.47	24.20	28.44	30.34	%
AbsCg	13.70	12.79	16.72	20.74	24.39	25.90	%
MFP	2.55	2.55	2.55	2.55	2.55	2.55	m
Diffs	15.61	23.95	32.29	39.27	46.08	52.99	%

Trunc	1000.0	ms
Rays	12732	(used/oct)
	0	(lost/oct)
	0	(absorbed/oct)
Angle	1.80	degrees

Figure 21 Global reverberation times for WICN's performance room with the suggested constructed performance stage.

APPENDIX D: Complete Echograms (Current room state)

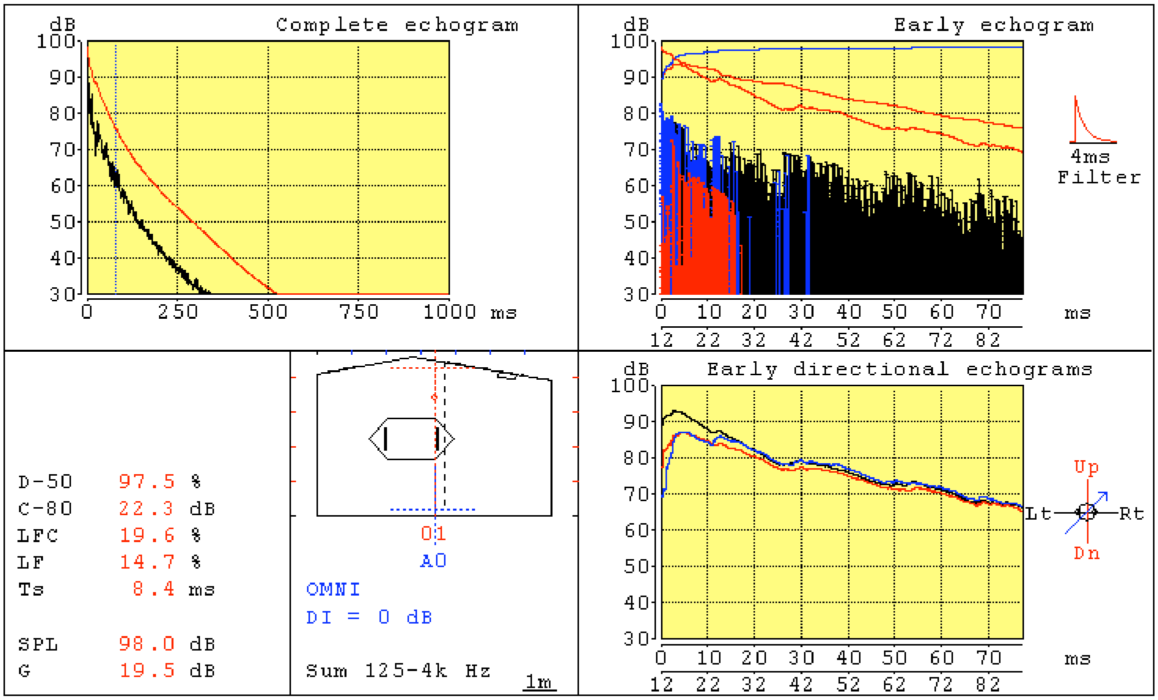


Figure 22 Echogram for source A0 and receiver 01

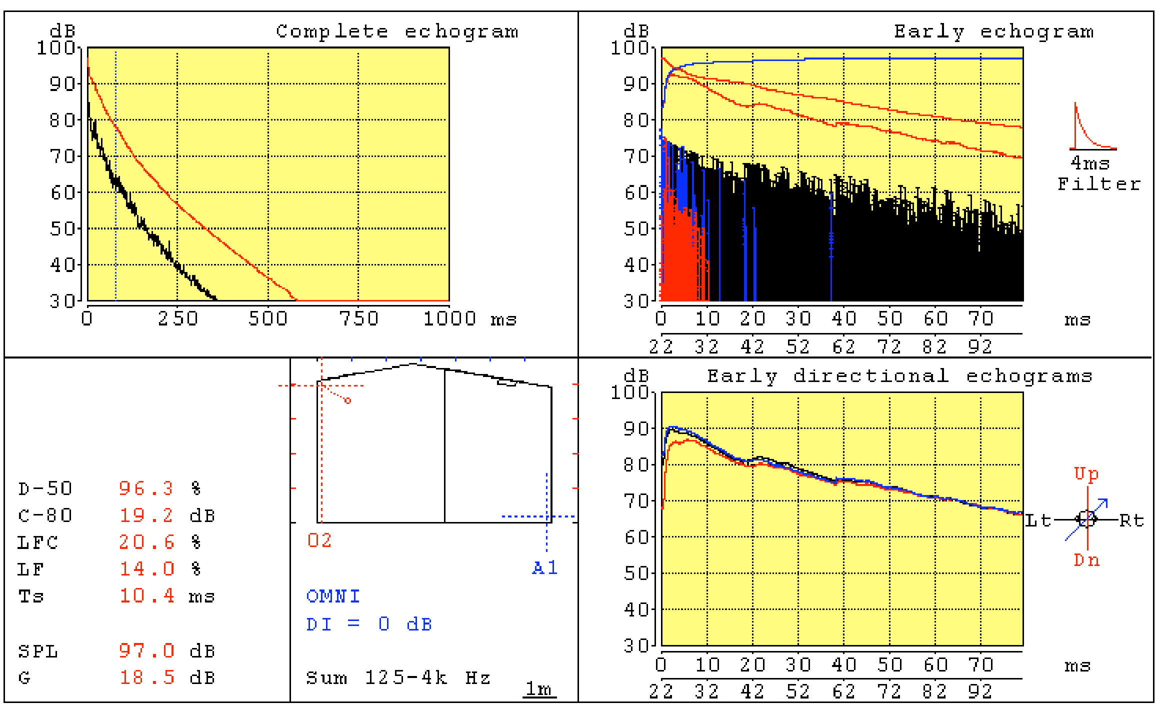


Figure 23 Echogram for source A1 and receiver 02

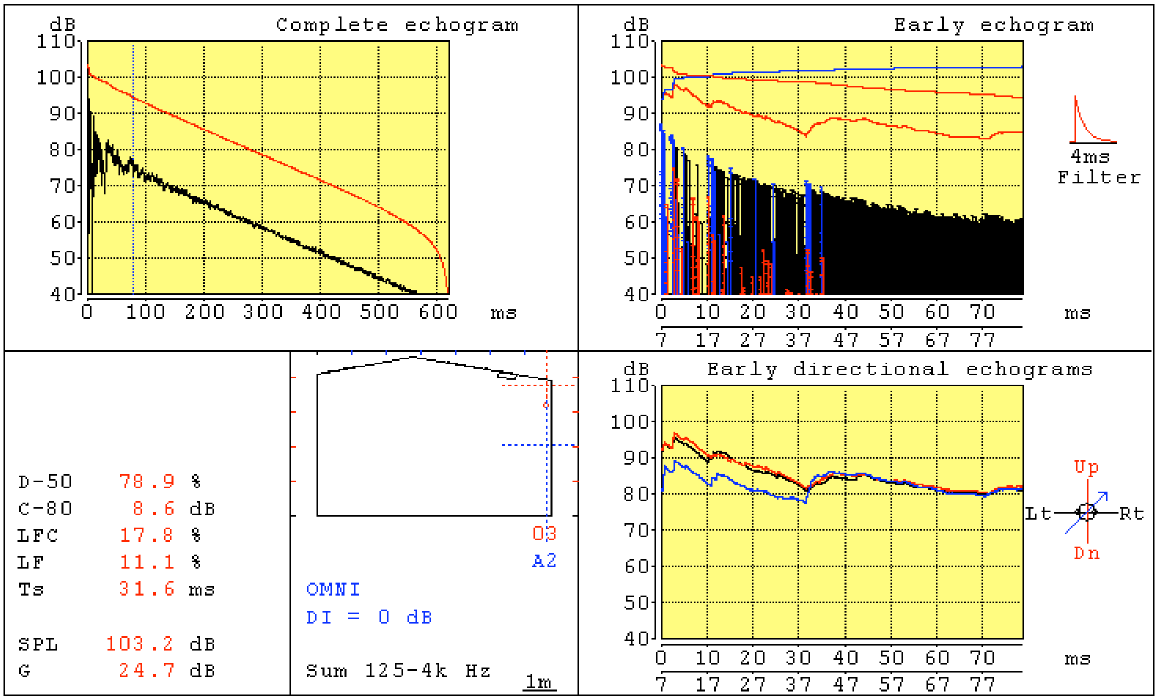


Figure 24 Echogram for source A2 and receiver 03. Note different relative irregularities, suspected due to large electrical metal box noted in top right corner.

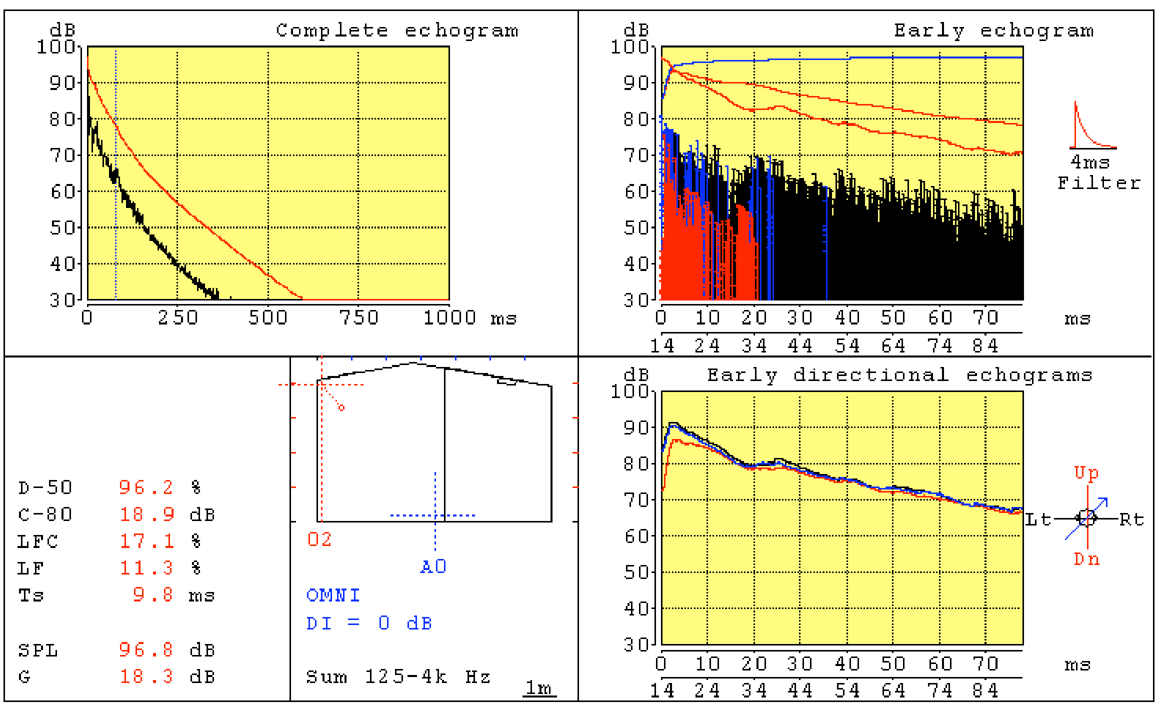


Figure 25 Echogram for source A0 and receiver 02

APPENDIX E: Raleigh Modal Formulations (Excel Solution)

Mode#	p	q	r	MODE FREQUENCY, Hz	Axial	Tangential	Oblique
0	0	0	0	0.0000000000			
1	0	1	0	25.2985074627	x		
2	1	0	0	39.6550831402	x		
3	1	1	0	47.0376455480		x	
4	0	2	0	50.5970149254	x		
5	0	0	1	59.6043956044	x		
6	1	2	0	64.2851735490		x	
7	0	1	1	64.7510498386		x	
8	1	0	1	71.5905691709		x	
9	0	3	0	75.8955223882	x		
10	1	1	1	75.9290726538			x
11	0	2	1	78.1840258284		x	
12	2	0	0	79.3101662804	x		
13	2	1	0	83.2473240127		x	
14	1	3	0	85.6309286265		x	
15	1	2	1	87.6656575495			x
16	2	2	0	94.0752910960		x	
17	0	3	1	96.5029237585		x	
18	2	0	1	99.2108182145		x	
19	2	1	1	102.3855503996			x
20	1	3	1	104.3328323817			x
21	2	3	0	109.7735523430		x	
22	2	2	1	111.3680581233			x
23	3	0	0	118.9652494207	x		
24	0	0	2	119.2087912087	x		
25	3	1	0	121.6254292883		x	
26	0	1	2	121.8636548824		x	
27	2	3	1	124.9116358446			x
28	1	0	2	125.6314511590		x	
29	1	1	2	128.1533300393			x
30	3	2	0	129.2779505139		x	
31	0	2	2	129.5020996773		x	
32	3	0	1	133.0616945070		x	
33	1	2	2	135.4375111986			x
34	3	1	1	135.4452990137			x
35	3	3	0	141.1129366440		x	
36	0	3	2	141.3183152320		x	
37	3	2	1	142.3568490254			x
38	2	0	2	143.1811383419		x	
39	2	1	2	145.3989437951			x
40	1	3	2	146.7766733472			x
41	2	2	2	151.8581453075			x
42	3	3	1	153.1846756815			x
43	2	3	2	162.0523640539			x

44	3	0	2	168.4145672772			x	
45	3	1	2	170.3040837767				x
46	3	2	2	175.8508583730				x
47	0	0	3	178.8131868131		x		
48	0	1	3	180.5939374899			x	
49	1	0	3	183.1575316418			x	
50	3	3	2	184.7257339673				x
51	1	1	3	184.8964463611				x
52	0	2	3	185.8338335655			x	
53	1	2	3	190.0177342158				x
54	0	3	3	194.2531495159			x	
55	2	0	3	195.6125206977			x	
56	2	1	3	197.2416607452				x
57	1	3	3	198.2594555518				x
58	2	2	3	202.0502812991				x
59	2	3	3	209.8198955587				x
60	3	0	3	214.7717075128			x	
61	3	1	3	216.2565625081				x
62	3	2	3	220.6511823384				x
63	3	3	3	227.7872179613				x
							1130	**c**
							14.24785816	**L**
							22.33333333	**W**
							9.479166667	**H**
				Raleigh Formula used:				
	*Frequency = (c/2) * sqrt((p^2/L^2) + (q^2/W^2) + (r^2/H^2))*							

Table 3 Modal Calculations in third octaves using the Raleigh Formula

Band Number	Freq Range	Modes
14	22.1 - 28.1	**1**
15	28.1 - 35.5	0
16	35.5 - 44.7	1
17	44.7 - 56.1	2
18	56.1 - 71.0	3
19	71.0 - 89.4	8
20	89.4 - 111.8	7
21	111.8 - 141.4	14
22	141.4 - 178.9	11
23	178.9 - 223.6	15
24	223.6 - 280.6	1

Table 4 Modal analysis based on Raleigh modal calculations

APPENDIX F: Performance Room code (performance.geo)

```
; Performance Room Geo
; WICN Radio - IQP E Term 2002
; Nedunceliyan Kulasekaran, Shukanth Reddy
; ****************************************

; ------------------------------------------------------------------------------------------
; ABS Values obtained from Everest:

  ABS concrete_floor = <1 1 1.5 2 2 2> L <10 20 30 40 50 60> {127 127 127}
  ABS concrete_painted = <10 5 6 7 9 8> L <10 20 30 40 50 60> {255 255 217}
  ; concrete block painted
  ABS concrete_coarse = <36 44 31 29 39 25> L <10 20 30 40 50 60>{103 101 101}
  ; concrete block coarse
  ABS glass_large_heavy = <18 6 4 3 2 2> {0 128 192}
  ABS glass_ordinary_window = <35 25 18 12 7 4>

; ABS Values obtained from Prof. Campbell

  ABS gyp <28 12 10 9 9 9> L <20 20 20 20 20 20>
  ABS sfoam <10 15 30 45 55 60> L <10 20 30 40 50 60> {255 128 64}
  ABS wood1 <17 13 10 10 10 10> L <30 30 30 30 30 30>  {88 44 44}
  ABS wood3 <17 13 10 10 10 10> L <30 30 30 30 30 30>  {100 50 0}
  ABS audience <40 50 60 70 80 80> L <30 40 50 60 70 80>
  ABS seats_empty <35 40 43 50 53 55> L <30 40 50 60 70 80>
  ABS glass <15 12 10 9 8 8> L <10 10 10 10 10 10> {183 183 219}
  ABS wood2 <20 15 12 10 7 5> L <30 30 30 30 30 30> {228 177 3}
  ABS alith <10 20 30 40 50 50> L <10 10 10 10 10 10>
  ABS books <10 20 30 40 50 50> L <20 30 40 50 60 70>
  ABS plaster <10 10 10 10 10 10> L <20 30 40 50 50 50> {255 128 0}
  ABS tile <10 10 10 10 10 10> L <10 10 10 10 10 10>
  ABS cabs1 <30 45 70 80 85 80> L <30 40 50 60 70 80>
  ABS carpet <35 40 45 50 60 70> L <30 40 50 50 50 50> {30 79 98}
  ABS tapinbox <40 50 60 75 85 85> L <30 40 50 60 60 60> ;tapestry in box frame

; ABS Values obtained from
http://www.saecollege.de/reference_material/pages/Coefficient%20Chart.htm

  ABS metal = <73 99 99 89 52 31> L <10 10 10 10 10 10> {0 255 0}
  ; Metal deck (perforated channels, 75mm(3") batts)
  ABS wood  = <1 7 5 4 4 4> {128 64 64} ; Doors (solid wood panels)

; ------------------------------------------------------------------------------------------
; PROMPTS USER FOR GROOM SETUP
```

```
GETGLOBAL step = 0 - 8; get input value

; bare empty room
       IF step = 0 THEN
          ABS floorabs = concrete_floor
          ABS ufabs = concrete_floor
       ENDIF

; room with table
       IF step = 1 THEN
          INCLUDE table.geo ; includes table
          ABS floorabs = concrete_floor
          ABS ufabs = concrete_floor
       ENDIF

; room with drop ceiling
       IF step = 2 THEN
          INCLUDE ceiling.geo
          ABS floorabs = concrete_floor
          ABS ufabs = concrete_floor
       ENDIF

; room with carpet floor
       IF step = 3 THEN
          ABS floorabs = carpet
          ABS ufabs = carpet
       ENDIF

; room with table and carpet floor
       IF step = 4 THEN
          ABS floorabs = carpet
          ABS ufabs = carpet
          INCLUDE table.geo
       ENDIF

; room with drop ceiling and carpet floor
       IF step = 5 THEN
          ABS floorabs = carpet
          ABS ufabs = carpet
          INCLUDE ceiling.geo
       ENDIF

; room with table, drop ceiling, concrete floor
       IF step = 6 THEN
          INCLUDE table.geo
          INCLUDE ceiling.geo
          ABS floorabs = concrete_floor
          ABS ufabs = concrete_floor
```

```
       ENDIF

; room with table, drop ceiling, carpet floor
       IF step = 7 THEN
          INCLUDE table.geo
          INCLUDE ceiling.geo
          ABS floorabs = carpet
          ABS ufabs = carpet
       ENDIF

; room with drop ceiling, carpet floor, and elevated wooden stage/flooring
       IF step = 8 THEN
          INCLUDE ceiling.geo
          ABS floorabs = carpet
          ABS ufabs = concrete_floor
          INCLUDE floor.geo
       ENDIF

; -----------------------------------------------------------------------------------------
  SCALE 0.0254 0.0254 0.0254 ; scaling English to Metric
; -----------------------------------------------------------------------------------------
; GLOBAL VARIABLES

  GLOBAL swa  = 161.25 ; side wall A
  GLOBAL dw   = 112 ; wall with door
  GLOBAL dwx  = 19.4485958987 ; wall with door X
  GLOBAL dwy  = 110.298468337 ; wall with door Y
  GLOBAL swb  = 160 ; side wall B
  GLOBAL swbx = 25.0295144064 ; side wall B X
  GLOBAL swby = 158.030134495 ; side wall B Y
  GLOBAL swc  = 154 ; side wall C
  GLOBAL swd  = 268 ; side wall D

  GLOBAL h = 113.75 ; actual ceiling height

  GLOBAL waxo = -53.535 ; distance of first edge of window A relative to origin
  GLOBAL wax  = 54.5 ; length of window A along wall A
  GLOBAL waz  = 33.625 ; height of glass panel of window A
  GLOBAL wazf = 42.3125 ; height of window A from the floor

  GLOBAL wbx  = 54.5 ; length of window B along wall B
  GLOBAL wbz  = 33.625 ; height of glass panel of window B
  GLOBAL wbzf = 43.3125 ; height of window B from the floor

  GLOBAL doorxo = 1.60624564342+swa ; first edge of door relative to origin (x-axis)
  GLOBAL dooryo = 9.10947171536 ; first edge of door relative to origin (y-axis)
  GLOBAL doorx  = 7.07616323993 ; length of door (x-axis)
  GLOBAL doory  = 40.1309159352 ; length of door (y-axis)
```

```
  GLOBAL doorz  = 78 ; height of door (to be changed/checked)

  GLOBAL lmby  = 19.8772278545 ; large metal box Y value
  GLOBAL lmby1 = 110.298468337+97.5979478079 ; Y value of lmb from origin point
  GLOBAL lmbzf = 22.875 ; height from floor of large metal box
  GLOBAL lmbz  = 35.125 ; height of the large metal box
  GLOBAL lmbcy = 1.38835587723 ; lmb corner difference constant within Y-axis
  GLOBAL lmbcx = 5.802669001 ; lmb corner difference constant within X-axis

; -----------------------------------------------------------------------------------------
; ABS name assignments/mappings:

  ABS ceilabs = concrete_coarse
  ABS wallabs = concrete_painted
  ABS winabs = glass
  ABS lmboxabs = metal
  ABS doorabs = wood1
  ABS wfloorabs = wood2

; --------------------------------------------------------------------------------
CORNERS

 ; half room floor corners
 1 0          0    0
 2 -swa       0    0
 3 -(dwx+swa) dwy  0
 4 -swc       swd  0
 5 0          swd  0


 ; walls
 50 x(1) y(1) h
 51 x(2) y(2) h
 52 x(3) y(3) h
 53 x(4) y(4) h
 54 x(5) y(5) h

 555  0                   2*(swd/3.7)   0
 556  lock(3 4 53)        2*(swd/3.7)   0
 557  -swc                swd           0
 558  0                   swd           0


 ; entrance door
 61 lock(2 3 52) dooryo        0
 62 lock(2 3 52) dooryo+doory  0
 63 lock(2 3 52) dooryo+doory  doorz
 64 lock(2 3 52) dooryo        doorz
```

```
 ; window A
 71 waxo        0  wazf
 72 (waxo-wax)  0  wazf
 73 (waxo-wax)  0  (wazf+waz)
 74 waxo        0  (wazf+waz)

 ; window B
 81 lock(3 4 53) (dwy+swby-126.235568816) wbzf
 82 lock(3 4 53) (dwy+swby-71.0727444577) wbzf
 83 lock(3 4 53) (dwy+swby-71.0727444577) (wbzf+wbz)
 84 lock(3 4 53) (dwy+swby-126.235568816) (wbzf+wbz)

 ; large electrical metal box a.k.a "large metal box"
 91 lock(3 4 53) lmby1              lmbzf
 92 lock(3 4 53) lmby1+lmby         lmbzf
 93 lock(3 4 53) lmby1+lmby         lmbzf+lmbz
 94 lock(3 4 53) lmby1              lmbzf+lmbz
 95 x(91)+lmbcx  lmby1-lmbcy        lmbzf
 96 x(92)+lmbcx  lmby1+lmby-lmbcy   lmbzf
 97 x(93)+lmbcx  lmby1+lmby-lmbcy   lmbzf+lmbz
 98 x(94)+lmbcx  lmby1-lmbcy        lmbzf+lmbz

; ---------------------------------------------------------------------------------------
;(uf / 555 558 557 556 / ufabs) (floortwo / 5 4 3 2 1 /

PLANES

 ; room plane surfaces
 [1 floor / 5 4 3 2 1 / (uf / 555 558 557 556 / ufabs) (floortwo / 5 4 3 2 1 / floorabs)]
 [2 ceiling / 50 51 52 53 54 / ceilabs]
 [3 wallA / 1 2 51 50 / (winA / 71 72 73 74 / winabs) (wallA1 / 1 2 51 50 /wallabs)]
 [4 walldoor / 2 3 52 51 / (door / 61 62 63 64 / doorabs) (walldoor1 / 2 3 52 51 / wallabs)]
 [5 wallB / 3 4 53 52 / (winB / 81 82 83 84 / winabs) (wallB1 / 3 4 53 52 /wallabs)]
 [6 wallC / 4 5 54 53 / wallabs]
 [7 wallD / 5 1 50 54 / wallabs]

 ; metal box planes
 ; [8 lmbox1 / 94 93 92 91 / lmboxabs] ; back plane facing wall not needed
 [9 lmbox2 / 95 96 97 98 / lmboxabs] ; front plane facing room space
 [10 lmbox3 / 95 98 94 91 / lmboxabs] ; side plane facing door
 [11 lmbox4 / 96 92 93 97 / lmboxabs] ; side plane facing wall c
 [12 lmbox5 / 98 97 93 94 / lmboxabs] ; top plane
 [13 lmbox6 / 96 95 91 92 / lmboxabs] ; bottom plane
```

APPENDIX G: Conference Table in Studio code (table.geo)

```
; Performance Room - Table Geo
; WICN Radio - IQP E Term 2002
; Nedunceliyan Kulasekaran, Shukanth Reddy
; ****************************************

; -----------------------------------------------------------
  SCALE 0.0254 0.0254 0.0254 ; scaling english to metric
; -----------------------------------------------------------

; GLOBAL VARIABLES

  GLOBAL tw = 46.875 ; table width
  GLOBAL tl = 95.5 ; table length
  GLOBAL td = 1.25 ; table depth
  GLOBAL tx = 64 ; table X
  GLOBAL ty = 60 ; table Y
  GLOBAL tz = 27.75 ; table Z

; -----------------------------------------------------------
  ABS tableabs = wood3
; -----------------------------------------------------------

CORNERS

 ; Table Bottom
 31 -tx        ty+20     tz
 32 -(tx+tw)   ty+20     tz
 33 -(tx+tw)   ty+tl-20  tz
 34 -tx        ty+tl-20  tz
 35 -tx-(tw/2) ty        tz
 36 -tx-(tw/2) ty+tl     tz

 ; Table Top
 41 -tx        ty+20     tz+td
 42 -(tx+tw)   ty+20     tz+td
 43 -(tx+tw)   ty+tl-20  tz+td
 44 -tx        ty+tl-20  tz+td
 45 -tx-(tw/2) ty        tz+td
 46 -tx-(tw/2) ty+tl     tz+td

 ; Table Leg A
 101 x(31)-11  y(35)+16.5    0
 102 x(32)+11  y(35)+16.5    0
 103 x(32)+11  y(102)+2.875  0
```

```
 104 x(31)-11  y(102)+2.875  0

 111 x(31)-11  y(35)+16.5    27.75
 112 x(32)+11  y(35)+16.5    27.75
 113 x(32)+11  y(102)+2.875  27.75
 114 x(31)-11  y(102)+2.875  27.75

 ; Table Leg B

 121 x(101)    y(36)-19.375   0
 122 x(102)    y(36)-19.375   0
 123 x(103)    y(36)-16.5     0
 124 x(104)    y(36)-16.5     0

 131 x(101)    y(36)-19.375   27.75
 132 x(102)    y(36)-19.375   27.75
 133 x(103)    y(36)-16.5     27.75
 134 x(104)    y(36)-16.5     27.75

; ------------------------------------------------------------------
PLANES

 [14 tablebottom / 34 31 35 32 33 36 / tableabs]
 [15 tabletop / 41 44 46 43 42 45 / tableabs]
 [16 tableSideA1 / 31 41 45 35 / tableabs]
 [17 tableSideA2 / 35 45 42 32 / tableabs]
 [18 tableSideB / 32 42 43 33  / tableabs]
 [19 tableSideC1 / 33 43 46 36 / tableabs]
 [20 tableSideC2 / 36 46 44 34 / tableabs]
 [21 tableSideD / 31 34 44 41 / tableabs]
 ;[22 tablelegAbottom / 101 102 103 104 / tableabs]
 ;[23 tablelegAtop / 111 112 113 114 / tableabs] ; need this??
 [24 tablelegAA / 101 111 112 102 / tableabs]
 [25 tablelegAB / 102 112 113 103 / tableabs]
 [26 tablelegAC / 103 113 114 104 / tableabs]
 [27 tablelegAD / 104 114 111 101 / tableabs]
 ;[28 tablelegBbottom / 121 122 123 124 / tableabs]
 ;[29 tablelegBtop / 131 132 133 134 / tableabs]
 [30 tablelegBA / 121 131 132 122 / tableabs]
 [31 tablelegBB / 122 132 133 123 / tableabs]
 [32 tablelegBC / 123 133 134 124 / tableabs]
 [33 tablelegBD / 124 134 131 121 /tableabs]
```

APPENDIX H: Wooden Stage code (floor.geo)

```
; Performance Room Geo - Floating Wooden Stage/Floor
; WICN Radio - IQP E Term 2002
; Nedunceliyan Kulasekaran, Shukanth Reddy
; **************************************************

; -----------------------------------------------------
  SCALE 0.0254 0.0254 0.0254 ; scaling english to metric
; -----------------------------------------------------

; GLOBAL VARIABLES

  GLOBAL fz = 1 ; floating floor height
  GLOBAL fwoodz = 2; thickness of wood

CORNERS

 ;floor corners to create reference point of plane to be locked
 993 -(dwx+swa) dwy  0
 994 -swc       swd  0

 ;walls corners to create reference point of plane to be locked
 9952 x(3) y(3) h
 9953 x(4) y(4) h

 ;elevated floor wooden
 500  0                   2*(swd/3.7)   fz+fwoodz
 505  lock(993 994 9953)  2*(swd/3.7)   0
 501  x(505)              2*(swd/3.7)   fz+fwoodz
 502  -swc                swd           fz+fwoodz
 503  0                   swd           fz+fwoodz
 504  0                   2*(swd/3.7)   0

 555  0                   2*(swd/3.7)   0
 556  x(505)              2*(swd/3.7)   0
 557  -swc                swd           0
 558  0                   swd           0



PLANES
 [200 wfloortop / 500 503 502 501 / wfloorabs] ; top plane of stage floor
 [201 wfloorstep / 504 500 501 505 / wfloorabs] ; step plane of stage floor
 ;[202 underfloor / 555 558 557 556 / concrete_floor]
```

APPENDIX I: Drop-Ceiling (Celotex Panels) code (ceiling.geo)

```
; Performance Room - Suspended Ceiling Geo
; WICN Radio - IQP E Term 2002
; Nedunceliyan Kulasekaran, Shukanth Reddy
; ****************************************

SCALE 0.0254 0.0254 0.0254 ; scaling english to metric

ABS panelabs = sfoam ; to be changed to styrofoam

; GLOBAL VARIABLES

GLOBAL ceilz = 1 ; suspended ceiling thickness
GLOBAL ceilzf = 98 ; suspended ceiling height from floor
GLOBAL panelx = 24
GLOBAL panely = 24
GLOBAL panelg = 1 ; panel gaps in between each other

CORNERS

 ;drop ceiling corners
 200  0           0    ceilzf
 201  -swa        0    ceilzf
 202  -(dwx+swa)  dwy  ceilzf
 203  -swc        swd  ceilzf
 204  0           swd  ceilzf


PLANES

 [100 panelbottom / 200 201 202 203 204 / panelabs]
 ; bottom surface of drop ceiling facing room floor
 ;[101 paneltop / 204 203 202 201 200 / panelabs]
 ; top surface of drop ceiling facing actual ceiling (not needed)
```

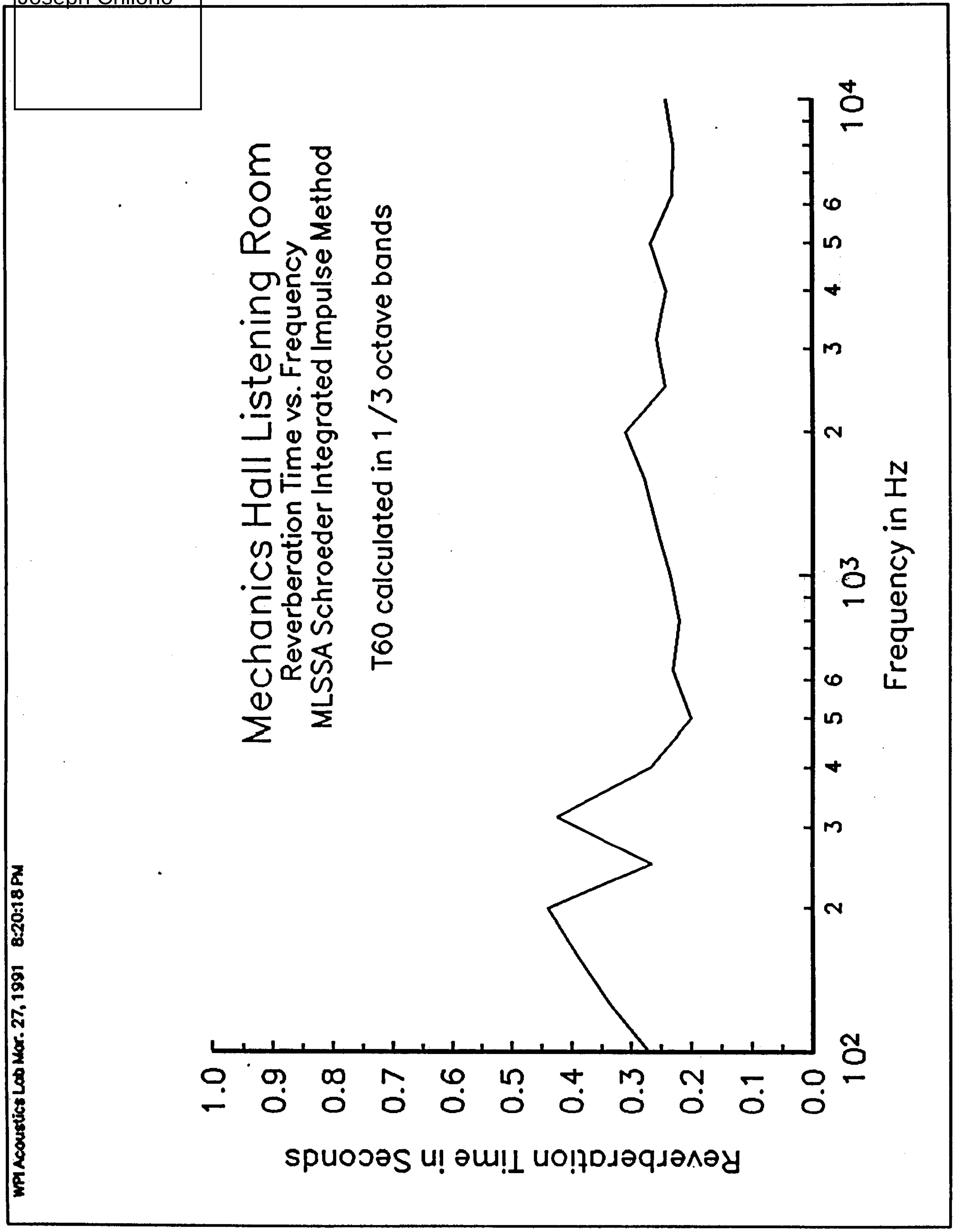
APPENDIX J: Receiver File (rec.loc)

```
; Receiver File
; WICN Radio - IQP E Term 2002
; Nedunceliyan Kulasekaran, Shukanth Reddy
; ****************************************

SCALE 0.0254 0.0254 0.0254 ; scaling english to metric

LOCAL rcv_z = 12 ; receiver's default height off the ground

RECEIVERS
1   -swa-dwx+12 swd/2 rcv_z
2   -swa+6      6     rcv_z
3   -swa+12     swd-6 94
4   -swa/2      6     26
```

APPENDIX K: Source File (src.loc)

```
; SRC.LOC
; WICN Radio - IQP E Term 2002
; Nedunceliyan Kulasekaran, Shukanth Reddy
; ****************************************

SCALE 0.0254 0.0254 0.0254 ; scaling english to metric

;SRC.LOC
LOCAL src_z = 2 ; height of source off the ground

SOURCEDEFS

  A0   -6     swd/2  src_z  OMNI  -swa/2  swd/2  src_z   ; Position A
  Lp1m_a = <70 73 76 79 82 95>

  A1   -6     swd-6  src_z+3  OMNI  -swa    0      src_z   ; Position B
  Lp1m_a = <70 73 76 79 82 95>

  A2   -swa/2 swd-6  20     OMNI  -swa/2  0      20      ; Position C
  Lp1m_a = <70 73 76 79 82 95>

  A3   -6      6      src_z  OMNI  -swa/2  swd      src_z ; Position D
  Lp1m_a = <70
```

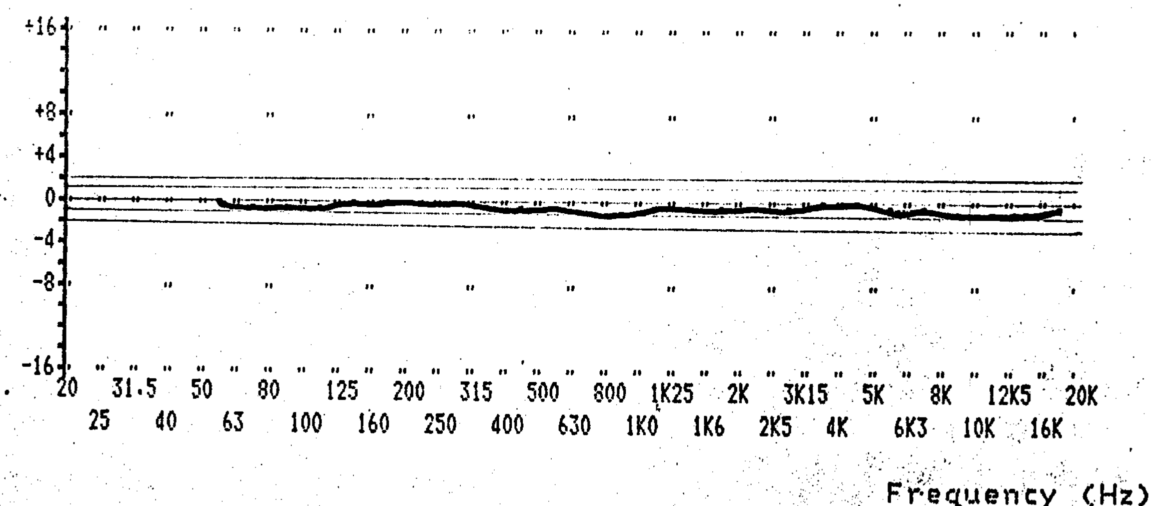
APPENDIX L:
Information from
Joseph Chilorio



SN 1516 (LEFT)

B&W 801-Matrix serial 0
tested by 0180 V3.4 @ 11:55 hours

SPL Deviation from Laboratory Standard (dB)



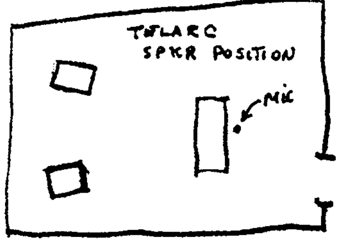
B&W 801-Matrix serial 0 was compared with our laboratory standard. The above plot shows the difference between its response and the standard's.
It has also been tested for:

- polarity
- protection circuit operation
- 100Hz THD 200Hz-22kHz bandwidth
- 315Hz narrow band third octave
- 6.3kHz THD 12kHz-22kHz bandwidth
- non-harmonically related distortion

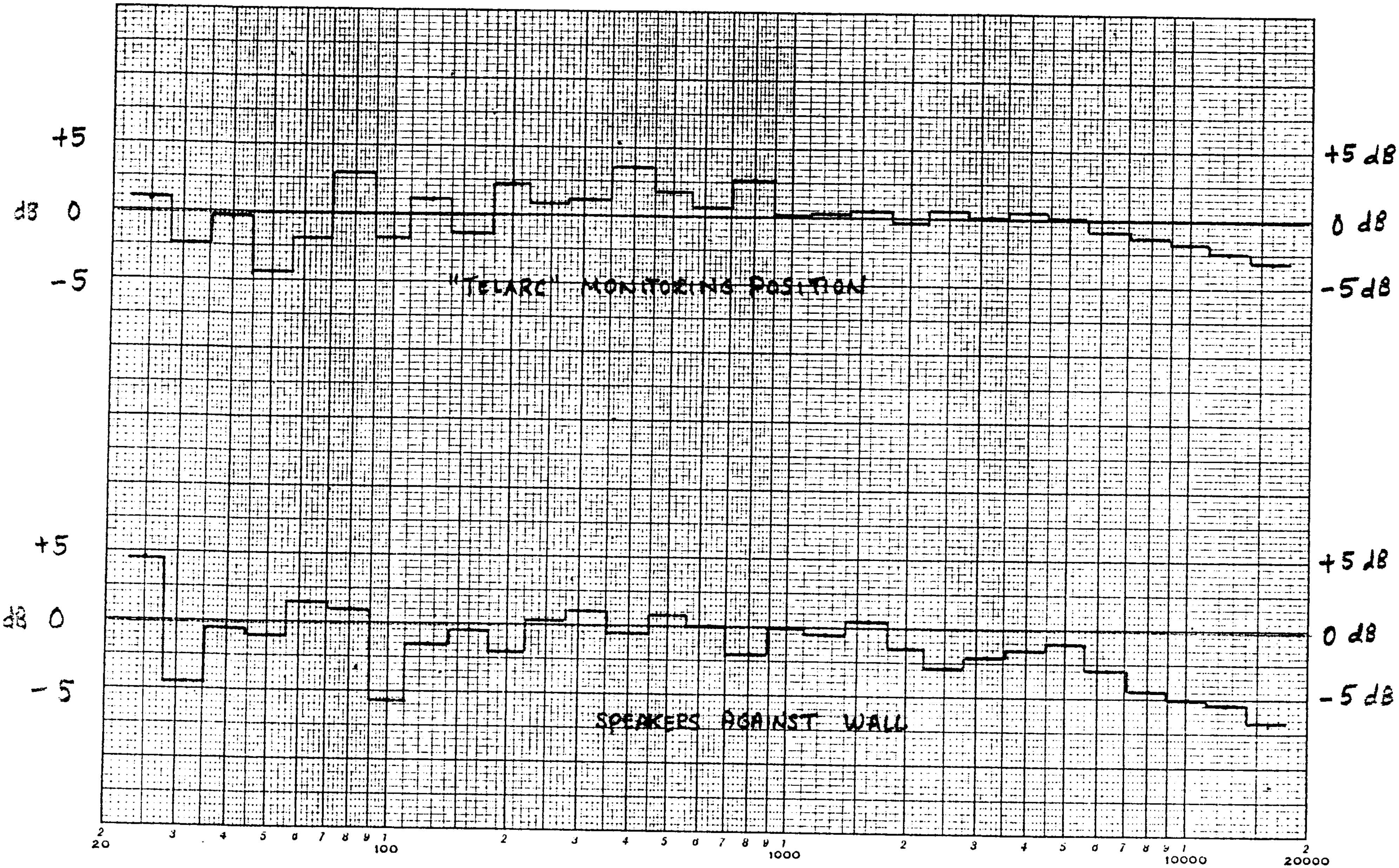
B&W 801-Matrix serial 0 is the partner of serial -1.

B&W Loudspeakers Ltd Meadow Rd, Worthing, BN11 2RX, England.

B&W 801 STUDIO MONITORS
MEASURED ACOUSTICAL FREQUENCY RESPONSE
1/3 OCTAVE PINK NOISE BANDS B+K 4006 MIC
AVERAGED LEFT + RIGHT RESPONSE



K+E AUDIO FREQUENCY 46 6882
MADE IN U.S.A.
KEUFFEL & ESSER CO.



11/3/88 JCC

Joseph - Listening Room 752-4400
ETF Curve -