# CHANGING SPACE AND SOUND:

# PARAMETRIC DESIGN AND VARIABLE ACOUSTICS

by

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## ABSTRACT

This thesis examines the potential for parametric design software to create performance based design using acoustic metrics as the design criteria. A former soundstage at the University of Southern California used by the Thornton School of Music is used as a case study for a multiuse space for orchestral, percussion, master class and recital use. The criteria used for each programmatic use include reverberation time, bass ratio, and the early energy ratios of the clarity index and objective support. Using a panelized ceiling as a design element to vary the parameters of volume, panel orientation and type of absorptive material, the relationships between these parameters and the design criteria are explored. These relationships and subsequently derived equations are applied to Grasshopper parametric modeling software for Rhino 3D (a NURBS modeling software). Using the target reverberation time and bass ratio for each programmatic use as input for the parametric model, the genomic optimization function of Grasshopper – Galapagos – is run to identify the optimum ceiling geometry and material distribution.

Hypothesis: Parametric modeling software can aid in designing multiuse performance spaces to accommodate variable acoustic situations.

# 1 PARAMETRIC DESIGN IN ARCHITECTURE

Digital design techniques in architecture have allowed designers to create and define endless possibilities of shapes that may not have been possible to be constructed or communicated without the use of computers. The standard image of contemporary architecture is now one of complexity. The computer allows for a number of calculations and iterative processes to be done in an instant what used to take hours or even days by hand. Many building designers use the power of computers and parametric design technology as a tool to develop their aesthetic vision, while the incorporation of structural and environmental systems that may lead to more efficient design and construction is often overlooked; this is a missed opportunity. There are examples of algorithmic and parametric tools used in conjunction with quantitative analysis to produce buildings of form as well as function. The object of this thesis is to utilize parametric design technologies to develop an effective architectural component that will enhance the acoustic performance of a multi-use facility.

To achieve this goal, this thesis will look at how to approach the parametric design process, research the science and art of sound to develop acoustic criteria for a multiuse facility, and develop a computer model of a case study building with a ceiling capable of creating a variable acoustic environment.

## 1.1 Opportunities in Acoustics

The field of architectural acoustics is broad and includes subjects such as the control of sound isolation between facilities, vibration control of mechanical systems, and room acoustic design in performance halls. The acoustic performance of concert halls will be the focus of this thesis as they heavily depend upon the properties of materials and the geometry of the room. Several different programmatic uses will be proposed for the same room, encompassing a wide range of values for different acoustic criteria. Solving for these criteria will involve changing proportions of the materials and the interior shape of the space. This lends itself to parametric design strategies. While the use of computer analysis in acoustics has improved the ability to analyze and predict the performance of concert halls, what many consider to be some of the world's best concert halls were built long before the use of computers in acoustics. The history of concert halls and the thought processes in designing today's venues offer some insight into both the success of these older concert halls and the failings of some of the newer concert halls. The use of parametric software can aid in providing a solution to the problems associated with multi-use facilities.

### 1.2 Historic Concert Halls

The concept of an indoor space that had the explicit purpose of exhibiting musical performances began to take hold in the Classical era of music in Europe around the mid-18$^{th}$ century. Before this, a person's musical experience existed mostly in the home or more notably in the Church. The architecture of cathedrals had a significant impact on the music performed within them. The traditional chants of services have simple rhythms as the entire congregation acted as performers. Complex rhythms and the intelligibility of the words would become cluttered in the highly reverberant spaces of cathedrals and keep the congregation from singing together.[1] In the early days of the Classical period, music was still performed in ballrooms and salons, which typically had shorter reverberation times than today's concert halls, and were performed by smaller orchestras due to the small size of the room. As public concert halls became more prevalent in Europe, composers began to compose music for specific rooms as Haydn did at the Hanover Square Rooms and the Redoutensal at Hofburg, altering the composition and size of the orchestra to compensate for acoustic variations including reverberation time and loudness.[2] The Grosser Musikvereinssaal in Vienna and the Concertgebouw in Amsterdam are regarded as two of the best concert halls in the world. However, they are each best suited for a different type of music; the Musikvereinssaal is commonly regarded best for Classical music while the Concertgebouw is better known for heavy, bombastic Romantic music, such as Wagner.[3] Resident composers often wrote their music specifically for the environment it was to be performed in, contributing significantly to the success of early public concert halls.

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[1] Marshall Long*, Architectural Acoustics* (New York, Academic Press, 2006), 10.

[2] Long, 21, 23

[3] Long, 29

## 1.3 Challenges with Contemporary Multi-Use Spaces

Modern concert hall designers have a significant problem in that they are expected to provide a space that will provide the greatest value for their clients. Unfortunately this does not mean that the acoustics will be great and render an aurally satisfactory experience, but rather that the venue will be able to be booked year round and host a variety of events including symphonic concerts, cinema, and stage productions. Most cities have developed performing arts centers that showcase multiple groups with varying needs, not the least of which is the concert halls acoustic characteristics. The early multi-use spaces became, as J. Christopher Jaffe describes, "no-use spaces" due to an acoustic approach of one-size fits all.[4] In the worst cases, the symphony sounded dry, the theatrical productions were unintelligible, and no one had a fully satisfying experience. While a one-size fits all approach to designing performance venues is now recognized as a major design problem, the current solutions in providing variable acoustic setting involve either a finite number of possible alternatives or require a large amount of labor or investment in equipment. Some of these variable acoustic systems will be presented in Chapter 3.

## 1.4 Parametric Design in Architectural Applications

Before examining how parametric design can be used for acoustic applications, it is important to understand what parametric design is and is not, and analyze

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[4] J. Christopher Jaffe, *The Acoustics of Performance Halls: Spaces for Music from Carnegie Hall to the Hollywood Bowl*. (London, WW Norton & Company, 2010), 100

other projects in which parametric designs have been used in order to optimize given criteria. This section will look at the differences between parametric and algorithmic design methods and look at a few case studies of how parametric design has been successfully implemented in other projects.

### 1.4.1 Defining Parametric

Parametric is a common buzzword in architecture; it allows architects to realize complex geometries that would be otherwise impossible to generate using standard drafting or modeling. However, not every building with complex geometries is designed parametrically and similarly not every building designed parametrically has complex geometries. Parameters in architecture are typically associated with area and volumetric geometries, which are limiting to achieve other parameters to achieve criteria set by the designer. Also involved in this process is the use of algorithms, which are simply a set of processes typically used to solve a problem. However, most times in architecture algorithms are utilized as pure form generation instead of in conjunction with parameters such as height, volume, and weight, or performance based parameters such as cost, energy efficiency, and constructability.

For instance, Toyo Ito's design of the 2002 Serpentine Gallery Pavilion used a geometric algorithm of inscribing a series of squares within the previous square set at specific ratios between generations. The resulting web of lines was then used as the structural lattice work for the structure of the pavilion, using the earlier generation lines as the primary load carrying members.[5] While the result of the algorithm may have an inherent structural hierarchy, the structural efficiency is not the primary focus of the design.

Parametric design should involve a deeper level of complexity than is apparent at first glance. The result of the parametric definition should be based upon the underlying algorithms defining the geometry based on constraints determined by the project's program, structure or environmental concerns. The essential pieces in creating a good parametric design are defined below:

**1. Criteria for Success** – Having a clear criteria allows the designer to translate the intent of the design into a quantifiable and therefore measurable result to judge success or not. The success of a project can be driven by anything including efficient structure and limited use of materials, ease of construction, efficient uses of space, or environmental performance.

**2. Parameters** – The parameters of the project are the conditions that the designer wishes to achieve and are defined to establish a criteria. For instance, if a project's criteria for success is to have a south facing glass façade that will not have a negative impact on the internal loads of the building, the parameter may be the amount of direct solar radiation the glazed area receives. This is a quantifiable variable that can be constrained and is dependent on a number of

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[55] Sakamoto, Tomoko et. al. *From Control to Design: Parametric/Algorithmic Architecture. (*Barcelona:,Actar-D, 2008), 36-43

design related issues as well as natural phenomenon including the time of the day and year.

**3. Geometrical and Material Associations** – The use of algorithms in parametric design is found in associating geometry and material properties with the specified parameters. How geometry is manipulated and evaluated can have a large impact on the final outcome of the structure. For instance, if the design intent is to minimize the amount of direct solar radiation on the example south facing facade, there may be two geometrical associations to control: the size of the window or the size of the overhang above the window. In both cases, the amount of direct solar radiation will be minimized. However, in one case the building will end up with very small windows at the top of the wall, and the other will end up with a large overhang. There are also material properties associated with this example that should be considered, including the solar heat gain coefficient of the glass. There are multiple ways to approach this problem each with their own positive and negative impacts on different areas of design. Because of the interrelatedness of material and geometry and their impact on design, it is crucial to select the appropriate relationships one wishes to manipulate with the defined parameters.

### 1.4.2 Parametric Uses in Structural Engineering

Structural engineering is an established field, providing architects and engineers with hundreds of years of experience, testing, and knowledge that can be converted into algorithms and design criteria. While the computer age has allowed designers to run calculations at a much faster speed than by hand, the concept of applying simple parameters to yield complex and functional geometries is not new.  Frei Otto was a pioneer in the field of complex structural systems utilizing minimal resources and his method involved a parametric approach even before using computers.  His approach to designing buildings was based on a purely performative aspect, giving little regard to the aesthetic qualities of the structure.  Working from a physical model of hanging chains and using parameters such as height, span and member size, Otto allowed the gravity acting on the model to do complex computations in place of today's computers and provide him with a structure that performed in pure tension.  The result of turning such a structure upside down is a structure that operates in pure compression.[6]   Computationally, this is a simple example, but the intent to use a process like Otto's in order to solve a specific problem (using a minimum amount of materials) is clear.  Today, computer algorithms representing the effects of gravity and other loads on structure define the geometrical associations that Frei used hanging chains to determine.

With a shape influenced by banyan trees and with the goal of creating a structural form with a uniform stress, Matsuro Sasaki "evolved" support structures for a train station competition in Florence using an iterative parametric analysis of the structure.[7]  In this case, there may have been many unique solutions that

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[6] Conrad Roland, *Frei Otto: Tension Structures. (*New York: Praeger Publications. 1970)
[7] Sakamoto, Tomoko et. al., 100-105

resulted in equally performative structures with different aesthetic qualities.

While defining the structural system of a building may be the most influential use of parametric software in regards to use of resources and determining the final form of the building, environmental parameters also significantly influence how a building will perform. One reason for the lack of precedents specifically in the field of acoustics is the complex and subjective nature of sound.

### 1.4.3 Parametric Design in Acoustics

Schroeder diffusers rely upon a series of wells with their width determined by the frequency the panel is to diffuse. The complex shapes of the diffusers, whose profiles can be expressed in one or two dimensions, are based on a pattern of geometrical sequences discovered by Manfred Schroeder. In addition to creating interesting forms, these panels are able to provide predictable and effective performance in acoustic diffusion and are based upon the defined parameter of frequency.

Optimization of the placement of reflecting, diffusing and absorbing panels at a pavilion in Copenhagen was achieved by use of an algorithm and acoustic analysis software. The goal of the project was to decrease the sound levels in the lounge areas and increase the sound levels and even the sound distribution in the audience areas, by redistributing an equal number of diffusing, reflecting and absorbing panels. Acoustic analysis was done in the program ODEON and examined across many points within the audience and lounge areas. Placement of the acoustic reflectors and absorbing panels were analyzed first with the diffusing panels filling in the remaining spaces.[8]

Each of the preceding examples had clear criteria for success and defined parameters in order to create an object constrained by the criteria of project. The next few chapters will examine the science of sound, acoustics, and music in order to understand what the criteria for a successful acoustic environment should be and what parameters will be the most effective in changing the acoustics environment of a space.

[8] Brady Peters. “Parametric Acoustic Surfaces” *ACADIA* (2009), 179

# 2 FUNDAMENTALS OF SOUND

Understanding the generation of sound, perception by the listener or audience, and the relation to music will form the basis for understanding and evaluating the room acoustic criteria for this thesis. This chapter examines the physical and quantitative components and the perceptive and qualitative factors of sound and music.

## 2.1 Sound Generation

What sound is and how it is generated is fundamental in understanding how it behaves. This section describes the physical phenomena associated with sound generation and transmission and the characteristics and physics of wave behavior.

### 2.1.1 Sound as Energy

The generation of sound begins with the vibration of an object and the displacement of a medium. The vibrations of an object, such as a string held in tension, will displace the medium in contact, usually air, and cause a cycle of compression and rarefaction through the medium above and below atmospheric pressure. This sinusoidal cycle of compression and rarefaction creates a wave with a frequency equal to the number of cycles per second (measured in Hertz, Hz) and an amplitude equal to the maximum displacement of the medium.[9] The speed of the wave is dependent on the medium. Subsequently, the speed of sound is variable depending on the medium of travel. Figure 2.1 displays the speed of sound through common materials.

| Substance | Temperature (°C) | Speed (m/sec) | Speed (ft/sec) |
|---|---|---|---|
| Air | 0 | 331.5 | 1087 |
| Air | 20 | 344 | 1130 |
| Water | 15 | 1437 | 4714 |
| Steel | - | 5000 | 16,400 |
| Water Vapor | 35 | 402 | 1320 |

**Table 2.1 – Speed of Sound in Various Mediums** [10]

As shown in Figure 2.1, sound will travel faster through mediums in which the molecules are closer together. For air, the speed is very dependent upon temperature and humidity. The wavelength of the wave, or the distance from peak to peak displacement of one cycle, is dependent upon both the frequency and speed of sound and related by the equation:

$$S = f * \lambda$$

Where S is the speed of sound, f is the frequency in Hertz and λ is the wavelength. [11]

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[9] John Backus, *The Acoustical Foundations of Music* (London, WW Norton & Company, 1976), 40

[10] Backus, 44

[11] Backus, 41

### 2.1.2 Frequency & Wavelength

The frequency of a sound wave is typically what is perceived as tone or pitch. Lower frequencies create “lower” tones and higher frequencies create “higher” tones. The typical human has a hearing range of approximately 20 Hz to 20,000 Hz, and this range generally decreases as people age.[12] Ultrasonic frequencies are detectable by other animals such as dogs or bats, but this is not important for concert hall design.

For analysis and specification purposes, frequencies are broken into octave bands. Octaves occur at exponential intervals, increasing at a ratio of 2:1, similar to octaves on a keyboard. The typical octave bands occur at 64, 125, 250, 500, 1000, 2000, 4000, 8000, and 16000 Hz. Harmonic frequencies are important for the perception of sound and are physical multiples of a base frequency. For example, a base frequency of 220 Hz will have harmonics at 440 Hz, 660 Hz, 880 Hz, 1100 Hz, etc…[13] The amplitude of a given harmonic is variable and is dependent on the object vibrating. The relative level of these harmonics is important in determining the quality of sound in human perception.

### 2.1.3 Amplitude

The amplitude of a given sound wave is a measure of the physical displacement of the medium the wave is traveling through. In the typical medium of air, the air

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[12] Daniel J. Levitin*, This Is Your Brain on Music: The Science of a Human Obsession,*(New York, Penguin, 2006) 25

[13] Levitin, 42

molecules displaced above and below atmospheric pressure have a certain mass. Due to the internal friction forces of air (or whatever other medium sound travels through) there is a force resisting the movement caused by a sound wave. This force multiplied by the displacement, or amplitude, results in the sound power generated. When sound propagates spherically from the source in a sphere there is a force of sound pressure impinging on the sphere at any given time at any given distance. The power acting on this surface area is known as the sound pressure and is used in calculating the relative loudness of a sound.[14] The standard measure of loudness is the decibel (dB) and is calculated as

$$dB = 20\log\left(\frac{P_{spl}}{P_{ref}}\right)$$

Where $P_{spl}$ is the measure sound pressure level and $P_{ref}$ is the reference sound pressure level. The reference sound pressure that is used as a basis for measurement is about 20 uPa which equates to threshold of hearing. Because of this logarithmic reference, doubling of the sound level equals a gain of about 6 dB. For example:

$$20\log(2) = 6.02$$

Table 2.2 displays the sound level in dB for everyday sounds as a reference.

| | |
|---|---|
| 0 dB | Mosquito flying in a quiet room, ten feet away from your ears |
| 20 dB | A recording studio or a very quiet executive office |
| 35 dB | A typical quiet office with the door closed and computers off |

[14] Backus, 53

| | |
|---|---|
| 50 dB | Typical conversation in a room |
| 75 dB | Typical, comfortable music listening level in headphones |
| 100-105 dB | Classical music or opera concert during loud passages; some portable music players go to 105 dB |
| 110 dB | A jackhammer three feet away |
| 120 dB | A jet engine heard on the runway from three hundred feet away; a typical rock concert |
| 126-130 dB | Threshold of pain and damage; a rock concert by The Who |
| 180 dB | Space shuttle launch |

**Table 2.2 – Relative Sound Pressure Levels (dB) of Various Sounds[15]**

### 2.1.4 Wave Phenomena

Just like ocean waves, sound waves are capable of interacting with one another. The results of these interactions are important in the discussion of room acoustics, which will be discussed in Chapter 3. Interference, reflection, and absorption are three wave behaviors that are the basis for most acoustic studies and analogous to the study of light waves.

Waves traveling in the same space have the ability to create interference. This is a bit misleading as the waves do not interfere with each other but rather affect the medium they pass through. Two waves with identical frequencies in the same location will result in some of the amplitude of the waves, either constructively or destructively interfering (Figures 2.1 and 2.2).[16] Noise canceling technologies are based upon destructive interference.

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[15] Levitin, 71

[16] Backus, 48

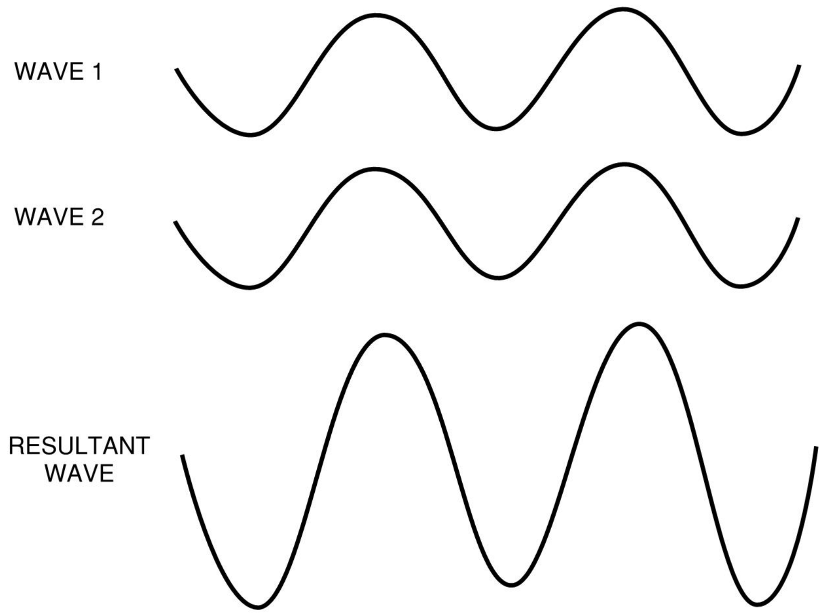


**Figure 2.1 – Constructive Wave Interference**

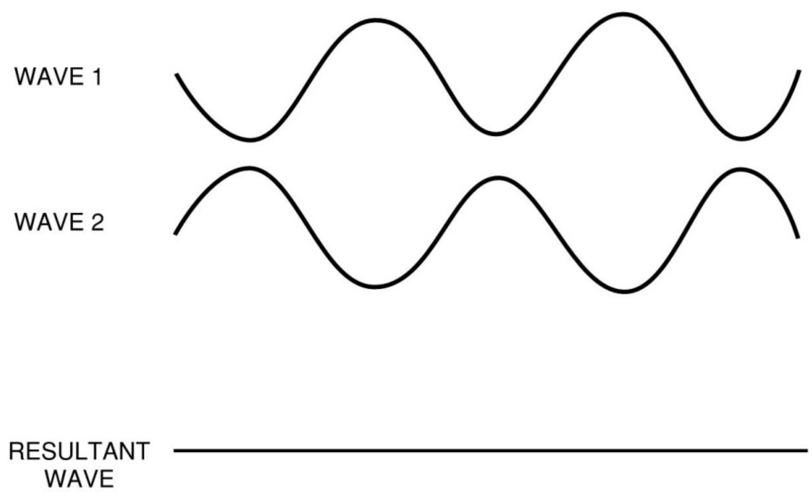


**Figure 2.2 – Destructive Wave Interference**

Sound waves approaching an obstacle will reflect a portion of their energy, while a portion will be absorbed by the material and another portion is transmitted through the material.[17] Although transmission is another important part of the overall study of sounds and acoustics, this thesis will focus on the reflection and absorptive properties of the room boundaries. The material finishes and geometries in an enclosed space are the key components in controlling sound wave behavior and the level of sound energy. Like light, the angle of reflectance is dependent upon the angle of incidence. Figure 2.3 demonstrates a typical reflection assuming a sound wave as a one-dimensional line.

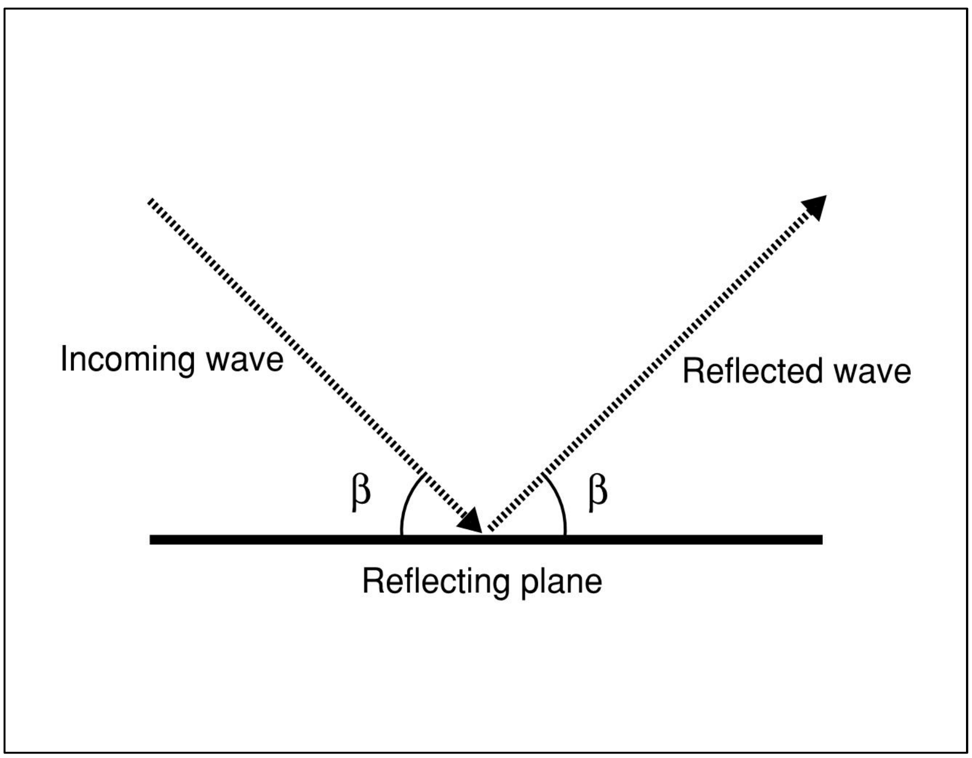


**Figure 2.3 – Reflection of Sound Waves**

[17] Backus, 46

Sound absorption at certain frequencies is dependent on the type and construction of the material the sound wave strikes. Different materials will absorb different quantities of sound energy across the range of frequencies. This will be discussed more in depth in the next chapter.

### 2.2 Sound Perception

While the physics of sound generation is a simple theory and relatively well understood, what creates the challenges in acoustics is human perception of sound. This section will explain the physiological and psychological phenomena linked to the human understanding of sound.

#### 2.2.1 Human Physiology

How humans understand sound is based on the interpretation of the vibrations generated by anything and everything in the physical world. Our interpretation of these vibrations begins with the ear. The ear consists of three distinct areas. The outer ear, the pinna, acts as an auditory funnel to direct sound through the auditory canal to the middle ear. At the interface between the outer and middle ear is the ear drum or tympanic membrane. As the name alludes to, the ear drum, the tympanic membrane, consists of a membrane stretched across the auditory canal that vibrates when subjected to sound pressure. The rest of the middle ear consists of the hammer, anvil, and stirrup, which are interconnected to transfer the vibrational energy from the ear drum to the inner ear through the oval window to the liquid filled cochlea. The cochlea is a rolled organ containing a fluid and lined with hair cells (the basilar membrane) and as the vibrations at the oval window create a wave of the fluid in the cochlea, these hair cells transfer the mechanical energy of the wave into neural information (electrical signals) processed by the brain as sound. [18]

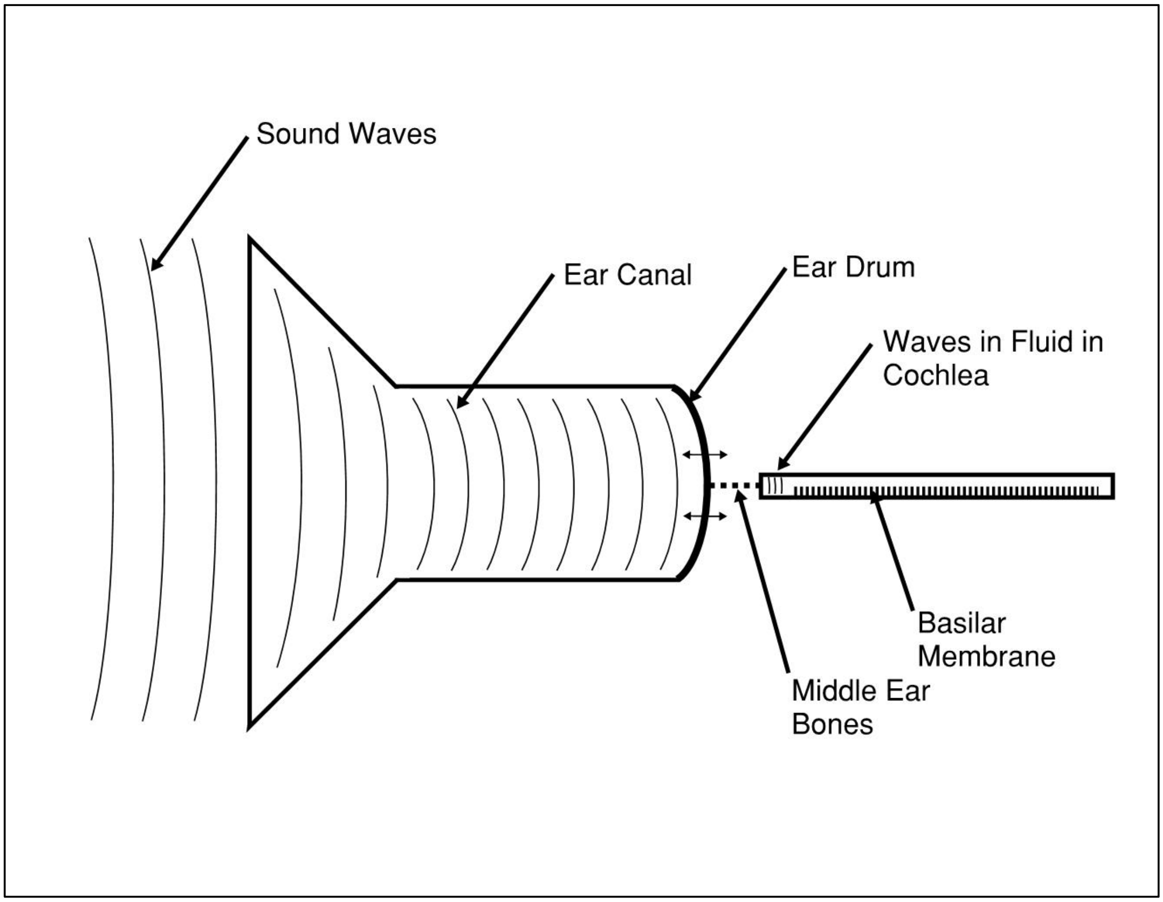


**Figure 2.4 – The Human Ear**

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[18] Yoichi Ando, *Concert Hall Acoustics* (New York, Springer, 1985), 27

### 2.2.2 Perception of Frequency

The frequency that is determined by the brain is a result of where on the basilar membrane the wave is at its peak amplitude. The human ear is capable of hearing from 20 Hz to 20 kHz, although this range decreases with age. The typical human adult cannot hear beyond 12 kHz.[19] This loss of hearing range is normal, but hearing can also be damaged by over exposure to loud sounds. The ability to recognize specific frequencies varies widely between people. While people with healthy hearing are able to determine frequencies by absolute or "perfect" pitch, most people identify frequencies relative to one another, always requiring a base tone on which to reference the second tone.

Our perception of frequencies is extremely important to our recognition of sounds, especially the combination of different frequencies. No sound, except for a sine wave, is heard as a pure tone, generated at a single frequency. Instead, sounds are produced with a variety of harmonic frequencies as previously discussed. These harmonic or overtones series in a sound source are what give different qualities or timbres to a specific source. This is important in speech as everyone's vocal cords generate a unique timbre, which allows others to recognize individuals' voices. These harmonics are a product of the natural resonance frequencies of the material the sound is generated from. The key of A above middle C played on a Stradivarius will sound different than the key of A on a piano because the construction and material composition of the instruments

[19] Levitin, 25

influence the perceived timbre. The timbre or tone quality of specific instruments is important in music as is discussed further in Section 2.3.

### 2.2.3 Perception of Amplitude

Our perception of loudness aids us in determining what is important and what is noise. The level of ambient or background noise for a given space is called the noise floor. Other sounds, if they are to be heard, must be louder than the noise floor or will blend in. This is also referred to as masking.[20] Some acoustic situations, such as recording studios, require bringing the noise floor as low as possible. Emergency sirens are always louder than the ambient street or freeway traffic in order to be heard. There are of course exceptions to this, especially if there is a large difference between the frequencies of the ambient and source sounds, but generally we perceive the louder sounds as more important. However, how we perceive loudness is not a constant across all frequencies.

Humans require significantly more sound energy at the low end of the frequency spectrum in order to create the same perceived level of loudness at 500-1000 Hz. Less sound energy is required to create the same perceived level of loudness between 2-5kHz. Physically this makes sense as the average auditory canal has a resonance frequency in this region.[21]

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[20] Backus, 101
[21] Backus, 96

### 2.2.4 Perception of Space

Our sense of hearing affects our perception of space in two different ways: identifying the scale of our surroundings and locating the source of sounds. Through the reverberance of an enclosed space (or lack thereof in an open area), we can identify the scale of the space we are in. Although the time difference between reflections from surfaces 40 feet away is on the scale of microseconds, the brain is able to process these differences and give us a sense of where we are.[22] Other processes aid us in identifying where sounds come from. Just as having two eyes enables us to perceive depth of space, having two ears allows us to perceive the location of sound source. Though the time difference between a sound reaching one ear versus the other is short, it is large enough for our brain to register and triangulate the placement of the source in space. [23]

[22] Levitin, 108

[23] Backus, 90

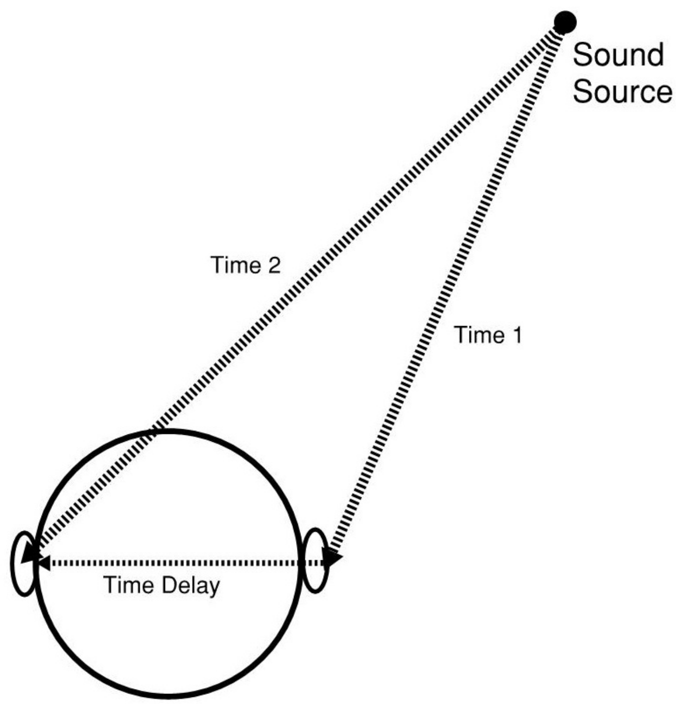


**Figure 2.5 – Binaural Hearing**

Stereophonic hearing allows us to place which direction an emergency vehicle is coming from or where a dangerous animal is lurking in the jungle. While we are rarely faced with dodging predators in the jungle, binaural hearing plays a large part in music, allowing us to associate the instruments we see with the sounds we hear. Failing acoustic situations may have issues with reflections and skewed aural images, creating a disconnection between what we see and what we hear.

### 2.3 Music

This section will identify the composition of music, define musical terms for the non-musician, and identify the difficulties of analyzing music in scientific terms.

### 2.3.1 Composition of Music

Music at its simplest is the organization of sound in the form of pitch, rhythm, and dynamics. Frequencies determine the tone or pitch of the melody and harmonies and define the key in which the piece is set. The key signature is a general rule for structuring which notes are important and “allowed” within the framework of the piece. Traditional Western music is comprised of 12 notes.
Rhythm is not related to a physical quality that has been discussed, but is rather a derivative of the amount of time notes are held, relative to one another. Like pitch, rhythm is also structured within the piece of music through the time signature. Time signature dictates what length of note is considered the beat and how many beats are in a measure. Another time related quality of music is tempo, or how fast a piece is played. Tempo is measured in beats per minute. Tempo is an important consideration in the acoustics of performance spaces when considering the clarity of individual notes. Music with faster tempos requires a higher level of clarity in order to distinguish and interpret notes and rhythms.

Dynamics, or the relative loudness of both different instruments and different passages within a piece, help to shape the flow and emotional qualities of the music. Dynamic markings are noted as variations of piano (quiet) and forte (loud). Table 2.3 displays the common dynamic markings and the typical sound pressure level of an orchestra.

| Dynamic Marking | Sound Pressure Level (dB) |
|---|---|
| Threshold of feeling | 120 |
| *fff* | 100 |
| *f* | 80 |
| *p* | 60 |
| *ppp* | 40 |
| Threshold of hearing | 0 |

**Table 2.3 – Dynamics and Associated Sound Pressure Levels**[24]

### 2.3.2 Subjectivity of Music

Music varies worldwide. For example, traditional Asian music uses a different set of frequencies that take advantage of the quarter-tones between the traditional Western notes. As with any other art, the music one likes is personal and subjective and based upon previous history and experiences with music. Subjective preference makes music and related fields of study an inexact science.

The science of sound is very much linked to physical quantities such as distances, areas, and orientations of reflecting planes. These are important when examining the geometrical and material relationships of a space. However, simply knowing how a sound wave will move in a room and how much the amount of sound drops over time is not enough information to define a successfully designed space. The next chapter will examine the principals of acoustic design and some of the general criteria acousticians review when designing a performance facility.

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[24] Backus, 92

# 3 ROOM ACOUSTICS

This chapter will focus on how sound behaves in enclosed spaces, examining the reaction of sound to materials and geometry, what metrics have been established to quantify acoustic parameters, and the issues of subjective preference. Acoustics as a science is young, having only been formally developed within the last 100 years. The equipment necessary to measure and record sound data has only been available since the invention of electronic amplification and microphones in the early part of the 20th century.[25] While there has been significant progress in defining how sound behaves, achieving specific metrics for judging architectural acoustics have no guarantee of producing a space with a satisfying listening experience. This chapter will also discuss the current technologies and methods utilized to vary acoustics in both passive and active form.

## 3.1 Behavior of Sound in Enclosed Spaces

Sound in a free field with no obstructions is heard directly from the source. Outdoor venues are common but are rarely considered good performance spaces without the addition of some architectural elements or technological system. The acoustics are usually enhanced with an orchestral shell or the use of electronic reinforcement to project the sound to the audience. The difficult part of analyzing sound is its interactions with the boundary of an enclosed space. This

[25] Leo Beranek, *Music, Acoustics, and Architecture*.(New York, John Wiley & Sons, Inc. 1962),4-5

section discusses the effects that material and geometry have on the behavior of sound in relation to music, the standard metrics of acoustic analysis, and the difficulties in establishing an “ideal” set of criteria for all acoustic situations.

### 3.1.1 Sound and Material

As with structures, material plays an important part in sound, either weakening or reinforcing the sound within a space. As mentioned in Chapter 2, one of the attributes of sound wave is that it will reflect off of a material. However, this is only one of the interactions a sound wave will have when encountering a material at the boundary of a space. In addition to reflecting sound energy, a surface may absorb or transmit sound energy. As sound is simply the vibration of molecules, the absorption, transmission and reflection characteristics of a material are dependent on the density and composition of the material. The reflective and absorptive qualities of materials, not transmission, are most important for acoustics in a space. Sound absorption occurs when a material converts sound energy into another form of energy, usually heat. The absorption coefficient (alpha) of a material is a measure of the percentage of sound energy absorbed by the material and will vary with respect to frequency. For example, heavy carpet on concrete will absorb 14% of the sound energy in a 500 Hz sound wave; therefore the alpha is 0.14. A table of sample materials and their absorption coefficients is displayed in Table 3.1.

| | Frequency (Hz) | | | | | |
|---|---|---|---|---|---|---|
| Material | 125 | 250 | 500 | 1k | 2k | 4k |
| Marble or glazed tile | .01 | .01 | .01 | .01 | .02 | .02 |
| Concrete, unpainted | .01 | .01 | .01 | .02 | .02 | .03 |
| Asphalt tile on concrete | .02 | .03 | .03 | .03 | .03 | .02 |
| Heavy carpets on concrete | .02 | .06 | .14 | .37 | .60 | .65 |
| Heavy carpets on felt | .08 | .27 | .39 | .34 | .48 | .63 |
| Plate glass | .18 | .06 | .04 | .03 | .02 | .02 |
| Plaster on lath on studs | .30 | .15 | .10 | .05 | .04 | .05 |

**Table 3.1 – Absorption Coefficients of Common Building Materials**[26]

### 3.1.2 Acoustical Metrics

A series of metrics have been devised to describe acoustical performance characteristics. One of the most important measures already mentioned is how reverberant a space is or how long a sound remains in a space after the source of sound has ceased. This is measured by an acoustic parameter called Reverberation time ($RT_{60}$ ) or the length of time (in seconds) it takes for a sound source to drop 60 dB after it has ceased. It is a function of the volume and the absorption properties of the surface materials in the room. Reverberation time can be expressed by

$$RT_{60} = \frac{(.049)V}{\sum_{1}^{n} s_n a_n}$$

where *V* is equal to the total volume of the room (in cubic feet), *s* is the exposed surface area of a material (in square feet), and *a* is the absorption coefficient of

[26] Backus, 172

that material. Each surface multiplied by its absorption coefficient are summed up.

Reverberation time will influence the clarity of notes and different styles of music will require different reverberation times. Spoken word will require a much shorter reverberation time in order to provide the speech intelligibility needed to understand each word. The optimal reverberation time for any given musical setting may vary based upon the volume of the room. Figure 2.2 displays common performance types and corresponding reverberation times (at 500 Hz) for spaces of a volume similar to the case study developed in Chapter 3, approximately 70,000 $ft^3$ (2,500 $m^3$) .

| Sound Source | Optimal Reverberation Time (s) |
|---|---|
| Spoken Word | 0.7 |
| Jazz/Pop | 0.8 |
| Orchestra | |
| Chamber | 1.4 - 1.7 |
| Opera | 1.3 - 1.8 |
| Romantic/Classical | 1.8 - 2.2 |

**Table 3.2 – Optimal Reverberation Times**[27]

A derivative of reverberation time, which aids in describing the presence of lower frequencies, is the bass ratio. Bass ratio is defined as

$$BR = \frac{RT_{125} + RT_{500}}{RT_{500} + RT_{1000}}$$

where $RT_n$ is the reverberation time (in seconds) at n Hz. While no studies are available to describe the optimal bass ratio for given musical settings, a general rule of thumb is to provide a bass ratio of at least 1.2 seconds in order to provide a desirable “warmth” of sound.

Early Decay Time (EDT) is also similar to the reverberation time but is defined as the time for sound to decay 10 dB and is associated with the perceived reverberation time of space. Beranek argues that EDT is a better gauge of the subjective preference of concert halls, especially those in which detailed rhythms need to be heard as EDT is more on scale with the time between successive notes.[28] Figure 3.1 demonstrates the principle of masking of successive notes as a product of reverberation.

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[27] S Ellison, R Schwenke. “The Case for Widely Variable Acoustics” *Proceedings of the International Symposium on Room Acoustics,* (2010), 2

[28] Beranek. 24

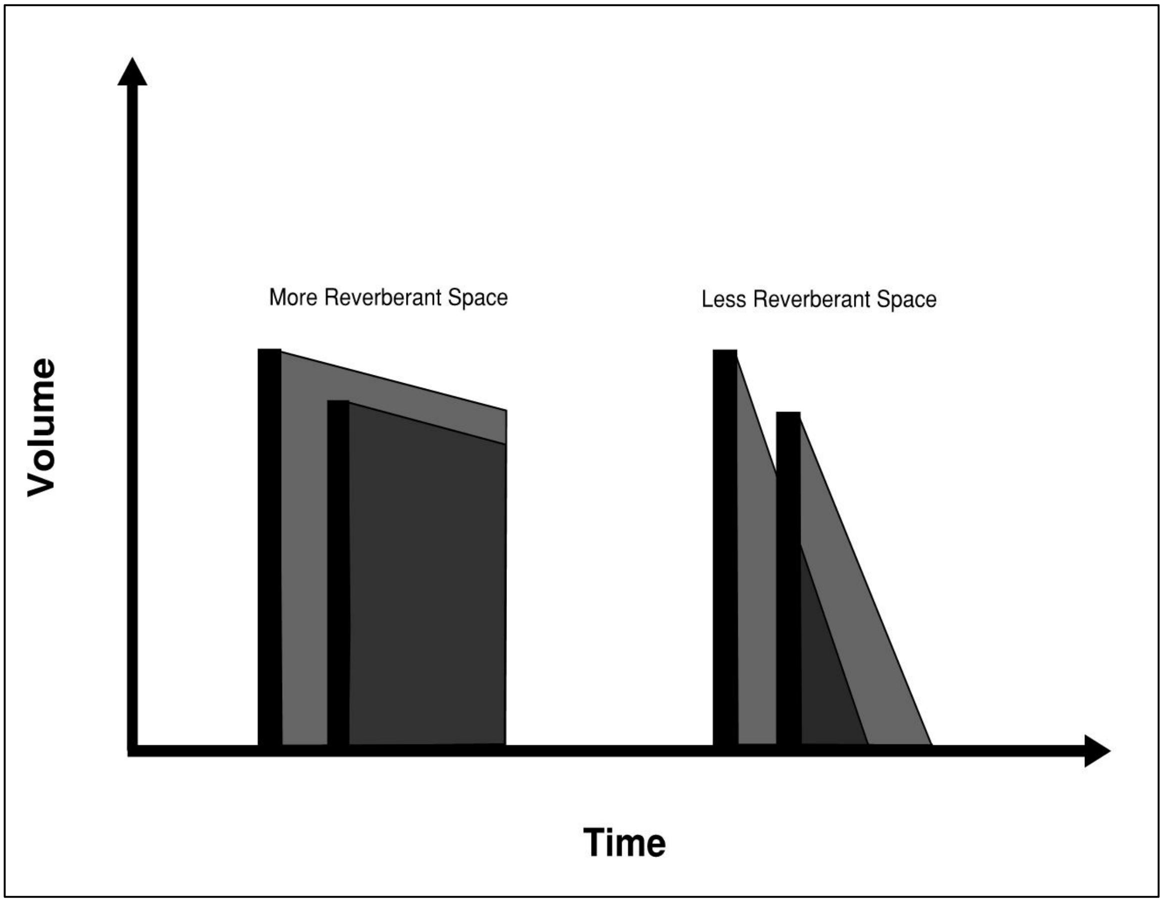


**Figure 3.1 – Masking of Notes in Reverberant Spaces**

The Clarity or Definition Indices are acoustic metrics that also play an important role in determining how easy it is to distinguish separate notes. This is a measured as a ratio (in decibels) of early sound energy (earlier than 80 milliseconds) to the reverberant sound energy (after 80 milliseconds).[29] In most modern situations, it is preferable to have a ratio favoring more early sound energy as this is better to distinguish individual instruments and rhythms. A hall

[29]Beranek. 23

for medieval choir music, originally performed in Gothic cathedrals with large spaces and a long reverberation time, would be better designed with less clarity.

The Intimacy Index, or the feeling of being close to the sound source, is a metric based on the specific geometry of the room. This is measured as the interval of time between the direct sound and the first reflection. The standard time interval of the initial time delay for creating an intimate space is considered to be 20 ms.[30] Determining intimacy requires more information about the geometry of the room and will change based upon where the sound source and receiver are placed. The first reflections in most concert halls come from the sidewalls as opposed to the ceiling, which is further away.

There are other considerations, particularly regarding the musician as a listener, in acoustic design that lack clear metrics but are crucial to understand in order to create an optimal acoustic setting. The Objective Support, or ability for performers to hear one another is extremely important in enabling performers to play as a cohesive group, or ensemble. Good ensemble can be achieved by ensuring that reflectors on stage reflect sound from one part of the orchestra to the other side of the orchestra.[31] Objective Support is defined as the energy from reflections arriving within 100 ms of the direct source sound from a receiver

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[30] Backus, 179.
[31] Beranek. 32

placed 3 meters from the source and measured in decibels. A desirable measure for this metric is between -13 and -11 dB.[32]

A musician should also be able to sense the acoustics of the room and how it responds to what he or she is playing. The immediacy of response, or attack, of a venue is similar to the intimacy felt by the audience in that it is dependent on the first reflections of the source sound arriving back at the musician's ears. [33]

### 3.1.3 Acoustics and Subjectivity

Part of the problem with defining a "perfect" set of acoustical parameters is that different sounds are perceived as better in different contexts. A drum set solo in a large Gothic cathedral would not offer the same experience as listening to the same solo in a recording studio. Yoichi Ando argues that the preferred qualities of the space are dependent on the function and qualities of the music (or other sounds) within the space.[34] To fully enjoy the rhythmic intricacies of a rock drum solo, the listener must be able to distinguish each attack of the drum, a quality not afforded in the highly reverberant spaces of a stone Gothic cathedral. This is not to say that all music will sound terrible in this setting. In fact, Gregorian chants have the best effect when performed in a highly reverberant space.[35]

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[32] Michael Barron, *Auditorium Acoustics and Architectural Design*, (New York, Routledge, 1993), 61

[33] Beranek. 33

[34] Ellison, Schwenke, 2

[35] Beranek, 44

Ando's argument for matching performance spaces with the qualities of music performed there is true, but historically composers have done the inverse and designed their music for the spaces in which they were to be performed. In either case, the goal is the same – the properties of the space enhance the performance.

### 3.2 Varying Acoustics

Not all music calls for the same acoustic environment. As demonstrated by the reverberation time, different styles of music can require widely different situations. Historically, composers in residence would compose for the setting in which their works were to be performed. Now, with a wealth of historic music that was composed for specific settings, modern concert venues attempt to provide multiple acoustic settings in order to provide the optimal concert going experience for the audience. This section focuses on the ways in which acousticians use variable and active means of manipulating the actual, or perceived, acoustics of a concert hall.

#### 3.2.1 Passive Variable Room Acoustics

Passive variable systems manipulate the acoustical qualities of the room by changing the material and geometrical properties of the room. The acoustical parameter with the greatest impact on the quality of listening is the reverberation time. Changing the reverberation time of a space requires changing the volume of the room and the sound absorbing and sound reflecting surfaces.

$$RT_{60} = \frac{(.049)V}{\sum_{1}^{n} s_n a_n}$$

Other factors in changing the acoustic properties of the space, which influence other important metrics such as clarity and definition, include relocating and moving ceiling and wall panels.

Changing the volume of a room can be accomplished in multiple ways. The first involves moving an entire partition of the room, such as a wall, or in most cases raising or lowering the ceiling. Many modern concert halls make use of the fly loft above the stage (used to “fly” set pieces in and out for theatrical productions) in order to add volume to the hall, raising and lowering a drop ceiling as necessary. Another practical system involves shutters that open up to include a larger volume of space.[36]

The fly loft at the Bass Performance Hall in Fort Worth, Texas allows the hall to have a reverberation time of 1.6 seconds for opera and a reverberation time 1.9 seconds for concerts by deploying a concert hall shaper, sealing off the fly loft.[37] While there is no fly loft at the KKL Concert Hall in Lucerne, Switzerland, there is

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[36] Barron, 340

[37] Beranek, 550

a large amount of volume on the sides of the hall accessed by moveable doors. The reverberation time can be varied by accessing the volume through opening or closing to the doors to any degree.[38] This, in combination with varying the absorbing surfaces, allows the reverberation time of the hall to range from 1.60 to 2.15 seconds.[39]

Varying the sound absorbing characteristics of the room is a much easier task and is a more common occurrence than changing the volume of a space. This usually involves movable panels or more commonly installing a sound absorbing banner across sound reflecting walls or in the attic spaces above the ceiling reflectors. Movable curtains, for example, are aesthetic and practical methods of creating more sound absorbing surfaces. Reflectors are traditionally used to bounce sound from the orchestra up to balcony areas and are relocated generally to enhance early reflections associated with speech. Just using the deployable curtains at the KKL Concert Hall with the doors closed allows the reverberation of the hall to range from 1.60 to 1.95 seconds.[40]

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[38] Beranek, 550

[39] Beranek, 613

[40] Beranek, 660

The movable reflector at the Queen Elizabeth Hall in London is used primarily to provide more early reflections from overhead during speech and rotated upward for orchestral performances.[41]

Many spaces combine these methods of varying the reverberation time. The Paris Espace de Projection is a space in which the entirety of the room is variable. The ceiling consists of three separate panels capable of raising and lowering in order to change the room volume. The largest of these configurations offers a volume four times larger than the smallest. In addition to changing the volume of the space, the surface characteristics of the ceiling and walls are variable through use of rotating prisms, each with an absorbing surface and two reflective surfaces, one specular and the other diffuse. This design allows for reverberation times ranging between 0.5 to 2.0 seconds.[42]

### 3.2.2 Active Variable Room Acoustics

Active systems use electronics to manipulate the sound and re-project it through speakers. The challenge in using electronic methods in acoustic variation is integrating the electronic sources (speakers) with the natural environment of the room. A good active system is one that is not noticed.[43]

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[41] Barron, 343
[42] Barron, 343, 344
[43] Barron, 348

In order to lengthen the low frequency reverberation times at the Royal Festival Hall in London, an active system termed Assisted Resonance was used to boost the sound energy of the lower frequencies. Multiple microphones across the room engage 72 different frequencies, all below 1kHz. The microphone placements throughout the room are based upon the natural peaks of that frequency due to the room. As lower frequencies have a longer wavelength, the peak position is much less susceptible to changes in temperature, humidity etc. For this reason, reinforcing of higher frequencies, which have shorter wavelengths and are much more influenced by environmental factors, is done across broadband channels.[44]

For venues in which voice is to be reinforced, it is important that the audience feel connected to the person and not the microphone projecting his or her voice. For this reason the Palast der Republik in Berlin, a 5000 seat hall, utilized the Delta Stereophony System or DSS to reinforce the speaker's voice but also provide a sense of directionality to the speaker's voice. This is accomplished by creating a delay in the signal from the microphone to the speaker. As long as the audience hears the first sound from the natural source first, the sounds arriving later from the electronic speakers will appear to be attributed to the natural source.[45]

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[44] Barron, 349, 350
[45] Barron 348

New active room acoustic systems use computer simulations and auralization techniques to pair the actual space with a digital model and reinforce the sound in order to achieve a number of desired effects.

In the next chapter, a specific multi-use space will be evaluated, first to determine the ideal acoustic characteristics for the different types of programs it is used for and then looking for ways to improve it. These will help to determine the constraints of the parameters and formulate a parametric definition.

# 4 CASE STUDY BUILDING AND APPROACH

Creating a parametric model based on structural requirements is fairly straightforward (although computationally complex); success is defined by a structure that will resist the specified loads. As discussed, designing a successful acoustic environment depends on a number of criteria. While there are various acoustic criteria to assess room acoustics, the physical parameters affecting these criteria are based on the room size, geometry, surface finishes, and the location of the sound source and listener. Assessing the room acoustics of an existing space will provide a practical approach by examining how various programmatic uses can be used in the existing building geometry. This chapter discusses a case study building, its programmatic uses, and the acoustic parameters that will be used to define an acoustic element within the venue.

## 4.1 The Harold Lloyd Soundstage

The Harold Lloyd Soundstage at the University of Southern California was originally built for the School of Cinematic Arts as a soundstage for film production. The Thornton School of Music acquired the building in 2010 for use as a rehearsal space for multiple ensembles. This section will give an overview of the building and space, its history, and the physical attributes of the space as it exists, construction assembly, and existing acoustic environment.

### 4.1.1 Background Information

The Harold Lloyd Soundstage was originally built as a soundstage for the production of student film projects at the University of Southern California. It is located on the University Park Campus, at 3450A W 35th St in Los Angeles, CA.


**Figure 4.1 – Exterior of Harold Lloyd Soundstage**

**Figure 4.2 – Interior of Soundstage**

After the completion of a new Cinematic Arts facility, including the construction of brand new soundstages immediately to the west of the existing soundstage, the Harold Lloyd Soundstage was transferred to the Thornton School of Music at the beginning of the 2010 fall semester.

### 4.1.2 Construction

The Harold Lloyd Soundstage is constructed of load bearing 8 inch concrete masonry unit (CMU) walls, with a total floor area of approximately 3,072 sq ft. The north and south walls are approximately 64 feet long, while the east and west walls measure approximately 48 feet. The interior height is 30 ft at the corners and approaches 35 ft at the center of the hip. An interior ceiling is framed out of dimensional lumber at 30 feet above the floor. A floor plan from the original construction is shown in Figure 4.3.

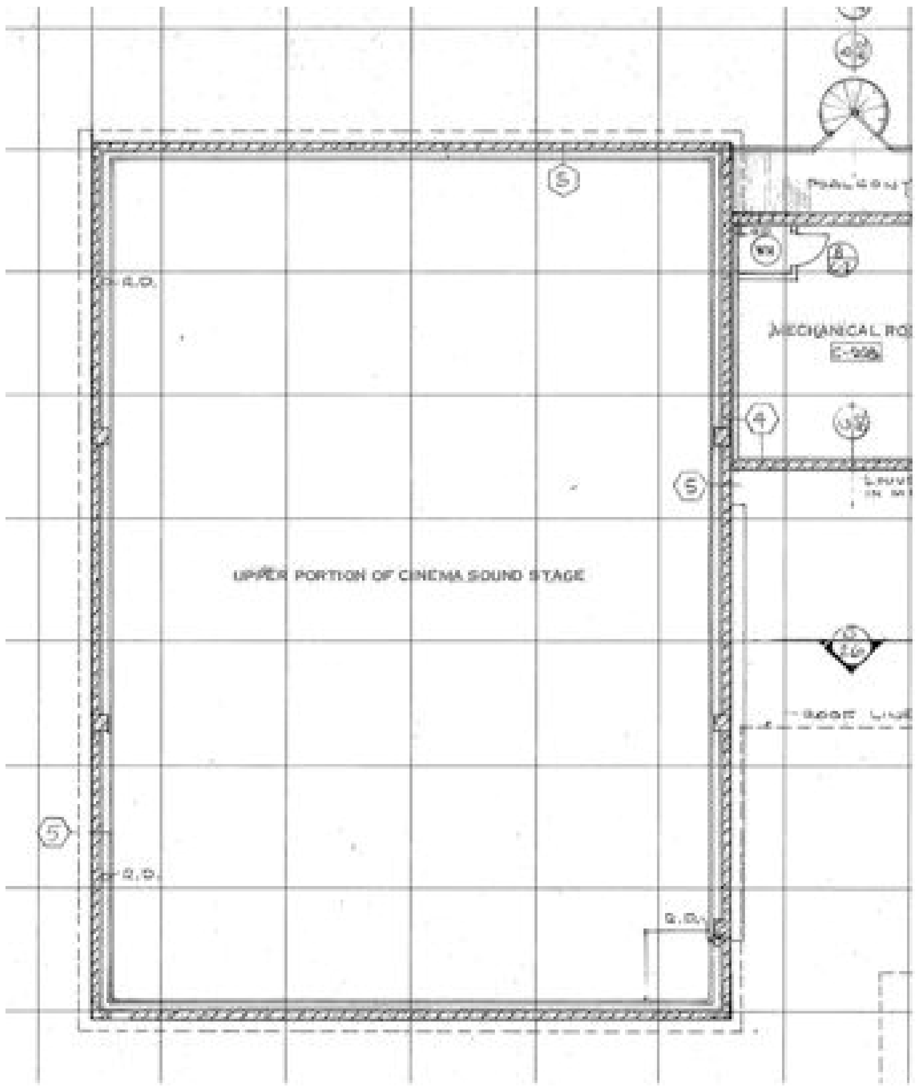


**Figure 4.3 – Floor plan of Harold Lloyd Soundstage**

For purposes of sound recording, a soundstage requires good sound isolation from the exterior environment. A secondary interior wall is built leaving a 6 inch space between it, and the CMU wall filled with fiberglass insulation. The interior wall is constructed of one layer of 3/8-inch gypsum drywall behind two layers of ½-inch fiber-board insulation. Figure 4.4 illustrates the wall construction.

**Figure 4.4 – Interior Wall Construction**

The soundstage is considered acoustically dead, meaning the reverberation time is extremely low. Although good for a soundstage, an extremely low reverberation time is not considered good for most music performances. Since acquiring the building, Thornton has attempted to temporarily mitigate the "deadness" of the soundstage by installing a series of 4 x 8 foot wood veneer panels at 4 foot intervals around the perimeter of the facility at approximately 3 ft off the floor to provide more reflective surfaces. Since these panels are temporary installations, they will not be considered in the calculations for the existing conditions.

## 4.2 Ensembles

This section describes four types of musical ensembles that use the soundstage and require specific acoustic environments for each. Each ensemble using the space will require a different set of acoustic parameters. This section will focus on four varied acoustic environments to achieve an acceptable condition that meets the acoustic criteria.

### 4.2.1 Orchestra

As the Thornton School of Music's flagship ensemble, it is important that the space be best tuned for the symphony orchestra. A symphony orchestra instrumentation typically consists of strings (including violins, violas, cellos and string basses), woodwinds (flutes, clarinets, oboe and bassoon), brass (trumpets, horns, trombones and tubas), and percussion including drums mallets and auxiliary. This is a rough guide as instrumentations change based on the piece played; a performance of *The Rite of Spring* includes more than the average number of musicians, and some performances require specific instruments such as a harp, grand piano, or even large wood box that are not typical. Depending on the selection of music, a symphony orchestra will require an appropriate reverberation time to realize an ideal acoustic setting. Ideal acoustic settings are also subjective to the conductor and opinions can vary considerably from conductor to conductor. Composer and USC faculty member Frank Tichelli prefers a less reverberant room for his works, which tend to have more rhythmic intricacy.[46] Based on the style of music and the director's own preferences, the reverberation time will range from 1.8-2.2.

### 4.2.2 Percussion

The Percussion Ensemble consists of a variety of percussive instruments including drums, mallets, and auxiliary equipment. Typically percussion focuses on the rhythmic intricacies of music. This necessitates a space in which rhythms can be clearly understood and perceived. Similar to jazz, this will necessitate a lower reverberation time of near 0.8 seconds.

### 4.2.3 Master Classes

Master Classes are instructional periods with a "master" musician aimed at improving technical performance in a group setting. Master Classes exist for the range of instruments, but the essential criteria is that the instructor is intelligible to the students. This will necessitate a reverberation time of not more than 0.7 seconds.

### 4.2.4 Recitals

The School also expressed interest in being able to utilize the soundstage as a location for recitals. Recitals exist for every instrument and typically involve an

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[46] Ellison, Schwenke, 2

ensemble of instruments, featuring a soloist. Unlike the other uses of the facility, the acoustics in a recital format would involve an audience in addition to the musicians. As recitals occur for every instrument, the reverberation time can vary from 0.8 for percussion to 2.2 for more Classical pieces.

### 4.3 Parameters and Constraints

After examining the potential uses of the space and having knowledge of the ways in which acoustics are measured and assessed, this section will explain the metrics that will serve as the principal criteria for achieving acoustic success and act as the drivers for altering the space. The metrics were chosen based upon their ability to account for the range of physical quantities of sound including amplitude, frequency, and timing. Reverberation time, bass ratio, and early energy ratios are critical metrics.

#### 4.3.1 Reverberation Time

The single most common metric in changing to assess the acoustic quality in a space is reverberation time, RT. This will act as the principal parameter to control the physical changes room acoustic quality of the space. The RTs designed in the space will be based on use and will range from 0.7 – 2.2 seconds. In order to change the reverberation time, both total room volume and the amount of sound absorbing material will need to be variable.

### 4.3.2 Bass Ratio

Varying the reverberation time of the room will have the greatest effect on the performance of the room, but is not the only acoustic parameter that should be considered. The Avery Fisher Hall in New York had a similar reverberation time to other concert halls when it opened in 1962, but was perceived as being a substandard performance venue for its lack of "warmth," technically a measure of the balance of low frequencies and bass ratio (despite several attempts to remedy the acoustical problems with the hall, many exist to this day).[47] While there will not be as much acoustic variability with Bass Ratio based on program use, it will be important to constrain the bass ratio to a range of possible values. This range of possible values will be considered 1.2-3. Constraining bass ratio will depend on the total room volume as well as the sound absorbing properties at the first 4 octave bands, 125, 250, 500 and 1000 Hertz.

### 4.3.3 Early Energy Ratios

The final metric taken into consideration will be Objective Support for rehearsal settings and Clarity for recital settings. These metrics will have more influence over the individual panel height and orientation and distribution of sound absorptive material. The range for constraining Objective Support will be between -13 and -11 dB. Because the Clarity index is in part based upon the late arriving sounds energy, which will not be calculated, the constraint will be to

[47] Backus, 180-181

maximize the amount of sound energy arriving at each location prior to 80 milliseconds.

Table 4.1 summarizes the constraints that each parameter will be held to as a criteria for judging success in each situation.

| | | Acoustic Parameters | | |
|---|---|---|---|---|
| Space Use | RT60 | Bass Ratio | Objective Support | Clarity |
| Orchestra | 1.8-2.2 s | 1.2+ | -13 – -11dB | |
| Percussion | .8 s | 1.2+ | -13 – -11dB | |
| Master Class | .7 s | 1.2+ | -13 – -11dB | |
| Recital | .7-2.2 s | 1.2+ | - | Max. $E_{80}$ |

**Table 4.1 – Acoustic Parameters and Values**

### 4.4 Proposed Solution

The proposed solution to varying reverberation time, bass ratio, and the amount of early energy is to design a ceiling canopy system that is able to change the room's volume, shape, and percentage of materials able to add more or less absorption to the room.

- Changing the ceiling's height provides variable acoustic volumes.
- Manipulating the ceiling shape will vary the sound reflecting surfaces.
- Exposing different materials through a panel system will allow the room to have varied amounts and type of sound absorption.

The geometry of the canopy system will be modeled in Rhino 3D and the parametric design will be done using a third party plugin called Grasshopper.

These programs will be further explained in the following chapter.  This section will detail the geometry and construction of the proposed ceiling canopy system and the ability of each component to impact varying the established metrics.

### 4.4.1 General Layout

The ceiling canopy will be divided into 32 triangular panels measuring 16 x 12 feet.  The use of approximate measurements at the nearest whole number is intended to simplify the calculations involved.  The system will use 25 different nodes in order to control the varying heights of the triangles' corners.

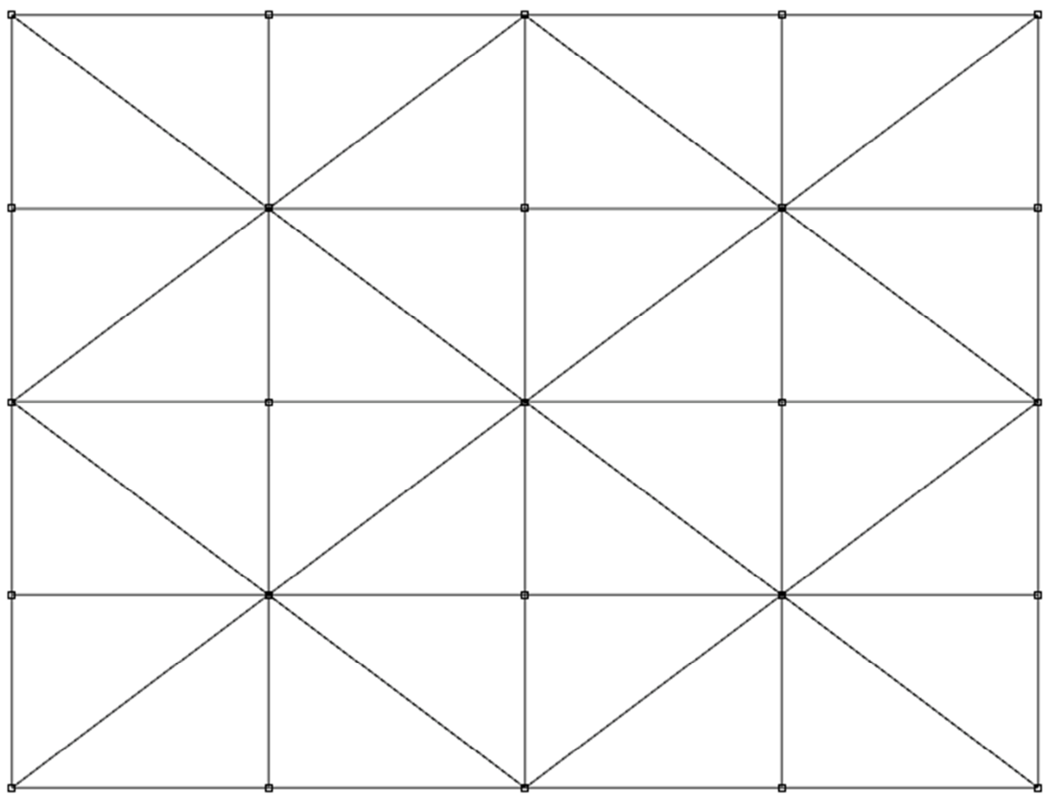

**Figure 4.5 – Ceiling Grid Layout**

The range of heights will be from 15-30 feet and flexible material will be placed between each panel to allow for the differential movement between the panel edges.  For the purposes of this study, it will be assumed that the space between the panels is negligible and will not contribute to increased absorption.

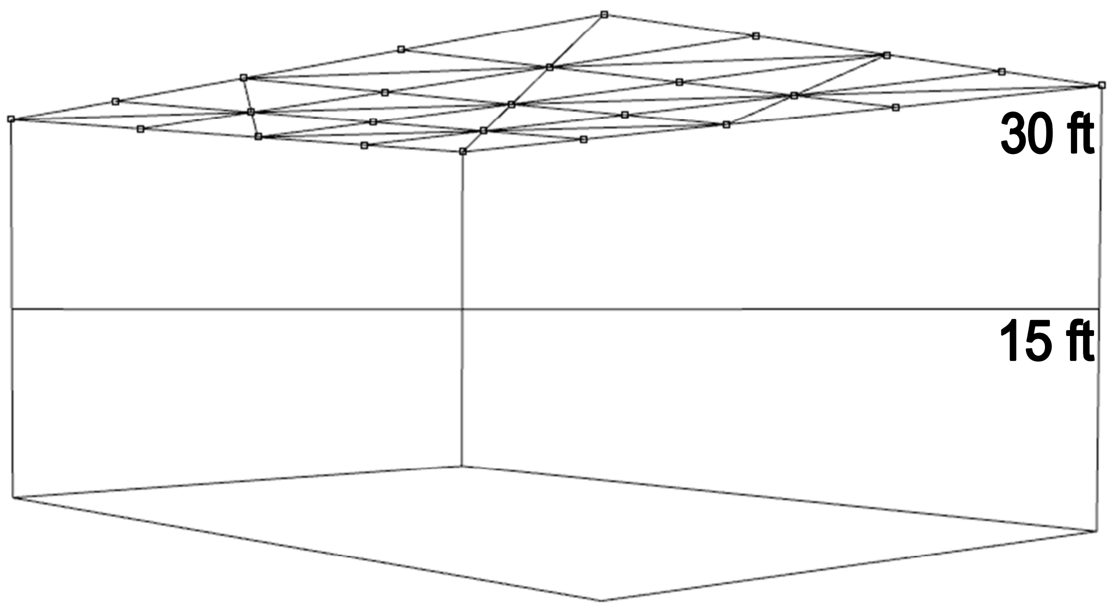


**Figure 4.6 – Range of Ceiling Panels**

This configuration allows for an easy algorithmic definition and a manageable scale for this project to identify and manipulate the movement of each panel.

### 4.4.2 Material

Similar to the prisms at the Espace de Projection in Paris, the system will utilize different materials to provide more or less sound absorption.  Each triangular panel will have a series of smaller triangular panels capable of rotating 360 degrees about one axis in order to expose one of two materials.

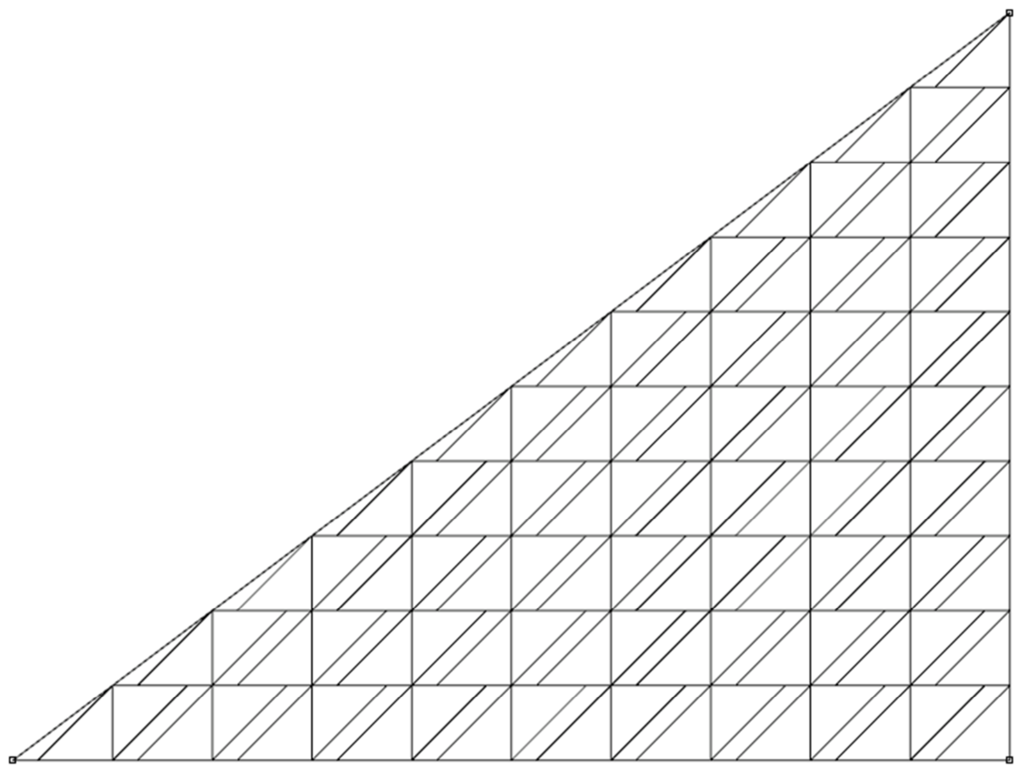

**Figure 4.7 – Make up of Individual Panel**

This will operate as the method to change the sound absorption characteristics of the ceiling. Specific materials will be chosen during the study based upon effectiveness and ability to change the acoustic environment.

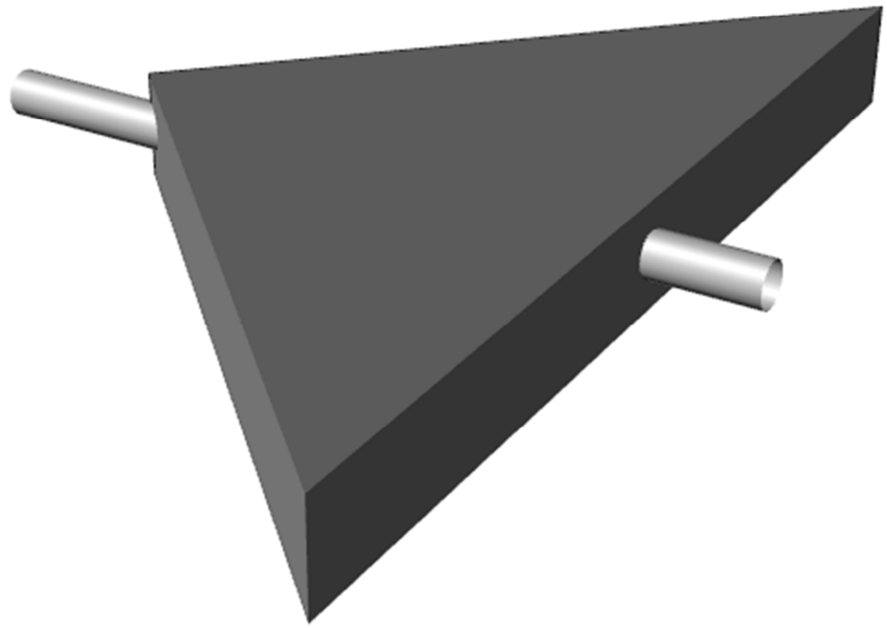

**Figure 4.8 – Example Panel**

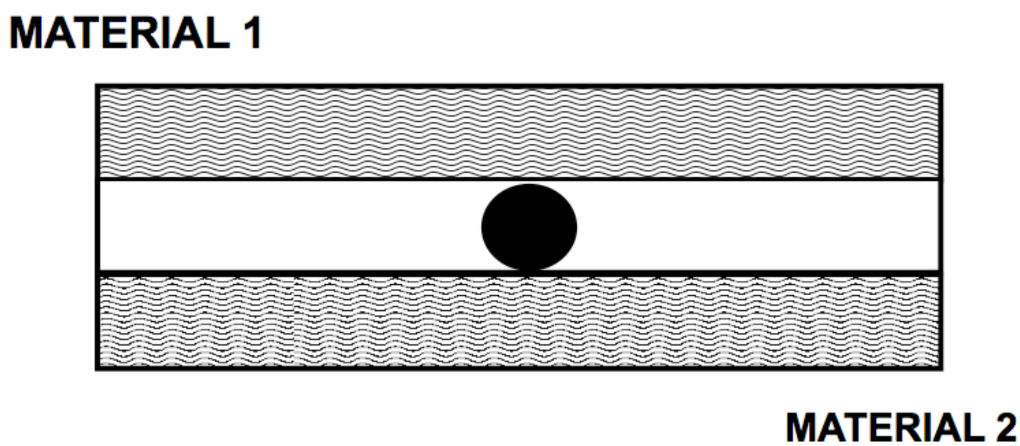


**Figure 4.9 – Panel Cross Section**

### 4.4.3 Assumptions and Acknowledgments

There are many issues that need to be examined when doing a proper acoustic study. The following case studies will operate on a number of assumptions; there will be gaps in the process that may not lead to the completely ideal acoustic situation if actually built. The case studies illustrate a method of studying optimization of a room for multiple uses, but do not take into account all the known constraints for designing. Weight is given to reverberation time, bass ratio, and clarity. For the purpose of this thesis, the floor treatment will be assumed as a wood floor over the existing concrete, while the wall treatments will be determined in conjunction with the materials for the ceiling panels. It is also assumed that the direction the sound arrives from does not matter, and hence only the first reflections from surfaces in the room will be calculated.

The main goal by the end of all the case studies is to determine what the ceiling's geometric configuration needs to be and what materials need to be applied to achieve the following metrics:

| | | Acoustic Parameters | | |
|---|---|---|---|---|
| Space Use | RT60 | Bass Ratio | Objective Support | Clarity |
| Orchestra | 1.8-2.2 s | 1.2+ | -13 – -11dB | |
| Percussion | .8 s | 1.2+ | -13 – -11dB | |
| Master Class | .7 s | 1.2+ | -13 – -11dB | |
| Recital | .7-2.2 s | 1.2+ | - | Max. $E_{80}$ |

**Table 4.2 – Goal Metrics for Each Condition**

## 5 GEOMETRIC OPTIMIZATION

In order to understand the different effects that distribution of absorption, ceiling height and the geometry of reflective surfaces have on reverberation time, bass ratio and objective support, a series of exercises were completed that focused on how to control the geometry of a room based upon these criteria. This chapter will cover the first exercise, the parametric definition and its results, the limitations and problems with the exercise and the lessons learned moving forward. These case studies use Rhino, Grasshopper, and Galapagos.

Rhino is a 3D computer modeling program that uses mathematical representations to define curves and lines that form surfaces and solids in 3D space.

Grasshopper is a plug-in for Rhino that utilizes a graphic interface to create parametric modeling streams through existing Rhino tools. Numbered “sliders” are used to vary input numbers.

Galapagos is a genomic algorithm within Grasshopper that generates a set of potential options (the base population) based upon the range of constraints designated as variable with Galapagos (the genome). Each proceeding generation of models is created from mating and eliminating previous options based upon their fitness level, as Galapagos attempts to optimize the value set by the user. The optimization is limited to a single fitness value but it could represent any combination of variables that can be evaluated within the Grasshopper definition. Galapagos allows the user to control the size of the initial population, the maximum number of generations before terminating, the number of "fruitless" generations before terminating, and a tolerance for approaching the fitness number.

### 5.1 First Exercise-Galapagos and Reverb Time

Since varying Reverberation Time will have the biggest impact on the quality of the acoustic performance, it is important to understand what effects moving the ceiling around will have on this criteria. The goal of this exercise was to begin to understand the effects of changing ceiling height on the ratio between volume and surface area. This relationship is necessary to understand how exposing more of the material on the walls will impact changing the volume of the space. This exercise covers varying the total room volume as a function of the height and surface area of a hypothetical ceiling panel system and also experiments in using the Galapagos genomic optimization feature in Grasshopper.

### 5.2 Building the Parametric Definition

Building the definition of the model is the real challenge of this thesis. The basis of the definition will lie in the relation of the room geometry to the desired performance characteristics. This exercise is the first step to identify the relations between the most important characteristic, reverberation time, and the room geometry as well as how to control this relation through Grasshopper.

### 5.2.1 Equations

Recalling that reverberation time is a function of both volume and surface area and that changing the ceiling height will have an impact on both total volume and surface area, this exercise will simplify the equation for Reverberation Time from Chapter 3 from

$$RT_{60} = \frac{(.049)V}{\sum_{1}^{n} s_n a_n}$$

to

$$RT_{60} = \frac{V}{S}$$

Where V is the room volume and S is the total surface area. While this is an oversimplification of the equation, it negates the effects of different materials and allows one to study just the impact of room geometry.

### 5.2.2 Base Model

The base model is a 30 by 30 foot room with a square grid ceiling composed of nine 10 by 10 foot panels. The ceiling height at each corner or node of the ceiling is independently variable from 15-30 feet. This also necessitates that the walls are variable as well from 15-30 feet as well. With these constraints, the largest possible dimensions, 30x30x30 ft, give a volume of 27000 cubic feet and a surface area of 5400 square feet.

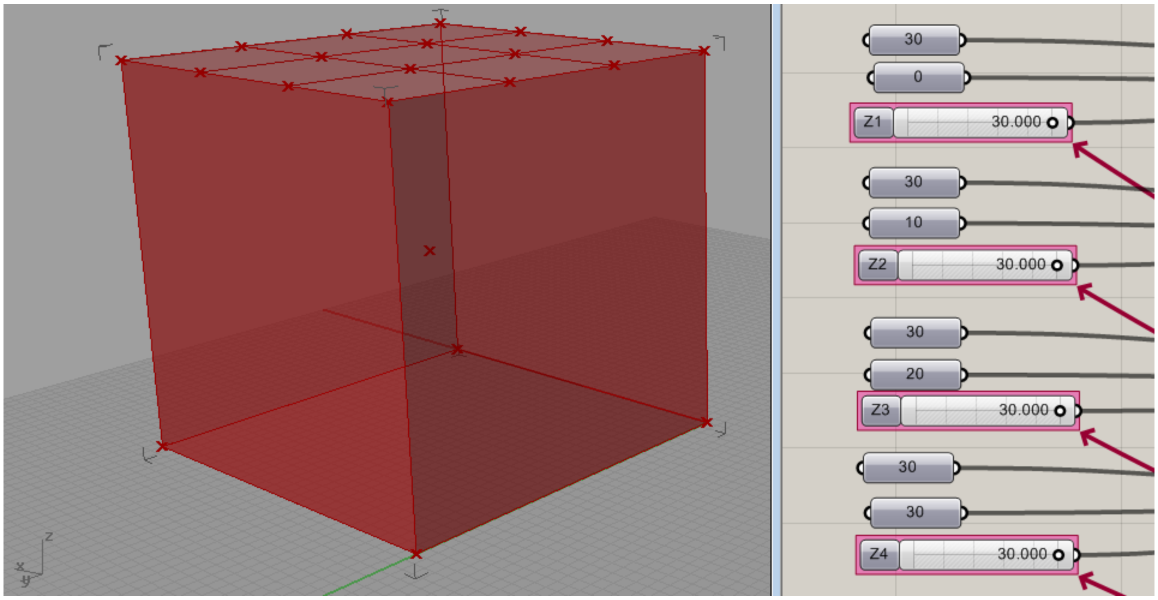


**Figure 5.1 – Model at Largest Ceiling Height Values**

This results in a volume to surface area ratio of 5. When set at the smallest possible dimensions, 30x30x15 ft, the model room has a volume of 13500 cubic feet and a surface area of 3600 square feet with a ratio of 3.75.

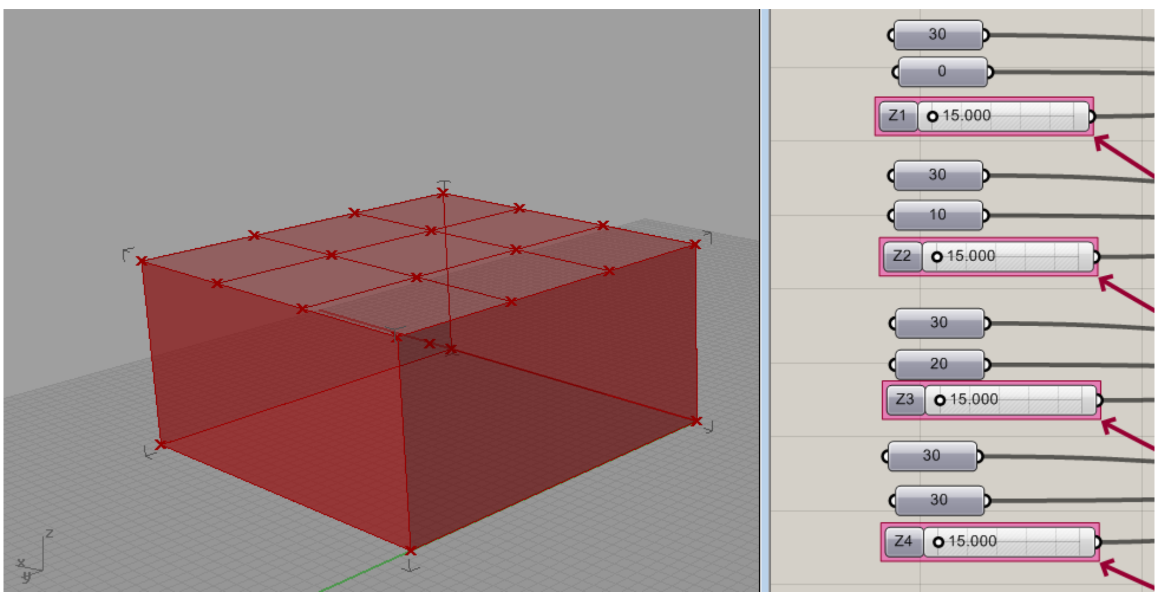


**Figure 5.2 – Model at Smallest Ceiling Height Values**

### 5.2.3 Sequencing/Controlling

The first challenge in setting up the definition is getting Galapagos to work in this context. Because Galapagos is set to optimize the fitness number, it is necessary to translate the target value into a value that Grasshopper will take and attempt to optimize. The way this was handled was taking the negative of the absolute value of the difference between the target and calculated values. This makes the fitness number optimize to 0, equal to no difference between the target value and the calculated value.

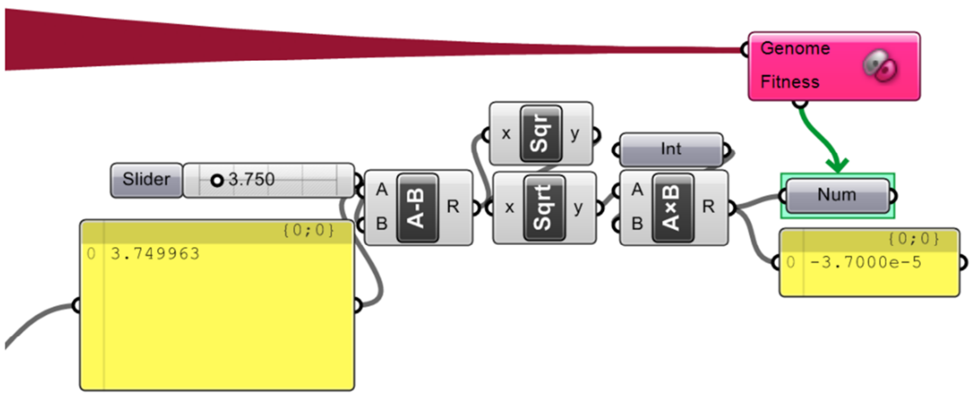


**Figure 5.3 – Fitness Number Process in Grasshopper**

The Genome or variable part of Galapagos is associated with the height of each ceiling panel node. The height of each node of the surface is variable from 15-30 ft, while the X and Y coordinates remain fixed. Surface area and room volume are determined by evaluation functions within Grasshopper and are fed back to the fitness number for the Galapagos function as previously discussed.

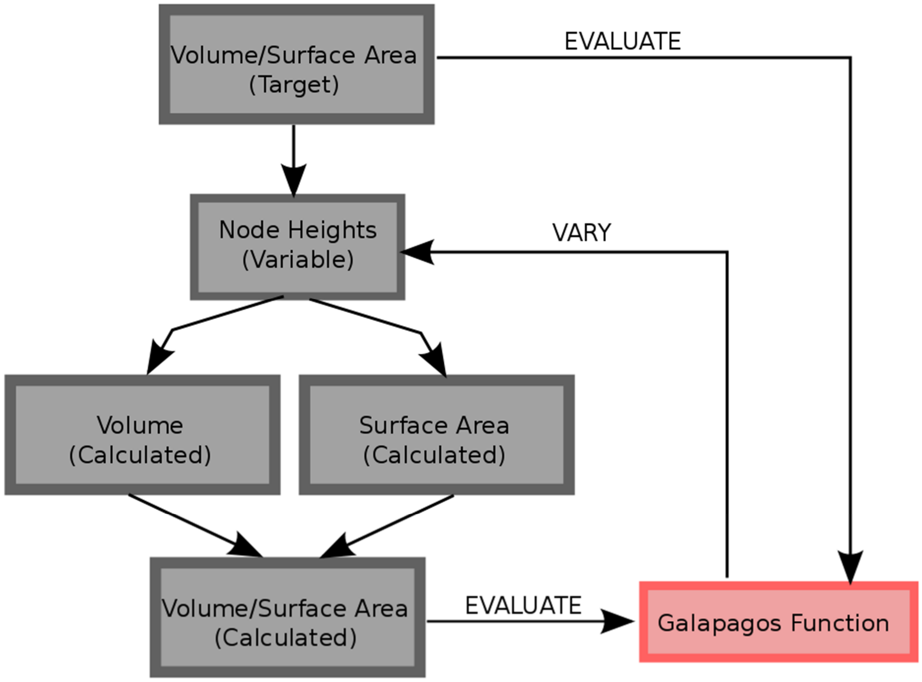


**Figure 5.4 – Schematic of Grasshopper Sequencing for Exercise 1**

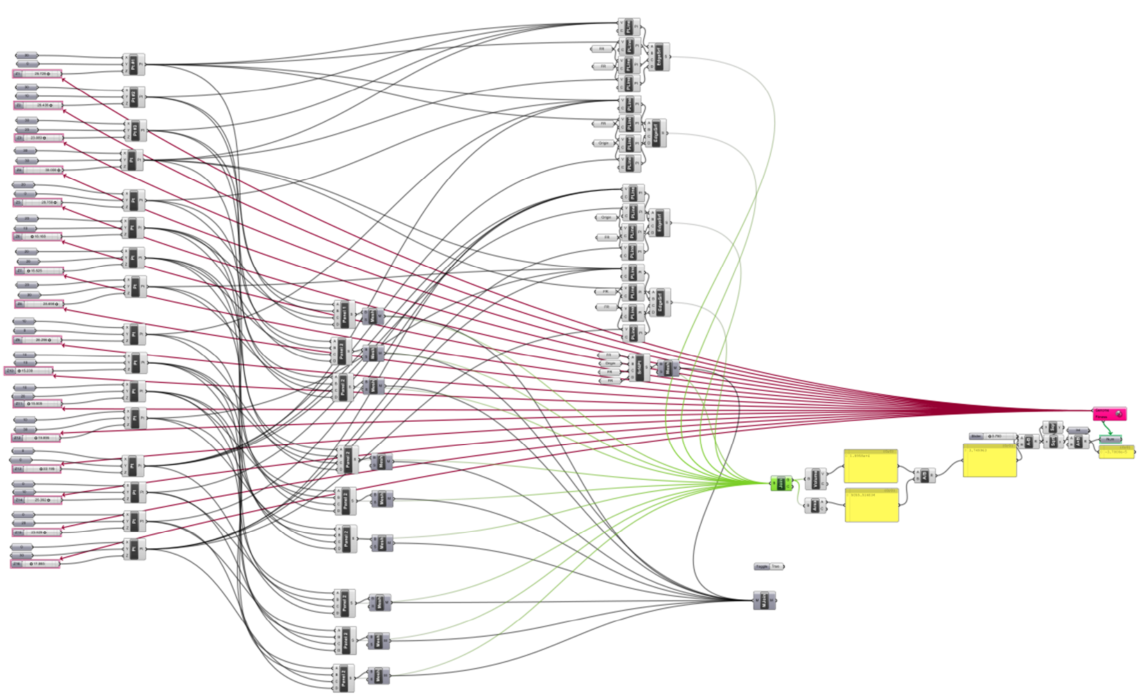

**Figure 5.5 – Full Grasshopper Model for Exercise 1**

## 5.3 Resulting Models

In order to evaluate this definition and gauge if Galapagos is a suitable tool for this application, the ratio for the minimum ratio, the maximum ratio, and multiple simulations at one target value were evaluated. Within Galapagos, the specific values were set as follows:

Maximum Generations 80. This number defines the maximum number of generations the application will run for before terminating.

Maximum Fruitless Generations 20. This number defines how many generations the application will run for with no improvement before terminating.

Initial Population 50. This number defines the initial number of solutions the application will evaluate.

Inbreeding Factor 50. This number defines how likely the breeding populations will combine with similar solutions (value of 100) or dissimilar solutions (value of -100).

Maintain High Fitness 10. This number defines the percentage of solutions retained from previous generations that outperform the new generation.

### 5.3.1 Minimum Value

The target slider was set to zero to obtain the smallest possible volume to surface area ratio, calculated as around 3.37. This required extending the total number of generations up to 240. The shape produced makes sense as a low ratio is produced by a high surface area and a small volume.  The inverted dome shape of the roof provides this sort of geometry, maximizing the amount of surface area for amount of volume gained.

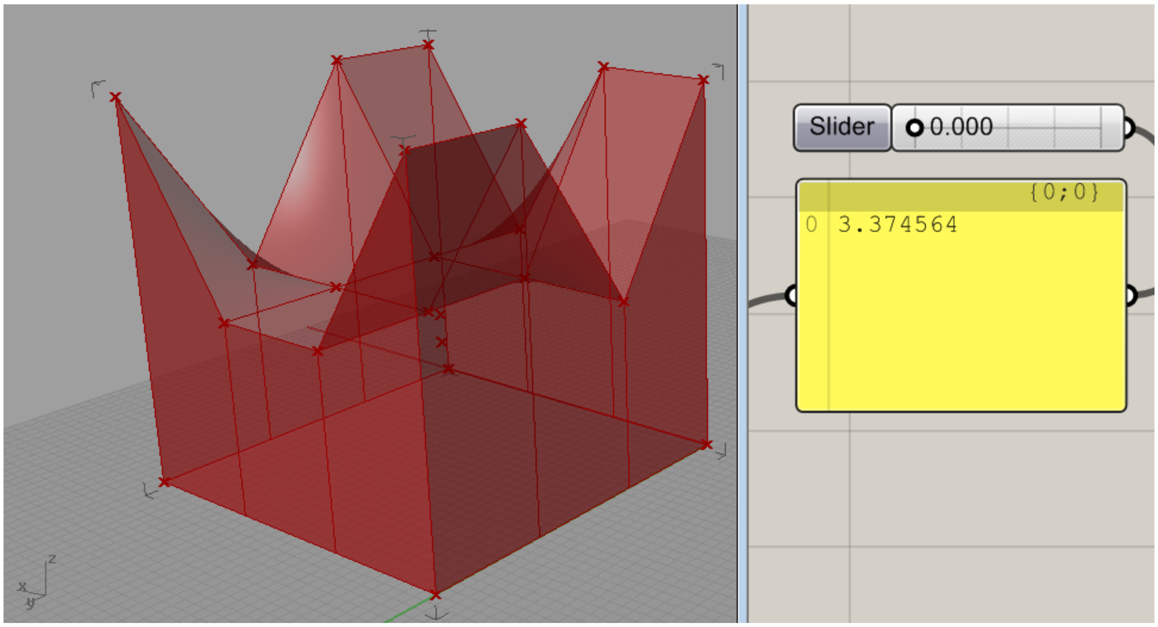


**Figure 5.6 – Minimum Ratio Shape**

### 5.3.2 Maximum Value

The target slider was set to 50 to obtain the largest possible volume to surface area ratio, which resulted in a ratio of 5.09. The shape of this model is essentially an inversion of the previous model using a domed shape to maximize the volume to surface area ratio.

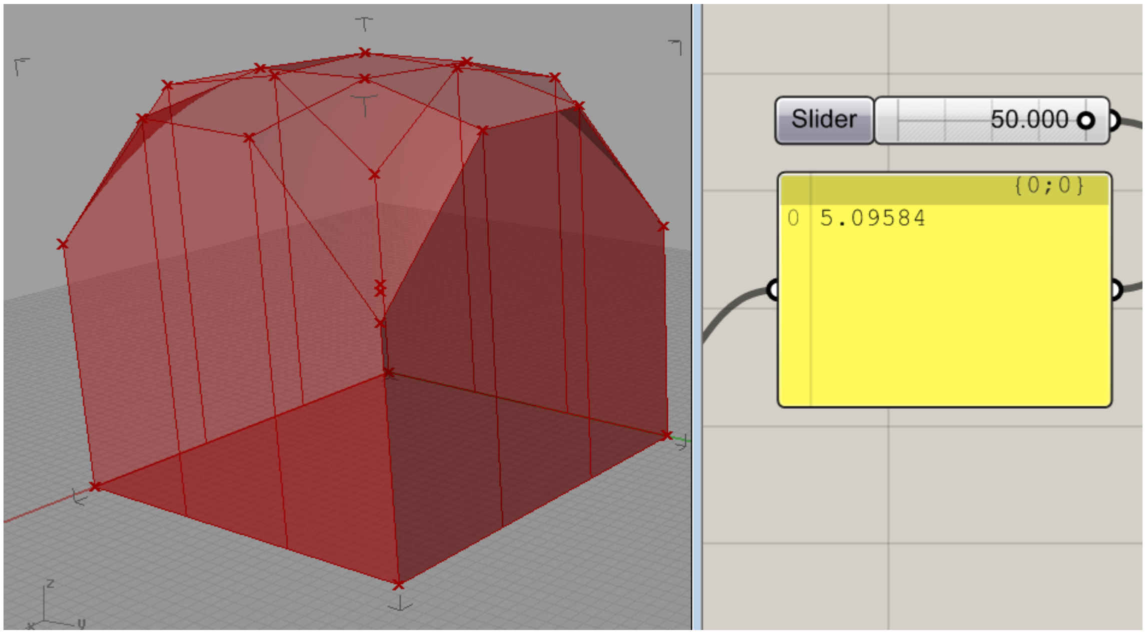


**Figure 5.7 – Maximum Ratio Shape**

### 5.3.3 Evaluating at Ratio of 3.75

The slider was set to 3.75, the ratio calculated using the lowest height for each node, to see what would be produced by Galapagos.

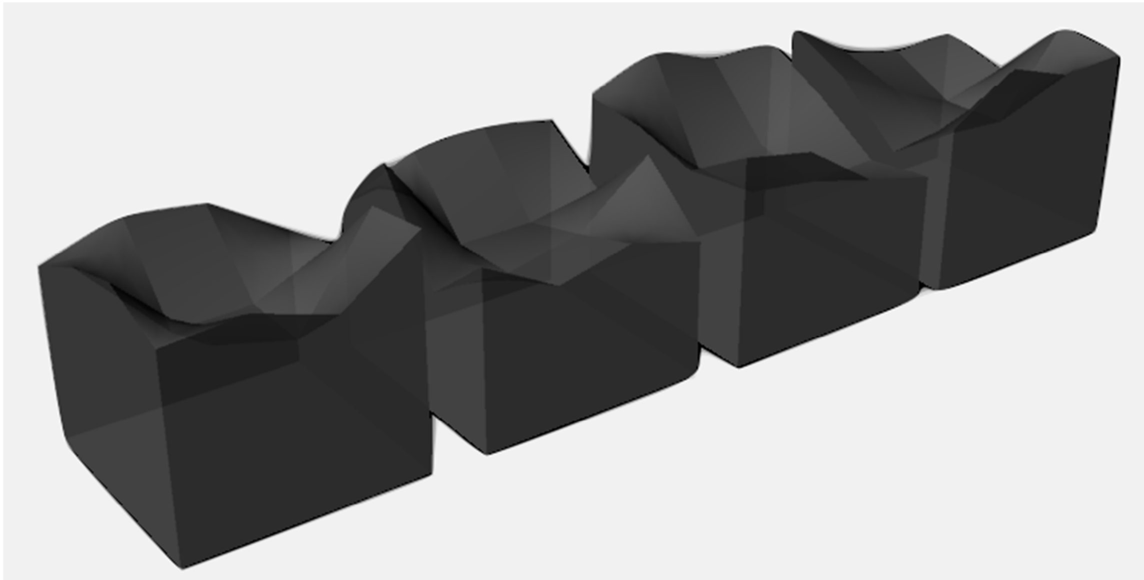

**Figure 5.8 – Models with V/SA Ratio of 3.75**

Each model produced had a volume to surface area ratio of 3.75, but each had different configurations and total volume and surface area.

| | Volume | Surface Area | Ratio |
|---|---|---|---|
| Model 1 | 18958.43 | 5055.51 | 3.7500 |
| Model 2 | 17120.43 | 4565.32 | 3.7501 |
| Model 3 | 17967.00 | 4791.20 | 3.7500 |
| Model 4 | 17794.45 | 4745.06 | 3.7501 |

**Table 5.1 – Volume and Surface Areas of Multiple Trials at 3.75**

## 5.4 Discussion and Conclusions

If this technique will be applied to finding the shape of the ceiling panel system, it will be necessary to restrict the height of the nodes relative to each other. While the panels can be expected to accommodate some flexibility and movement from panel to panel, there needs to be a tolerance limit in order to maintain the assumption that the space between the panels is negligible.

Using Galapagos also takes care in realizing if the optimized number has reached its limit and in setting up the fitness number so that it is solving for a specific value rather than for the largest or smallest value. This requires that the genome actually has an effect on the fitness number, and that enough generations are programmed into Galapagos, especially when the genome consists of a large amount of sliders.

The result of using Galapagos to perform this function is that it produces an array of variations with very different geometries. Limiting the variation in height from panel to panel will limit these variations, but there is the potential that some of these models will result in unfavorable geometries.

## 6 SECOND EXERCISE

As demonstrated by the failures of Avery Fisher Hall, the balance of frequencies is an important factor in the quality of the acoustics of a space. Varying both ceiling height and the different type of absorptive materials should be able to achieve the control of both reverberation time and bass ratio. The goal of this exercise was to examine the interaction of absorption and room volume with the effects on reverberation time and bass ratio and determine an equation for material ratios and room volume as a function of reverberation time and bass ratio. A secondary goal in this exercise was to establish the best materials to use on the walls, floor, and ceiling that would allow the widest range of possible values.

### 6.1 Determining Geometric Relationships

The equations for reverberation time and bass ratio are written such that they are functions of (a) room volume, (b) the properties of the finishes, and (c) the surface area of the finish materials. In order to vary the acoustic parameters of the room, it will be necessary to rewrite these equations so that the room volume (or at least the ceiling height) and the percentage of each material is a function of the prescribed reverberation time and bass ratio. This required some assumption of the materials within the space, deriving equations for the general form of the equation as well as calculating coefficients for the use of specific materials.

### 6.1.1 Equation Overview

This exercise will assume four materials present in the room. The ceiling will consist of the two materials under investigation, the floor as carpet over the existing concrete floor, and the walls as plaster with 25% of the wall space covered by 2” fiberglass absorbers. A flat ceiling will be used in this case study in order to keep variables to a minimum. Under these conditions the equation for reverberation time will look like:

$$RT_{60} = \frac{(.049) * 3072 * h}{\sum s_{C1}a_{C1} + s_{C2}a_{C2} + s_F a_F + s_W a_W}$$

Where 3072 is the square footage of the floor, h is the height of the ceiling, C1 and C2 are the first and second ceiling materials, F is the floor, and W is walls. Reverberation time will be assumed to be at 500 Hz, but will also have to be calculated at 125, 250, 500 and 1000 Hz to figure out bass ratio:

$$BR = \frac{RT_{125} + RT_{250}}{RT_{500} + RT_{1000}}$$

### 6.1.2 Early Attempts at Setting Up Data

This exercise began as a trial and error attempt to try to confirm the possibility of achieving a targeted reverberation time of 2.0 seconds and a bass ratio of 1.2. Using the assumptions previously mentioned, the height and ceiling material percentages were varied within a Microsoft Excel spreadsheet (Table 6.1) to try to achieve the specified parameters. This would help later in verifying the results in Galapagos.

| Variables | | | Reverberation Times | | | | | | Results | |
|---|---|---|---|---|---|---|---|---|---|---|
| Ceiling Height | Material 1 (%) | Material 2 (%) | 125 Hz | 250 Hz | 500 Hz | 1 kHz | 2 kHz | 4 kHz | RT @ 500 | Bass Ratio |
| 15 | 1 | 0 | 1.59 | 2.66 | 2.06 | 1.85 | 1.87 | 1.79 | 2.06 | 1.09 |

**Table 6.1 – Sample Calculations of RT and BR**

This resulted in two positive outcomes: an understanding of what types of materials would be most useful and a form for generating different sets of curves based upon two materials. The trial and error portion became a very tedious task as it involved a very limited view of the effect of using different materials. This led to the creation of full spreadsheets of reverberation times and bass ratios at the full range of material percentages (0-100%) at 5% intervals and the full range of ceiling heights (15-30 feet) at 5 foot intervals. A full set of these spreadsheets can be found in the Appendix. These spreadsheets were also useful in transforming the numerical data into a visual display of curves and to fit equations through Excel's curve fitting functions.

### 6.1.3 Families of Curves and Deriving Equations

The graphs of the 15 and 30 foot curves were used to determine which sets of materials would be the most useful in looking at how the curves compared with the target values of reverberation time and bass ratio. Figure 6.1 illustrates an example of the material curves used in this process.

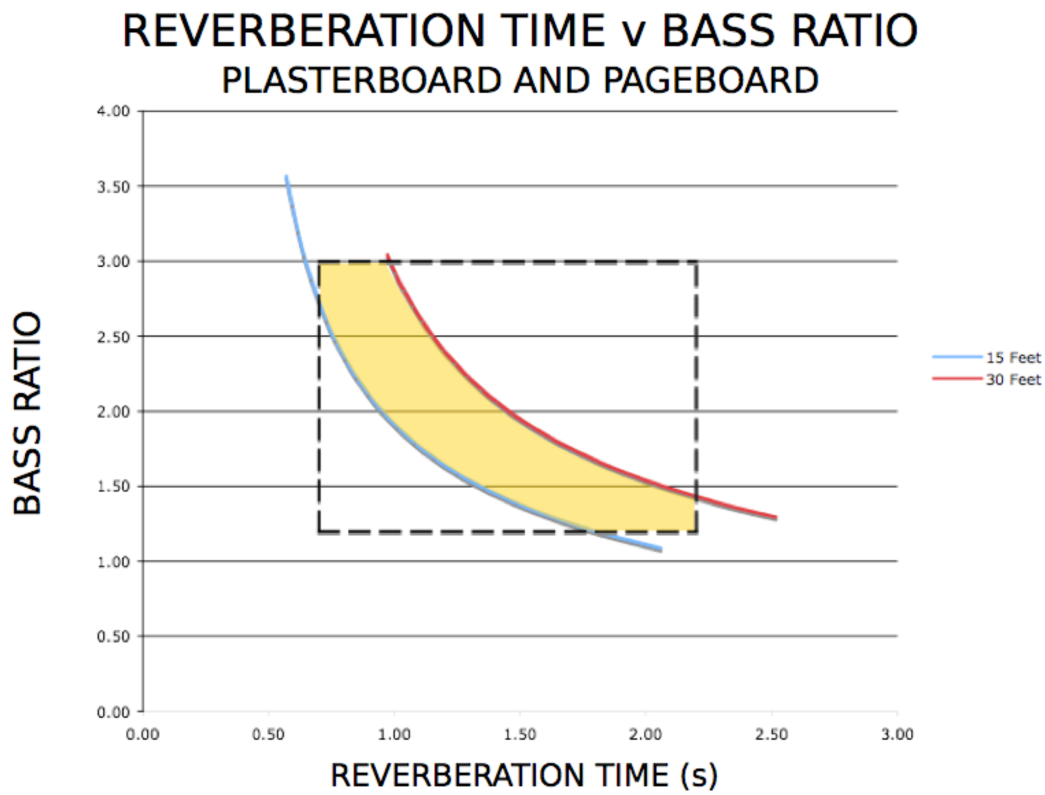


**Figure 6.1 – Graph of Reverberation Time v Bass Ratio**

After examining a number of common building materials, pageboard over 1" of fiberboard and ½" plasterboard appeared to be the most viable as ceiling materials. Plasterboard, or drywall, is 1/2 in. gypsum sandwiched between fiber or paper facers. The pageboard material is a perforated wood particleboard over a 1 in. thick fiber board and has a unique characteristic in absorbing a percentage of the mid-range frequencies. The absorption coefficients for all of the materials in the room are as follows:

| | 125 Hz | 250 Hz | 500 Hz | 1 kHz | 2 kHz | 4 kHz |
|---|---|---|---|---|---|---|
| Plasterboard | 0.29 | 0.1 | 0.06 | 0.05 | 0.04 | 0.04 |
| Pageboard | 0.08 | 0.32 | 0.99 | 0.76 | 0.34 | 0.12 |
| Walls | 0.12 | 0.13 | 0.21 | 0.26 | 0.27 | 0.28 |
| Floor | 0.04 | 0.04 | 0.07 | 0.06 | 0.06 | 0.07 |

**Table 6.2 – Absorption Coefficients of Room Materials**

Figure 6.2 displays the resulting curves of bass ratio as a function of reverberation time for pageboard and plasterboard as materials, with a range of each material from 0-100% at the 15, 20, 25 and 30 foot ceiling heights.

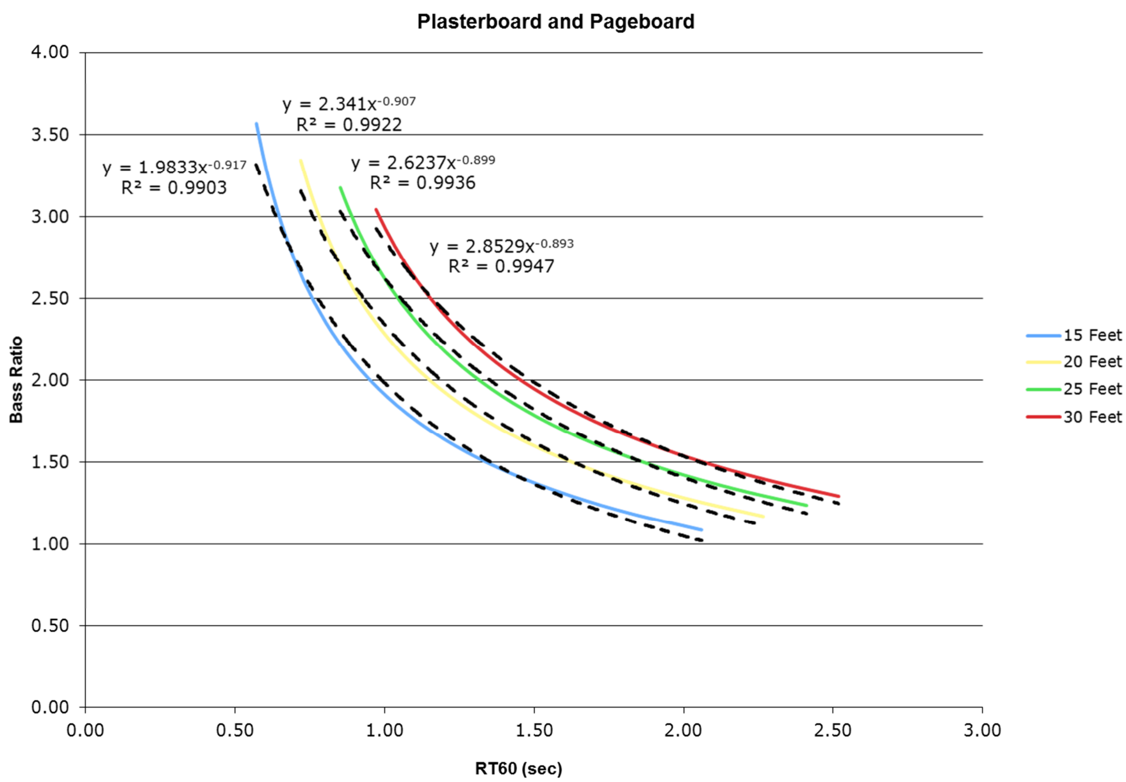


**Figure 6.2 – Graph of Bass Ratio as Function of Reverberation Time – Plasterboard and Pageboard**

Fitting a power trend line (black line in the above graphs) for each of the ceiling heights yields the following equations:

15 Feet $BR = 1.9833(RT_{60})^{-0.917}$ $R^2 = 0.9903$

20 Feet $BR = 2.341(RT_{60})^{-0.907}$ $R^2 = 0.9922$

25 Feet $BR = 2.6237(RT_{60})^{-0.899}$ $R^2 = 0.9936$

30 Feet $BR = 2.8529(RT_{60})^{-0.893}$ $R^2 = 0.9947$

The high R squared numbers (least squares regression) indicate a strong fit for a power trend line yielding an equation relating Reverberation Time and Bass Ratio in the general form of

$$BR = f(h) * RT_{60}{}^{k}$$

Where the coefficient f(h) is a function dependent upon the height of the ceiling and k is based on the height of the ceiling and the absorption coefficients of both materials. As there is a negligible variation in k from 15-30 feet, this value will remain constant across each height. For these materials k will be equal to -0.90. Taking the coefficient f(h) and plotting it as a function of ceiling height yields the following curve:

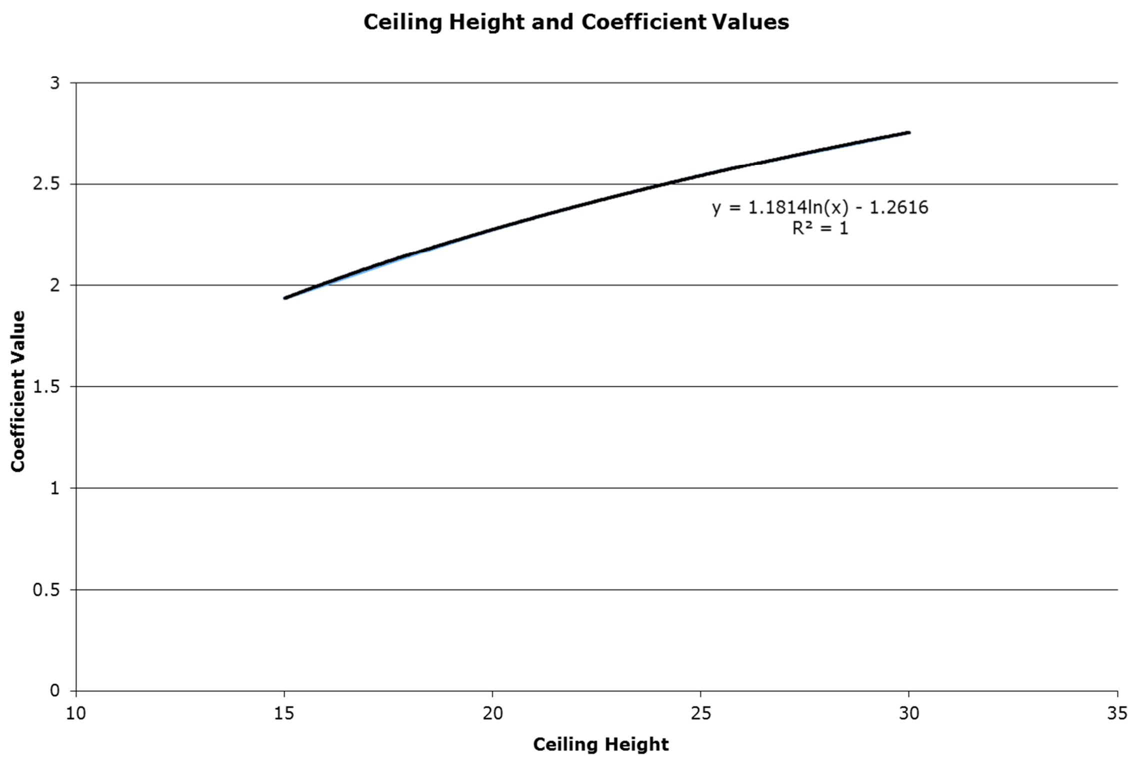


**Figure 6.3 – Graph of Ceiling Height and Coefficient Values**

Creating a logarithmic trend line yields the equation of form:

$$f(h) = a * \ln(h) + b$$

Where *a* and *b* are derivatives of the specific ceiling materials. For plasterboard and pageboard *a* is 1.1814 and *b* is -1.2616.

€

Substituting this into the first equation gives

$$BR = (1.1814 * \ln(h) - 1.2616) * RT_{60}{}^{-0.90}$$

Rearranged in terms of BR and RT gives an equation for the height of the room:

€

$$h = e^{\left(\frac{\frac{BR}{RT_{60}{}^{-0.90}}+1.2616}{1.1814}\right)}$$

Being able to calculate the height of the ceiling in terms of the reverberation time and bass ratio removes another variable from the original reverberation time equation. Recall:

$$RT_{60} = \frac{(.049)*3072*h}{\sum s_{C1}a_{C1} + s_{C2}a_{C2} + s_F a_F + s_W a_W}$$

The only unsolved variables are now the total surface areas of C1 and C2. However, there is another equation relating the two considering the total surface area is constrained to 3072 square feet, therefore:

$$s_{C1} + s_{C2} = 3072$$

Substituting for $S_{C1}$ yields

$$s_{C1} = \frac{\frac{(.049)(3072)h}{RT_{60}} - (s_F a_F + s_W a_W + (3072)a_{C2})}{a_{C1} - a_{C2}}$$

Now that one can determine the total room volume and area of both materials based upon Bass Ratio and Reverberation Time, this sequence can be brought into Grasshopper.

### 6.1.4 Sequencing/Controls

While the underlying equations on this sequence are fairly complex to derive, the processing for incorporating this into a Grasshopper model is straightforward. The inputs consist of the target reverberation time and bass ratio.

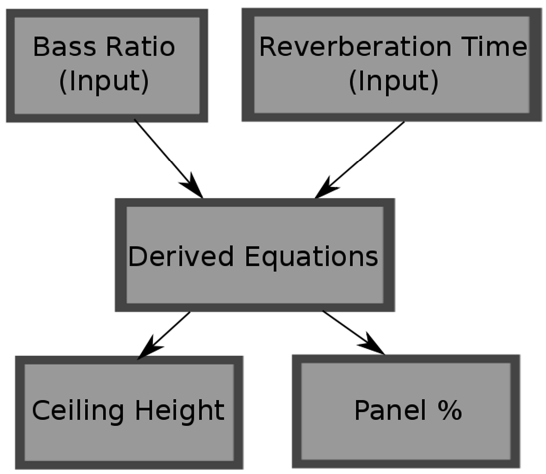


**Figure 6.4 – Schematic of Grasshopper Sequencing for Exercise 2**

The outputs are the ceiling height and the percentage of the ceiling area covered by each material (recall that there are two materials).

Within Grasshopper, the algorithm begins with inputting the reverberation time and bass ratios into the sliders. Based upon the reverberation time, a general guideline is given for the lower and upper limits of the bass ratio.

The reverberation time and bass ratio are run through the functions and the ceiling height is applied as the magnitude of a vector in the z direction to move a rectangle representing the ceiling. As a visual representation of the percentage of materials, the ceiling is divided into 3072 different squares representing individual panels that have an area of one square foot each.

## 6.2 Results

The results in this section will survey the reverberation times of each scenario and confirm that the output height and material proportions will create the desired reverberation time and bass ratio.

**Orchestra**

At a reverberation time of 1.8 and a bass ratio of 1.4 (Figure 6.5), the resulting geometry is shown in Figure 6.6. Note that for this case study, the location of the two ceiling materials (red and yellow) do not matter; it is the amount of them that is critical. Also, recall that the ceiling is constrained to being flat.

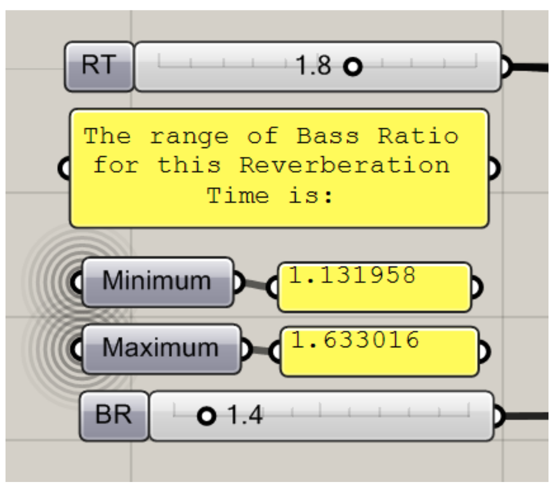


**Figure 6.5 – Input Values for Orchestra**

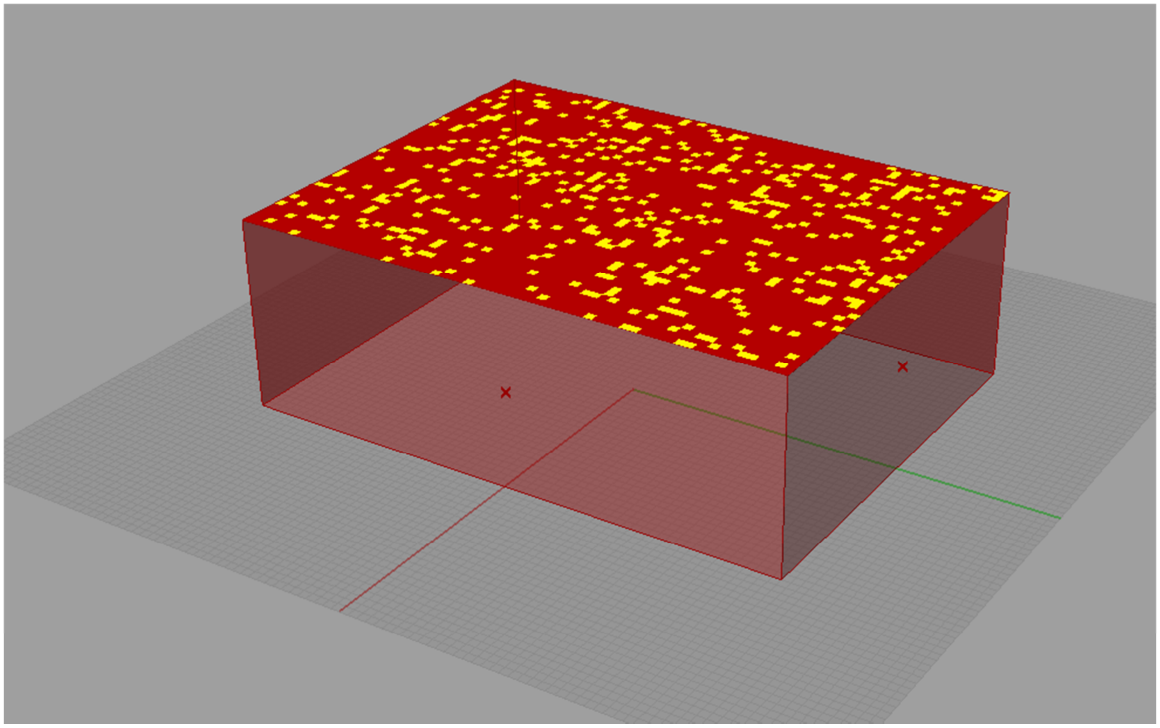

**Figure 6.6 – Output Geometry for Orchestra**

The height of this ceiling is 21.7 ft and the material breakdown is 2633 square feet of plasterboard and 439 square feet of pageboard. To validate the result, these values were substituted back into the original equations; this yields a reverberation time of 1.80s and a bass ratio of 1.45, what was input as the goal.

**Percussion Ensemble**

At a reverberation time of 0.8s and a bass ratio of 2.5 (Figure 6.7), the resulting geometry is shown in Figure 6.8.

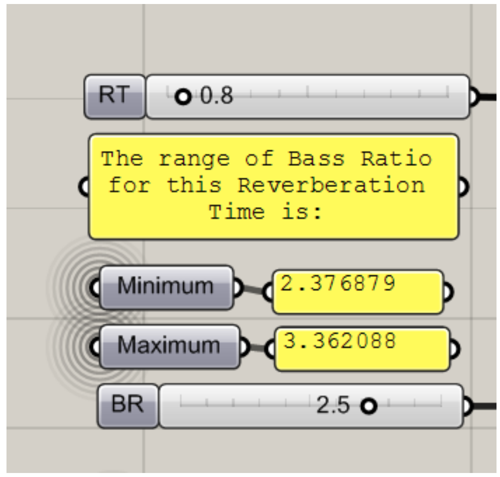


**Figure 6.7 – Input Values for Percussion Ensemble**

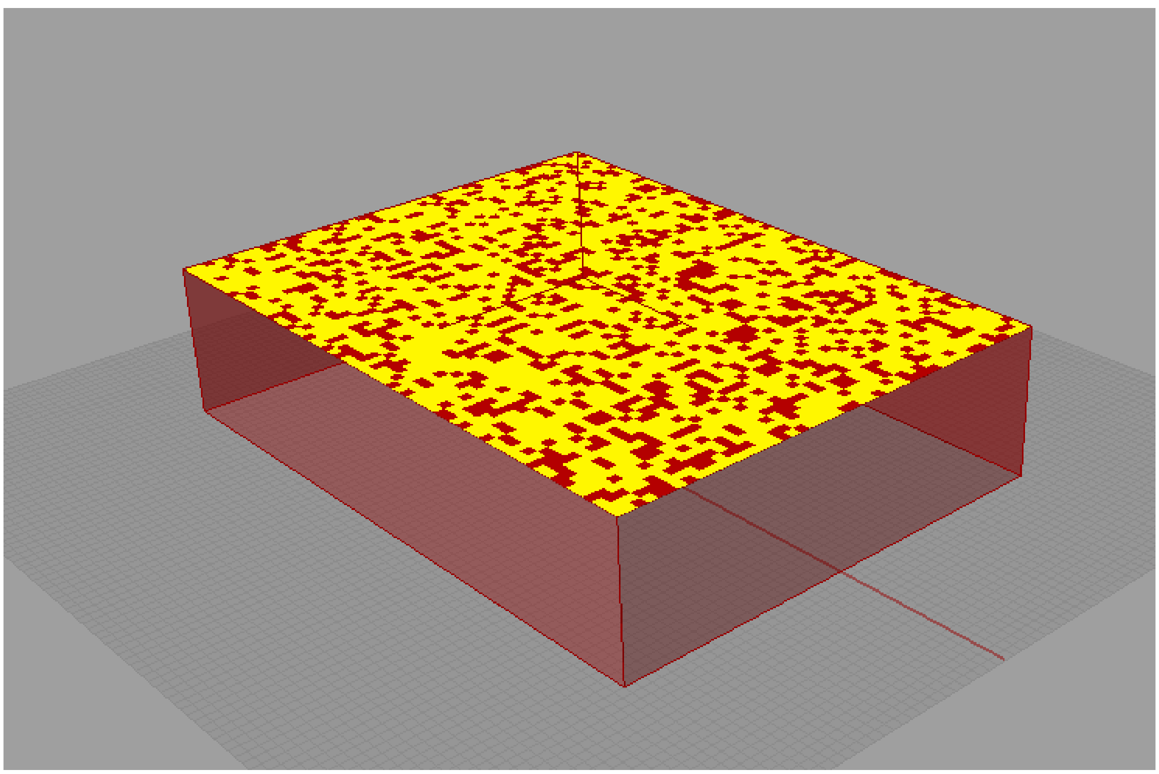

**Figure 6.8 – Output Geometry for Percussion Ensemble**

The height of this ceiling is 16.4 ft and the material breakdown is 999 sq ft of plasterboard and 2073 sqft of pageboard.  Substituting these back into the original equations, this yields a reverberation time of .80s and a bass ratio of 2.52; this checks with the original values.

### Master Classes

At a reverberation time of .7 s and a bass ratio of 1.4 (Figure 6.9), the resulting geometry is shown in Figure 6.10.

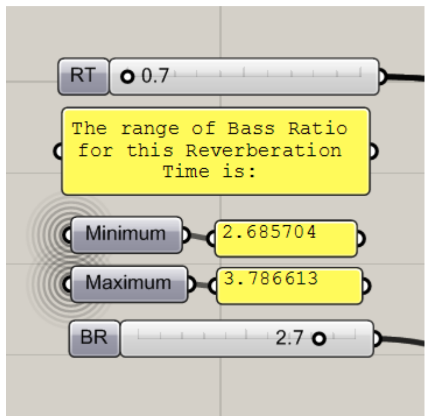


**Figure 6.9 – Input Values for Master Classes**

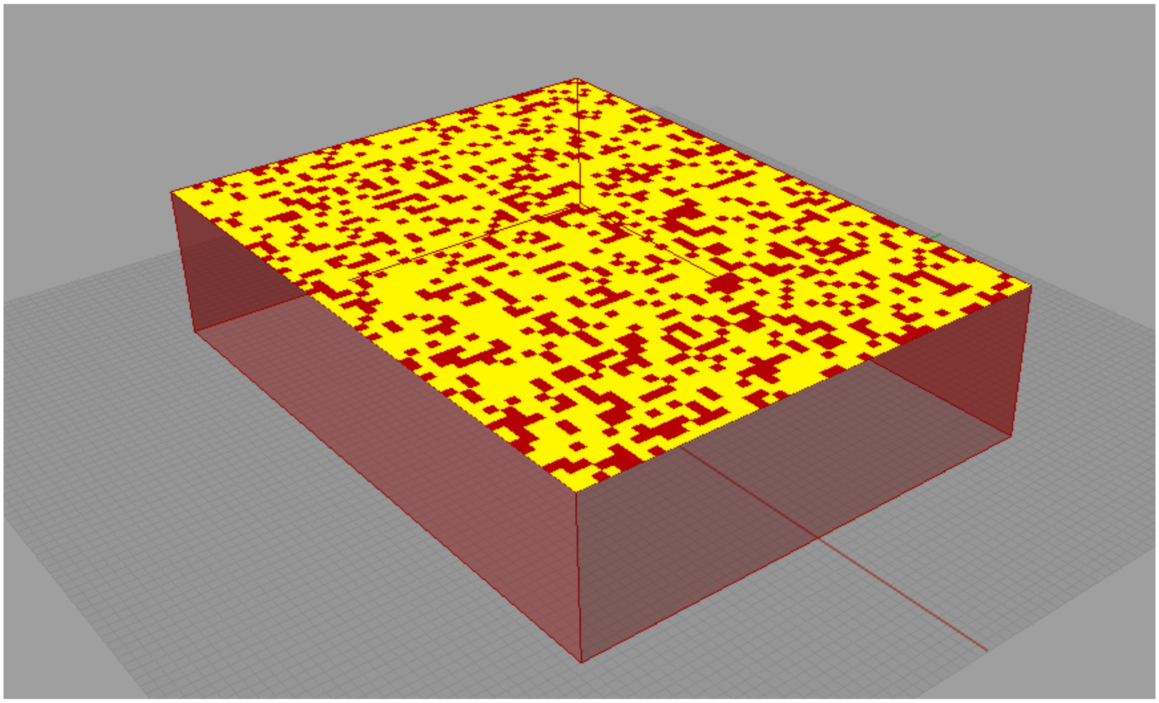

**Figure 6.10 – Output Geometry for Master Classes**

The height of this ceiling is 15.3 ft and the material breakdown is 734 sq ft of plasterboard and 2338 sq ft of pageboard. Substituting these back into the original equations, this yields a reverberation time of 0.70s and a bass ratio of 2.77.

**Recitals**

At a reverberation time of 2.2 and a bass ratio of 1.3 (Figure 6.11), the resulting geometry is shown in Figure 6.12.

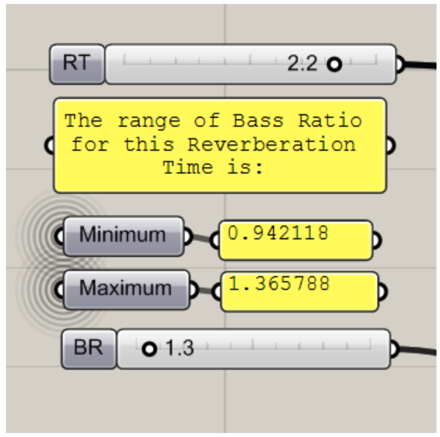


**Figure 6.11 – Input Values for Recitals**

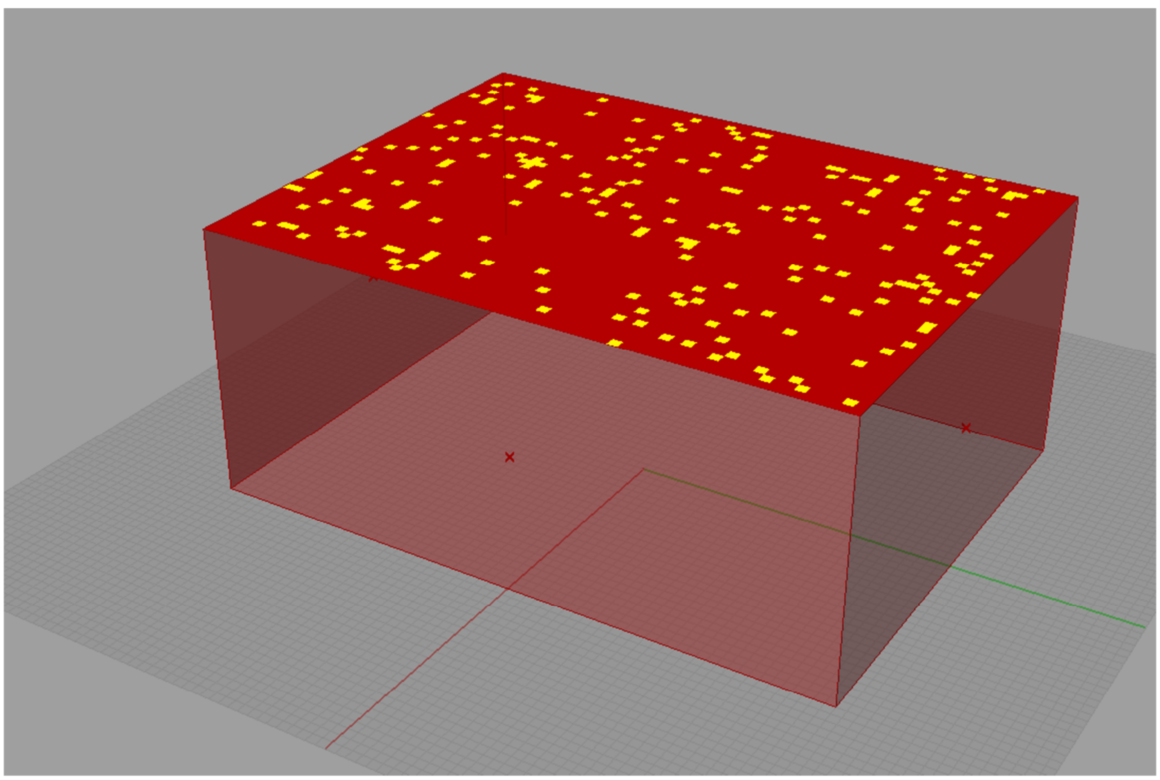

**Figure 6.12 – Output Geometry for Recitals**

The height of this ceiling is 27.25 ft and the material breakdown is 2858 sq ft of plasterboard and 213 sq ft of pageboard. Substituting these back into the original equations, this yields a reverberation time of 2.2 and a bass ratio of 1.37.

Table 6.3 summarizes the input values for each case, the heights, and material portions and the recalculated reverberation times and bass ratios. The "results column" shows that the hand calculations agree with the Galapagos calculated results.

| | Input Variables | | Grasshopper Results | | Results (% dif) | |
|---|---|---|---|---|---|---|
| Setting | RT60 (s) | BR | Height (ft) | Plasterboard/ Pageboard (sq ft) | RT60 (s) | BR |
| Orchestra | 1.8 | 1.4 | 21.7 | 2633/439 | 1.8 (0%) | 1.45 (3.4%) |
| Percussion | 0.8 | 2.4 | 16.4 | 999/2073 | 0.8 (0%) | 2.52 (0.8%) |
| Master Class | 0.7 | 2.7 | 15.3 | 734/2338 | 0.7 (0%) | 2.77 (2.5%) |
| Recital | 2.2 | 1.3 | 27.25 | 2858/214 | 2.2 (0%) | 1.37 (5.1%) |

**Table 6.3 – Results of Grasshopper Defined Geometries**

## 6.3 Discussion and Conclusions

Recalculating the reverberation times and bass ratios was important to ensure that the assumptions made in forming the equations did not cause a substantial deviation in the actual results. Overall, the reverberation times matched hand calculations to a 1/100$^{th}$ of a second and the bass ratio times varied up to 5.1% from the input bass ratio.

Several limitations of this method were made apparent. There is a general limitation based upon the materials -- it is the inability to find a consistent range of bass ratios across the entire range of reverberation times. The general lower limit for bass ratios was established at 1.2, but the lower limit, based upon materials, is well above this for the lower reverberation times. This may be a general limitation of the materials and could be eliminated by introducing a third material variable. Another one of the limitations of this set of equations is that the height of the ceiling influences two different other variables: the amount of exposed wall area and the room volume. As seen in the first exercise there can be a number of different geometries that yield the same physical measurements, so it will be safe to assume that for any given total volume and wall surface area values, there will be a variety of ceiling shapes that fit this criteria. Deciding which of these variations is the most ideal will require the input of another criteria, clarity/support, which is explored in the next exercise.

# 7 CREATING REFLECTION PATHS

While the previous two exercises have concentrated on the general geometry of the room and reverberation time, this exercise will focus on the specific geometry of the space and the ceiling's effect on reflections. The object of this specific exercise is to use Grasshopper to provide a simple ray tracing analysis limited to one reflection between a source and a receiver. The length of each ray and the specific point of reflection will be used later to calculate early sound energy measurements.

## 7.1 Geometrical Relationships

This exercise, more than the previous two, will depend on the actual geometry of the room and the shape of the ceiling surface. For simplicity's sake, this exercise will only deal with creating the reflections and measuring results, not attempting to optimize or target a specific value.

### 7.1.1 Equations

Both types of early energy measurements, Clarity and Support, will depend on the amount of sound energy arriving at a location relative to a particular source. The equation for the intensity at a location based upon a singular specular reflection is

$$I = \frac{(1-\alpha)}{4\pi(x+y)^2}$$

where I is the intensity, $\alpha$ is the absorption coefficient, and $x$ and $y$ total the entire path of the incoming and reflected wave, as illustrated in Figure 7.1.

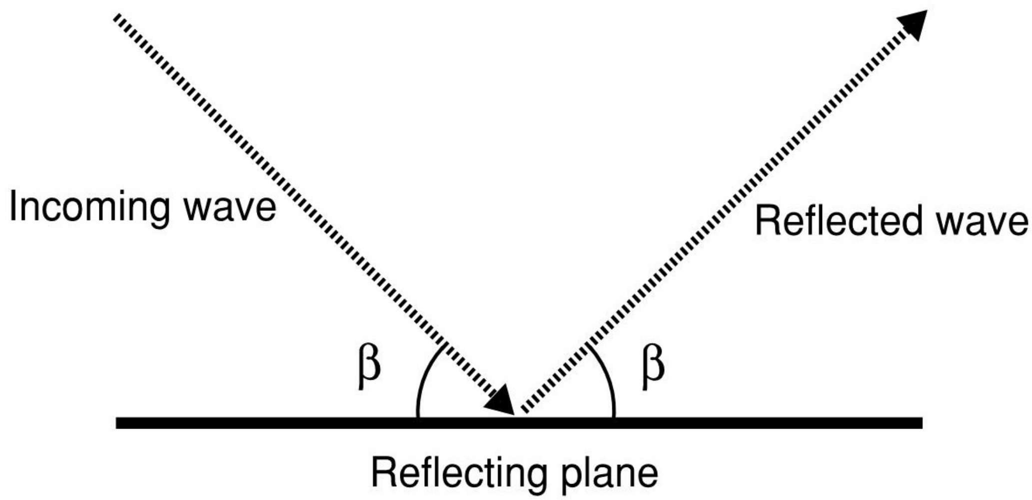


**Figure 7.1 – Path of Reflected Ray**

Because the measurements used will be relative and not absolute, the sound power will be assumed as 1. The numerator is the total intensity after absorption lost due to the reflection off the surface while the denominator is associated to the intensity lost due to distance from the source (the sound pressure at a point of an equivalent sphere).

When calculating by hand, a reflection path in two dimensions can be found by first reflecting the receiver point, R, over the reflection plane, creating R', and drawing a line between the source, S, and R'. The intersection of this line with the reflection plane is the point of reflection. A line between this point and the receiver completes the path of the sound ray.

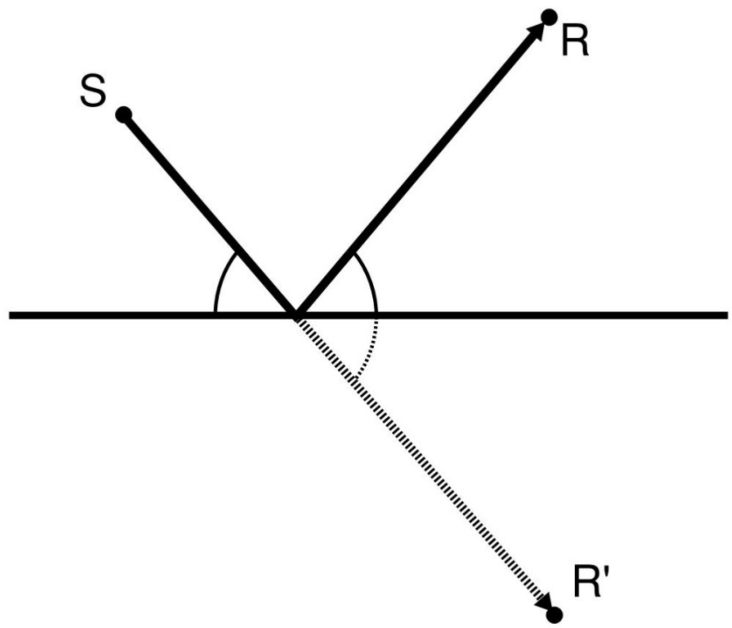


**Figure 7.2 – Construction of Reflection**

This geometry can be checked by measuring the angle between each of the ray paths and the normal vector of the plane and verifying that the angles are equal. This process can be duplicated in Grasshopper by using the transformation tools. The other measurement needed in this process is the amount of time it takes for the sound to travel the full distance from the source to the receiver.  This can be calculated by dividing the distance by the speed of sound (C), resulting in time.

$$t = \frac{(x + y)}{C}$$

### 7.1.2 Sequencing/Controlling

To start the construction of the reflection paths within Grasshopper, two points are defined within the space of a 48 foot by 64 foot rectangular room. The source point (S) and receiver point (R) are each located 3 feet off of the floor and 12 feet from the center of the room on opposite sides in the center the room. The roof of the room is split into two halves (each 32 foot by 48 foot) allowing for variation at the middle inflection point (Figure 7.4). The receiver point is reflected on opposite sides of the planes defined by the walls, floor and ceiling panels, creating a series of R's, one for each reflecting plane. A line is created between the source and each R' and using the *Plane/Line Intersection* tool, a point is established at the intersection of each of each plane and line. If the intersection of the line and plane does not exist with the specified surface, the point is determined as "null". Lines are then constructed between the intersection point and the source and receiver. The measurement tool is able to determine the length of the lines and feed this into the intensity function. That length is also used in determining the time it takes for the sound to travel from the source to the receiver. For measuring support, the time for each ray is used to separate the respective rays into groups, from 0-10 ms and 20-80 ms. These groups can then be summed and used to create a ratio of early to late energy values.

## 7.2 Results

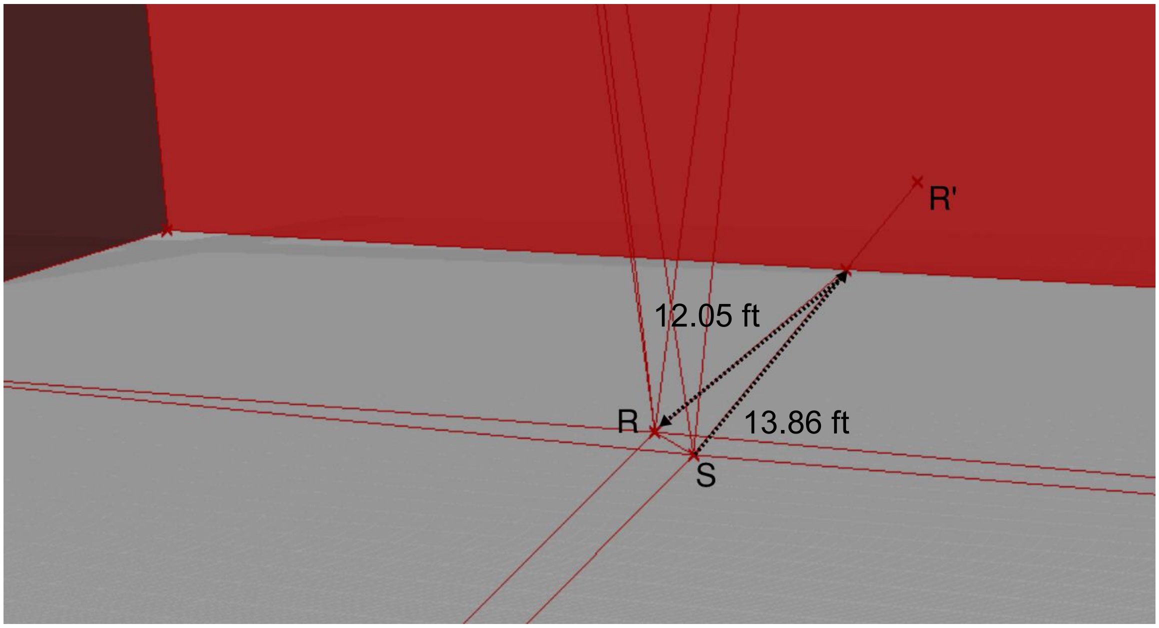


**Figure 7.3 – Reflection Points within Room**

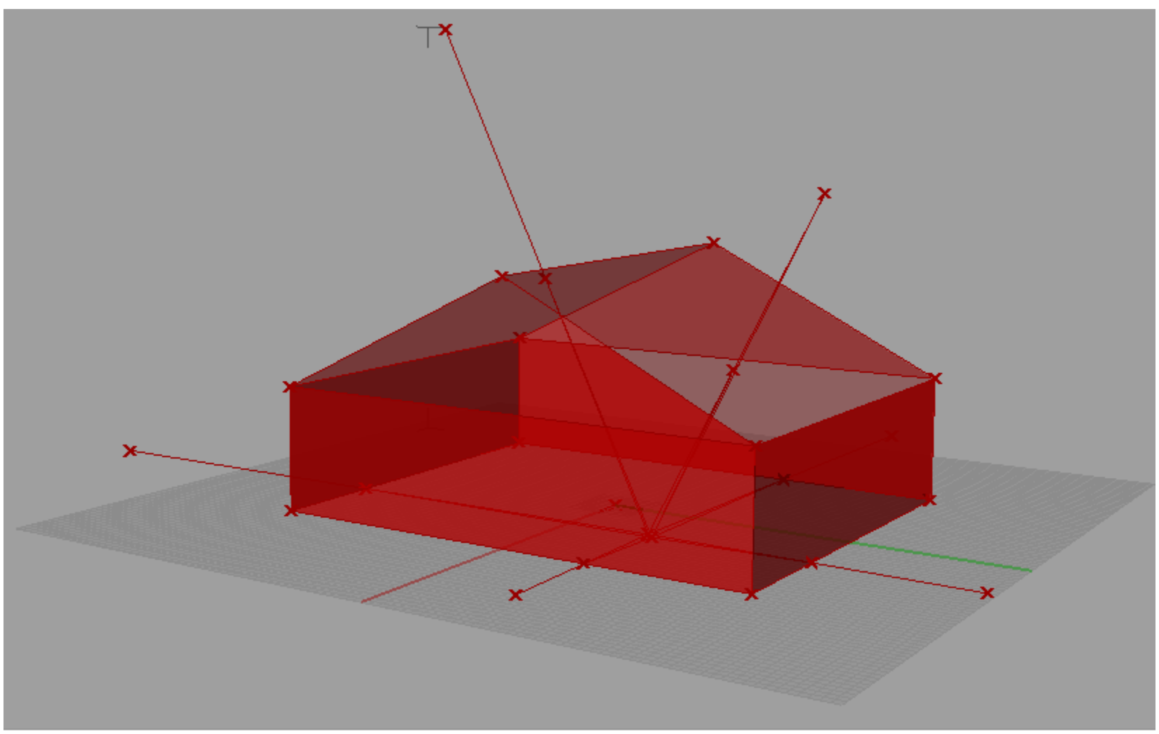


**Figure 7.4 – Reflection Points at High Hip in Ceiling**

To verify the reflected angles at the ceiling are correct and the algorithm functions as intended, the angle at the plane of each line was calculated and compared within Grasshopper, as shown in Figure 7.5.

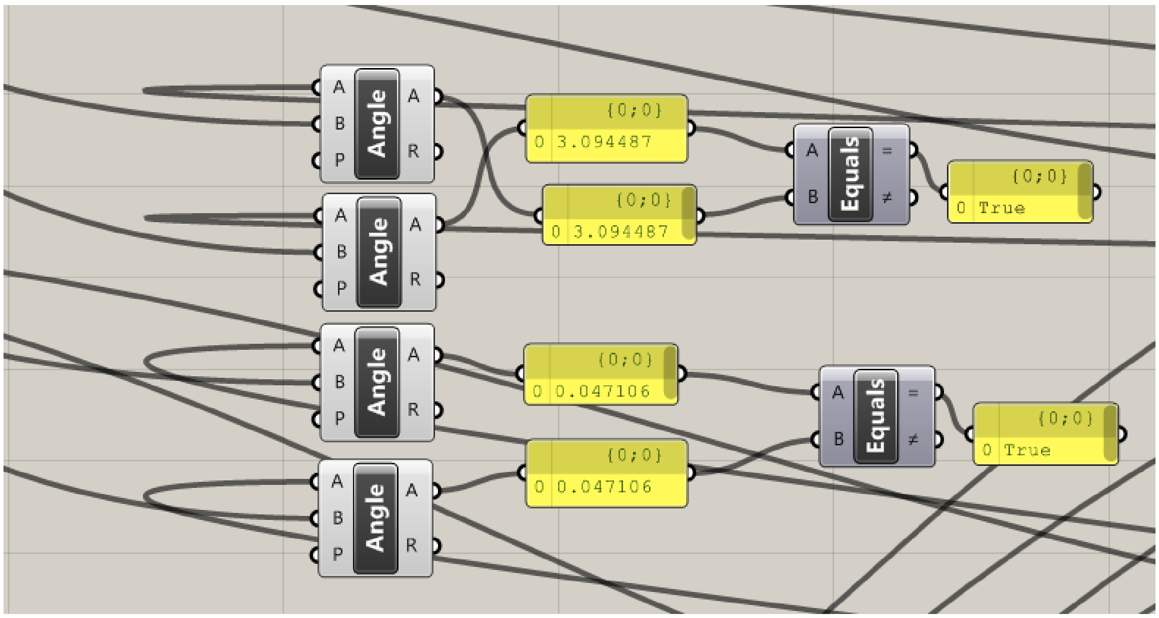


**Figure 7.5 – Verification of Angles**

## 7.3 Discussion and Limitations

The virtual image method of defining in this context works as the program is able to calculate the information needed to process calculations related to early energies. This method of ray tracing only creates a very small portion of the reflections happening within the room. To create a series of higher order reflections and rays is beyond the scope of this exercise when associated with this genomic optimization tool, but further study could improve upon this method to allow for more reflections.

# 8 FINAL MODEL

The final model incorporates elements of each of the previous exercises: the use of Galapagos from Exercise 1, the calculation of the total room volume and wall surface area described in Exercise 2, and ray tracing from Exercise 3. In addition, there is a combination of ray tracing from Exercise 3 and the use of Galapagos from Exercise 1 in order to determine individual ceiling panel orientation and sound absorption material distribution. This chapter details the algorithm used to determine the ceiling configuration and the final results for each programmatic use. For this model, the ceiling will be defined by 25 separate nodes capable of moving independently with each of the 32 triangular panels made up of 100 panels capable of rotating to expose either of two materials, as described in Chapter 4.

## 8.1 Parametric Definition

The added complexity of controlling the amount of early energy (either the Objective Support or Clarity) indices will be dependent on the specific geometry and material of the ceiling panels. Because these indices are generally averaged over a number of areas, the model will have to incorporate and average the targets from a number of specific locations. This section details the parametric definition used to create the ceiling panel system including the heights of each node and the determination of the location of each type of material.

### 8.1.1 Geometric Set Up

The room volume and wall surface area are determined by the height equation produced in Exercise 2:

$$h = e^{\left(\frac{\frac{BR}{RT_{60}^{-0.90}} + 1.2616}{1.1814}\right)}$$

These variables are a function of the reverberation and bass ratio as well as the overall proportion of material between pageboard and plasterboard is determined by the equation:

$$s_{C1} = \frac{\frac{(.049)(3072)h}{RT_{60}} - (s_F a_F + s_W a_W + (3072)a_{C2})}{a_{C1} - a_{C2}}$$

As illustrated in previous chapters, these two equations will ensure that the first two parameters, reverberation and bass ratio, are satisfied.  The goal of the final exercise is to use either the Support or Clarity indices (dependent on the application) to influence the orientation and absorptive qualities of the individual ceiling panels while still maintaining the desired reverberation time and bass ratio.  The Support and Clarity indices are averaged from four locations within the room.

For Support, the source locations are based on the extents of where musicians would be positioned for a rehearsal at 12 feet from the longer walls and 16 feet from the shorter walls.  The receiver locations are placed at a distance of 3 feet away from the source location, directed towards the center of the room as detailed in Figure 8.1.

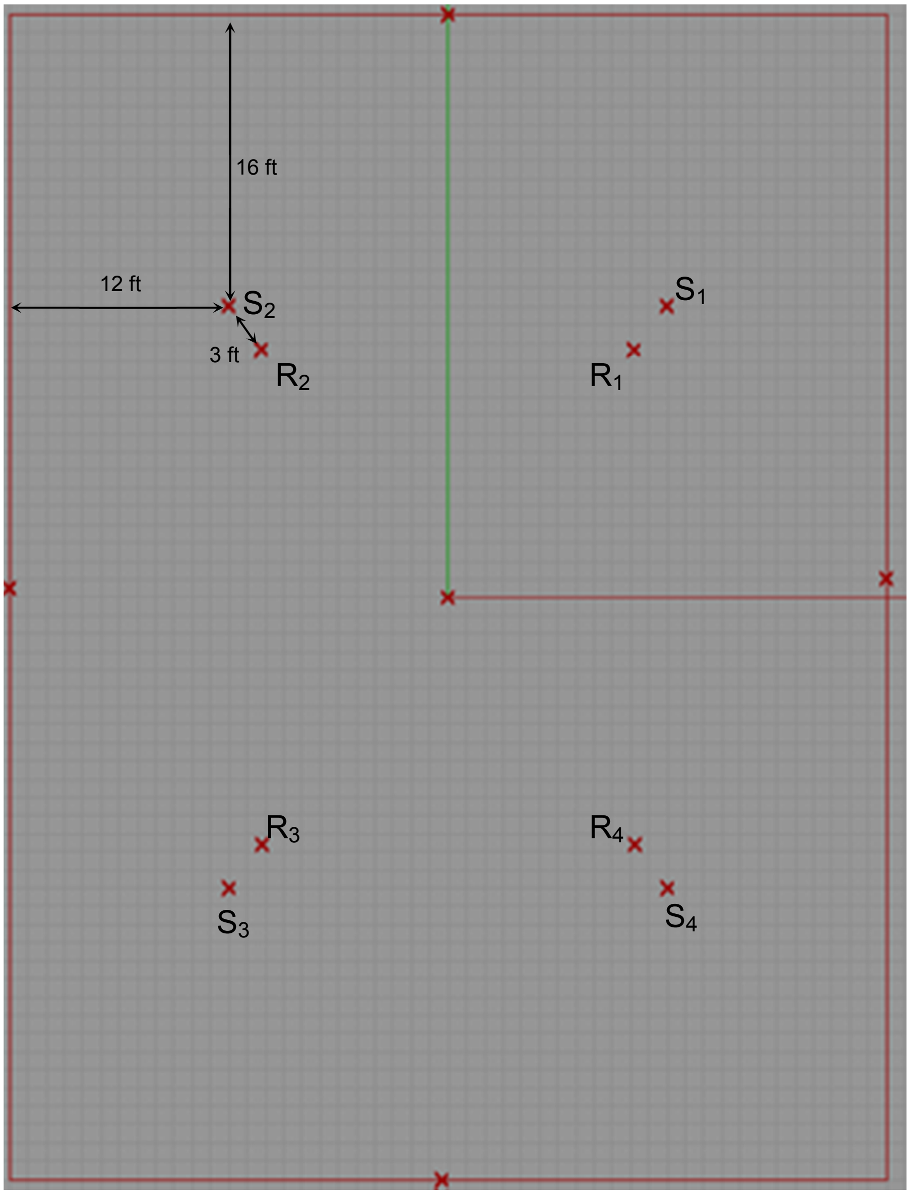


**Figure 8.1 – Source/Receiver Locations – Objective Support**

For Clarity, the source location is placed midway between the longer walls at a distance of 8 from the wall as a performer would be situated for a recital. The receiver locations are located in 4 different areas where an audience would be seated as detailed in Figure 8.2.

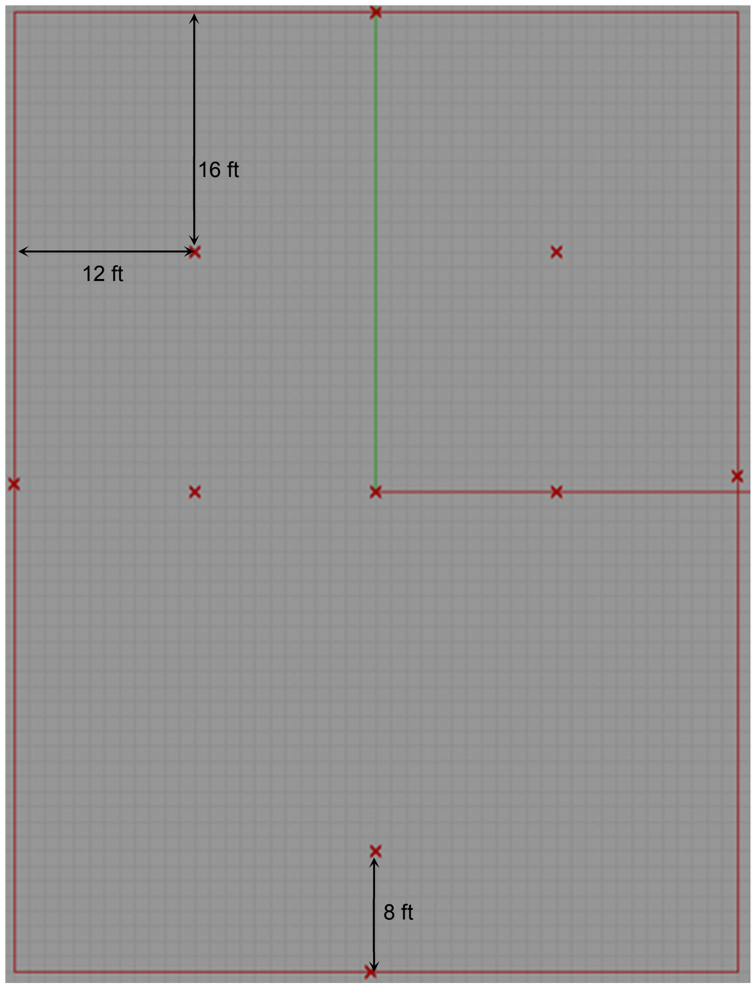


**Figure 8.2 – Source/Receiver Locations – Clarity**

The ray tracing aspects of Exercise 3 are used to create reflection paths from the ceiling panels in order to calculate the distance traveled, the time it took, and the relative sound energy lost. In constructing the reflection paths, if the line does not intersect the plane where the surface of the panel exists, the line is defined as null and is removed from the list. Not only is this model more complex than Exercise 3 because of the number of panels, but it must also account for the absorption coefficient of each panel.  This equation assumes the sound power is 1 where x and y are the distances from the source to the reflecting plane and the plane to the receiver position, respectively.

$$I = \frac{(1-\alpha)}{4\pi(x+y)^2}$$

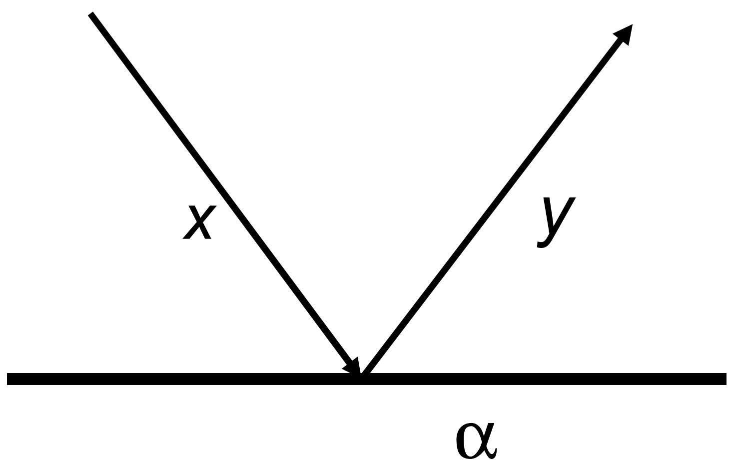


**Figure 8.3 – Absorption at Reflection Point**

### 8.1.2 Varying Ceiling/Panel Heights

In Exercise 2, the target reverberation times and bass ratios defined a height for the ceiling. Because the room in this instance was a box, the height defined both a room volume and an amount of wall surface area. The challenge in using 32 panels instead of one large ceiling panel comes in ensuring that with each different geometric possibility, the volume and wall surface area will remain consistent. Once the height of the room is determined, this is used as a basis to vary the ceiling panels form. To produce the heights by which the panels will vary, a group of eight number sliders is used to produce a list of numbers from 0 to 2.5. The negatives of these numbers are then taken and added to the list. The full range of numbers (-2.5 to 2.5) ensures that no two panels are more than 5 feet different in height. The outer ring of nodes, which affect the amount of wall area exposed, are grouped together to ensure the wall surface area stays as close as possible to the one given by a flat ceiling shape. A similar set of four sliders is used to control the second ring of eight nodes and the center node operates off of its own slider from -2.5 to 2.5. Each set of numbers is “jittered” to scramble their order using a pseudorandom number generator application within Grasshopper. The number generator creates repeatable lists based off of seed number that is defined by another number slider. The seed number and other number sliders are all then defined as genome terms by Galapagos. To ensure that no nodes go lower than 15 feet or higher than 30 feet, a series of “if-then” statements are applied to each number to constrict the possible range of numbers.

### 8.1.3 Varying Absorption Distribution

The target reverberation time and bass ratio also produce a square footage number for the entire ceiling for both materials, but the distribution of this material can have an effect on the early energy levels. This is different from Exercise 2 where only the relative amount of each of the two materials was important, not their locations. Determining how the material is spread around the room is determined by first assigning each panel a number 0-100 by a number slider and summing these numbers. Dividing this number by the individual panel number will result in a percentage of the total area of pageboard each panel will contribute. Each panel has a maximum limited to the area of the panel of 96 sq ft. The number sliders are also a part of the genome of Galapagos.

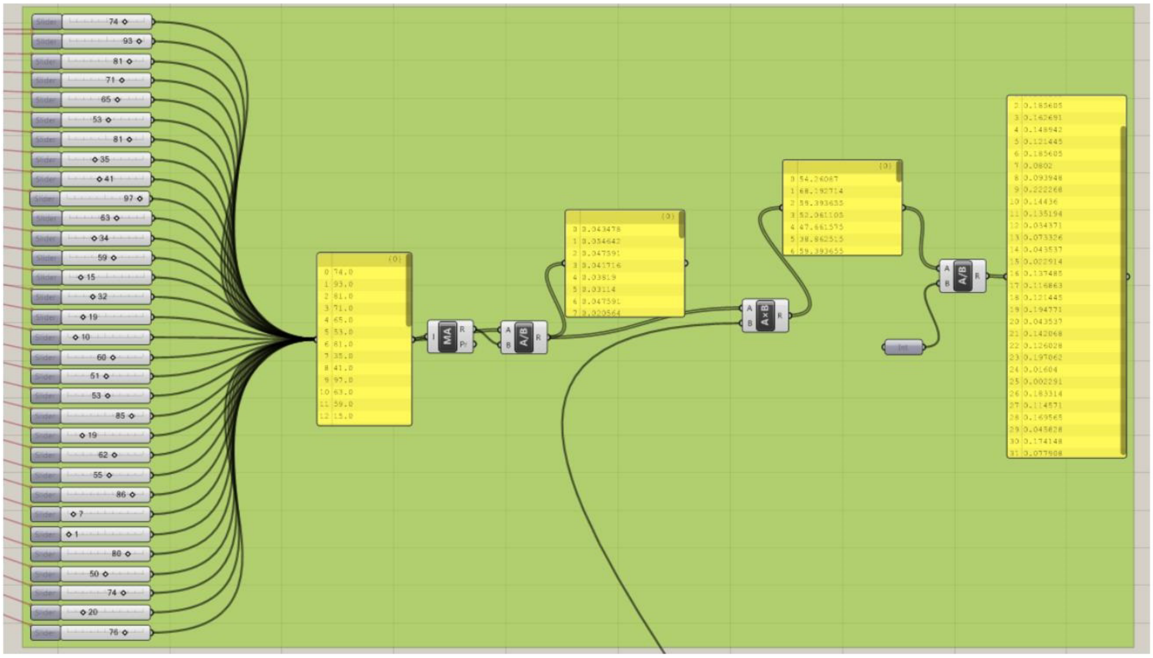

**Figure 8.4 – Grasshopper Definition Assigning Surface Area Proportions**

### 8.1.4 Full Grasshopper Definition

Inputs to this definition are the reverberation time and bass ratio. There are two separate halves of the definition, the first of which involves these inputs and the second half involving changing the target value for Galapagos to either a rehearsal or recital setting and running Galapagos. A schematic diagram of the definition and the full Grasshopper definition are pictured in Figure 8.5 and Figure 8.6 respectively..

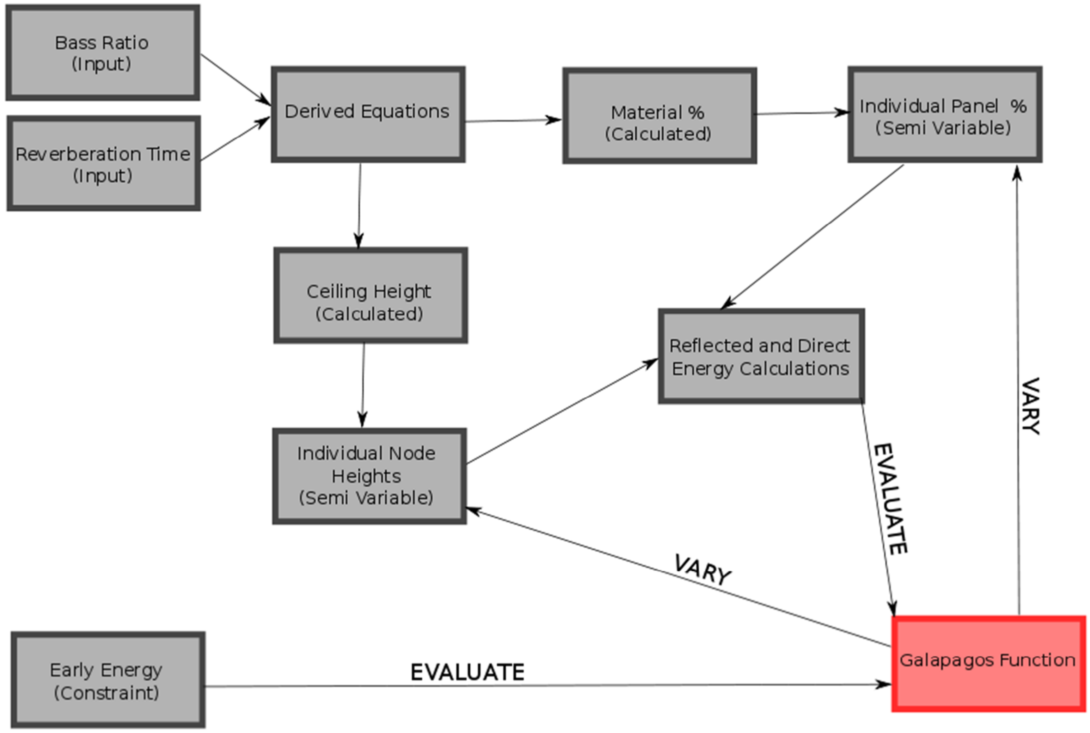


**Figure 8.5 – Schematic Diagram of Grasshopper Definition**

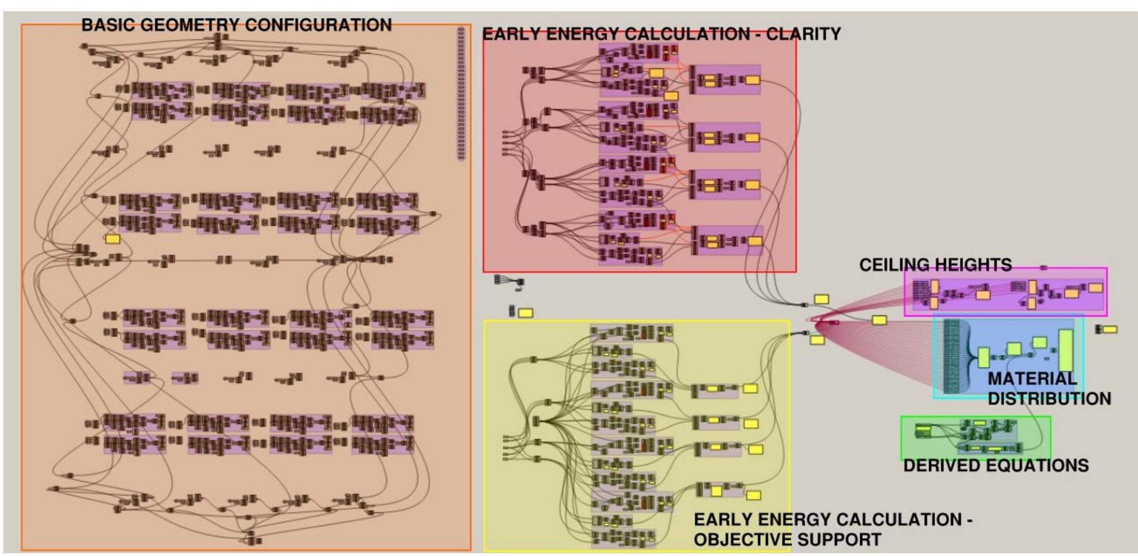


**Figure 8.6 – Screenshot of Grasshopper Definition**

Each node is separately defined in a graphical layout to keep each point organized especially while defining the planes of the walls. While the x and y coordinates are static, the z coordinates of each node is determined by the method discussed previously. The first half of the definition is exactly the same as Exercise 2, determining the height and surface area mathematically. The second half of the definition is similar to Exercise 3 as it measures, separates and sums relative sound energy according to either a rehearsal or recital program usage. Running Galapagos is the final step, specifying the target number as -12 for dB for rehearsal settings or maximizing the target number for a recital setting.

In summary, the basic room geometry is defined by set points in Grasshopper and remains static. The average ceiling height and total proportions of materials are defined by the equations derived in Exercise 2. The distribution of materials on the ceiling surface and orientation of ceiling panels is defined by Galapagos, based on early energy calculations for either Clarity or Objective Support (depending on the program use). For Objective Support, there are four receiver and source nodes placed in each quadrant of the room, and located 3 feet apart. For Clarity there is a single source at the front of the room with four receivers in the audience area. In each case the user inputs are the Reverberation Time and Bass Ratio. The Grasshopper results will define the surface geometry and the material distribution.

## 8.2 Results

This section details the results of the parametric definition based on inputs specific to the programmatic uses described in Chapter 4. To verify the program, the reverberation times and bass ratios are calculated from the actual room volume and surface areas defined by the model.

### 8.2.1 Orchestra

A reverberation time of 1.8 and a bass ratio of 1.4 (Figure 8.7) were used as the input data.

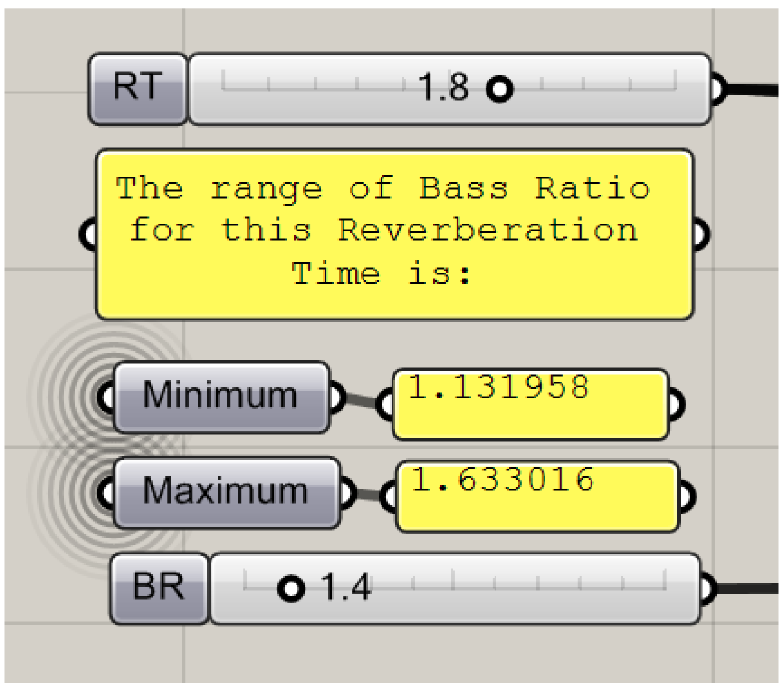


**Figure 8.7 – Input Values for Orchestra Configuration**

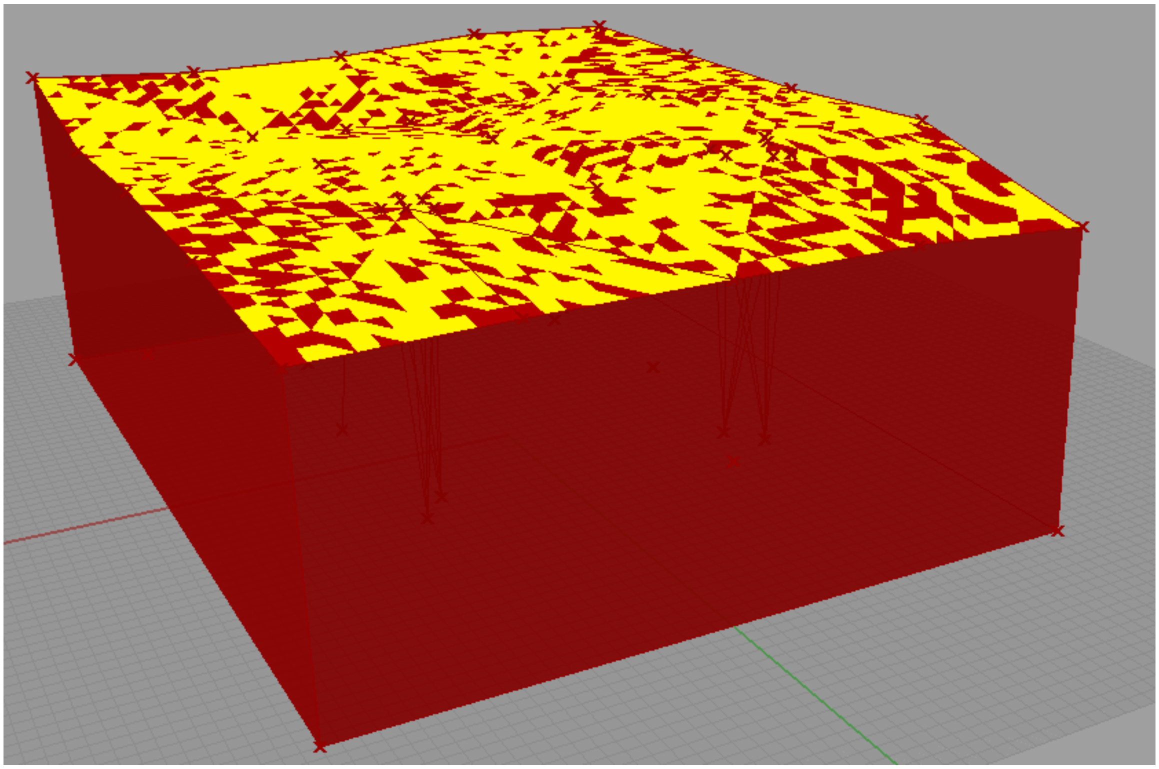

**Figure 8.8 – Final Configuration of Room Model for Orchestra Configuration**

The resultant volume of the space was 66863 with a wall surface area of 4870 square feet and the ceiling divided into 2633 square feet of plasterboard (86%) and 439 square feet of pageboard (14%). The corresponding reverberation time and bass ratio for these conditions are 1.79 seconds and 1.45 respectively. This is a variation of 0.01 seconds (0.6%) from the input reverberation time and a variation of 0.05 (3.6%) from the input bass ratio. The resulting average Objective Support value was -13.399 dB.

### 8.2.2 Percussion

A reverberation time of 0.8 and a bass ratio of 2.5 (Figure 8.9) were used as the input data.

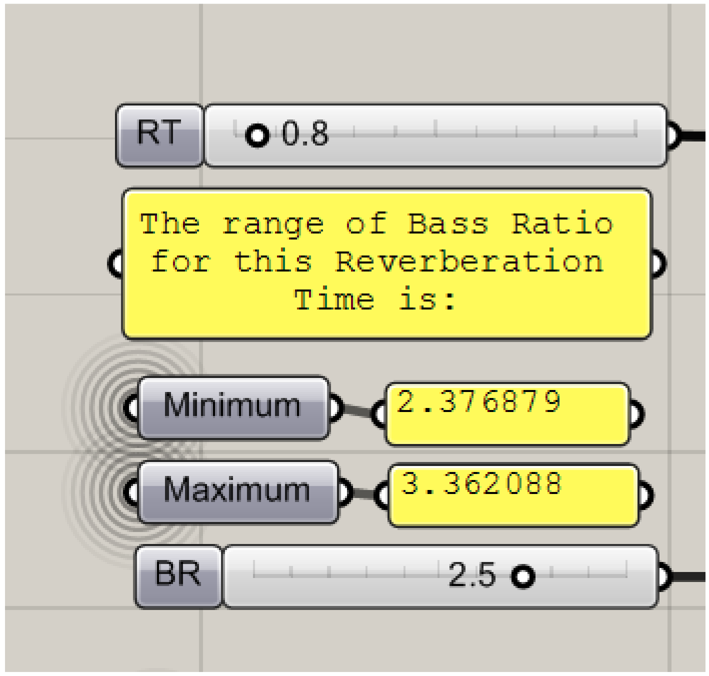


**Figure 8.9 – Input Values for Percussion Configuration**

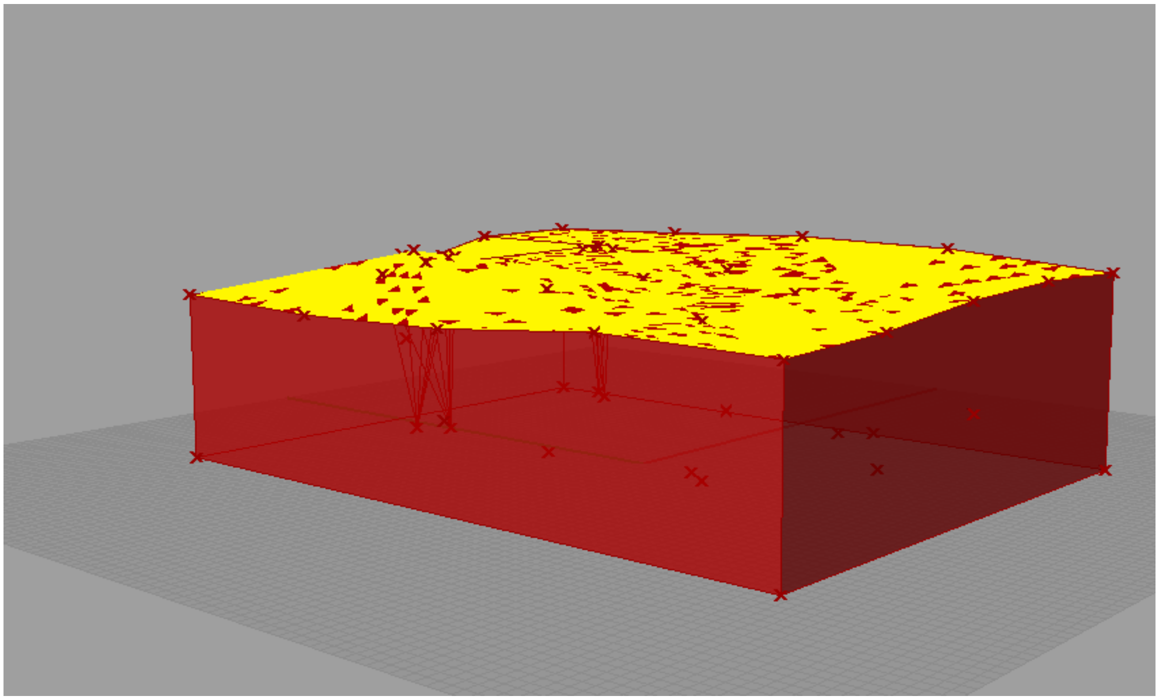

**Figure 8.10 – Final Configuration of Room Model for Percussion Configuration**

The resultant volume of the space was equal to 50,596 cubic feet with a wall surface area of 3676 square feet, and the surface area of the ceiling divided in 1188 square feet of plasterboard (39%) and 1884 square feet of pageboard (61%). The corresponding reverberation time and bass ratio for these conditions are 0.85 seconds and 2.37 respectively. This is a variation of 0.05 seconds (6.3%) from the input reverberation time and a variation of 0.13 (5.2%) from the input bass ratio. The resulting average Objective Support value was -12.824 dB.

### 8.2.3 Master Classes

A reverberation time of 0.7 and a bass ratio of 2.7 (Figure 8.11) were used as the input data.

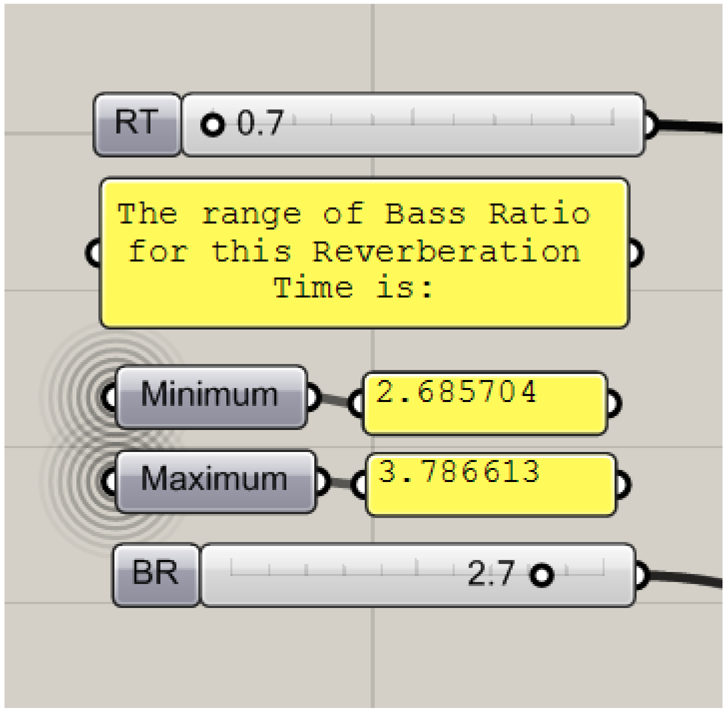


**Figure 8.11 – Input Values for Master Class Configuration**

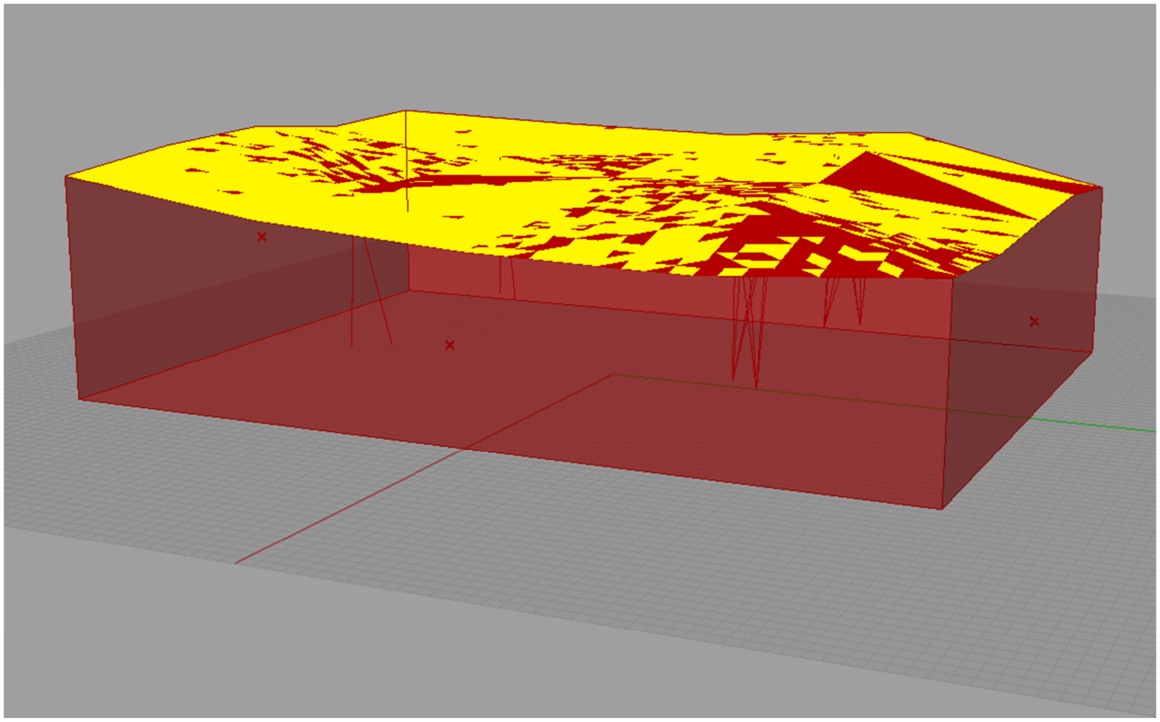

**Figure 8.12 – Final Configuration of Room Model for Master Class Configuration**

The resultant volume of the space was equal to 47,066 cubic feet with a wall surface area of 3413 square feet, and the surface area of the ceiling divided in 729 square feet of plasterboard (24%) and 2333 square feet of pageboard (76%). The corresponding reverberation time and bass ratio for these conditions are 0.7 and 2.78 respectively. This is a variation of 0.0 seconds (0%) from the input reverberation time and a variation of 0.08 (2.9%) from the input bass ratio. The resulting average Objective Support value was -12.399 dB.

### 8.2.4 Recitals

A reverberation time of 2.2 and a bass ratio of 1.3 (Figure 8.12) were used as the input data.

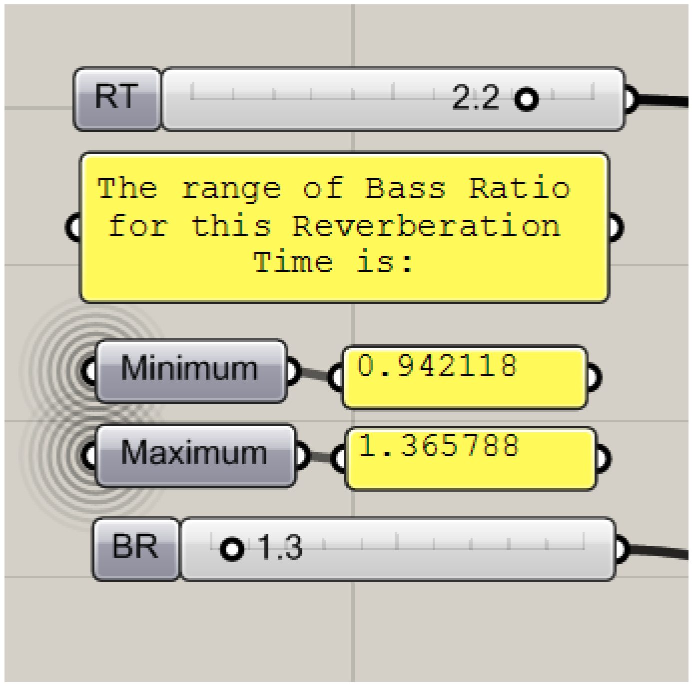


**Figure 8.13 – Input Values for Recital Configuration**

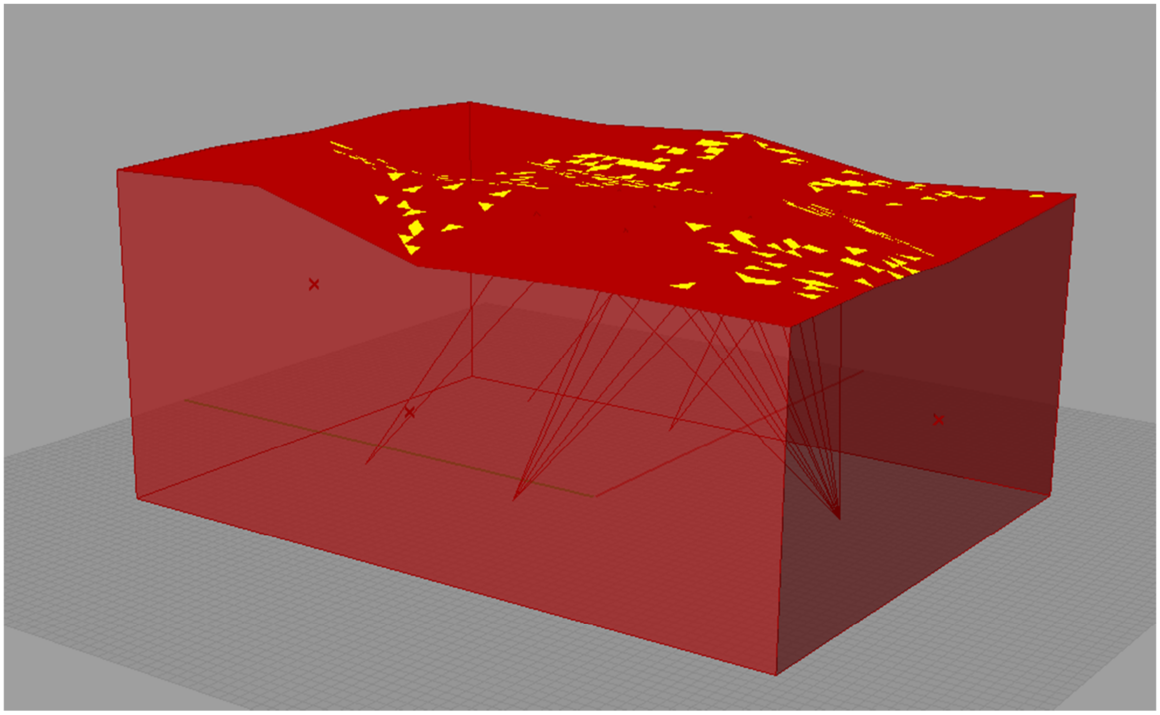

**Figure 8.14 – Final Configuration of Room Model for Recital Configuration**

The resultant volume of the space was equal to 83,654 cubic feet with a wall surface area of 6,102 square feet, and the surface area of the ceiling divided into 2850 square feet of plasterboard (93%) and 222 square feet of pageboard (7%). The corresponding reverberation time and bass ratio for these conditions are 2.17 seconds and 1.38 respectively. This is a variation of 0.03 (1.3%) from the input reverberation time and a variation of 0.08 (6.1%) from the input bass ratio. For the Clarity Index calculation, the average amount of sound energy arriving prior to 80 milliseconds is 2.9319 $x10^{-4}$ of the original source sound energy.

Table 8.1 summarizes the input values for each case, the volumes and material portions and the recalculated reverberation times and bass ratios and the related energy metrics.

| | Input Variables | | Calculated Results | | Results (% dif) | | Early Energy Measurement |
|---|---|---|---|---|---|---|---|
| Setting | RT60 (s) | BR | Avg Height (ft) | Plasterboard/ Pageboard (sq ft) | RT60 (s) | BR | |
| Orchestra | 1.8 | 1.4 | 21.7 | 2633/439 | 1.79(0.6%) | 1.45(3.8%) | -13.399 dB |
| Percussion | .8 | 2.5 | 16.43 | 1188/1884 | .85(6.3%) | 2.37(5.2) | -12.824 dB |
| Master Class | .7 | 2.7 | 15.27 | 729/2333 | .7(0%) | 2.78(2.9%) | -12.399 dB |
| Recital | 2.2 | 1.3 | 27.25 | 2850/222 | 2.17 (1.3%) | 1.38(6.1%) | $2.9319 \times 10^{-4}$ |

**Table 8.1 – Final Results**

# 9 CONCLUSIONS

From the results of the final model, it is clear that it is possible to create forms and provide a solution to variable acoustic settings using a parametric definition for an architectural element. However, there are several shortcomings with this model, both from a design standpoint and from a practicality standpoint.

Due to the optimization tool used within the algorithm, there are many different versions of each ceiling profile that may result from running the model. Each of these versions may have a different effect on other parameters not designated as part of the algorithm. The effect of multiple reflections, acoustical metrics such as loudness, and the overall impulse response of the room are not taken into account in the model but are factors that should be analyzed to create an overall successful acoustic environment.

The metrics used may be improved upon, namely the objective support. As a metric that looks at a measurement in close proximity to the source, this may not give an accurate feel for the entire room. The number of source –receiver pairs and locations have a large effect on the final shape of the ceiling.

The design of a large ceiling panel works within the context of this case study as it is a significant portion of the overall surface area. There may not be a direct correlation of such a system having success in a larger, more audience centric environment. For instance, in a concert theater the reflections off the walls have a much more significant impact on early reflections and would make more sense as the architectural element to manipulate. However, a wall system would not necessarily have the same flexibility to move in and out as the ceiling panel in this example. Another method of altering the space would have to be explored. The practicality of such a system would have to be analyzed as well. The structural requirements for the ceiling system to be installed would have to be looked at as well as the cost effectiveness of such a system as compared to the installation of an electronic system, capable of simulating variable acoustic settings. These current limitations lead to potential areas of future work.

**Further Research Topics**

There are many areas where work in acoustic parameter optimization can be improved including researching methods of variability, effects based on different metrics, and deeper analysis.

Further exploration into the research of parametric design and variable acoustics should look at other settings and venues that might deploy a variable acoustic program such as larger concert halls or performing arts centers. Within these venues there is more opportunity to explore other ways of altering the acoustics including different architectural elements such as the walls or concert shell as well as different ways to alter their properties. Absorption panels that are reliant on the depth of their assemblies and Schroeder diffusers both naturally offer opportunities for parametric design.

There are many other metrics within the field of acoustics that were not a part of this study that have an impact on the overall performance that should be looked at including loudness and the overall impulse response of the room. The distribution and density of sound reflections across the audience listening plane would also be an effective tool to shape the ceiling panels. Some of these metrics are extremely complex and rely on many different parameters. Analysis for larger more complex venues with multiple reflections would require more computing time to handle multiple reflections or coordination with a comprehensive acoustic analysis program to provide a thorough analysis of multiple audience points and with multiple reflections and the ability to calculate the late sound energy used to fully define Clarity. Additionally, comprehensive analysis software would allow for qualitative analysis with auralization software. To fill the gap between design and actual performance, real time feedback may be included with microphones at certain positions to analyze and confirm the performance or make adjustments as needed. The real life feasibility of such a system should be examined as well as many assumptions are made in this study to make an idealized condition. The assembly and mechanics of such a system will have its own effect on the acoustics and physical mockups should be made to evaluate the actual acoustic conditions.

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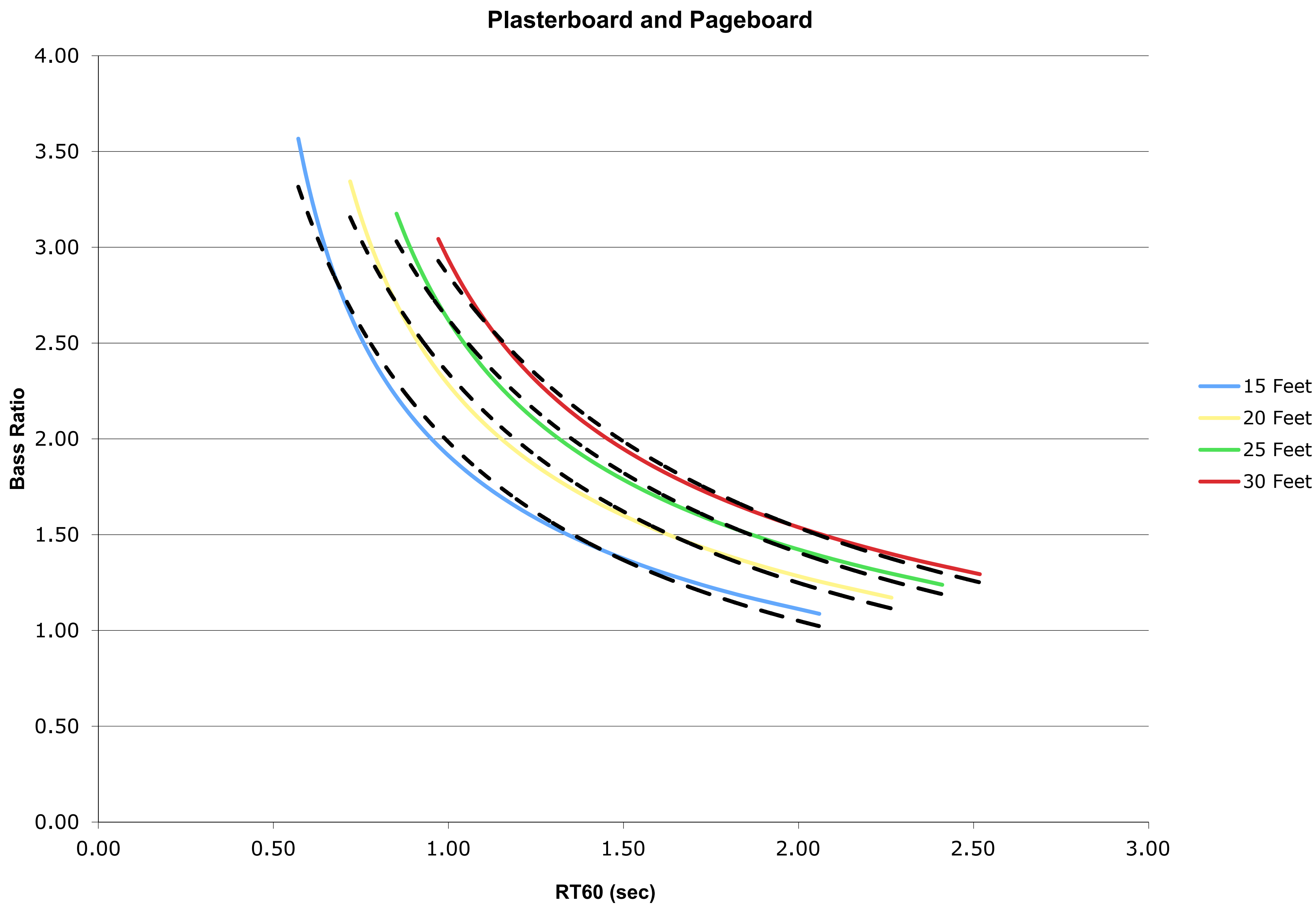
# 11 APPENDIX

## Plasterboard and Pageboard

| Variables | | | Reverberation Times | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Ceiling Height | Material 1 (%) | Material 2 (%) | 125 Hz | 250 Hz | 500 Hz | 1 kHz | 2 kHz | 4 kHz | RT @ 500 | Bass Ratio |
| 15 | 1 | 0 | 1.59 | 2.66 | 2.06 | 1.85 | 1.87 | 1.79 | 2.06 | 1.09 |
| 15 | 0.95 | 0.05 | 1.63 | 2.55 | 1.82 | 1.70 | 1.80 | 1.77 | 1.82 | 1.19 |
| 15 | 0.9 | 0.1 | 1.67 | 2.46 | 1.63 | 1.57 | 1.74 | 1.76 | 1.63 | 1.29 |
| 15 | 0.85 | 0.15 | 1.71 | 2.37 | 1.48 | 1.46 | 1.68 | 1.74 | 1.48 | 1.39 |
| 15 | 0.8 | 0.2 | 1.75 | 2.29 | 1.35 | 1.36 | 1.62 | 1.72 | 1.35 | 1.49 |
| 15 | 0.75 | 0.25 | 1.80 | 2.22 | 1.25 | 1.28 | 1.57 | 1.71 | 1.25 | 1.59 |
| 15 | 0.7 | 0.3 | 1.85 | 2.14 | 1.16 | 1.20 | 1.52 | 1.69 | 1.16 | 1.69 |
| 15 | 0.65 | 0.35 | 1.90 | 2.08 | 1.08 | 1.14 | 1.48 | 1.68 | 1.08 | 1.79 |
| 15 | 0.6 | 0.4 | 1.95 | 2.02 | 1.01 | 1.08 | 1.43 | 1.66 | 1.01 | 1.90 |
| 15 | 0.55 | 0.45 | 2.00 | 1.96 | 0.95 | 1.03 | 1.39 | 1.65 | 0.95 | 2.01 |
| 15 | 0.5 | 0.5 | 2.06 | 1.90 | 0.89 | 0.98 | 1.35 | 1.63 | 0.89 | 2.12 |
| 15 | 0.45 | 0.55 | 2.13 | 1.85 | 0.85 | 0.93 | 1.32 | 1.62 | 0.85 | 2.23 |
| 15 | 0.4 | 0.6 | 2.19 | 1.80 | 0.80 | 0.89 | 1.28 | 1.60 | 0.80 | 2.35 |
| 15 | 0.35 | 0.65 | 2.26 | 1.75 | 0.76 | 0.86 | 1.25 | 1.59 | 0.76 | 2.48 |
| 15 | 0.3 | 0.7 | 2.34 | 1.71 | 0.73 | 0.82 | 1.22 | 1.57 | 0.73 | 2.61 |
| 15 | 0.25 | 0.75 | 2.42 | 1.66 | 0.70 | 0.79 | 1.19 | 1.56 | 0.70 | 2.74 |
| 15 | 0.2 | 0.8 | 2.51 | 1.62 | 0.67 | 0.76 | 1.16 | 1.55 | 0.67 | 2.89 |
| 15 | 0.15 | 0.85 | 2.60 | 1.59 | 0.64 | 0.73 | 1.13 | 1.54 | 0.64 | 3.04 |
| 15 | 0.1 | 0.9 | 2.70 | 1.55 | 0.62 | 0.71 | 1.11 | 1.52 | 0.62 | 3.21 |
| 15 | 0.05 | 0.95 | 2.81 | 1.51 | 0.59 | 0.69 | 1.08 | 1.51 | 0.59 | 3.38 |
| 15 | 0 | 1 | 2.93 | 1.48 | 0.57 | 0.66 | 1.06 | 1.50 | 0.57 | 3.57 |
| 20 | 1 | 0 | 1.94 | 3.04 | 2.27 | 1.99 | 2.00 | 1.92 | 2.27 | 1.17 |
| 20 | 0.95 | 0.05 | 1.98 | 2.94 | 2.05 | 1.85 | 1.94 | 1.90 | 2.05 | 1.26 |
| 20 | 0.9 | 0.1 | 2.02 | 2.85 | 1.86 | 1.74 | 1.88 | 1.89 | 1.86 | 1.35 |
| 20 | 0.85 | 0.15 | 2.07 | 2.76 | 1.71 | 1.64 | 1.83 | 1.87 | 1.71 | 1.44 |
| 20 | 0.8 | 0.2 | 2.12 | 2.68 | 1.58 | 1.54 | 1.78 | 1.86 | 1.58 | 1.53 |
| 20 | 0.75 | 0.25 | 2.17 | 2.60 | 1.47 | 1.46 | 1.73 | 1.85 | 1.47 | 1.62 |
| 20 | 0.7 | 0.3 | 2.22 | 2.52 | 1.38 | 1.39 | 1.69 | 1.83 | 1.38 | 1.71 |
| 20 | 0.65 | 0.35 | 2.27 | 2.45 | 1.29 | 1.32 | 1.65 | 1.82 | 1.29 | 1.81 |
| 20 | 0.6 | 0.4 | 2.33 | 2.39 | 1.22 | 1.26 | 1.61 | 1.80 | 1.22 | 1.90 |
| 20 | 0.55 | 0.45 | 2.39 | 2.33 | 1.15 | 1.21 | 1.57 | 1.79 | 1.15 | 2.00 |
| 20 | 0.5 | 0.5 | 2.45 | 2.27 | 1.09 | 1.16 | 1.53 | 1.78 | 1.09 | 2.10 |
| 20 | 0.45 | 0.55 | 2.52 | 2.21 | 1.04 | 1.11 | 1.50 | 1.77 | 1.04 | 2.20 |
| 20 | 0.4 | 0.6 | 2.59 | 2.16 | 0.99 | 1.07 | 1.46 | 1.75 | 0.99 | 2.31 |
| 20 | 0.35 | 0.65 | 2.66 | 2.11 | 0.94 | 1.03 | 1.43 | 1.74 | 0.94 | 2.42 |
| 20 | 0.3 | 0.7 | 2.74 | 2.06 | 0.90 | 0.99 | 1.40 | 1.73 | 0.90 | 2.53 |
| 20 | 0.25 | 0.75 | 2.82 | 2.01 | 0.87 | 0.96 | 1.37 | 1.72 | 0.87 | 2.65 |
| 20 | 0.2 | 0.8 | 2.91 | 1.97 | 0.83 | 0.92 | 1.34 | 1.70 | 0.83 | 2.77 |
| 20 | 0.15 | 0.85 | 3.00 | 1.92 | 0.80 | 0.89 | 1.32 | 1.69 | 0.80 | 2.91 |
| 20 | 0.1 | 0.9 | 3.10 | 1.88 | 0.77 | 0.87 | 1.29 | 1.68 | 0.77 | 3.04 |
| 20 | 0.05 | 0.95 | 3.21 | 1.84 | 0.74 | 0.84 | 1.26 | 1.67 | 0.74 | 3.19 |
| 20 | 0 | 1 | 3.32 | 1.81 | 0.72 | 0.81 | 1.24 | 1.66 | 0.72 | 3.34 |
| 25 | 1 | 0 | 2.23 | 3.33 | 2.41 | 2.08 | 2.08 | 2.00 | 2.41 | 1.24 |
| 25 | 0.95 | 0.05 | 2.28 | 3.23 | 2.21 | 1.96 | 2.03 | 1.99 | 2.21 | 1.32 |
| 25 | 0.9 | 0.1 | 2.32 | 3.14 | 2.04 | 1.86 | 1.98 | 1.98 | 2.04 | 1.40 |
| 25 | 0.85 | 0.15 | 2.37 | 3.06 | 1.89 | 1.76 | 1.94 | 1.97 | 1.89 | 1.48 |
| 25 | 0.8 | 0.2 | 2.42 | 2.97 | 1.76 | 1.68 | 1.89 | 1.95 | 1.76 | 1.57 |
| 25 | 0.75 | 0.25 | 2.47 | 2.90 | 1.65 | 1.60 | 1.85 | 1.94 | 1.65 | 1.65 |
| 25 | 0.7 | 0.3 | 2.52 | 2.82 | 1.56 | 1.53 | 1.81 | 1.93 | 1.56 | 1.73 |
| 25 | 0.65 | 0.35 | 2.58 | 2.75 | 1.47 | 1.46 | 1.77 | 1.92 | 1.47 | 1.82 |
| 25 | 0.6 | 0.4 | 2.64 | 2.69 | 1.39 | 1.40 | 1.73 | 1.90 | 1.39 | 1.90 |
| 25 | 0.55 | 0.45 | 2.70 | 2.62 | 1.32 | 1.35 | 1.70 | 1.89 | 1.32 | 1.99 |
| 25 | 0.5 | 0.5 | 2.76 | 2.56 | 1.26 | 1.30 | 1.66 | 1.88 | 1.26 | 2.08 |
| 25 | 0.45 | 0.55 | 2.83 | 2.51 | 1.20 | 1.25 | 1.63 | 1.87 | 1.20 | 2.17 |
| 25 | 0.4 | 0.6 | 2.90 | 2.45 | 1.15 | 1.21 | 1.60 | 1.86 | 1.15 | 2.27 |
| 25 | 0.35 | 0.65 | 2.97 | 2.40 | 1.10 | 1.17 | 1.57 | 1.85 | 1.10 | 2.37 |
| 25 | 0.3 | 0.7 | 3.05 | 2.35 | 1.06 | 1.13 | 1.54 | 1.84 | 1.06 | 2.47 |
| 25 | 0.25 | 0.75 | 3.13 | 2.30 | 1.02 | 1.09 | 1.51 | 1.82 | 1.02 | 2.57 |
| 25 | 0.2 | 0.8 | 3.22 | 2.25 | 0.98 | 1.06 | 1.48 | 1.81 | 0.98 | 2.68 |
| 25 | 0.15 | 0.85 | 3.31 | 2.21 | 0.94 | 1.03 | 1.45 | 1.80 | 0.94 | 2.80 |
| 25 | 0.1 | 0.9 | 3.41 | 2.16 | 0.91 | 1.00 | 1.43 | 1.79 | 0.91 | 2.92 |
| 25 | 0.05 | 0.95 | 3.51 | 2.12 | 0.88 | 0.97 | 1.40 | 1.78 | 0.88 | 3.04 |
| 25 | 0 | 1 | 3.62 | 2.08 | 0.85 | 0.94 | 1.38 | 1.77 | 0.85 | 3.18 |
| 30 | 1 | 0 | 2.48 | 3.56 | 2.52 | 2.15 | 2.15 | 2.07 | 2.52 | 1.29 |
| 30 | 0.95 | 0.05 | 2.53 | 3.46 | 2.33 | 2.04 | 2.10 | 2.05 | 2.33 | 1.37 |
| 30 | 0.9 | 0.1 | 2.57 | 3.38 | 2.17 | 1.95 | 2.06 | 2.04 | 2.17 | 1.44 |
| 30 | 0.85 | 0.15 | 2.62 | 3.29 | 2.03 | 1.86 | 2.01 | 2.03 | 2.03 | 1.52 |
| 30 | 0.8 | 0.2 | 2.67 | 3.21 | 1.91 | 1.78 | 1.97 | 2.02 | 1.91 | 1.60 |
| 30 | 0.75 | 0.25 | 2.72 | 3.14 | 1.80 | 1.71 | 1.93 | 2.01 | 1.80 | 1.67 |
| 30 | 0.7 | 0.3 | 2.78 | 3.07 | 1.70 | 1.64 | 1.90 | 2.00 | 1.70 | 1.75 |
| 30 | 0.65 | 0.35 | 2.83 | 3.00 | 1.62 | 1.58 | 1.86 | 1.99 | 1.62 | 1.83 |
| 30 | 0.6 | 0.4 | 2.89 | 2.93 | 1.54 | 1.52 | 1.83 | 1.98 | 1.54 | 1.91 |
| 30 | 0.55 | 0.45 | 2.95 | 2.87 | 1.47 | 1.46 | 1.79 | 1.97 | 1.47 | 1.99 |
| 30 | 0.5 | 0.5 | 3.02 | 2.81 | 1.40 | 1.41 | 1.76 | 1.96 | 1.40 | 2.07 |
| 30 | 0.45 | 0.55 | 3.08 | 2.75 | 1.34 | 1.37 | 1.73 | 1.95 | 1.34 | 2.15 |
| 30 | 0.4 | 0.6 | 3.15 | 2.70 | 1.29 | 1.32 | 1.70 | 1.94 | 1.29 | 2.24 |
| 30 | 0.35 | 0.65 | 3.22 | 2.64 | 1.24 | 1.28 | 1.67 | 1.93 | 1.24 | 2.33 |
| 30 | 0.3 | 0.7 | 3.30 | 2.59 | 1.19 | 1.24 | 1.64 | 1.92 | 1.19 | 2.42 |
| 30 | 0.25 | 0.75 | 3.38 | 2.54 | 1.15 | 1.21 | 1.62 | 1.91 | 1.15 | 2.51 |
| 30 | 0.2 | 0.8 | 3.46 | 2.49 | 1.11 | 1.17 | 1.59 | 1.90 | 1.11 | 2.61 |
| 30 | 0.15 | 0.85 | 3.55 | 2.45 | 1.07 | 1.14 | 1.56 | 1.89 | 1.07 | 2.71 |
| 30 | 0.1 | 0.9 | 3.64 | 2.40 | 1.03 | 1.11 | 1.54 | 1.88 | 1.03 | 2.82 |
| 30 | 0.05 | 0.95 | 3.74 | 2.36 | 1.00 | 1.08 | 1.52 | 1.87 | 1.00 | 2.93 |
| 30 | 0 | 1 | 3.84 | 2.32 | 0.97 | 1.05 | 1.49 | 1.86 | 0.97 | 3.04 |

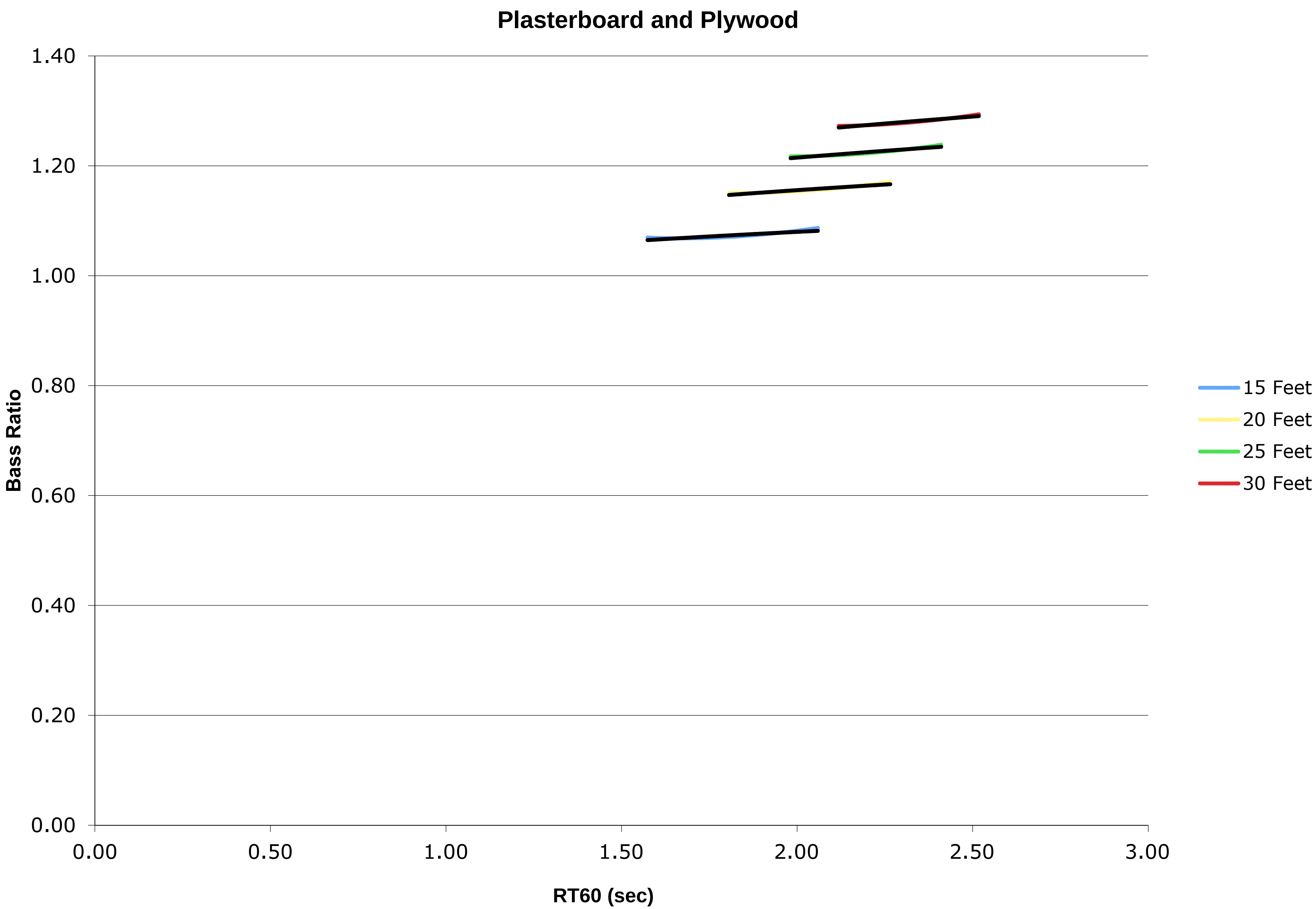
| | 125 Hz | 250 Hz | 500 Hz | 1 kHz | 2 kHz | 4 kHz |
|---|---|---|---|---|---|---|
| Plasterboard | 0.29 | 0.1 | 0.06 | 0.05 | 0.04 | 0.04 |
| Pageboard | 0.08 | 0.32 | 0.99 | 0.76 | 0.34 | 0.12 |
| Walls | 0.12 | 0.13 | 0.21 | 0.26 | 0.27 | 0.28 |
| Floor | 0.04 | 0.04 | 0.07 | 0.06 | 0.06 | 0.07 |


Plasterboard and Pageboard
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Bass Ratio
0.00
0.50
1.00
1.50
2.00
2.50
3.00
RT60 (sec)
15 Feet
20 Feet
25 Feet
30 Feet

## Plasterboard and Plywood

| Variables | | | Reverberation Times | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Ceiling Height** | **Material 1 (%)** | **Material 2 (%)** | **125 Hz** | **250 Hz** | **500 Hz** | **1 kHz** | **2 kHz** | **4 kHz** | **RT @ 500** | **Bass Ratio** |
| 15 | 1 | 0 | 1.59 | 2.66 | 2.06 | 1.85 | 1.87 | 1.79 | 2.06 | 1.09 |
| 15 | 0.95 | 0.05 | 1.60 | 2.60 | 2.03 | 1.84 | 1.86 | 1.77 | 2.03 | 1.08 |
| 15 | 0.9 | 0.1 | 1.60 | 2.55 | 2.00 | 1.83 | 1.84 | 1.76 | 2.00 | 1.08 |
| 15 | 0.85 | 0.15 | 1.60 | 2.49 | 1.97 | 1.82 | 1.83 | 1.74 | 1.97 | 1.08 |
| 15 | 0.8 | 0.2 | 1.60 | 2.44 | 1.94 | 1.81 | 1.82 | 1.73 | 1.94 | 1.08 |
| 15 | 0.75 | 0.25 | 1.60 | 2.40 | 1.91 | 1.81 | 1.80 | 1.72 | 1.91 | 1.08 |
| 15 | 0.7 | 0.3 | 1.60 | 2.35 | 1.88 | 1.80 | 1.79 | 1.70 | 1.88 | 1.07 |
| 15 | 0.65 | 0.35 | 1.61 | 2.31 | 1.86 | 1.79 | 1.78 | 1.69 | 1.86 | 1.07 |
| 15 | 0.6 | 0.4 | 1.61 | 2.26 | 1.83 | 1.78 | 1.76 | 1.68 | 1.83 | 1.07 |
| 15 | 0.55 | 0.45 | 1.61 | 2.22 | 1.81 | 1.77 | 1.75 | 1.66 | 1.81 | 1.07 |
| 15 | 0.5 | 0.5 | 1.61 | 2.18 | 1.78 | 1.76 | 1.74 | 1.65 | 1.78 | 1.07 |
| 15 | 0.45 | 0.55 | 1.61 | 2.14 | 1.76 | 1.75 | 1.73 | 1.64 | 1.76 | 1.07 |
| 15 | 0.4 | 0.6 | 1.61 | 2.11 | 1.74 | 1.75 | 1.71 | 1.62 | 1.74 | 1.07 |
| 15 | 0.35 | 0.65 | 1.62 | 2.07 | 1.72 | 1.74 | 1.70 | 1.61 | 1.72 | 1.07 |
| 15 | 0.3 | 0.7 | 1.62 | 2.04 | 1.69 | 1.73 | 1.69 | 1.60 | 1.69 | 1.07 |
| 15 | 0.25 | 0.75 | 1.62 | 2.00 | 1.67 | 1.72 | 1.68 | 1.59 | 1.67 | 1.07 |
| 15 | 0.2 | 0.8 | 1.62 | 1.97 | 1.65 | 1.71 | 1.67 | 1.57 | 1.65 | 1.07 |
| 15 | 0.15 | 0.85 | 1.62 | 1.94 | 1.63 | 1.70 | 1.66 | 1.56 | 1.63 | 1.07 |
| 15 | 0.1 | 0.9 | 1.63 | 1.91 | 1.61 | 1.70 | 1.65 | 1.55 | 1.61 | 1.07 |
| 15 | 0.05 | 0.95 | 1.63 | 1.88 | 1.59 | 1.69 | 1.63 | 1.54 | 1.59 | 1.07 |
| 15 | 0 | 1 | 1.63 | 1.85 | 1.57 | 1.68 | 1.62 | 1.53 | 1.57 | 1.07 |
| | | | | | | | | | | |
| 20 | 1 | 0 | 1.94 | 3.04 | 2.27 | 1.99 | 2.00 | 1.92 | 2.27 | 1.17 |
| 20 | 0.95 | 0.05 | 1.94 | 2.99 | 2.24 | 1.98 | 1.99 | 1.90 | 2.24 | 1.17 |
| 20 | 0.9 | 0.1 | 1.94 | 2.93 | 2.21 | 1.97 | 1.98 | 1.89 | 2.21 | 1.17 |
| 20 | 0.85 | 0.15 | 1.95 | 2.88 | 2.18 | 1.96 | 1.96 | 1.88 | 2.18 | 1.16 |
| 20 | 0.8 | 0.2 | 1.95 | 2.83 | 2.16 | 1.96 | 1.95 | 1.87 | 2.16 | 1.16 |
| 20 | 0.75 | 0.25 | 1.95 | 2.78 | 2.13 | 1.95 | 1.94 | 1.85 | 2.13 | 1.16 |
| 20 | 0.7 | 0.3 | 1.95 | 2.74 | 2.10 | 1.94 | 1.93 | 1.84 | 2.10 | 1.16 |
| 20 | 0.65 | 0.35 | 1.95 | 2.69 | 2.08 | 1.93 | 1.92 | 1.83 | 2.08 | 1.16 |
| 20 | 0.6 | 0.4 | 1.96 | 2.65 | 2.06 | 1.93 | 1.91 | 1.82 | 2.06 | 1.16 |
| 20 | 0.55 | 0.45 | 1.96 | 2.60 | 2.03 | 1.92 | 1.90 | 1.81 | 2.03 | 1.15 |
| 20 | 0.5 | 0.5 | 1.96 | 2.56 | 2.01 | 1.91 | 1.88 | 1.79 | 2.01 | 1.15 |
| 20 | 0.45 | 0.55 | 1.96 | 2.52 | 1.99 | 1.90 | 1.87 | 1.78 | 1.99 | 1.15 |
| 20 | 0.4 | 0.6 | 1.96 | 2.49 | 1.97 | 1.90 | 1.86 | 1.77 | 1.97 | 1.15 |
| 20 | 0.35 | 0.65 | 1.97 | 2.45 | 1.94 | 1.89 | 1.85 | 1.76 | 1.94 | 1.15 |
| 20 | 0.3 | 0.7 | 1.97 | 2.41 | 1.92 | 1.88 | 1.84 | 1.75 | 1.92 | 1.15 |
| 20 | 0.25 | 0.75 | 1.97 | 2.38 | 1.90 | 1.87 | 1.83 | 1.74 | 1.90 | 1.15 |
| 20 | 0.2 | 0.8 | 1.97 | 2.34 | 1.88 | 1.87 | 1.82 | 1.73 | 1.88 | 1.15 |
| 20 | 0.15 | 0.85 | 1.97 | 2.31 | 1.86 | 1.86 | 1.81 | 1.72 | 1.86 | 1.15 |
| 20 | 0.1 | 0.9 | 1.98 | 2.28 | 1.84 | 1.85 | 1.80 | 1.71 | 1.84 | 1.15 |
| 20 | 0.05 | 0.95 | 1.98 | 2.25 | 1.82 | 1.85 | 1.79 | 1.70 | 1.82 | 1.15 |
| 20 | 0 | 1 | 1.98 | 2.22 | 1.81 | 1.84 | 1.78 | 1.69 | 1.81 | 1.15 |
| | | | | | | | | | | |
| 25 | 1 | 0 | 2.23 | 3.33 | 2.41 | 2.08 | 2.08 | 2.00 | 2.41 | 1.24 |
| 25 | 0.95 | 0.05 | 2.23 | 3.28 | 2.38 | 2.07 | 2.07 | 1.99 | 2.38 | 1.24 |
| 25 | 0.9 | 0.1 | 2.24 | 3.22 | 2.36 | 2.07 | 2.06 | 1.98 | 2.36 | 1.23 |
| 25 | 0.85 | 0.15 | 2.24 | 3.17 | 2.33 | 2.06 | 2.05 | 1.97 | 2.33 | 1.23 |
| 25 | 0.8 | 0.2 | 2.24 | 3.13 | 2.31 | 2.05 | 2.04 | 1.96 | 2.31 | 1.23 |
| 25 | 0.75 | 0.25 | 2.24 | 3.08 | 2.29 | 2.05 | 2.03 | 1.95 | 2.29 | 1.23 |
| 25 | 0.7 | 0.3 | 2.24 | 3.03 | 2.26 | 2.04 | 2.02 | 1.94 | 2.26 | 1.23 |
| 25 | 0.65 | 0.35 | 2.25 | 2.99 | 2.24 | 2.03 | 2.01 | 1.93 | 2.24 | 1.23 |
| 25 | 0.6 | 0.4 | 2.25 | 2.95 | 2.22 | 2.03 | 2.00 | 1.92 | 2.22 | 1.22 |
| 25 | 0.55 | 0.45 | 2.25 | 2.90 | 2.20 | 2.02 | 1.99 | 1.91 | 2.20 | 1.22 |
| 25 | 0.5 | 0.5 | 2.25 | 2.86 | 2.17 | 2.01 | 1.98 | 1.90 | 2.17 | 1.22 |
| 25 | 0.45 | 0.55 | 2.25 | 2.82 | 2.15 | 2.01 | 1.97 | 1.89 | 2.15 | 1.22 |
| 25 | 0.4 | 0.6 | 2.26 | 2.78 | 2.13 | 2.00 | 1.96 | 1.88 | 2.13 | 1.22 |
| 25 | 0.35 | 0.65 | 2.26 | 2.75 | 2.11 | 1.99 | 1.95 | 1.87 | 2.11 | 1.22 |
| 25 | 0.3 | 0.7 | 2.26 | 2.71 | 2.09 | 1.99 | 1.95 | 1.86 | 2.09 | 1.22 |
| 25 | 0.25 | 0.75 | 2.26 | 2.68 | 2.07 | 1.98 | 1.94 | 1.85 | 2.07 | 1.22 |
| 25 | 0.2 | 0.8 | 2.27 | 2.64 | 2.05 | 1.97 | 1.93 | 1.84 | 2.05 | 1.22 |
| 25 | 0.15 | 0.85 | 2.27 | 2.61 | 2.04 | 1.97 | 1.92 | 1.83 | 2.04 | 1.22 |
| 25 | 0.1 | 0.9 | 2.27 | 2.57 | 2.02 | 1.96 | 1.91 | 1.82 | 2.02 | 1.22 |
| 25 | 0.05 | 0.95 | 2.27 | 2.54 | 2.00 | 1.96 | 1.90 | 1.81 | 2.00 | 1.22 |
| 25 | 0 | 1 | 2.27 | 2.51 | 1.98 | 1.95 | 1.89 | 1.80 | 1.98 | 1.22 |
| | | | | | | | | | | |
| 30 | 1 | 0 | 2.48 | 3.56 | 2.52 | 2.15 | 2.15 | 2.07 | 2.52 | 1.29 |
| 30 | 0.95 | 0.05 | 2.48 | 3.50 | 2.49 | 2.14 | 2.14 | 2.06 | 2.49 | 1.29 |
| 30 | 0.9 | 0.1 | 2.49 | 3.46 | 2.47 | 2.14 | 2.13 | 2.05 | 2.47 | 1.29 |
| 30 | 0.85 | 0.15 | 2.49 | 3.41 | 2.45 | 2.13 | 2.12 | 2.04 | 2.45 | 1.29 |
| 30 | 0.8 | 0.2 | 2.49 | 3.36 | 2.43 | 2.12 | 2.11 | 2.03 | 2.43 | 1.29 |
| 30 | 0.75 | 0.25 | 2.49 | 3.32 | 2.40 | 2.12 | 2.10 | 2.02 | 2.40 | 1.28 |
| 30 | 0.7 | 0.3 | 2.49 | 3.27 | 2.38 | 2.11 | 2.09 | 2.01 | 2.38 | 1.28 |
| 30 | 0.65 | 0.35 | 2.50 | 3.23 | 2.36 | 2.11 | 2.08 | 2.00 | 2.36 | 1.28 |
| 30 | 0.6 | 0.4 | 2.50 | 3.19 | 2.34 | 2.10 | 2.07 | 1.99 | 2.34 | 1.28 |
| 30 | 0.55 | 0.45 | 2.50 | 3.14 | 2.32 | 2.09 | 2.06 | 1.98 | 2.32 | 1.28 |
| 30 | 0.5 | 0.5 | 2.50 | 3.10 | 2.30 | 2.09 | 2.06 | 1.97 | 2.30 | 1.28 |
| 30 | 0.45 | 0.55 | 2.50 | 3.07 | 2.28 | 2.08 | 2.05 | 1.96 | 2.28 | 1.28 |
| 30 | 0.4 | 0.6 | 2.51 | 3.03 | 2.26 | 2.08 | 2.04 | 1.95 | 2.26 | 1.28 |
| 30 | 0.35 | 0.65 | 2.51 | 2.99 | 2.24 | 2.07 | 2.03 | 1.94 | 2.24 | 1.28 |
| 30 | 0.3 | 0.7 | 2.51 | 2.96 | 2.22 | 2.06 | 2.02 | 1.93 | 2.22 | 1.27 |
| 30 | 0.25 | 0.75 | 2.51 | 2.92 | 2.21 | 2.06 | 2.01 | 1.92 | 2.21 | 1.27 |
| 30 | 0.2 | 0.8 | 2.51 | 2.89 | 2.19 | 2.05 | 2.01 | 1.92 | 2.19 | 1.27 |
| 30 | 0.15 | 0.85 | 2.52 | 2.85 | 2.17 | 2.05 | 2.00 | 1.91 | 2.17 | 1.27 |
| 30 | 0.1 | 0.9 | 2.52 | 2.82 | 2.15 | 2.04 | 1.99 | 1.90 | 2.15 | 1.27 |
| 30 | 0.05 | 0.95 | 2.52 | 2.79 | 2.14 | 2.04 | 1.98 | 1.89 | 2.14 | 1.27 |
| 30 | 0 | 1 | 2.52 | 2.76 | 2.12 | 2.03 | 1.97 | 1.88 | 2.12 | 1.27 |

| | 125 Hz | 250 Hz | 500 Hz | 1 kHz | 2 kHz | 4 kHz |
|---|---|---|---|---|---|---|
| Plasterboard | 0.29 | 0.1 | 0.06 | 0.05 | 0.04 | 0.04 |
| 3/8 in. Plywood | 0.28 | 0.22 | 0.17 | 0.09 | 0.1 | 0.11 |
| Walls | 0.12 | 0.13 | 0.21 | 0.26 | 0.27 | 0.28 |
| Floor | 0.04 | 0.04 | 0.07 | 0.06 | 0.06 | 0.07 |

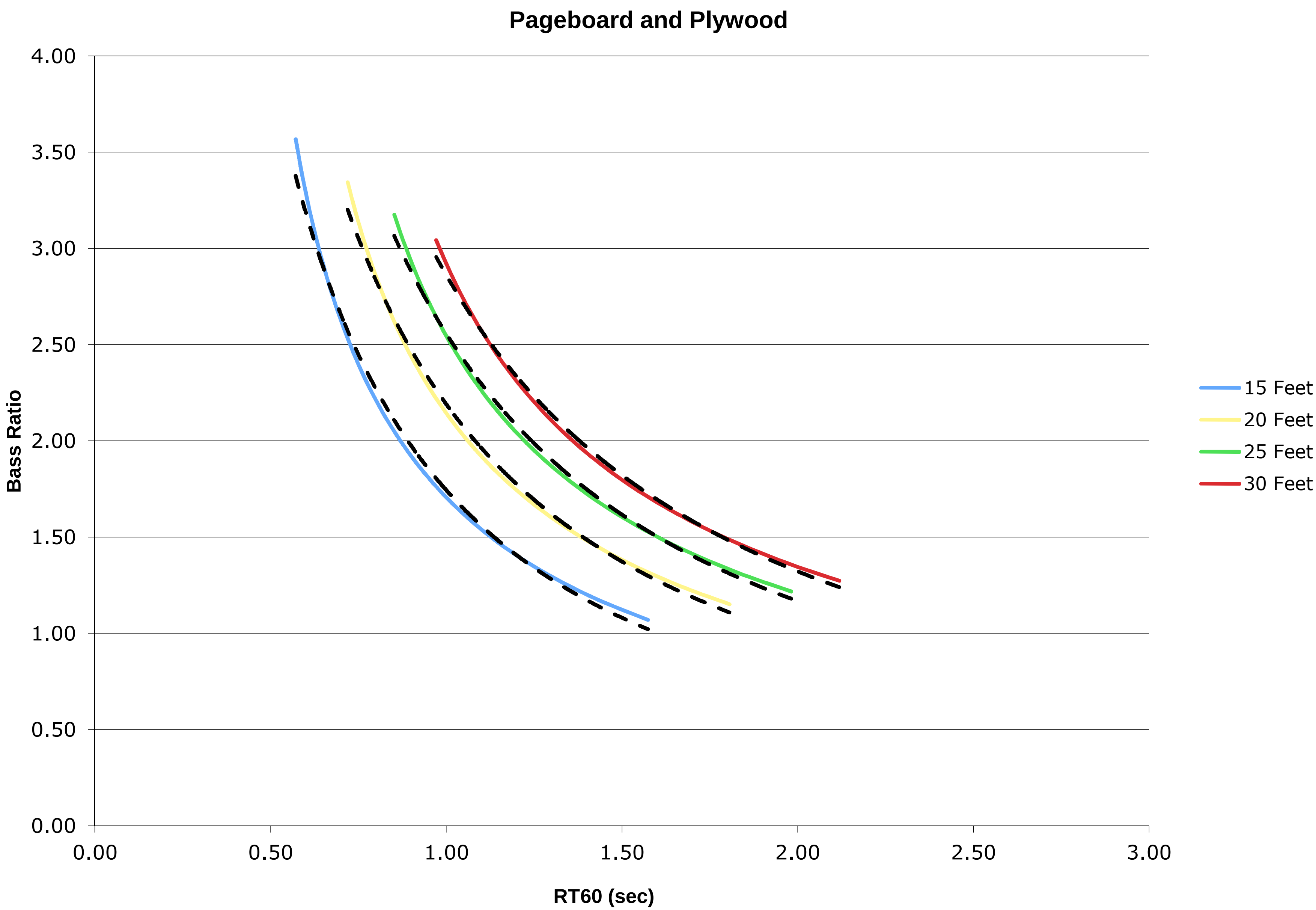


Plasterboard and Plywood
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Bass Ratio
0.00
0.50
1.00
1.50
2.00
2.50
3.00
RT60 (sec)
15 Feet
20 Feet
25 Feet
30 Feet

## Pageboard and Plywood

| Variables | | | Reverberation Times | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Ceiling Height** | **Material 1 (%)** | **Material 2 (%)** | **125 Hz** | **250 Hz** | **500 Hz** | **1 kHz** | **2 kHz** | **4 kHz** | **RT @ 500** | **Bass Ratio** |
| 15 | 1 | 0 | 2.93 | 1.48 | 0.57 | 0.66 | 1.06 | 1.50 | 0.57 | 3.57 |
| 15 | 0.95 | 0.05 | 2.81 | 1.49 | 0.59 | 0.68 | 1.08 | 1.50 | 0.59 | 3.38 |
| 15 | 0.9 | 0.1 | 2.71 | 1.51 | 0.61 | 0.71 | 1.10 | 1.50 | 0.61 | 3.20 |
| 15 | 0.85 | 0.15 | 2.61 | 1.53 | 0.63 | 0.73 | 1.12 | 1.50 | 0.63 | 3.04 |
| 15 | 0.8 | 0.2 | 2.52 | 1.54 | 0.65 | 0.76 | 1.14 | 1.50 | 0.65 | 2.88 |
| 15 | 0.75 | 0.25 | 2.44 | 1.56 | 0.68 | 0.78 | 1.16 | 1.51 | 0.68 | 2.74 |
| 15 | 0.7 | 0.3 | 2.36 | 1.57 | 0.71 | 0.81 | 1.18 | 1.51 | 0.71 | 2.59 |
| 15 | 0.65 | 0.35 | 2.29 | 1.59 | 0.74 | 0.84 | 1.21 | 1.51 | 0.74 | 2.46 |
| 15 | 0.6 | 0.4 | 2.22 | 1.61 | 0.77 | 0.88 | 1.23 | 1.51 | 0.77 | 2.33 |
| 15 | 0.55 | 0.45 | 2.15 | 1.63 | 0.80 | 0.91 | 1.26 | 1.51 | 0.80 | 2.21 |
| 15 | 0.5 | 0.5 | 2.09 | 1.65 | 0.84 | 0.95 | 1.28 | 1.51 | 0.84 | 2.09 |
| 15 | 0.45 | 0.55 | 2.03 | 1.66 | 0.88 | 1.00 | 1.31 | 1.51 | 0.88 | 1.97 |
| 15 | 0.4 | 0.6 | 1.98 | 1.68 | 0.92 | 1.04 | 1.34 | 1.52 | 0.92 | 1.86 |
| 15 | 0.35 | 0.65 | 1.93 | 1.70 | 0.97 | 1.09 | 1.37 | 1.52 | 0.97 | 1.75 |
| 15 | 0.3 | 0.7 | 1.88 | 1.72 | 1.03 | 1.15 | 1.40 | 1.52 | 1.03 | 1.65 |
| 15 | 0.25 | 0.75 | 1.83 | 1.74 | 1.09 | 1.22 | 1.43 | 1.52 | 1.09 | 1.55 |
| 15 | 0.2 | 0.8 | 1.79 | 1.76 | 1.16 | 1.29 | 1.47 | 1.52 | 1.16 | 1.45 |
| 15 | 0.15 | 0.85 | 1.74 | 1.79 | 1.25 | 1.37 | 1.50 | 1.52 | 1.25 | 1.35 |
| 15 | 0.1 | 0.9 | 1.70 | 1.81 | 1.34 | 1.46 | 1.54 | 1.53 | 1.34 | 1.26 |
| 15 | 0.05 | 0.95 | 1.67 | 1.83 | 1.45 | 1.56 | 1.58 | 1.53 | 1.45 | 1.16 |
| 15 | 0 | 1 | 1.63 | 1.85 | 1.57 | 1.68 | 1.62 | 1.53 | 1.57 | 1.07 |
| 20 | 1 | 0 | 3.32 | 1.81 | 0.72 | 0.81 | 1.24 | 1.66 | 0.72 | 3.34 |
| 20 | 0.95 | 0.05 | 3.21 | 1.82 | 0.74 | 0.84 | 1.26 | 1.66 | 0.74 | 3.19 |
| 20 | 0.9 | 0.1 | 3.11 | 1.84 | 0.77 | 0.86 | 1.28 | 1.66 | 0.77 | 3.04 |
| 20 | 0.85 | 0.15 | 3.02 | 1.86 | 0.79 | 0.89 | 1.30 | 1.66 | 0.79 | 2.90 |
| 20 | 0.8 | 0.2 | 2.93 | 1.88 | 0.82 | 0.92 | 1.32 | 1.66 | 0.82 | 2.77 |
| 20 | 0.75 | 0.25 | 2.84 | 1.89 | 0.85 | 0.95 | 1.34 | 1.67 | 0.85 | 2.64 |
| 20 | 0.7 | 0.3 | 2.76 | 1.91 | 0.88 | 0.98 | 1.36 | 1.67 | 0.88 | 2.52 |
| 20 | 0.65 | 0.35 | 2.68 | 1.93 | 0.91 | 1.01 | 1.39 | 1.67 | 0.91 | 2.40 |
| 20 | 0.6 | 0.4 | 2.61 | 1.95 | 0.95 | 1.05 | 1.41 | 1.67 | 0.95 | 2.29 |
| 20 | 0.55 | 0.45 | 2.55 | 1.97 | 0.99 | 1.09 | 1.44 | 1.67 | 0.99 | 2.18 |
| 20 | 0.5 | 0.5 | 2.48 | 1.99 | 1.03 | 1.13 | 1.46 | 1.67 | 1.03 | 2.07 |
| 20 | 0.45 | 0.55 | 2.42 | 2.01 | 1.08 | 1.17 | 1.49 | 1.67 | 1.08 | 1.97 |
| 20 | 0.4 | 0.6 | 2.36 | 2.03 | 1.13 | 1.22 | 1.52 | 1.68 | 1.13 | 1.87 |
| 20 | 0.35 | 0.65 | 2.31 | 2.05 | 1.18 | 1.28 | 1.55 | 1.68 | 1.18 | 1.77 |
| 20 | 0.3 | 0.7 | 2.25 | 2.07 | 1.24 | 1.34 | 1.58 | 1.68 | 1.24 | 1.68 |
| 20 | 0.25 | 0.75 | 2.20 | 2.10 | 1.31 | 1.40 | 1.61 | 1.68 | 1.31 | 1.59 |
| 20 | 0.2 | 0.8 | 2.15 | 2.12 | 1.39 | 1.47 | 1.64 | 1.68 | 1.39 | 1.50 |
| 20 | 0.15 | 0.85 | 2.11 | 2.14 | 1.47 | 1.55 | 1.67 | 1.68 | 1.47 | 1.41 |
| 20 | 0.1 | 0.9 | 2.06 | 2.17 | 1.57 | 1.63 | 1.71 | 1.68 | 1.57 | 1.32 |
| 20 | 0.05 | 0.95 | 2.02 | 2.19 | 1.68 | 1.73 | 1.74 | 1.69 | 1.68 | 1.24 |
| 20 | 0 | 1 | 1.98 | 2.22 | 1.81 | 1.84 | 1.78 | 1.69 | 1.81 | 1.15 |
| 25 | 1 | 0 | 3.62 | 2.08 | 0.85 | 0.94 | 1.38 | 1.77 | 0.85 | 3.18 |
| 25 | 0.95 | 0.05 | 3.51 | 2.10 | 0.88 | 0.97 | 1.40 | 1.77 | 0.88 | 3.04 |
| 25 | 0.9 | 0.1 | 3.41 | 2.12 | 0.90 | 0.99 | 1.42 | 1.77 | 0.90 | 2.92 |
| 25 | 0.85 | 0.15 | 3.32 | 2.14 | 0.93 | 1.02 | 1.44 | 1.78 | 0.93 | 2.79 |
| 25 | 0.8 | 0.2 | 3.23 | 2.16 | 0.96 | 1.05 | 1.46 | 1.78 | 0.96 | 2.68 |
| 25 | 0.75 | 0.25 | 3.15 | 2.18 | 0.99 | 1.08 | 1.48 | 1.78 | 0.99 | 2.57 |
| 25 | 0.7 | 0.3 | 3.07 | 2.20 | 1.03 | 1.12 | 1.50 | 1.78 | 1.03 | 2.46 |
| 25 | 0.65 | 0.35 | 3.00 | 2.22 | 1.06 | 1.15 | 1.52 | 1.78 | 1.06 | 2.35 |
| 25 | 0.6 | 0.4 | 2.93 | 2.24 | 1.10 | 1.19 | 1.55 | 1.78 | 1.10 | 2.25 |
| 25 | 0.55 | 0.45 | 2.86 | 2.26 | 1.15 | 1.23 | 1.57 | 1.78 | 1.15 | 2.15 |
| 25 | 0.5 | 0.5 | 2.79 | 2.28 | 1.19 | 1.27 | 1.60 | 1.78 | 1.19 | 2.06 |
| 25 | 0.45 | 0.55 | 2.73 | 2.30 | 1.24 | 1.32 | 1.62 | 1.79 | 1.24 | 1.97 |
| 25 | 0.4 | 0.6 | 2.67 | 2.32 | 1.29 | 1.37 | 1.65 | 1.79 | 1.29 | 1.88 |
| 25 | 0.35 | 0.65 | 2.61 | 2.34 | 1.35 | 1.42 | 1.67 | 1.79 | 1.35 | 1.79 |
| 25 | 0.3 | 0.7 | 2.56 | 2.37 | 1.42 | 1.48 | 1.70 | 1.79 | 1.42 | 1.70 |
| 25 | 0.25 | 0.75 | 2.51 | 2.39 | 1.49 | 1.54 | 1.73 | 1.79 | 1.49 | 1.62 |
| 25 | 0.2 | 0.8 | 2.46 | 2.41 | 1.57 | 1.61 | 1.76 | 1.79 | 1.57 | 1.53 |
| 25 | 0.15 | 0.85 | 2.41 | 2.44 | 1.65 | 1.68 | 1.79 | 1.79 | 1.65 | 1.45 |
| 25 | 0.1 | 0.9 | 2.36 | 2.46 | 1.75 | 1.76 | 1.82 | 1.80 | 1.75 | 1.37 |
| 25 | 0.05 | 0.95 | 2.32 | 2.49 | 1.86 | 1.85 | 1.86 | 1.80 | 1.86 | 1.29 |
| 25 | 0 | 1 | 2.27 | 2.51 | 1.98 | 1.95 | 1.89 | 1.80 | 1.98 | 1.22 |
| 30 | 1 | 0 | 3.84 | 2.32 | 0.97 | 1.05 | 1.49 | 1.86 | 0.97 | 3.04 |
| 30 | 0.95 | 0.05 | 3.75 | 2.34 | 1.00 | 1.08 | 1.51 | 1.86 | 1.00 | 2.93 |
| 30 | 0.9 | 0.1 | 3.65 | 2.36 | 1.03 | 1.11 | 1.53 | 1.86 | 1.03 | 2.82 |
| 30 | 0.85 | 0.15 | 3.56 | 2.38 | 1.06 | 1.14 | 1.55 | 1.86 | 1.06 | 2.71 |
| 30 | 0.8 | 0.2 | 3.48 | 2.40 | 1.09 | 1.17 | 1.57 | 1.86 | 1.09 | 2.61 |
| 30 | 0.75 | 0.25 | 3.40 | 2.42 | 1.12 | 1.20 | 1.59 | 1.86 | 1.12 | 2.50 |
| 30 | 0.7 | 0.3 | 3.32 | 2.44 | 1.16 | 1.23 | 1.61 | 1.86 | 1.16 | 2.41 |
| 30 | 0.65 | 0.35 | 3.25 | 2.46 | 1.20 | 1.27 | 1.63 | 1.87 | 1.20 | 2.31 |
| 30 | 0.6 | 0.4 | 3.18 | 2.48 | 1.24 | 1.31 | 1.65 | 1.87 | 1.24 | 2.22 |
| 30 | 0.55 | 0.45 | 3.11 | 2.50 | 1.28 | 1.35 | 1.68 | 1.87 | 1.28 | 2.13 |
| 30 | 0.5 | 0.5 | 3.05 | 2.52 | 1.33 | 1.39 | 1.70 | 1.87 | 1.33 | 2.05 |
| 30 | 0.45 | 0.55 | 2.98 | 2.54 | 1.38 | 1.43 | 1.72 | 1.87 | 1.38 | 1.96 |
| 30 | 0.4 | 0.6 | 2.93 | 2.56 | 1.44 | 1.48 | 1.75 | 1.87 | 1.44 | 1.88 |
| 30 | 0.35 | 0.65 | 2.87 | 2.59 | 1.50 | 1.53 | 1.77 | 1.87 | 1.50 | 1.80 |
| 30 | 0.3 | 0.7 | 2.81 | 2.61 | 1.56 | 1.59 | 1.80 | 1.87 | 1.56 | 1.72 |
| 30 | 0.25 | 0.75 | 2.76 | 2.63 | 1.64 | 1.65 | 1.83 | 1.87 | 1.64 | 1.64 |
| 30 | 0.2 | 0.8 | 2.71 | 2.66 | 1.71 | 1.71 | 1.85 | 1.88 | 1.71 | 1.57 |
| 30 | 0.15 | 0.85 | 2.66 | 2.68 | 1.80 | 1.78 | 1.88 | 1.88 | 1.80 | 1.49 |
| 30 | 0.1 | 0.9 | 2.61 | 2.71 | 1.89 | 1.86 | 1.91 | 1.88 | 1.89 | 1.42 |
| 30 | 0.05 | 0.95 | 2.57 | 2.73 | 2.00 | 1.94 | 1.94 | 1.88 | 2.00 | 1.34 |
| 30 | 0 | 1 | 2.52 | 2.76 | 2.12 | 2.03 | 1.97 | 1.88 | 2.12 | 1.27 |

| | 125 Hz | 250 Hz | 500 Hz | 1 kHz | 2 kHz | 4 kHz |
|---|---|---|---|---|---|---|
| Pageboard | 0.08 | 0.32 | 0.99 | 0.76 | 0.34 | 0.12 |
| 3/8 in. Plywood | 0.28 | 0.22 | 0.17 | 0.09 | 0.1 | 0.11 |
| Walls | 0.12 | 0.13 | 0.21 | 0.26 | 0.27 | 0.28 |
| Floor | 0.04 | 0.04 | 0.07 | 0.06 | 0.06 | 0.07 |

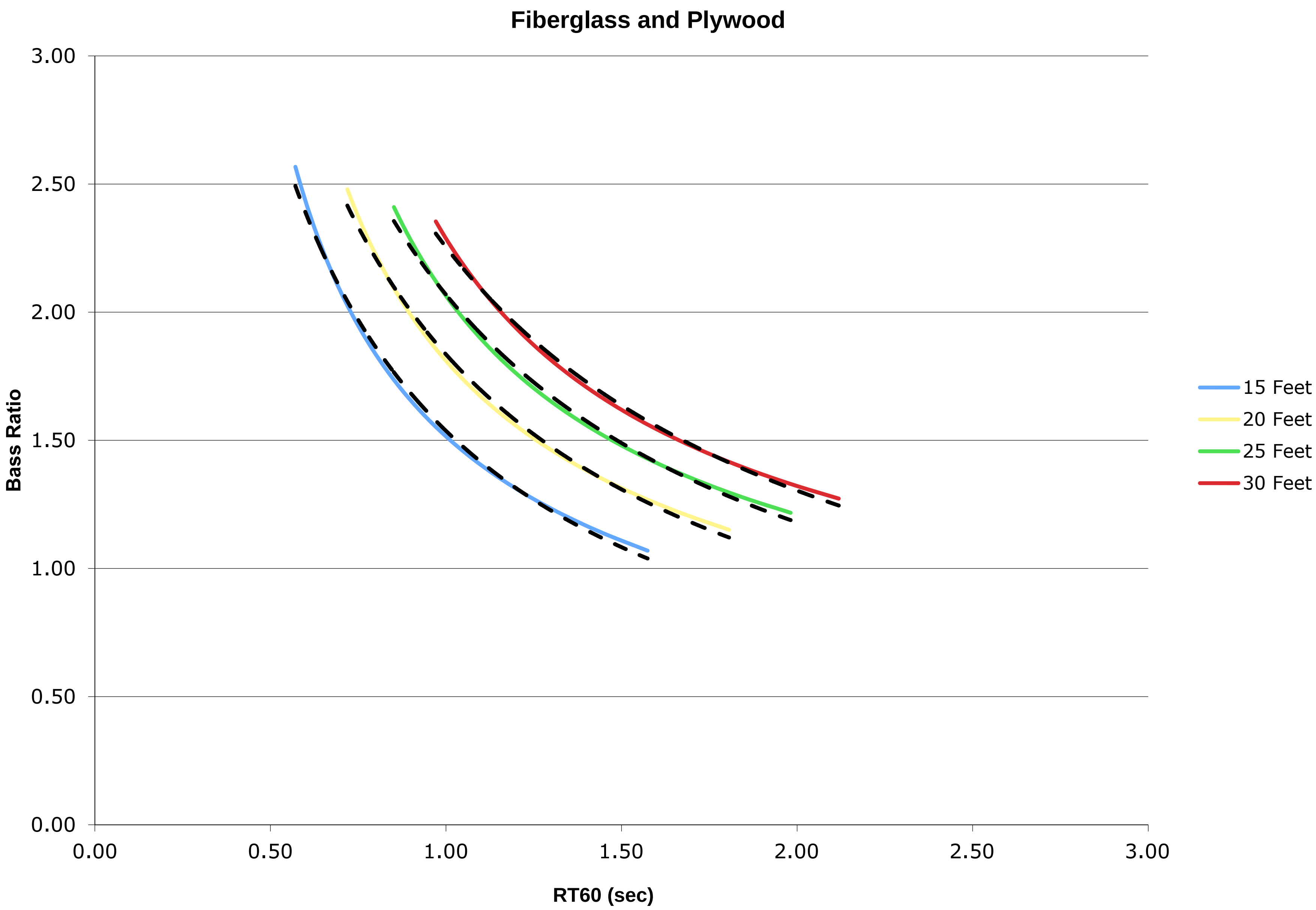


Pageboard and Plywood
Bass Ratio
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0.00
0.50
1.00
1.50
2.00
2.50
3.00
RT60 (sec)
15 Feet
20 Feet
25 Feet
30 Feet

## Fiberglass and Plywood

| Variables | | | Reverberation Times | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Ceiling Height | Material 1 (%) | Material 2 (%) | 125 Hz | 250 Hz | 500 Hz | 1 kHz | 2 kHz | 4 kHz | RT @ 500 | Bass Ratio |
| 15 | 1 | 0 | 2.09 | 0.78 | 0.57 | 0.55 | 0.55 | 0.54 | 0.57 | 2.57 |
| 15 | 0.95 | 0.05 | 2.06 | 0.81 | 0.59 | 0.57 | 0.57 | 0.56 | 0.59 | 2.48 |
| 15 | 0.9 | 0.1 | 2.03 | 0.83 | 0.61 | 0.59 | 0.59 | 0.58 | 0.61 | 2.39 |
| 15 | 0.85 | 0.15 | 2.01 | 0.86 | 0.63 | 0.61 | 0.61 | 0.60 | 0.63 | 2.31 |
| 15 | 0.8 | 0.2 | 1.98 | 0.89 | 0.65 | 0.64 | 0.63 | 0.62 | 0.65 | 2.22 |
| 15 | 0.75 | 0.25 | 1.95 | 0.92 | 0.68 | 0.66 | 0.66 | 0.64 | 0.68 | 2.14 |
| 15 | 0.7 | 0.3 | 1.93 | 0.95 | 0.71 | 0.69 | 0.68 | 0.67 | 0.71 | 2.06 |
| 15 | 0.65 | 0.35 | 1.90 | 0.98 | 0.74 | 0.72 | 0.71 | 0.70 | 0.74 | 1.98 |
| 15 | 0.6 | 0.4 | 1.88 | 1.02 | 0.77 | 0.75 | 0.74 | 0.73 | 0.77 | 1.91 |
| 15 | 0.55 | 0.45 | 1.85 | 1.06 | 0.80 | 0.79 | 0.78 | 0.76 | 0.80 | 1.83 |
| 15 | 0.5 | 0.5 | 1.83 | 1.10 | 0.84 | 0.83 | 0.82 | 0.80 | 0.84 | 1.76 |
| 15 | 0.45 | 0.55 | 1.81 | 1.15 | 0.88 | 0.87 | 0.86 | 0.84 | 0.88 | 1.69 |
| 15 | 0.4 | 0.6 | 1.79 | 1.20 | 0.92 | 0.92 | 0.91 | 0.88 | 0.92 | 1.62 |
| 15 | 0.35 | 0.65 | 1.77 | 1.25 | 0.97 | 0.98 | 0.96 | 0.93 | 0.97 | 1.55 |
| 15 | 0.3 | 0.7 | 1.74 | 1.32 | 1.03 | 1.04 | 1.02 | 0.99 | 1.03 | 1.48 |
| 15 | 0.25 | 0.75 | 1.72 | 1.38 | 1.09 | 1.11 | 1.09 | 1.05 | 1.09 | 1.41 |
| 15 | 0.2 | 0.8 | 1.70 | 1.46 | 1.16 | 1.19 | 1.17 | 1.12 | 1.16 | 1.34 |
| 15 | 0.15 | 0.85 | 1.68 | 1.54 | 1.25 | 1.28 | 1.25 | 1.20 | 1.25 | 1.27 |
| 15 | 0.1 | 0.9 | 1.67 | 1.63 | 1.34 | 1.39 | 1.36 | 1.29 | 1.34 | 1.21 |
| 15 | 0.05 | 0.95 | 1.65 | 1.73 | 1.45 | 1.52 | 1.48 | 1.40 | 1.45 | 1.14 |
| 15 | 0 | 1 | 1.63 | 1.85 | 1.57 | 1.68 | 1.62 | 1.53 | 1.57 | 1.07 |
| 20 | 1 | 0 | 2.48 | 1.00 | 0.72 | 0.68 | 0.68 | 0.67 | 0.72 | 2.48 |
| 20 | 0.95 | 0.05 | 2.45 | 1.03 | 0.74 | 0.71 | 0.70 | 0.69 | 0.74 | 2.40 |
| 20 | 0.9 | 0.1 | 2.42 | 1.06 | 0.77 | 0.73 | 0.73 | 0.71 | 0.77 | 2.32 |
| 20 | 0.85 | 0.15 | 2.39 | 1.09 | 0.79 | 0.76 | 0.75 | 0.74 | 0.79 | 2.25 |
| 20 | 0.8 | 0.2 | 2.36 | 1.12 | 0.82 | 0.78 | 0.78 | 0.76 | 0.82 | 2.18 |
| 20 | 0.75 | 0.25 | 2.33 | 1.16 | 0.85 | 0.81 | 0.80 | 0.79 | 0.85 | 2.10 |
| 20 | 0.7 | 0.3 | 2.31 | 1.19 | 0.88 | 0.84 | 0.84 | 0.82 | 0.88 | 2.03 |
| 20 | 0.65 | 0.35 | 2.28 | 1.24 | 0.91 | 0.88 | 0.87 | 0.85 | 0.91 | 1.97 |
| 20 | 0.6 | 0.4 | 2.25 | 1.28 | 0.95 | 0.91 | 0.90 | 0.88 | 0.95 | 1.90 |
| 20 | 0.55 | 0.45 | 2.23 | 1.33 | 0.99 | 0.95 | 0.94 | 0.92 | 0.99 | 1.83 |
| 20 | 0.5 | 0.5 | 2.20 | 1.38 | 1.03 | 1.00 | 0.98 | 0.96 | 1.03 | 1.77 |
| 20 | 0.45 | 0.55 | 2.18 | 1.43 | 1.08 | 1.04 | 1.03 | 1.00 | 1.08 | 1.70 |
| 20 | 0.4 | 0.6 | 2.15 | 1.49 | 1.13 | 1.10 | 1.08 | 1.05 | 1.13 | 1.64 |
| 20 | 0.35 | 0.65 | 2.13 | 1.55 | 1.18 | 1.16 | 1.14 | 1.10 | 1.18 | 1.58 |
| 20 | 0.3 | 0.7 | 2.11 | 1.62 | 1.24 | 1.22 | 1.20 | 1.16 | 1.24 | 1.51 |
| 20 | 0.25 | 0.75 | 2.09 | 1.70 | 1.31 | 1.29 | 1.27 | 1.22 | 1.31 | 1.45 |
| 20 | 0.2 | 0.8 | 2.06 | 1.78 | 1.39 | 1.37 | 1.35 | 1.29 | 1.39 | 1.39 |
| 20 | 0.15 | 0.85 | 2.04 | 1.87 | 1.47 | 1.47 | 1.43 | 1.37 | 1.47 | 1.33 |
| 20 | 0.1 | 0.9 | 2.02 | 1.97 | 1.57 | 1.57 | 1.53 | 1.46 | 1.57 | 1.27 |
| 20 | 0.05 | 0.95 | 2.00 | 2.09 | 1.68 | 1.70 | 1.65 | 1.57 | 1.68 | 1.21 |
| 20 | 0 | 1 | 1.98 | 2.22 | 1.81 | 1.84 | 1.78 | 1.69 | 1.81 | 1.15 |
| 25 | 1 | 0 | 2.79 | 1.19 | 0.85 | 0.80 | 0.80 | 0.78 | 0.85 | 2.41 |
| 25 | 0.95 | 0.05 | 2.76 | 1.22 | 0.88 | 0.83 | 0.82 | 0.81 | 0.88 | 2.34 |
| 25 | 0.9 | 0.1 | 2.73 | 1.26 | 0.90 | 0.85 | 0.85 | 0.83 | 0.90 | 2.27 |
| 25 | 0.85 | 0.15 | 2.70 | 1.29 | 0.93 | 0.88 | 0.87 | 0.86 | 0.93 | 2.21 |
| 25 | 0.8 | 0.2 | 2.67 | 1.33 | 0.96 | 0.91 | 0.90 | 0.88 | 0.96 | 2.14 |
| 25 | 0.75 | 0.25 | 2.64 | 1.37 | 0.99 | 0.94 | 0.93 | 0.91 | 0.99 | 2.08 |
| 25 | 0.7 | 0.3 | 2.61 | 1.41 | 1.03 | 0.97 | 0.96 | 0.94 | 1.03 | 2.01 |
| 25 | 0.65 | 0.35 | 2.59 | 1.46 | 1.06 | 1.01 | 1.00 | 0.98 | 1.06 | 1.95 |
| 25 | 0.6 | 0.4 | 2.56 | 1.51 | 1.10 | 1.05 | 1.04 | 1.01 | 1.10 | 1.89 |
| 25 | 0.55 | 0.45 | 2.53 | 1.56 | 1.15 | 1.09 | 1.08 | 1.05 | 1.15 | 1.83 |
| 25 | 0.5 | 0.5 | 2.51 | 1.62 | 1.19 | 1.14 | 1.12 | 1.09 | 1.19 | 1.77 |
| 25 | 0.45 | 0.55 | 2.48 | 1.68 | 1.24 | 1.19 | 1.17 | 1.14 | 1.24 | 1.71 |
| 25 | 0.4 | 0.6 | 2.46 | 1.74 | 1.29 | 1.24 | 1.22 | 1.19 | 1.29 | 1.66 |
| 25 | 0.35 | 0.65 | 2.43 | 1.81 | 1.35 | 1.30 | 1.28 | 1.24 | 1.35 | 1.60 |
| 25 | 0.3 | 0.7 | 2.41 | 1.89 | 1.42 | 1.36 | 1.34 | 1.30 | 1.42 | 1.54 |
| 25 | 0.25 | 0.75 | 2.38 | 1.97 | 1.49 | 1.44 | 1.41 | 1.36 | 1.49 | 1.49 |
| 25 | 0.2 | 0.8 | 2.36 | 2.06 | 1.57 | 1.52 | 1.48 | 1.43 | 1.57 | 1.43 |
| 25 | 0.15 | 0.85 | 2.34 | 2.15 | 1.65 | 1.60 | 1.57 | 1.51 | 1.65 | 1.38 |
| 25 | 0.1 | 0.9 | 2.32 | 2.26 | 1.75 | 1.70 | 1.66 | 1.59 | 1.75 | 1.33 |
| 25 | 0.05 | 0.95 | 2.30 | 2.38 | 1.86 | 1.82 | 1.77 | 1.69 | 1.86 | 1.27 |
| 25 | 0 | 1 | 2.27 | 2.51 | 1.98 | 1.95 | 1.89 | 1.80 | 1.98 | 1.22 |
| 30 | 1 | 0 | 3.05 | 1.37 | 0.97 | 0.91 | 0.90 | 0.88 | 0.97 | 2.35 |
| 30 | 0.95 | 0.05 | 3.02 | 1.40 | 1.00 | 0.93 | 0.92 | 0.91 | 1.00 | 2.29 |
| 30 | 0.9 | 0.1 | 2.98 | 1.44 | 1.03 | 0.96 | 0.95 | 0.93 | 1.03 | 2.23 |
| 30 | 0.85 | 0.15 | 2.95 | 1.48 | 1.06 | 0.99 | 0.98 | 0.96 | 1.06 | 2.17 |
| 30 | 0.8 | 0.2 | 2.93 | 1.52 | 1.09 | 1.02 | 1.01 | 0.99 | 1.09 | 2.11 |
| 30 | 0.75 | 0.25 | 2.90 | 1.57 | 1.12 | 1.05 | 1.04 | 1.02 | 1.12 | 2.05 |
| 30 | 0.7 | 0.3 | 2.87 | 1.61 | 1.16 | 1.09 | 1.07 | 1.05 | 1.16 | 2.00 |
| 30 | 0.65 | 0.35 | 2.84 | 1.66 | 1.20 | 1.12 | 1.11 | 1.09 | 1.20 | 1.94 |
| 30 | 0.6 | 0.4 | 2.81 | 1.71 | 1.24 | 1.16 | 1.15 | 1.12 | 1.24 | 1.88 |
| 30 | 0.55 | 0.45 | 2.79 | 1.77 | 1.28 | 1.21 | 1.19 | 1.16 | 1.28 | 1.83 |
| 30 | 0.5 | 0.5 | 2.76 | 1.83 | 1.33 | 1.25 | 1.24 | 1.20 | 1.33 | 1.78 |
| 30 | 0.45 | 0.55 | 2.73 | 1.89 | 1.38 | 1.30 | 1.28 | 1.25 | 1.38 | 1.72 |
| 30 | 0.4 | 0.6 | 2.71 | 1.96 | 1.44 | 1.36 | 1.33 | 1.30 | 1.44 | 1.67 |
| 30 | 0.35 | 0.65 | 2.68 | 2.03 | 1.50 | 1.41 | 1.39 | 1.35 | 1.50 | 1.62 |
| 30 | 0.3 | 0.7 | 2.66 | 2.11 | 1.56 | 1.48 | 1.45 | 1.41 | 1.56 | 1.57 |
| 30 | 0.25 | 0.75 | 2.64 | 2.20 | 1.64 | 1.55 | 1.52 | 1.47 | 1.64 | 1.52 |
| 30 | 0.2 | 0.8 | 2.61 | 2.29 | 1.71 | 1.63 | 1.59 | 1.54 | 1.71 | 1.47 |
| 30 | 0.15 | 0.85 | 2.59 | 2.39 | 1.80 | 1.71 | 1.67 | 1.61 | 1.80 | 1.42 |
| 30 | 0.1 | 0.9 | 2.57 | 2.50 | 1.89 | 1.81 | 1.76 | 1.69 | 1.89 | 1.37 |
| 30 | 0.05 | 0.95 | 2.55 | 2.62 | 2.00 | 1.91 | 1.86 | 1.78 | 2.00 | 1.32 |
| 30 | 0 | 1 | 2.52 | 2.76 | 2.12 | 2.03 | 1.97 | 1.88 | 2.12 | 1.27 |

| | 125 Hz | 250 Hz | 500 Hz | 1 kHz | 2 kHz | 4 kHz |
|---|---|---|---|---|---|---|
| 2" Fiberglass Board | 0.18 | 0.76 | 0.99 | 0.99 | 0.99 | 0.99 |
| 3/8 in. Plywood | 0.28 | 0.22 | 0.17 | 0.09 | 0.1 | 0.11 |
| Walls | 0.12 | 0.13 | 0.21 | 0.26 | 0.27 | 0.28 |
| Floor | 0.04 | 0.04 | 0.07 | 0.06 | 0.06 | 0.07 |

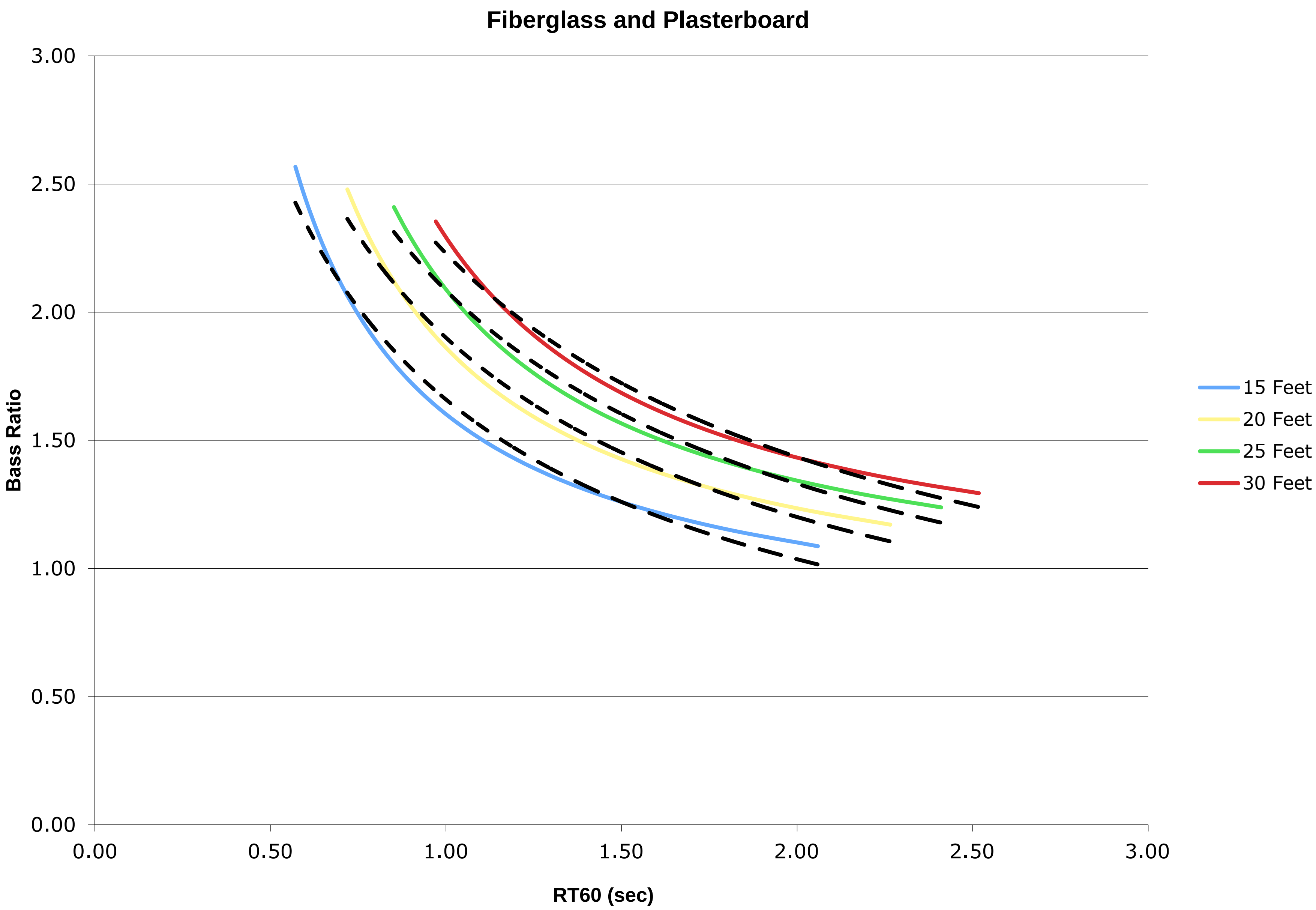


Fiberglass and Plywood
Bass Ratio
RT60 (sec)
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0.00
0.50
1.00
1.50
2.00
2.50
3.00
15 Feet
20 Feet
25 Feet
30 Feet

# Fiberglass and Plasterboard

| Variables | | | Reverberation Times | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Ceiling Height** | **Material 1 (%)** | **Material 2 (%)** | **125 Hz** | **250 Hz** | **500 Hz** | **1 kHz** | **2 kHz** | **4 kHz** | **RT @ 500** | **Bass Ratio** |
| 15 | 1 | 0 | 2.09 | 0.78 | 0.57 | 0.55 | 0.55 | 0.54 | 0.57 | 2.57 |
| 15 | 0.95 | 0.05 | 2.06 | 0.81 | 0.59 | 0.57 | 0.57 | 0.56 | 0.59 | 2.47 |
| 15 | 0.9 | 0.1 | 2.03 | 0.84 | 0.62 | 0.59 | 0.59 | 0.58 | 0.62 | 2.38 |
| 15 | 0.85 | 0.15 | 2.00 | 0.88 | 0.64 | 0.61 | 0.61 | 0.60 | 0.64 | 2.29 |
| 15 | 0.8 | 0.2 | 1.97 | 0.91 | 0.67 | 0.64 | 0.64 | 0.63 | 0.67 | 2.21 |
| 15 | 0.75 | 0.25 | 1.94 | 0.95 | 0.70 | 0.67 | 0.67 | 0.65 | 0.70 | 2.12 |
| 15 | 0.7 | 0.3 | 1.91 | 0.99 | 0.73 | 0.70 | 0.69 | 0.68 | 0.73 | 2.04 |
| 15 | 0.65 | 0.35 | 1.89 | 1.04 | 0.76 | 0.73 | 0.73 | 0.71 | 0.76 | 1.96 |
| 15 | 0.6 | 0.4 | 1.86 | 1.09 | 0.80 | 0.76 | 0.76 | 0.75 | 0.80 | 1.88 |
| 15 | 0.55 | 0.45 | 1.83 | 1.15 | 0.85 | 0.80 | 0.80 | 0.79 | 0.85 | 1.81 |
| 15 | 0.5 | 0.5 | 1.81 | 1.21 | 0.89 | 0.85 | 0.85 | 0.83 | 0.89 | 1.73 |
| 15 | 0.45 | 0.55 | 1.79 | 1.28 | 0.95 | 0.90 | 0.90 | 0.88 | 0.95 | 1.66 |
| 15 | 0.4 | 0.6 | 1.76 | 1.36 | 1.01 | 0.95 | 0.95 | 0.93 | 1.01 | 1.59 |
| 15 | 0.35 | 0.65 | 1.74 | 1.45 | 1.08 | 1.01 | 1.01 | 0.99 | 1.08 | 1.53 |
| 15 | 0.3 | 0.7 | 1.72 | 1.55 | 1.16 | 1.08 | 1.08 | 1.06 | 1.16 | 1.46 |
| 15 | 0.25 | 0.75 | 1.69 | 1.66 | 1.25 | 1.16 | 1.17 | 1.13 | 1.25 | 1.39 |
| 15 | 0.2 | 0.8 | 1.67 | 1.80 | 1.35 | 1.26 | 1.26 | 1.22 | 1.35 | 1.33 |
| 15 | 0.15 | 0.85 | 1.65 | 1.96 | 1.48 | 1.37 | 1.37 | 1.33 | 1.48 | 1.27 |
| 15 | 0.1 | 0.9 | 1.63 | 2.14 | 1.63 | 1.50 | 1.51 | 1.45 | 1.63 | 1.21 |
| 15 | 0.05 | 0.95 | 1.61 | 2.37 | 1.82 | 1.65 | 1.67 | 1.60 | 1.82 | 1.15 |
| 15 | 0 | 1 | 1.59 | 2.66 | 2.06 | 1.85 | 1.87 | 1.79 | 2.06 | 1.09 |
| 20 | 1 | 0 | 2.48 | 1.00 | 0.72 | 0.68 | 0.68 | 0.67 | 0.72 | 2.48 |
| 20 | 0.95 | 0.05 | 2.45 | 1.03 | 0.74 | 0.71 | 0.70 | 0.69 | 0.74 | 2.40 |
| 20 | 0.9 | 0.1 | 2.41 | 1.07 | 0.77 | 0.73 | 0.73 | 0.72 | 0.77 | 2.32 |
| 20 | 0.85 | 0.15 | 2.38 | 1.11 | 0.80 | 0.76 | 0.76 | 0.74 | 0.80 | 2.24 |
| 20 | 0.8 | 0.2 | 2.35 | 1.15 | 0.83 | 0.79 | 0.78 | 0.77 | 0.83 | 2.16 |
| 20 | 0.75 | 0.25 | 2.32 | 1.20 | 0.87 | 0.82 | 0.81 | 0.80 | 0.87 | 2.09 |
| 20 | 0.7 | 0.3 | 2.29 | 1.25 | 0.90 | 0.85 | 0.85 | 0.83 | 0.90 | 2.02 |
| 20 | 0.65 | 0.35 | 2.26 | 1.30 | 0.94 | 0.89 | 0.88 | 0.87 | 0.94 | 1.95 |
| 20 | 0.6 | 0.4 | 2.23 | 1.36 | 0.99 | 0.93 | 0.92 | 0.91 | 0.99 | 1.88 |
| 20 | 0.55 | 0.45 | 2.20 | 1.43 | 1.04 | 0.97 | 0.97 | 0.95 | 1.04 | 1.81 |
| 20 | 0.5 | 0.5 | 2.18 | 1.50 | 1.09 | 1.02 | 1.02 | 0.99 | 1.09 | 1.74 |
| 20 | 0.45 | 0.55 | 2.15 | 1.58 | 1.15 | 1.07 | 1.07 | 1.04 | 1.15 | 1.68 |
| 20 | 0.4 | 0.6 | 2.13 | 1.67 | 1.22 | 1.13 | 1.13 | 1.10 | 1.22 | 1.62 |
| 20 | 0.35 | 0.65 | 2.10 | 1.77 | 1.29 | 1.19 | 1.19 | 1.16 | 1.29 | 1.56 |
| 20 | 0.3 | 0.7 | 2.08 | 1.88 | 1.38 | 1.26 | 1.26 | 1.23 | 1.38 | 1.50 |
| 20 | 0.25 | 0.75 | 2.05 | 2.01 | 1.47 | 1.35 | 1.35 | 1.31 | 1.47 | 1.44 |
| 20 | 0.2 | 0.8 | 2.03 | 2.16 | 1.58 | 1.44 | 1.44 | 1.40 | 1.58 | 1.38 |
| 20 | 0.15 | 0.85 | 2.01 | 2.33 | 1.71 | 1.55 | 1.55 | 1.50 | 1.71 | 1.33 |
| 20 | 0.1 | 0.9 | 1.98 | 2.52 | 1.86 | 1.67 | 1.67 | 1.62 | 1.86 | 1.28 |
| 20 | 0.05 | 0.95 | 1.96 | 2.76 | 2.05 | 1.82 | 1.82 | 1.75 | 2.05 | 1.22 |
| 20 | 0 | 1 | 1.94 | 3.04 | 2.27 | 1.99 | 2.00 | 1.92 | 2.27 | 1.17 |
| 25 | 1 | 0 | 2.79 | 1.19 | 0.85 | 0.80 | 0.80 | 0.78 | 0.85 | 2.41 |
| 25 | 0.95 | 0.05 | 2.76 | 1.23 | 0.88 | 0.83 | 0.82 | 0.81 | 0.88 | 2.34 |
| 25 | 0.9 | 0.1 | 2.72 | 1.27 | 0.91 | 0.85 | 0.85 | 0.84 | 0.91 | 2.27 |
| 25 | 0.85 | 0.15 | 2.69 | 1.32 | 0.94 | 0.88 | 0.88 | 0.86 | 0.94 | 2.20 |
| 25 | 0.8 | 0.2 | 2.66 | 1.37 | 0.98 | 0.91 | 0.91 | 0.89 | 0.98 | 2.13 |
| 25 | 0.75 | 0.25 | 2.63 | 1.42 | 1.02 | 0.95 | 0.94 | 0.93 | 1.02 | 2.06 |
| 25 | 0.7 | 0.3 | 2.60 | 1.48 | 1.06 | 0.98 | 0.98 | 0.96 | 1.06 | 2.00 |
| 25 | 0.65 | 0.35 | 2.57 | 1.54 | 1.10 | 1.02 | 1.02 | 1.00 | 1.10 | 1.93 |
| 25 | 0.6 | 0.4 | 2.54 | 1.60 | 1.15 | 1.06 | 1.06 | 1.04 | 1.15 | 1.87 |
| 25 | 0.55 | 0.45 | 2.51 | 1.68 | 1.20 | 1.11 | 1.10 | 1.08 | 1.20 | 1.81 |
| 25 | 0.5 | 0.5 | 2.48 | 1.76 | 1.26 | 1.16 | 1.15 | 1.13 | 1.26 | 1.75 |
| 25 | 0.45 | 0.55 | 2.45 | 1.84 | 1.32 | 1.21 | 1.21 | 1.18 | 1.32 | 1.70 |
| 25 | 0.4 | 0.6 | 2.43 | 1.94 | 1.39 | 1.27 | 1.27 | 1.24 | 1.39 | 1.64 |
| 25 | 0.35 | 0.65 | 2.40 | 2.05 | 1.47 | 1.34 | 1.33 | 1.30 | 1.47 | 1.59 |
| 25 | 0.3 | 0.7 | 2.38 | 2.16 | 1.56 | 1.41 | 1.40 | 1.37 | 1.56 | 1.53 |
| 25 | 0.25 | 0.75 | 2.35 | 2.30 | 1.65 | 1.49 | 1.48 | 1.44 | 1.65 | 1.48 |
| 25 | 0.2 | 0.8 | 2.33 | 2.45 | 1.76 | 1.58 | 1.58 | 1.53 | 1.76 | 1.43 |
| 25 | 0.15 | 0.85 | 2.30 | 2.62 | 1.89 | 1.68 | 1.68 | 1.63 | 1.89 | 1.38 |
| 25 | 0.1 | 0.9 | 2.28 | 2.82 | 2.04 | 1.79 | 1.79 | 1.73 | 2.04 | 1.33 |
| 25 | 0.05 | 0.95 | 2.25 | 3.06 | 2.21 | 1.93 | 1.93 | 1.86 | 2.21 | 1.28 |
| 25 | 0 | 1 | 2.23 | 3.33 | 2.41 | 2.08 | 2.08 | 2.00 | 2.41 | 1.24 |
| 30 | 1 | 0 | 3.05 | 1.37 | 0.97 | 0.91 | 0.90 | 0.88 | 0.97 | 2.35 |
| 30 | 0.95 | 0.05 | 3.01 | 1.41 | 1.00 | 0.93 | 0.93 | 0.91 | 1.00 | 2.29 |
| 30 | 0.9 | 0.1 | 2.98 | 1.46 | 1.03 | 0.96 | 0.95 | 0.94 | 1.03 | 2.22 |
| 30 | 0.85 | 0.15 | 2.95 | 1.51 | 1.07 | 0.99 | 0.98 | 0.97 | 1.07 | 2.16 |
| 30 | 0.8 | 0.2 | 2.91 | 1.56 | 1.11 | 1.02 | 1.02 | 1.00 | 1.11 | 2.10 |
| 30 | 0.75 | 0.25 | 2.88 | 1.62 | 1.15 | 1.06 | 1.05 | 1.03 | 1.15 | 2.04 |
| 30 | 0.7 | 0.3 | 2.85 | 1.68 | 1.19 | 1.10 | 1.09 | 1.07 | 1.19 | 1.98 |
| 30 | 0.65 | 0.35 | 2.82 | 1.74 | 1.24 | 1.13 | 1.13 | 1.11 | 1.24 | 1.93 |
| 30 | 0.6 | 0.4 | 2.79 | 1.82 | 1.29 | 1.18 | 1.17 | 1.15 | 1.29 | 1.87 |
| 30 | 0.55 | 0.45 | 2.76 | 1.89 | 1.34 | 1.22 | 1.22 | 1.19 | 1.34 | 1.81 |
| 30 | 0.5 | 0.5 | 2.73 | 1.98 | 1.40 | 1.27 | 1.27 | 1.24 | 1.40 | 1.76 |
| 30 | 0.45 | 0.55 | 2.71 | 2.07 | 1.47 | 1.33 | 1.32 | 1.29 | 1.47 | 1.71 |
| 30 | 0.4 | 0.6 | 2.68 | 2.17 | 1.54 | 1.39 | 1.38 | 1.35 | 1.54 | 1.66 |
| 30 | 0.35 | 0.65 | 2.65 | 2.28 | 1.62 | 1.45 | 1.44 | 1.41 | 1.62 | 1.61 |
| 30 | 0.3 | 0.7 | 2.63 | 2.40 | 1.70 | 1.52 | 1.52 | 1.48 | 1.70 | 1.56 |
| 30 | 0.25 | 0.75 | 2.60 | 2.54 | 1.80 | 1.60 | 1.59 | 1.55 | 1.80 | 1.51 |
| 30 | 0.2 | 0.8 | 2.58 | 2.70 | 1.91 | 1.69 | 1.68 | 1.63 | 1.91 | 1.47 |
| 30 | 0.15 | 0.85 | 2.55 | 2.87 | 2.03 | 1.78 | 1.78 | 1.72 | 2.03 | 1.42 |
| 30 | 0.1 | 0.9 | 2.53 | 3.07 | 2.17 | 1.89 | 1.88 | 1.82 | 2.17 | 1.38 |
| 30 | 0.05 | 0.95 | 2.50 | 3.29 | 2.33 | 2.01 | 2.01 | 1.94 | 2.33 | 1.34 |
| 30 | 0 | 1 | 2.48 | 3.56 | 2.52 | 2.15 | 2.15 | 2.07 | 2.52 | 1.29 |

| | 125 Hz | 250 Hz | 500 Hz | 1 kHz | 2 kHz | 4 kHz |
|---|---|---|---|---|---|---|
| 2" Fiberglass Board | 0.18 | 0.76 | 0.99 | 0.99 | 0.99 | 0.99 |
| Plasterboard | 0.29 | 0.1 | 0.06 | 0.05 | 0.04 | 0.04 |
| Walls | 0.12 | 0.13 | 0.21 | 0.26 | 0.27 | 0.28 |
| Floor | 0.04 | 0.04 | 0.07 | 0.06 | 0.06 | 0.07 |

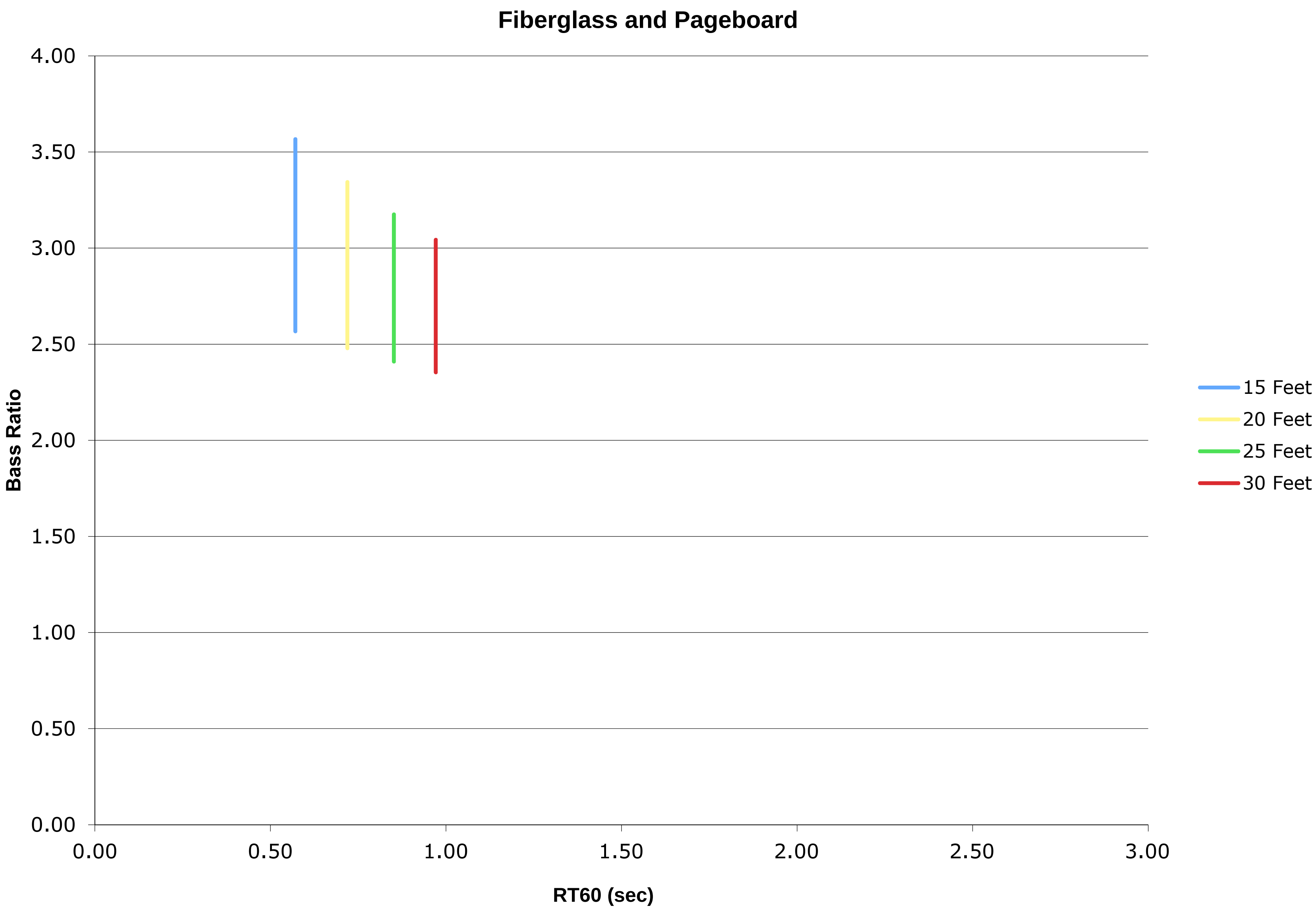


Fiberglass and Plasterboard
Bass Ratio
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0.00
0.50
1.00
1.50
2.00
2.50
3.00
RT60 (sec)
15 Feet
20 Feet
25 Feet
30 Feet

## Fiberglass and Pageboard

| Variables | | | Reverberation Times | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Ceiling Height | Material 1 (%) | Material 2 (%) | 125 Hz | 250 Hz | 500 Hz | 1 kHz | 2 kHz | 4 kHz | RT @ 500 | Bass Ratio |
| 15 | 1 | 0 | 2.09 | 0.78 | 0.57 | 0.55 | 0.55 | 0.54 | 0.57 | 2.57 |
| 15 | 0.95 | 0.05 | 2.12 | 0.80 | 0.57 | 0.55 | 0.56 | 0.56 | 0.57 | 2.60 |
| 15 | 0.9 | 0.1 | 2.15 | 0.82 | 0.57 | 0.56 | 0.58 | 0.58 | 0.57 | 2.63 |
| 15 | 0.85 | 0.15 | 2.19 | 0.84 | 0.57 | 0.56 | 0.59 | 0.60 | 0.57 | 2.67 |
| 15 | 0.8 | 0.2 | 2.22 | 0.87 | 0.57 | 0.57 | 0.61 | 0.62 | 0.57 | 2.71 |
| 15 | 0.75 | 0.25 | 2.25 | 0.89 | 0.57 | 0.57 | 0.62 | 0.64 | 0.57 | 2.74 |
| 15 | 0.7 | 0.3 | 2.29 | 0.91 | 0.57 | 0.58 | 0.64 | 0.67 | 0.57 | 2.78 |
| 15 | 0.65 | 0.35 | 2.32 | 0.94 | 0.57 | 0.58 | 0.66 | 0.70 | 0.57 | 2.82 |
| 15 | 0.6 | 0.4 | 2.36 | 0.97 | 0.57 | 0.59 | 0.68 | 0.73 | 0.57 | 2.87 |
| 15 | 0.55 | 0.45 | 2.40 | 0.99 | 0.57 | 0.60 | 0.70 | 0.76 | 0.57 | 2.91 |
| 15 | 0.5 | 0.5 | 2.44 | 1.03 | 0.57 | 0.60 | 0.72 | 0.79 | 0.57 | 2.96 |
| 15 | 0.45 | 0.55 | 2.48 | 1.06 | 0.57 | 0.61 | 0.75 | 0.83 | 0.57 | 3.00 |
| 15 | 0.4 | 0.6 | 2.52 | 1.09 | 0.57 | 0.61 | 0.77 | 0.88 | 0.57 | 3.05 |
| 15 | 0.35 | 0.65 | 2.57 | 1.13 | 0.57 | 0.62 | 0.80 | 0.92 | 0.57 | 3.11 |
| 15 | 0.3 | 0.7 | 2.61 | 1.17 | 0.57 | 0.62 | 0.83 | 0.98 | 0.57 | 3.16 |
| 15 | 0.25 | 0.75 | 2.66 | 1.21 | 0.57 | 0.63 | 0.86 | 1.04 | 0.57 | 3.22 |
| 15 | 0.2 | 0.8 | 2.71 | 1.26 | 0.57 | 0.64 | 0.89 | 1.11 | 0.57 | 3.28 |
| 15 | 0.15 | 0.85 | 2.76 | 1.31 | 0.57 | 0.64 | 0.93 | 1.18 | 0.57 | 3.35 |
| 15 | 0.1 | 0.9 | 2.81 | 1.36 | 0.57 | 0.65 | 0.97 | 1.27 | 0.57 | 3.42 |
| 15 | 0.05 | 0.95 | 2.87 | 1.42 | 0.57 | 0.66 | 1.01 | 1.38 | 0.57 | 3.49 |
| 15 | 0 | 1 | 2.93 | 1.48 | 0.57 | 0.66 | 1.06 | 1.50 | 0.57 | 3.57 |
| 20 | 1 | 0 | 2.48 | 1.00 | 0.72 | 0.68 | 0.68 | 0.67 | 0.72 | 2.48 |
| 20 | 0.95 | 0.05 | 2.51 | 1.02 | 0.72 | 0.69 | 0.70 | 0.69 | 0.72 | 2.51 |
| 20 | 0.9 | 0.1 | 2.55 | 1.04 | 0.72 | 0.70 | 0.71 | 0.71 | 0.72 | 2.54 |
| 20 | 0.85 | 0.15 | 2.58 | 1.07 | 0.72 | 0.70 | 0.73 | 0.74 | 0.72 | 2.57 |
| 20 | 0.8 | 0.2 | 2.61 | 1.10 | 0.72 | 0.71 | 0.75 | 0.76 | 0.72 | 2.60 |
| 20 | 0.75 | 0.25 | 2.65 | 1.12 | 0.72 | 0.71 | 0.77 | 0.79 | 0.72 | 2.63 |
| 20 | 0.7 | 0.3 | 2.68 | 1.15 | 0.72 | 0.72 | 0.79 | 0.82 | 0.72 | 2.67 |
| 20 | 0.65 | 0.35 | 2.72 | 1.18 | 0.72 | 0.72 | 0.81 | 0.85 | 0.72 | 2.70 |
| 20 | 0.6 | 0.4 | 2.76 | 1.22 | 0.72 | 0.73 | 0.83 | 0.88 | 0.72 | 2.74 |
| 20 | 0.55 | 0.45 | 2.80 | 1.25 | 0.72 | 0.74 | 0.85 | 0.92 | 0.72 | 2.78 |
| 20 | 0.5 | 0.5 | 2.84 | 1.29 | 0.72 | 0.74 | 0.88 | 0.96 | 0.72 | 2.82 |
| 20 | 0.45 | 0.55 | 2.88 | 1.32 | 0.72 | 0.75 | 0.91 | 1.00 | 0.72 | 2.86 |
| 20 | 0.4 | 0.6 | 2.93 | 1.36 | 0.72 | 0.76 | 0.93 | 1.04 | 0.72 | 2.91 |
| 20 | 0.35 | 0.65 | 2.97 | 1.41 | 0.72 | 0.76 | 0.96 | 1.09 | 0.72 | 2.95 |
| 20 | 0.3 | 0.7 | 3.02 | 1.45 | 0.72 | 0.77 | 0.99 | 1.15 | 0.72 | 3.00 |
| 20 | 0.25 | 0.75 | 3.06 | 1.50 | 0.72 | 0.78 | 1.03 | 1.21 | 0.72 | 3.05 |
| 20 | 0.2 | 0.8 | 3.11 | 1.55 | 0.72 | 0.78 | 1.07 | 1.28 | 0.72 | 3.10 |
| 20 | 0.15 | 0.85 | 3.16 | 1.61 | 0.72 | 0.79 | 1.10 | 1.36 | 0.72 | 3.16 |
| 20 | 0.1 | 0.9 | 3.21 | 1.67 | 0.72 | 0.80 | 1.15 | 1.45 | 0.72 | 3.22 |
| 20 | 0.05 | 0.95 | 3.27 | 1.74 | 0.72 | 0.81 | 1.19 | 1.54 | 0.72 | 3.28 |
| 20 | 0 | 1 | 3.32 | 1.81 | 0.72 | 0.81 | 1.24 | 1.66 | 0.72 | 3.34 |
| 25 | 1 | 0 | 2.79 | 1.19 | 0.85 | 0.80 | 0.80 | 0.78 | 0.85 | 2.41 |
| 25 | 0.95 | 0.05 | 2.82 | 1.22 | 0.85 | 0.81 | 0.81 | 0.81 | 0.85 | 2.44 |
| 25 | 0.9 | 0.1 | 2.86 | 1.25 | 0.85 | 0.81 | 0.83 | 0.83 | 0.85 | 2.46 |
| 25 | 0.85 | 0.15 | 2.89 | 1.27 | 0.85 | 0.82 | 0.85 | 0.86 | 0.85 | 2.49 |
| 25 | 0.8 | 0.2 | 2.93 | 1.30 | 0.85 | 0.83 | 0.87 | 0.88 | 0.85 | 2.52 |
| 25 | 0.75 | 0.25 | 2.96 | 1.33 | 0.85 | 0.83 | 0.89 | 0.91 | 0.85 | 2.55 |
| 25 | 0.7 | 0.3 | 3.00 | 1.37 | 0.85 | 0.84 | 0.91 | 0.94 | 0.85 | 2.58 |
| 25 | 0.65 | 0.35 | 3.03 | 1.40 | 0.85 | 0.85 | 0.94 | 0.97 | 0.85 | 2.61 |
| 25 | 0.6 | 0.4 | 3.07 | 1.44 | 0.85 | 0.85 | 0.96 | 1.01 | 0.85 | 2.65 |
| 25 | 0.55 | 0.45 | 3.11 | 1.48 | 0.85 | 0.86 | 0.98 | 1.05 | 0.85 | 2.68 |
| 25 | 0.5 | 0.5 | 3.15 | 1.52 | 0.85 | 0.87 | 1.01 | 1.09 | 0.85 | 2.72 |
| 25 | 0.45 | 0.55 | 3.19 | 1.56 | 0.85 | 0.87 | 1.04 | 1.13 | 0.85 | 2.75 |
| 25 | 0.4 | 0.6 | 3.23 | 1.60 | 0.85 | 0.88 | 1.07 | 1.18 | 0.85 | 2.79 |
| 25 | 0.35 | 0.65 | 3.28 | 1.65 | 0.85 | 0.89 | 1.10 | 1.23 | 0.85 | 2.83 |
| 25 | 0.3 | 0.7 | 3.32 | 1.70 | 0.85 | 0.90 | 1.13 | 1.29 | 0.85 | 2.87 |
| 25 | 0.25 | 0.75 | 3.37 | 1.76 | 0.85 | 0.90 | 1.17 | 1.35 | 0.85 | 2.92 |
| 25 | 0.2 | 0.8 | 3.41 | 1.81 | 0.85 | 0.91 | 1.20 | 1.42 | 0.85 | 2.97 |
| 25 | 0.15 | 0.85 | 3.46 | 1.87 | 0.85 | 0.92 | 1.24 | 1.49 | 0.85 | 3.01 |
| 25 | 0.1 | 0.9 | 3.51 | 1.94 | 0.85 | 0.93 | 1.29 | 1.57 | 0.85 | 3.06 |
| 25 | 0.05 | 0.95 | 3.56 | 2.01 | 0.85 | 0.94 | 1.33 | 1.67 | 0.85 | 3.12 |
| 25 | 0 | 1 | 3.62 | 2.08 | 0.85 | 0.94 | 1.38 | 1.77 | 0.85 | 3.18 |
| 30 | 1 | 0 | 3.05 | 1.37 | 0.97 | 0.91 | 0.90 | 0.88 | 0.97 | 2.35 |
| 30 | 0.95 | 0.05 | 3.08 | 1.40 | 0.97 | 0.91 | 0.92 | 0.91 | 0.97 | 2.38 |
| 30 | 0.9 | 0.1 | 3.11 | 1.43 | 0.97 | 0.92 | 0.94 | 0.93 | 0.97 | 2.40 |
| 30 | 0.85 | 0.15 | 3.14 | 1.46 | 0.97 | 0.92 | 0.96 | 0.96 | 0.97 | 2.43 |
| 30 | 0.8 | 0.2 | 3.18 | 1.49 | 0.97 | 0.93 | 0.98 | 0.99 | 0.97 | 2.45 |
| 30 | 0.75 | 0.25 | 3.21 | 1.53 | 0.97 | 0.94 | 1.00 | 1.02 | 0.97 | 2.48 |
| 30 | 0.7 | 0.3 | 3.25 | 1.56 | 0.97 | 0.95 | 1.02 | 1.05 | 0.97 | 2.51 |
| 30 | 0.65 | 0.35 | 3.28 | 1.60 | 0.97 | 0.95 | 1.04 | 1.08 | 0.97 | 2.54 |
| 30 | 0.6 | 0.4 | 3.32 | 1.64 | 0.97 | 0.96 | 1.07 | 1.12 | 0.97 | 2.57 |
| 30 | 0.55 | 0.45 | 3.36 | 1.68 | 0.97 | 0.97 | 1.09 | 1.16 | 0.97 | 2.60 |
| 30 | 0.5 | 0.5 | 3.40 | 1.72 | 0.97 | 0.97 | 1.12 | 1.20 | 0.97 | 2.63 |
| 30 | 0.45 | 0.55 | 3.44 | 1.77 | 0.97 | 0.98 | 1.15 | 1.24 | 0.97 | 2.67 |
| 30 | 0.4 | 0.6 | 3.48 | 1.82 | 0.97 | 0.99 | 1.18 | 1.29 | 0.97 | 2.70 |
| 30 | 0.35 | 0.65 | 3.52 | 1.87 | 0.97 | 1.00 | 1.21 | 1.34 | 0.97 | 2.74 |
| 30 | 0.3 | 0.7 | 3.56 | 1.92 | 0.97 | 1.00 | 1.25 | 1.40 | 0.97 | 2.78 |
| 30 | 0.25 | 0.75 | 3.61 | 1.98 | 0.97 | 1.01 | 1.28 | 1.46 | 0.97 | 2.82 |
| 30 | 0.2 | 0.8 | 3.65 | 2.04 | 0.97 | 1.02 | 1.32 | 1.52 | 0.97 | 2.86 |
| 30 | 0.15 | 0.85 | 3.70 | 2.10 | 0.97 | 1.03 | 1.36 | 1.59 | 0.97 | 2.90 |
| 30 | 0.1 | 0.9 | 3.75 | 2.17 | 0.97 | 1.04 | 1.40 | 1.67 | 0.97 | 2.95 |
| 30 | 0.05 | 0.95 | 3.79 | 2.24 | 0.97 | 1.05 | 1.44 | 1.76 | 0.97 | 2.99 |
| 30 | 0 | 1 | 3.84 | 2.32 | 0.97 | 1.05 | 1.49 | 1.86 | 0.97 | 3.04 |

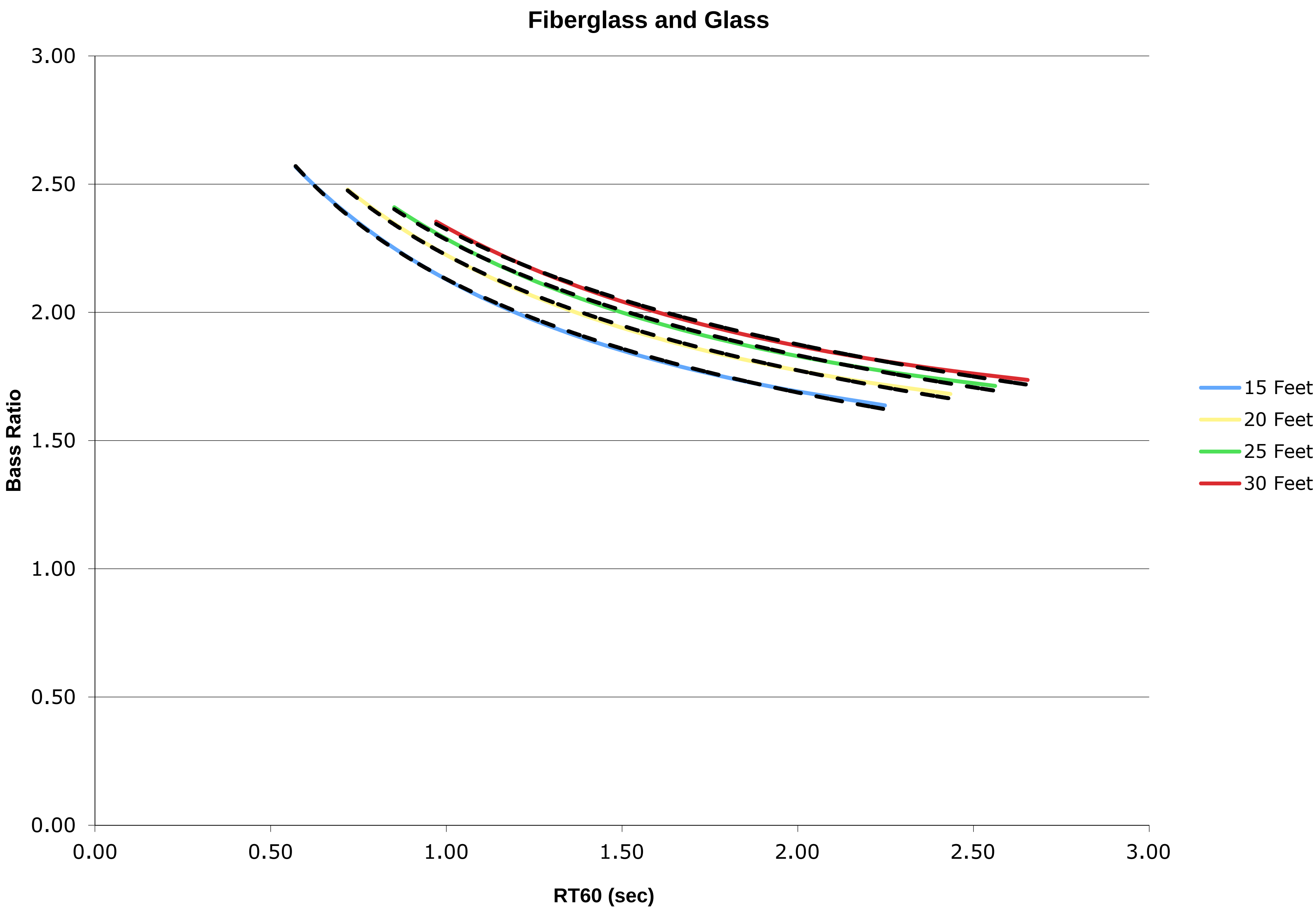
| | 125 Hz | 250 Hz | 500 Hz | 1 kHz | 2 kHz | 4 kHz |
|---|---|---|---|---|---|---|
| 2" Fiberglass Board | 0.18 | 0.76 | 0.99 | 0.99 | 0.99 | 0.99 |
| Pageboard | 0.08 | 0.32 | 0.99 | 0.76 | 0.34 | 0.12 |
| Walls | 0.12 | 0.13 | 0.21 | 0.26 | 0.27 | 0.28 |
| Floor | 0.04 | 0.04 | 0.07 | 0.06 | 0.06 | 0.07 |


Fiberglass and Pageboard
Bass Ratio
RT60 (sec)
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0.00
0.50
1.00
1.50
2.00
2.50
3.00
15 Feet
20 Feet
25 Feet
30 Feet

# Fiberglass and Glass

| Variables | | | Reverberation Times | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Ceiling Height | Material 1 (%) | Material 2 (%) | 125 Hz | 250 Hz | 500 Hz | 1 kHz | 2 kHz | 4 kHz | RT @ 500 | Bass Ratio |
| 15 | 1 | 0 | 2.09 | 0.78 | 0.57 | 0.55 | 0.55 | 0.54 | 0.57 | 2.57 |
| 15 | 0.95 | 0.05 | 2.14 | 0.82 | 0.59 | 0.57 | 0.57 | 0.56 | 0.59 | 2.54 |
| 15 | 0.9 | 0.1 | 2.18 | 0.85 | 0.62 | 0.59 | 0.59 | 0.58 | 0.62 | 2.50 |
| 15 | 0.85 | 0.15 | 2.23 | 0.89 | 0.64 | 0.62 | 0.61 | 0.60 | 0.64 | 2.47 |
| 15 | 0.8 | 0.2 | 2.27 | 0.93 | 0.67 | 0.64 | 0.64 | 0.63 | 0.67 | 2.44 |
| 15 | 0.75 | 0.25 | 2.32 | 0.97 | 0.70 | 0.67 | 0.67 | 0.66 | 0.70 | 2.40 |
| 15 | 0.7 | 0.3 | 2.38 | 1.02 | 0.74 | 0.70 | 0.70 | 0.69 | 0.74 | 2.36 |
| 15 | 0.65 | 0.35 | 2.43 | 1.07 | 0.77 | 0.73 | 0.73 | 0.72 | 0.77 | 2.33 |
| 15 | 0.6 | 0.4 | 2.49 | 1.13 | 0.81 | 0.77 | 0.77 | 0.76 | 0.81 | 2.29 |
| 15 | 0.55 | 0.45 | 2.55 | 1.20 | 0.86 | 0.81 | 0.81 | 0.80 | 0.86 | 2.24 |
| 15 | 0.5 | 0.5 | 2.61 | 1.27 | 0.91 | 0.86 | 0.86 | 0.84 | 0.91 | 2.20 |
| 15 | 0.45 | 0.55 | 2.68 | 1.36 | 0.97 | 0.91 | 0.91 | 0.89 | 0.97 | 2.15 |
| 15 | 0.4 | 0.6 | 2.75 | 1.46 | 1.03 | 0.97 | 0.97 | 0.94 | 1.03 | 2.10 |
| 15 | 0.35 | 0.65 | 2.82 | 1.57 | 1.11 | 1.03 | 1.03 | 1.01 | 1.11 | 2.05 |
| 15 | 0.3 | 0.7 | 2.90 | 1.70 | 1.20 | 1.11 | 1.11 | 1.08 | 1.20 | 2.00 |
| 15 | 0.25 | 0.75 | 2.98 | 1.85 | 1.30 | 1.19 | 1.19 | 1.16 | 1.30 | 1.94 |
| 15 | 0.2 | 0.8 | 3.07 | 2.04 | 1.42 | 1.29 | 1.30 | 1.26 | 1.42 | 1.89 |
| 15 | 0.15 | 0.85 | 3.16 | 2.26 | 1.56 | 1.41 | 1.42 | 1.37 | 1.56 | 1.83 |
| 15 | 0.1 | 0.9 | 3.26 | 2.55 | 1.74 | 1.55 | 1.57 | 1.51 | 1.74 | 1.76 |
| 15 | 0.05 | 0.95 | 3.37 | 2.91 | 1.96 | 1.73 | 1.75 | 1.67 | 1.96 | 1.70 |
| 15 | 0 | 1 | 3.48 | 3.39 | 2.25 | 1.95 | 1.97 | 1.88 | 2.25 | 1.64 |
| 20 | 1 | 0 | 2.48 | 1.00 | 0.72 | 0.68 | 0.68 | 0.67 | 0.72 | 2.48 |
| 20 | 0.95 | 0.05 | 2.53 | 1.04 | 0.75 | 0.71 | 0.70 | 0.69 | 0.75 | 2.45 |
| 20 | 0.9 | 0.1 | 2.57 | 1.08 | 0.77 | 0.73 | 0.73 | 0.72 | 0.77 | 2.42 |
| 20 | 0.85 | 0.15 | 2.62 | 1.12 | 0.80 | 0.76 | 0.76 | 0.74 | 0.80 | 2.39 |
| 20 | 0.8 | 0.2 | 2.67 | 1.17 | 0.84 | 0.79 | 0.79 | 0.77 | 0.84 | 2.36 |
| 20 | 0.75 | 0.25 | 2.72 | 1.22 | 0.87 | 0.82 | 0.82 | 0.80 | 0.87 | 2.33 |
| 20 | 0.7 | 0.3 | 2.78 | 1.28 | 0.91 | 0.86 | 0.85 | 0.84 | 0.91 | 2.29 |
| 20 | 0.65 | 0.35 | 2.83 | 1.34 | 0.95 | 0.89 | 0.89 | 0.87 | 0.95 | 2.26 |
| 20 | 0.6 | 0.4 | 2.89 | 1.41 | 1.00 | 0.93 | 0.93 | 0.91 | 1.00 | 2.22 |
| 20 | 0.55 | 0.45 | 2.95 | 1.49 | 1.05 | 0.98 | 0.98 | 0.96 | 1.05 | 2.18 |
| 20 | 0.5 | 0.5 | 3.02 | 1.57 | 1.11 | 1.03 | 1.03 | 1.00 | 1.11 | 2.15 |
| 20 | 0.45 | 0.55 | 3.08 | 1.67 | 1.17 | 1.08 | 1.08 | 1.06 | 1.17 | 2.11 |
| 20 | 0.4 | 0.6 | 3.15 | 1.78 | 1.25 | 1.14 | 1.14 | 1.11 | 1.25 | 2.06 |
| 20 | 0.35 | 0.65 | 3.22 | 1.91 | 1.33 | 1.21 | 1.21 | 1.18 | 1.33 | 2.02 |
| 20 | 0.3 | 0.7 | 3.30 | 2.05 | 1.42 | 1.29 | 1.29 | 1.25 | 1.42 | 1.98 |
| 20 | 0.25 | 0.75 | 3.38 | 2.22 | 1.53 | 1.37 | 1.38 | 1.34 | 1.53 | 1.93 |
| 20 | 0.2 | 0.8 | 3.46 | 2.41 | 1.65 | 1.47 | 1.48 | 1.43 | 1.65 | 1.88 |
| 20 | 0.15 | 0.85 | 3.55 | 2.65 | 1.79 | 1.59 | 1.59 | 1.54 | 1.79 | 1.83 |
| 20 | 0.1 | 0.9 | 3.64 | 2.93 | 1.97 | 1.72 | 1.73 | 1.67 | 1.97 | 1.78 |
| 20 | 0.05 | 0.95 | 3.74 | 3.29 | 2.17 | 1.88 | 1.89 | 1.82 | 2.17 | 1.73 |
| 20 | 0 | 1 | 3.84 | 3.74 | 2.43 | 2.07 | 2.08 | 2.00 | 2.43 | 1.68 |
| 25 | 1 | 0 | 2.79 | 1.19 | 0.85 | 0.80 | 0.80 | 0.78 | 0.85 | 2.41 |
| 25 | 0.95 | 0.05 | 2.84 | 1.24 | 0.88 | 0.83 | 0.82 | 0.81 | 0.88 | 2.38 |
| 25 | 0.9 | 0.1 | 2.88 | 1.28 | 0.91 | 0.86 | 0.85 | 0.84 | 0.91 | 2.36 |
| 25 | 0.85 | 0.15 | 2.93 | 1.33 | 0.95 | 0.88 | 0.88 | 0.87 | 0.95 | 2.33 |
| 25 | 0.8 | 0.2 | 2.98 | 1.39 | 0.98 | 0.92 | 0.91 | 0.90 | 0.98 | 2.30 |
| 25 | 0.75 | 0.25 | 3.03 | 1.44 | 1.02 | 0.95 | 0.95 | 0.93 | 1.02 | 2.27 |
| 25 | 0.7 | 0.3 | 3.09 | 1.51 | 1.06 | 0.99 | 0.98 | 0.96 | 1.06 | 2.24 |
| 25 | 0.65 | 0.35 | 3.14 | 1.58 | 1.11 | 1.03 | 1.02 | 1.00 | 1.11 | 2.21 |
| 25 | 0.6 | 0.4 | 3.20 | 1.66 | 1.16 | 1.07 | 1.07 | 1.04 | 1.16 | 2.18 |
| 25 | 0.55 | 0.45 | 3.26 | 1.74 | 1.22 | 1.12 | 1.11 | 1.09 | 1.22 | 2.14 |
| 25 | 0.5 | 0.5 | 3.32 | 1.83 | 1.28 | 1.17 | 1.16 | 1.14 | 1.28 | 2.11 |
| 25 | 0.45 | 0.55 | 3.39 | 1.94 | 1.35 | 1.22 | 1.22 | 1.19 | 1.35 | 2.07 |
| 25 | 0.4 | 0.6 | 3.45 | 2.06 | 1.42 | 1.29 | 1.28 | 1.25 | 1.42 | 2.04 |
| 25 | 0.35 | 0.65 | 3.52 | 2.19 | 1.50 | 1.35 | 1.35 | 1.32 | 1.50 | 2.00 |
| 25 | 0.3 | 0.7 | 3.60 | 2.34 | 1.60 | 1.43 | 1.43 | 1.39 | 1.60 | 1.96 |
| 25 | 0.25 | 0.75 | 3.67 | 2.51 | 1.71 | 1.52 | 1.51 | 1.47 | 1.71 | 1.92 |
| 25 | 0.2 | 0.8 | 3.75 | 2.71 | 1.83 | 1.61 | 1.61 | 1.56 | 1.83 | 1.88 |
| 25 | 0.15 | 0.85 | 3.83 | 2.95 | 1.97 | 1.72 | 1.72 | 1.66 | 1.97 | 1.84 |
| 25 | 0.1 | 0.9 | 3.92 | 3.22 | 2.13 | 1.84 | 1.84 | 1.78 | 2.13 | 1.80 |
| 25 | 0.05 | 0.95 | 4.01 | 3.56 | 2.33 | 1.99 | 1.99 | 1.91 | 2.33 | 1.75 |
| 25 | 0 | 1 | 4.10 | 3.98 | 2.56 | 2.15 | 2.16 | 2.07 | 2.56 | 1.71 |
| 30 | 1 | 0 | 3.05 | 1.37 | 0.97 | 0.91 | 0.90 | 0.88 | 0.97 | 2.35 |
| 30 | 0.95 | 0.05 | 3.09 | 1.42 | 1.00 | 0.93 | 0.93 | 0.91 | 1.00 | 2.33 |
| 30 | 0.9 | 0.1 | 3.14 | 1.47 | 1.04 | 0.96 | 0.96 | 0.94 | 1.04 | 2.30 |
| 30 | 0.85 | 0.15 | 3.19 | 1.52 | 1.07 | 0.99 | 0.99 | 0.97 | 1.07 | 2.28 |
| 30 | 0.8 | 0.2 | 3.23 | 1.58 | 1.11 | 1.03 | 1.02 | 1.00 | 1.11 | 2.25 |
| 30 | 0.75 | 0.25 | 3.28 | 1.65 | 1.15 | 1.06 | 1.06 | 1.04 | 1.15 | 2.22 |
| 30 | 0.7 | 0.3 | 3.34 | 1.71 | 1.20 | 1.10 | 1.09 | 1.07 | 1.20 | 2.20 |
| 30 | 0.65 | 0.35 | 3.39 | 1.79 | 1.25 | 1.14 | 1.13 | 1.11 | 1.25 | 2.17 |
| 30 | 0.6 | 0.4 | 3.45 | 1.87 | 1.30 | 1.19 | 1.18 | 1.15 | 1.30 | 2.14 |
| 30 | 0.55 | 0.45 | 3.50 | 1.96 | 1.36 | 1.23 | 1.23 | 1.20 | 1.36 | 2.11 |
| 30 | 0.5 | 0.5 | 3.56 | 2.06 | 1.42 | 1.28 | 1.28 | 1.25 | 1.42 | 2.08 |
| 30 | 0.45 | 0.55 | 3.63 | 2.17 | 1.49 | 1.34 | 1.33 | 1.30 | 1.49 | 2.05 |
| 30 | 0.4 | 0.6 | 3.69 | 2.29 | 1.57 | 1.40 | 1.40 | 1.36 | 1.57 | 2.01 |
| 30 | 0.35 | 0.65 | 3.75 | 2.43 | 1.65 | 1.47 | 1.46 | 1.43 | 1.65 | 1.98 |
| 30 | 0.3 | 0.7 | 3.82 | 2.58 | 1.75 | 1.54 | 1.54 | 1.50 | 1.75 | 1.95 |
| 30 | 0.25 | 0.75 | 3.89 | 2.76 | 1.85 | 1.63 | 1.62 | 1.57 | 1.85 | 1.91 |
| 30 | 0.2 | 0.8 | 3.97 | 2.96 | 1.97 | 1.72 | 1.71 | 1.66 | 1.97 | 1.88 |
| 30 | 0.15 | 0.85 | 4.04 | 3.19 | 2.11 | 1.82 | 1.81 | 1.76 | 2.11 | 1.84 |
| 30 | 0.1 | 0.9 | 4.12 | 3.46 | 2.26 | 1.93 | 1.93 | 1.86 | 2.26 | 1.81 |
| 30 | 0.05 | 0.95 | 4.21 | 3.77 | 2.44 | 2.06 | 2.06 | 1.99 | 2.44 | 1.77 |
| 30 | 0 | 1 | 4.29 | 4.16 | 2.65 | 2.21 | 2.21 | 2.13 | 2.65 | 1.74 |

| | 125 Hz | 250 Hz | 500 Hz | 1 kHz | 2 kHz | 4 kHz |
|---|---|---|---|---|---|---|
| 2" Fiberglass Board | 0.18 | 0.76 | 0.99 | 0.99 | 0.99 | 0.99 |
| Glass | 0.04 | 0.04 | 0.03 | 0.03 | 0.02 | 0.02 |
| Walls | 0.12 | 0.13 | 0.21 | 0.26 | 0.27 | 0.28 |
| Floor | 0.04 | 0.04 | 0.07 | 0.06 | 0.06 | 0.07 |

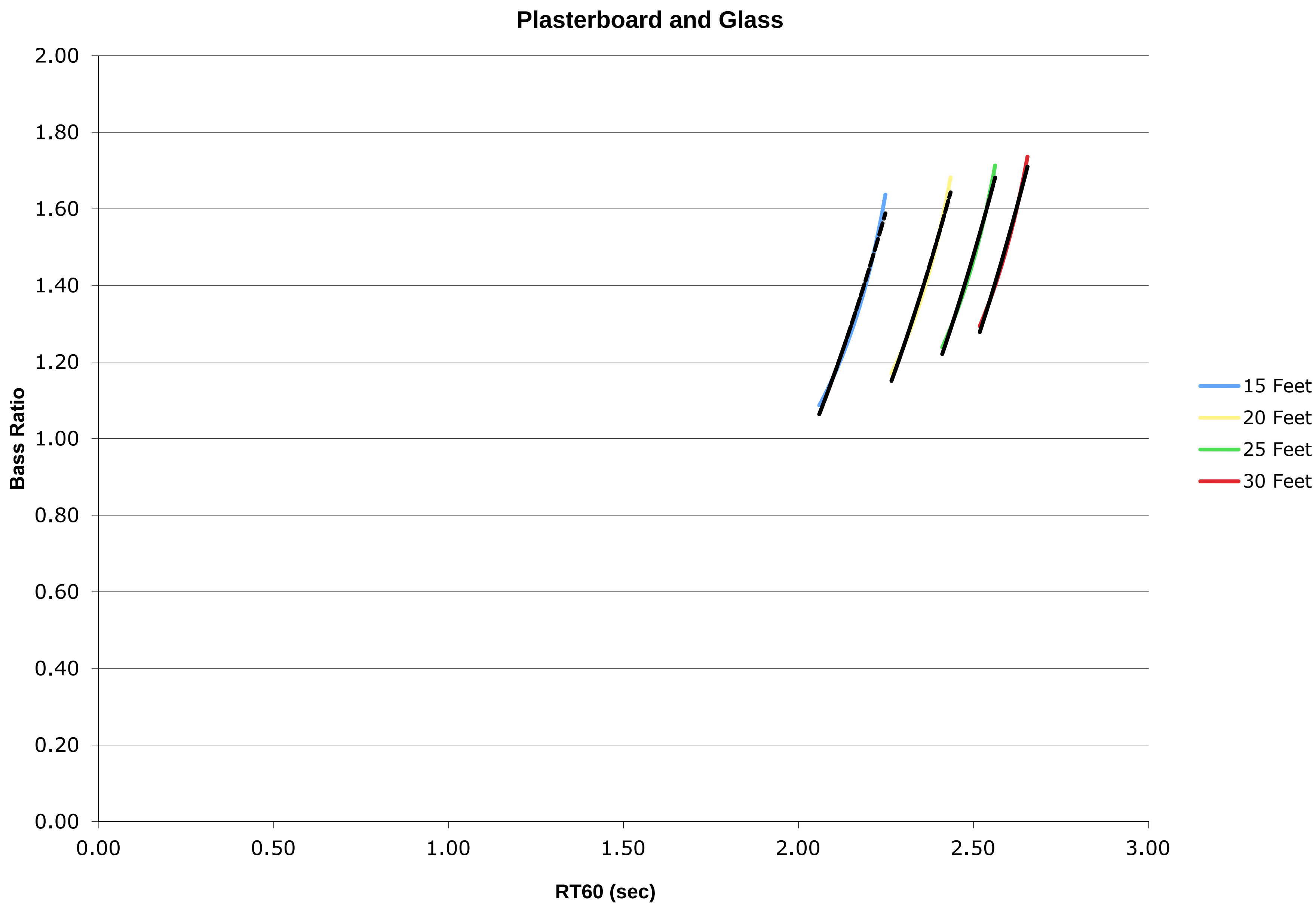


Fiberglass and Glass
Bass Ratio
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0.00
0.50
1.00
1.50
2.00
2.50
3.00
RT60 (sec)
15 Feet
20 Feet
25 Feet
30 Feet

## Plasterboard and Glass

| Variables | | | Reverberation Times | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Ceiling Height** | **Material 1 (%)** | **Material 2 (%)** | **125 Hz** | **250 Hz** | **500 Hz** | **1 kHz** | **2 kHz** | **4 kHz** | **RT @ 500** | **Bass Ratio** |
| 15 | 1 | 0 | 1.59 | 2.66 | 2.06 | 1.85 | 1.87 | 1.79 | 2.06 | 1.09 |
| 15 | 0.95 | 0.05 | 1.64 | 2.69 | 2.07 | 1.86 | 1.88 | 1.79 | 2.07 | 1.10 |
| 15 | 0.9 | 0.1 | 1.68 | 2.71 | 2.08 | 1.86 | 1.88 | 1.80 | 2.08 | 1.12 |
| 15 | 0.85 | 0.15 | 1.73 | 2.75 | 2.09 | 1.86 | 1.89 | 1.80 | 2.09 | 1.13 |
| 15 | 0.8 | 0.2 | 1.79 | 2.78 | 2.09 | 1.87 | 1.89 | 1.81 | 2.09 | 1.15 |
| 15 | 0.75 | 0.25 | 1.84 | 2.81 | 2.10 | 1.87 | 1.90 | 1.81 | 2.10 | 1.17 |
| 15 | 0.7 | 0.3 | 1.90 | 2.84 | 2.11 | 1.88 | 1.90 | 1.82 | 2.11 | 1.19 |
| 15 | 0.65 | 0.35 | 1.97 | 2.87 | 2.12 | 1.88 | 1.91 | 1.82 | 2.12 | 1.21 |
| 15 | 0.6 | 0.4 | 2.03 | 2.91 | 2.13 | 1.89 | 1.91 | 1.82 | 2.13 | 1.23 |
| 15 | 0.55 | 0.45 | 2.11 | 2.94 | 2.14 | 1.89 | 1.92 | 1.83 | 2.14 | 1.25 |
| 15 | 0.5 | 0.5 | 2.19 | 2.98 | 2.15 | 1.90 | 1.92 | 1.83 | 2.15 | 1.28 |
| 15 | 0.45 | 0.55 | 2.27 | 3.02 | 2.16 | 1.90 | 1.93 | 1.84 | 2.16 | 1.30 |
| 15 | 0.4 | 0.6 | 2.36 | 3.05 | 2.17 | 1.91 | 1.93 | 1.84 | 2.17 | 1.33 |
| 15 | 0.35 | 0.65 | 2.46 | 3.09 | 2.18 | 1.91 | 1.94 | 1.85 | 2.18 | 1.36 |
| 15 | 0.3 | 0.7 | 2.57 | 3.13 | 2.19 | 1.92 | 1.94 | 1.85 | 2.19 | 1.39 |
| 15 | 0.25 | 0.75 | 2.68 | 3.17 | 2.20 | 1.92 | 1.95 | 1.86 | 2.20 | 1.42 |
| 15 | 0.2 | 0.8 | 2.81 | 3.21 | 2.21 | 1.93 | 1.95 | 1.86 | 2.21 | 1.46 |
| 15 | 0.15 | 0.85 | 2.95 | 3.26 | 2.22 | 1.93 | 1.96 | 1.87 | 2.22 | 1.50 |
| 15 | 0.1 | 0.9 | 3.11 | 3.30 | 2.23 | 1.94 | 1.96 | 1.87 | 2.23 | 1.54 |
| 15 | 0.05 | 0.95 | 3.28 | 3.35 | 2.24 | 1.94 | 1.97 | 1.88 | 2.24 | 1.59 |
| 15 | 0 | 1 | 3.48 | 3.39 | 2.25 | 1.95 | 1.97 | 1.88 | 2.25 | 1.64 |
| 20 | 1 | 0 | 1.94 | 3.04 | 2.27 | 1.99 | 2.00 | 1.92 | 2.27 | 1.17 |
| 20 | 0.95 | 0.05 | 1.99 | 3.07 | 2.27 | 1.99 | 2.00 | 1.92 | 2.27 | 1.19 |
| 20 | 0.9 | 0.1 | 2.04 | 3.10 | 2.28 | 2.00 | 2.01 | 1.93 | 2.28 | 1.20 |
| 20 | 0.85 | 0.15 | 2.10 | 3.13 | 2.29 | 2.00 | 2.01 | 1.93 | 2.29 | 1.22 |
| 20 | 0.8 | 0.2 | 2.15 | 3.16 | 2.30 | 2.00 | 2.02 | 1.93 | 2.30 | 1.23 |
| 20 | 0.75 | 0.25 | 2.21 | 3.19 | 2.31 | 2.01 | 2.02 | 1.94 | 2.31 | 1.25 |
| 20 | 0.7 | 0.3 | 2.28 | 3.22 | 2.31 | 2.01 | 2.02 | 1.94 | 2.31 | 1.27 |
| 20 | 0.65 | 0.35 | 2.35 | 3.25 | 2.32 | 2.02 | 2.03 | 1.94 | 2.32 | 1.29 |
| 20 | 0.6 | 0.4 | 2.42 | 3.29 | 2.33 | 2.02 | 2.03 | 1.95 | 2.33 | 1.31 |
| 20 | 0.55 | 0.45 | 2.50 | 3.32 | 2.34 | 2.03 | 2.04 | 1.95 | 2.34 | 1.33 |
| 20 | 0.5 | 0.5 | 2.58 | 3.35 | 2.35 | 2.03 | 2.04 | 1.96 | 2.35 | 1.36 |
| 20 | 0.45 | 0.55 | 2.67 | 3.39 | 2.36 | 2.03 | 2.05 | 1.96 | 2.36 | 1.38 |
| 20 | 0.4 | 0.6 | 2.76 | 3.42 | 2.36 | 2.04 | 2.05 | 1.96 | 2.36 | 1.40 |
| 20 | 0.35 | 0.65 | 2.86 | 3.46 | 2.37 | 2.04 | 2.05 | 1.97 | 2.37 | 1.43 |
| 20 | 0.3 | 0.7 | 2.97 | 3.50 | 2.38 | 2.05 | 2.06 | 1.97 | 2.38 | 1.46 |
| 20 | 0.25 | 0.75 | 3.09 | 3.53 | 2.39 | 2.05 | 2.06 | 1.98 | 2.39 | 1.49 |
| 20 | 0.2 | 0.8 | 3.21 | 3.57 | 2.40 | 2.06 | 2.07 | 1.98 | 2.40 | 1.52 |
| 20 | 0.15 | 0.85 | 3.35 | 3.61 | 2.41 | 2.06 | 2.07 | 1.98 | 2.41 | 1.56 |
| 20 | 0.1 | 0.9 | 3.50 | 3.65 | 2.42 | 2.06 | 2.08 | 1.99 | 2.42 | 1.60 |
| 20 | 0.05 | 0.95 | 3.66 | 3.69 | 2.43 | 2.07 | 2.08 | 1.99 | 2.43 | 1.64 |
| 20 | 0 | 1 | 3.84 | 3.74 | 2.43 | 2.07 | 2.08 | 2.00 | 2.43 | 1.68 |
| 25 | 1 | 0 | 2.23 | 3.33 | 2.41 | 2.08 | 2.08 | 2.00 | 2.41 | 1.24 |
| 25 | 0.95 | 0.05 | 2.28 | 3.36 | 2.42 | 2.09 | 2.09 | 2.01 | 2.42 | 1.25 |
| 25 | 0.9 | 0.1 | 2.34 | 3.39 | 2.42 | 2.09 | 2.09 | 2.01 | 2.42 | 1.27 |
| 25 | 0.85 | 0.15 | 2.40 | 3.41 | 2.43 | 2.09 | 2.10 | 2.01 | 2.43 | 1.28 |
| 25 | 0.8 | 0.2 | 2.46 | 3.44 | 2.44 | 2.10 | 2.10 | 2.02 | 2.44 | 1.30 |
| 25 | 0.75 | 0.25 | 2.52 | 3.47 | 2.45 | 2.10 | 2.10 | 2.02 | 2.45 | 1.32 |
| 25 | 0.7 | 0.3 | 2.59 | 3.50 | 2.45 | 2.10 | 2.11 | 2.02 | 2.45 | 1.34 |
| 25 | 0.65 | 0.35 | 2.66 | 3.53 | 2.46 | 2.11 | 2.11 | 2.03 | 2.46 | 1.35 |
| 25 | 0.6 | 0.4 | 2.73 | 3.56 | 2.47 | 2.11 | 2.11 | 2.03 | 2.47 | 1.37 |
| 25 | 0.55 | 0.45 | 2.81 | 3.59 | 2.48 | 2.11 | 2.12 | 2.03 | 2.48 | 1.39 |
| 25 | 0.5 | 0.5 | 2.89 | 3.63 | 2.48 | 2.12 | 2.12 | 2.04 | 2.48 | 1.42 |
| 25 | 0.45 | 0.55 | 2.98 | 3.66 | 2.49 | 2.12 | 2.12 | 2.04 | 2.49 | 1.44 |
| 25 | 0.4 | 0.6 | 3.07 | 3.69 | 2.50 | 2.12 | 2.13 | 2.04 | 2.50 | 1.46 |
| 25 | 0.35 | 0.65 | 3.17 | 3.72 | 2.51 | 2.13 | 2.13 | 2.05 | 2.51 | 1.49 |
| 25 | 0.3 | 0.7 | 3.28 | 3.76 | 2.51 | 2.13 | 2.14 | 2.05 | 2.51 | 1.51 |
| 25 | 0.25 | 0.75 | 3.39 | 3.79 | 2.52 | 2.14 | 2.14 | 2.05 | 2.52 | 1.54 |
| 25 | 0.2 | 0.8 | 3.51 | 3.83 | 2.53 | 2.14 | 2.14 | 2.06 | 2.53 | 1.57 |
| 25 | 0.15 | 0.85 | 3.64 | 3.87 | 2.54 | 2.14 | 2.15 | 2.06 | 2.54 | 1.60 |
| 25 | 0.1 | 0.9 | 3.78 | 3.90 | 2.55 | 2.15 | 2.15 | 2.06 | 2.55 | 1.64 |
| 25 | 0.05 | 0.95 | 3.94 | 3.94 | 2.55 | 2.15 | 2.15 | 2.07 | 2.55 | 1.67 |
| 25 | 0 | 1 | 4.10 | 3.98 | 2.56 | 2.15 | 2.16 | 2.07 | 2.56 | 1.71 |
| 30 | 1 | 0 | 2.48 | 3.56 | 2.52 | 2.15 | 2.15 | 2.07 | 2.52 | 1.29 |
| 30 | 0.95 | 0.05 | 2.53 | 3.58 | 2.52 | 2.15 | 2.15 | 2.07 | 2.52 | 1.31 |
| 30 | 0.9 | 0.1 | 2.59 | 3.61 | 2.53 | 2.15 | 2.15 | 2.07 | 2.53 | 1.32 |
| 30 | 0.85 | 0.15 | 2.65 | 3.63 | 2.54 | 2.16 | 2.15 | 2.07 | 2.54 | 1.34 |
| 30 | 0.8 | 0.2 | 2.71 | 3.66 | 2.54 | 2.16 | 2.16 | 2.08 | 2.54 | 1.35 |
| 30 | 0.75 | 0.25 | 2.77 | 3.69 | 2.55 | 2.16 | 2.16 | 2.08 | 2.55 | 1.37 |
| 30 | 0.7 | 0.3 | 2.84 | 3.72 | 2.56 | 2.17 | 2.16 | 2.08 | 2.56 | 1.39 |
| 30 | 0.65 | 0.35 | 2.91 | 3.75 | 2.56 | 2.17 | 2.17 | 2.09 | 2.56 | 1.41 |
| 30 | 0.6 | 0.4 | 2.98 | 3.77 | 2.57 | 2.17 | 2.17 | 2.09 | 2.57 | 1.42 |
| 30 | 0.55 | 0.45 | 3.06 | 3.80 | 2.58 | 2.18 | 2.17 | 2.09 | 2.58 | 1.44 |
| 30 | 0.5 | 0.5 | 3.14 | 3.83 | 2.58 | 2.18 | 2.18 | 2.10 | 2.58 | 1.46 |
| 30 | 0.45 | 0.55 | 3.23 | 3.86 | 2.59 | 2.18 | 2.18 | 2.10 | 2.59 | 1.49 |
| 30 | 0.4 | 0.6 | 3.32 | 3.89 | 2.60 | 2.19 | 2.18 | 2.10 | 2.60 | 1.51 |
| 30 | 0.35 | 0.65 | 3.42 | 3.93 | 2.60 | 2.19 | 2.19 | 2.10 | 2.60 | 1.53 |
| 30 | 0.3 | 0.7 | 3.52 | 3.96 | 2.61 | 2.19 | 2.19 | 2.11 | 2.61 | 1.56 |
| 30 | 0.25 | 0.75 | 3.63 | 3.99 | 2.62 | 2.20 | 2.19 | 2.11 | 2.62 | 1.58 |
| 30 | 0.2 | 0.8 | 3.75 | 4.02 | 2.63 | 2.20 | 2.20 | 2.11 | 2.63 | 1.61 |
| 30 | 0.15 | 0.85 | 3.87 | 4.06 | 2.63 | 2.20 | 2.20 | 2.12 | 2.63 | 1.64 |
| 30 | 0.1 | 0.9 | 4.00 | 4.09 | 2.64 | 2.21 | 2.20 | 2.12 | 2.64 | 1.67 |
| 30 | 0.05 | 0.95 | 4.14 | 4.12 | 2.65 | 2.21 | 2.21 | 2.12 | 2.65 | 1.70 |
| 30 | 0 | 1 | 4.29 | 4.16 | 2.65 | 2.21 | 2.21 | 2.13 | 2.65 | 1.74 |

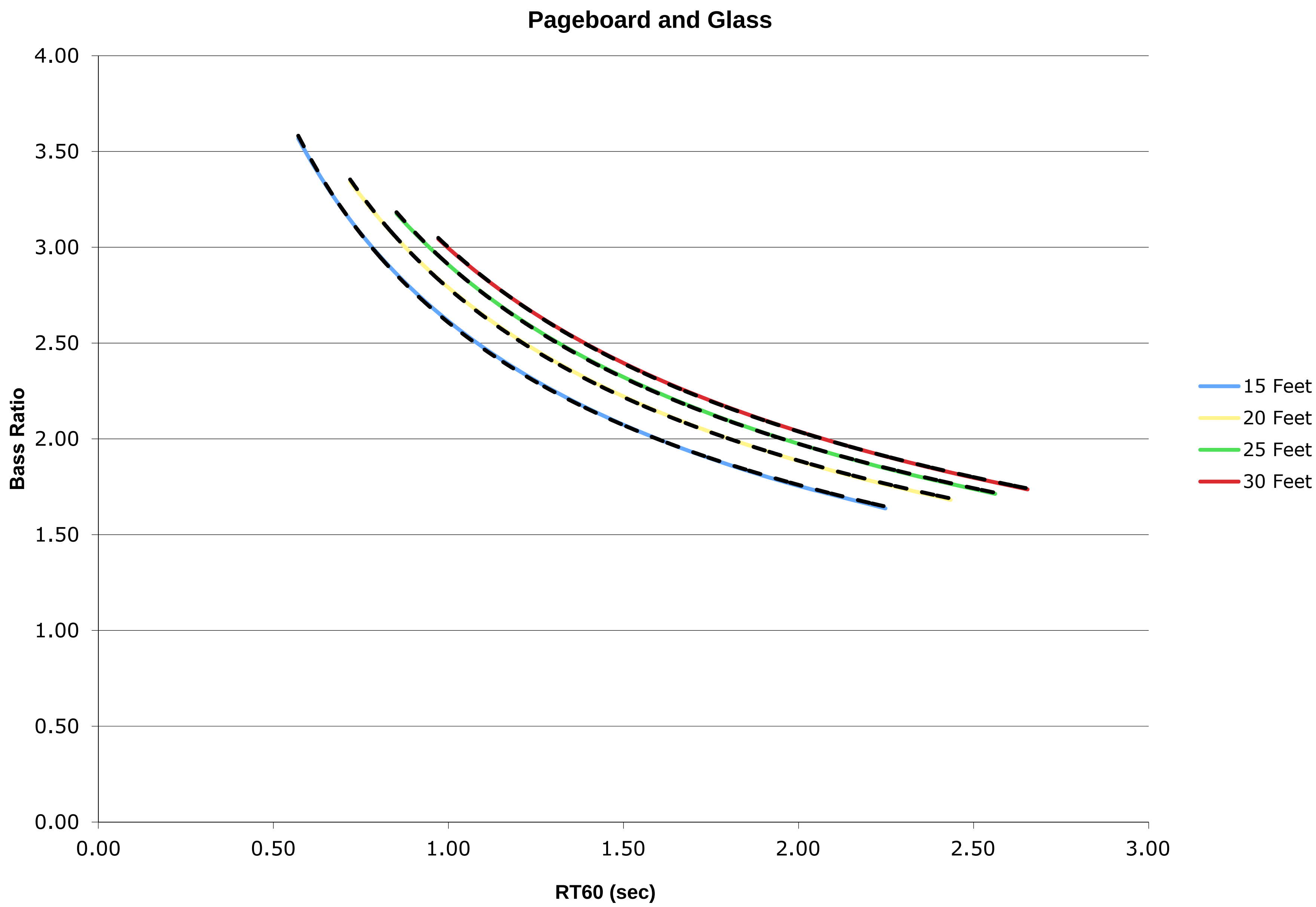
| | 125 Hz | 250 Hz | 500 Hz | 1 kHz | 2 kHz | 4 kHz |
|---|---|---|---|---|---|---|
| Plasterboard | 0.29 | 0.1 | 0.06 | 0.05 | 0.04 | 0.04 |
| Glass | 0.04 | 0.04 | 0.03 | 0.03 | 0.02 | 0.02 |
| Walls | 0.12 | 0.13 | 0.21 | 0.26 | 0.27 | 0.28 |
| Floor | 0.04 | 0.04 | 0.07 | 0.06 | 0.06 | 0.07 |


Plasterboard and Glass
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Bass Ratio
0.00
0.50
1.00
1.50
2.00
2.50
3.00
RT60 (sec)
15 Feet
20 Feet
25 Feet
30 Feet

## Pageboard and Glass

| Variables | | | Reverberation Times | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Ceiling Height** | **Material 1 (%)** | **Material 2 (%)** | **125 Hz** | **250 Hz** | **500 Hz** | **1 kHz** | **2 kHz** | **4 kHz** | **RT @ 500** | **Bass Ratio** |
| 15 | 1 | 0 | 2.93 | 1.48 | 0.57 | 0.66 | 1.06 | 1.50 | 0.57 | 3.57 |
| 15 | 0.95 | 0.05 | 2.95 | 1.52 | 0.59 | 0.69 | 1.09 | 1.51 | 0.59 | 3.49 |
| 15 | 0.9 | 0.1 | 2.97 | 1.57 | 0.62 | 0.71 | 1.11 | 1.53 | 0.62 | 3.42 |
| 15 | 0.85 | 0.15 | 3.00 | 1.62 | 0.64 | 0.74 | 1.14 | 1.54 | 0.64 | 3.34 |
| 15 | 0.8 | 0.2 | 3.02 | 1.67 | 0.67 | 0.76 | 1.17 | 1.56 | 0.67 | 3.27 |
| 15 | 0.75 | 0.25 | 3.05 | 1.72 | 0.70 | 0.79 | 1.20 | 1.58 | 0.70 | 3.19 |
| 15 | 0.7 | 0.3 | 3.07 | 1.78 | 0.74 | 0.83 | 1.23 | 1.60 | 0.74 | 3.10 |
| 15 | 0.65 | 0.35 | 3.10 | 1.84 | 0.77 | 0.86 | 1.27 | 1.61 | 0.77 | 3.02 |
| 15 | 0.6 | 0.4 | 3.12 | 1.91 | 0.81 | 0.90 | 1.30 | 1.63 | 0.81 | 2.93 |
| 15 | 0.55 | 0.45 | 3.15 | 1.98 | 0.86 | 0.94 | 1.34 | 1.65 | 0.86 | 2.85 |
| 15 | 0.5 | 0.5 | 3.18 | 2.06 | 0.91 | 0.99 | 1.38 | 1.67 | 0.91 | 2.76 |
| 15 | 0.45 | 0.55 | 3.21 | 2.14 | 0.97 | 1.04 | 1.42 | 1.69 | 0.97 | 2.66 |
| 15 | 0.4 | 0.6 | 3.23 | 2.24 | 1.03 | 1.10 | 1.47 | 1.71 | 1.03 | 2.57 |
| 15 | 0.35 | 0.65 | 3.26 | 2.34 | 1.11 | 1.16 | 1.52 | 1.73 | 1.11 | 2.47 |
| 15 | 0.3 | 0.7 | 3.29 | 2.44 | 1.20 | 1.23 | 1.57 | 1.75 | 1.20 | 2.36 |
| 15 | 0.25 | 0.75 | 3.32 | 2.56 | 1.30 | 1.31 | 1.62 | 1.77 | 1.30 | 2.26 |
| 15 | 0.2 | 0.8 | 3.35 | 2.70 | 1.42 | 1.41 | 1.68 | 1.79 | 1.42 | 2.14 |
| 15 | 0.15 | 0.85 | 3.38 | 2.84 | 1.56 | 1.51 | 1.75 | 1.81 | 1.56 | 2.03 |
| 15 | 0.1 | 0.9 | 3.41 | 3.00 | 1.74 | 1.63 | 1.82 | 1.83 | 1.74 | 1.90 |
| 15 | 0.05 | 0.95 | 3.45 | 3.19 | 1.96 | 1.78 | 1.89 | 1.86 | 1.96 | 1.77 |
| 15 | 0 | 1 | 3.48 | 3.39 | 2.25 | 1.95 | 1.97 | 1.88 | 2.25 | 1.64 |
| | | | | | | | | | | |
| 20 | 1 | 0 | 3.32 | 1.81 | 0.72 | 0.81 | 1.24 | 1.66 | 0.72 | 3.34 |
| 20 | 0.95 | 0.05 | 3.34 | 1.86 | 0.75 | 0.84 | 1.27 | 1.67 | 0.75 | 3.28 |
| 20 | 0.9 | 0.1 | 3.37 | 1.91 | 0.77 | 0.87 | 1.29 | 1.69 | 0.77 | 3.21 |
| 20 | 0.85 | 0.15 | 3.39 | 1.96 | 0.80 | 0.90 | 1.32 | 1.70 | 0.80 | 3.15 |
| 20 | 0.8 | 0.2 | 3.41 | 2.02 | 0.84 | 0.93 | 1.35 | 1.72 | 0.84 | 3.08 |
| 20 | 0.75 | 0.25 | 3.44 | 2.07 | 0.87 | 0.96 | 1.38 | 1.73 | 0.87 | 3.01 |
| 20 | 0.7 | 0.3 | 3.46 | 2.14 | 0.91 | 1.00 | 1.41 | 1.75 | 0.91 | 2.94 |
| 20 | 0.65 | 0.35 | 3.49 | 2.21 | 0.95 | 1.03 | 1.45 | 1.76 | 0.95 | 2.86 |
| 20 | 0.6 | 0.4 | 3.51 | 2.28 | 1.00 | 1.08 | 1.48 | 1.78 | 1.00 | 2.79 |
| 20 | 0.55 | 0.45 | 3.54 | 2.35 | 1.05 | 1.12 | 1.52 | 1.79 | 1.05 | 2.71 |
| 20 | 0.5 | 0.5 | 3.56 | 2.44 | 1.11 | 1.17 | 1.56 | 1.81 | 1.11 | 2.63 |
| 20 | 0.45 | 0.55 | 3.59 | 2.52 | 1.17 | 1.22 | 1.60 | 1.83 | 1.17 | 2.55 |
| 20 | 0.4 | 0.6 | 3.62 | 2.62 | 1.25 | 1.28 | 1.64 | 1.85 | 1.25 | 2.47 |
| 20 | 0.35 | 0.65 | 3.64 | 2.72 | 1.33 | 1.35 | 1.68 | 1.86 | 1.33 | 2.38 |
| 20 | 0.3 | 0.7 | 3.67 | 2.83 | 1.42 | 1.42 | 1.73 | 1.88 | 1.42 | 2.29 |
| 20 | 0.25 | 0.75 | 3.70 | 2.95 | 1.53 | 1.50 | 1.78 | 1.90 | 1.53 | 2.20 |
| 20 | 0.2 | 0.8 | 3.73 | 3.08 | 1.65 | 1.58 | 1.83 | 1.92 | 1.65 | 2.11 |
| 20 | 0.15 | 0.85 | 3.75 | 3.22 | 1.79 | 1.68 | 1.89 | 1.94 | 1.79 | 2.01 |
| 20 | 0.1 | 0.9 | 3.78 | 3.38 | 1.97 | 1.80 | 1.95 | 1.96 | 1.97 | 1.90 |
| 20 | 0.05 | 0.95 | 3.81 | 3.55 | 2.17 | 1.92 | 2.02 | 1.98 | 2.17 | 1.80 |
| 20 | 0 | 1 | 3.84 | 3.74 | 2.43 | 2.07 | 2.08 | 2.00 | 2.43 | 1.68 |
| | | | | | | | | | | |
| 25 | 1 | 0 | 3.62 | 2.08 | 0.85 | 0.94 | 1.38 | 1.77 | 0.85 | 3.18 |
| 25 | 0.95 | 0.05 | 3.64 | 2.13 | 0.88 | 0.97 | 1.41 | 1.78 | 0.88 | 3.12 |
| 25 | 0.9 | 0.1 | 3.66 | 2.19 | 0.91 | 1.00 | 1.43 | 1.80 | 0.91 | 3.06 |
| 25 | 0.85 | 0.15 | 3.68 | 2.24 | 0.95 | 1.03 | 1.46 | 1.81 | 0.95 | 3.00 |
| 25 | 0.8 | 0.2 | 3.70 | 2.30 | 0.98 | 1.06 | 1.49 | 1.82 | 0.98 | 2.94 |
| 25 | 0.75 | 0.25 | 3.73 | 2.37 | 1.02 | 1.10 | 1.52 | 1.84 | 1.02 | 2.87 |
| 25 | 0.7 | 0.3 | 3.75 | 2.43 | 1.06 | 1.13 | 1.55 | 1.85 | 1.06 | 2.81 |
| 25 | 0.65 | 0.35 | 3.77 | 2.50 | 1.11 | 1.17 | 1.58 | 1.87 | 1.11 | 2.74 |
| 25 | 0.6 | 0.4 | 3.80 | 2.57 | 1.16 | 1.22 | 1.61 | 1.88 | 1.16 | 2.68 |
| 25 | 0.55 | 0.45 | 3.82 | 2.65 | 1.22 | 1.26 | 1.65 | 1.90 | 1.22 | 2.61 |
| 25 | 0.5 | 0.5 | 3.84 | 2.74 | 1.28 | 1.31 | 1.68 | 1.91 | 1.28 | 2.54 |
| 25 | 0.45 | 0.55 | 3.87 | 2.82 | 1.35 | 1.37 | 1.72 | 1.93 | 1.35 | 2.47 |
| 25 | 0.4 | 0.6 | 3.89 | 2.92 | 1.42 | 1.42 | 1.76 | 1.94 | 1.42 | 2.39 |
| 25 | 0.35 | 0.65 | 3.92 | 3.02 | 1.50 | 1.49 | 1.80 | 1.96 | 1.50 | 2.32 |
| 25 | 0.3 | 0.7 | 3.94 | 3.13 | 1.60 | 1.56 | 1.85 | 1.97 | 1.60 | 2.24 |
| 25 | 0.25 | 0.75 | 3.97 | 3.24 | 1.71 | 1.63 | 1.89 | 1.99 | 1.71 | 2.16 |
| 25 | 0.2 | 0.8 | 3.99 | 3.37 | 1.83 | 1.71 | 1.94 | 2.00 | 1.83 | 2.08 |
| 25 | 0.15 | 0.85 | 4.02 | 3.50 | 1.97 | 1.81 | 1.99 | 2.02 | 1.97 | 1.99 |
| 25 | 0.1 | 0.9 | 4.05 | 3.65 | 2.13 | 1.91 | 2.04 | 2.04 | 2.13 | 1.90 |
| 25 | 0.05 | 0.95 | 4.07 | 3.81 | 2.33 | 2.02 | 2.10 | 2.05 | 2.33 | 1.81 |
| 25 | 0 | 1 | 4.10 | 3.98 | 2.56 | 2.15 | 2.16 | 2.07 | 2.56 | 1.71 |
| | | | | | | | | | | |
| 30 | 1 | 0 | 3.84 | 2.32 | 0.97 | 1.05 | 1.49 | 1.86 | 0.97 | 3.04 |
| 30 | 0.95 | 0.05 | 3.86 | 2.37 | 1.00 | 1.08 | 1.52 | 1.87 | 1.00 | 2.99 |
| 30 | 0.9 | 0.1 | 3.88 | 2.43 | 1.04 | 1.11 | 1.54 | 1.88 | 1.04 | 2.94 |
| 30 | 0.85 | 0.15 | 3.90 | 2.49 | 1.07 | 1.14 | 1.57 | 1.89 | 1.07 | 2.88 |
| 30 | 0.8 | 0.2 | 3.93 | 2.55 | 1.11 | 1.18 | 1.60 | 1.91 | 1.11 | 2.83 |
| 30 | 0.75 | 0.25 | 3.95 | 2.61 | 1.15 | 1.21 | 1.62 | 1.92 | 1.15 | 2.77 |
| 30 | 0.7 | 0.3 | 3.97 | 2.68 | 1.20 | 1.25 | 1.65 | 1.93 | 1.20 | 2.71 |
| 30 | 0.65 | 0.35 | 3.99 | 2.75 | 1.25 | 1.29 | 1.68 | 1.94 | 1.25 | 2.65 |
| 30 | 0.6 | 0.4 | 4.01 | 2.82 | 1.30 | 1.33 | 1.71 | 1.96 | 1.30 | 2.59 |
| 30 | 0.55 | 0.45 | 4.03 | 2.90 | 1.36 | 1.38 | 1.75 | 1.97 | 1.36 | 2.53 |
| 30 | 0.5 | 0.5 | 4.06 | 2.98 | 1.42 | 1.43 | 1.78 | 1.98 | 1.42 | 2.47 |
| 30 | 0.45 | 0.55 | 4.08 | 3.07 | 1.49 | 1.48 | 1.82 | 2.00 | 1.49 | 2.40 |
| 30 | 0.4 | 0.6 | 4.10 | 3.16 | 1.57 | 1.54 | 1.85 | 2.01 | 1.57 | 2.34 |
| 30 | 0.35 | 0.65 | 4.12 | 3.26 | 1.65 | 1.60 | 1.89 | 2.02 | 1.65 | 2.27 |
| 30 | 0.3 | 0.7 | 4.15 | 3.36 | 1.75 | 1.66 | 1.93 | 2.04 | 1.75 | 2.20 |
| 30 | 0.25 | 0.75 | 4.17 | 3.47 | 1.85 | 1.74 | 1.97 | 2.05 | 1.85 | 2.13 |
| 30 | 0.2 | 0.8 | 4.19 | 3.59 | 1.97 | 1.81 | 2.02 | 2.07 | 1.97 | 2.06 |
| 30 | 0.15 | 0.85 | 4.22 | 3.72 | 2.11 | 1.90 | 2.06 | 2.08 | 2.11 | 1.98 |
| 30 | 0.1 | 0.9 | 4.24 | 3.85 | 2.26 | 1.99 | 2.11 | 2.10 | 2.26 | 1.90 |
| 30 | 0.05 | 0.95 | 4.27 | 4.00 | 2.44 | 2.10 | 2.16 | 2.11 | 2.44 | 1.82 |
| 30 | 0 | 1 | 4.29 | 4.16 | 2.65 | 2.21 | 2.21 | 2.13 | 2.65 | 1.74 |

| | 125 Hz | 250 Hz | 500 Hz | 1 kHz | 2 kHz | 4 kHz |
|---|---|---|---|---|---|---|
| Pageboard | 0.08 | 0.32 | 0.99 | 0.76 | 0.34 | 0.12 |
| Glass | 0.04 | 0.04 | 0.03 | 0.03 | 0.02 | 0.02 |
| Walls | 0.12 | 0.13 | 0.21 | 0.26 | 0.27 | 0.28 |
| Floor | 0.04 | 0.04 | 0.07 | 0.06 | 0.06 | 0.07 |

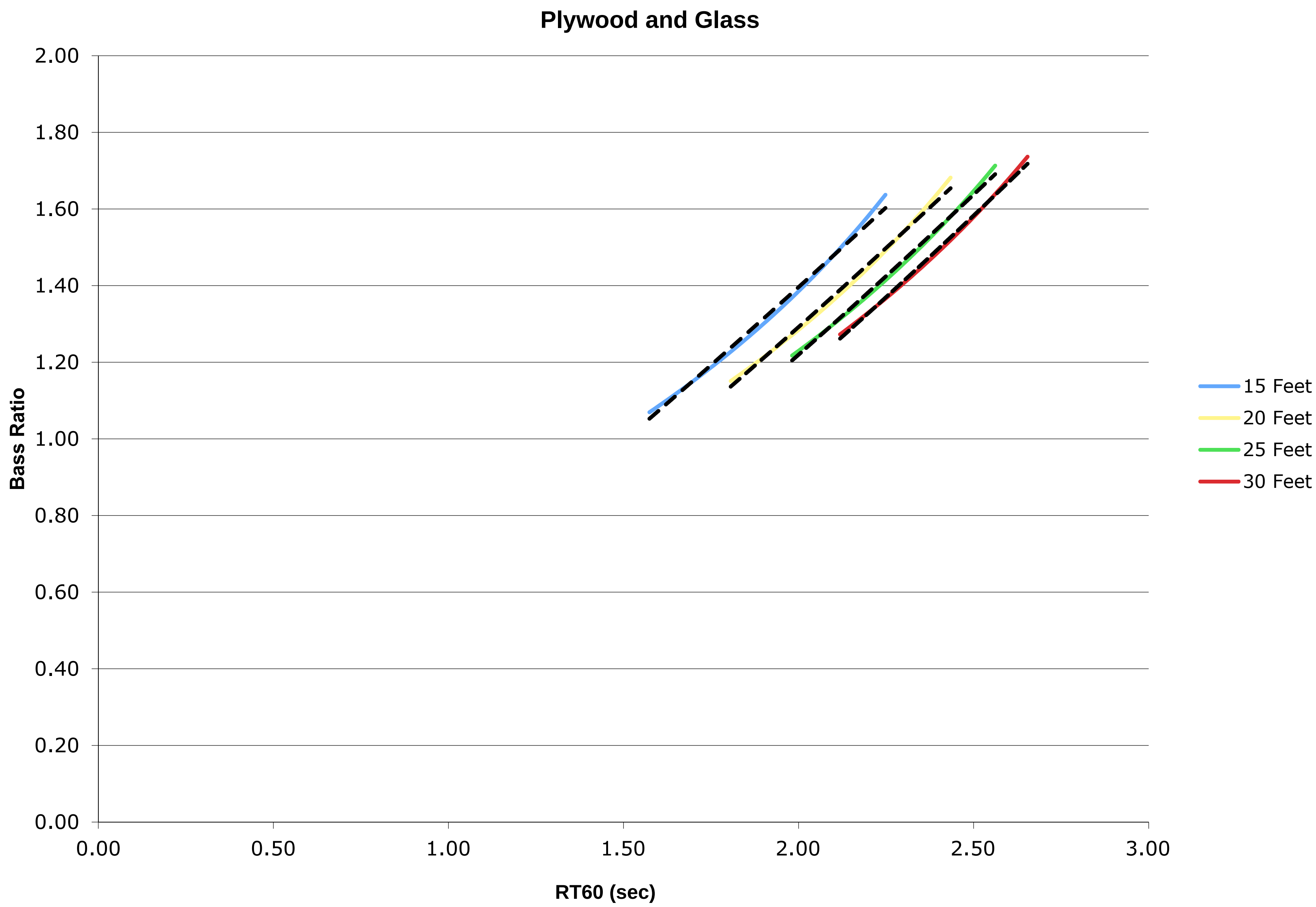


Pageboard and Glass
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Bass Ratio
0.00
0.50
1.00
1.50
2.00
2.50
3.00
RT60 (sec)
15 Feet
20 Feet
25 Feet
30 Feet

# Plywood and Glass

| | Variables | | | | Reverberation Times | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Ceiling Height** | **Material 1 (%)** | **Material 2 (%)** | **125 Hz** | **250 Hz** | **500 Hz** | **1 kHz** | **2 kHz** | **4 kHz** | **RT @ 500** | **Bass Ratio** |
| 15 | 1 | 0 | 1.63 | 1.85 | 1.57 | 1.68 | 1.62 | 1.53 | 1.57 | 1.07 |
| 15 | 0.95 | 0.05 | 1.67 | 1.90 | 1.60 | 1.69 | 1.64 | 1.54 | 1.60 | 1.08 |
| 15 | 0.9 | 0.1 | 1.72 | 1.94 | 1.62 | 1.70 | 1.65 | 1.56 | 1.62 | 1.10 |
| 15 | 0.85 | 0.15 | 1.77 | 1.99 | 1.65 | 1.72 | 1.67 | 1.57 | 1.65 | 1.12 |
| 15 | 0.8 | 0.2 | 1.82 | 2.04 | 1.67 | 1.73 | 1.68 | 1.59 | 1.67 | 1.13 |
| 15 | 0.75 | 0.25 | 1.88 | 2.09 | 1.70 | 1.74 | 1.70 | 1.60 | 1.70 | 1.15 |
| 15 | 0.7 | 0.3 | 1.94 | 2.14 | 1.73 | 1.75 | 1.71 | 1.62 | 1.73 | 1.17 |
| 15 | 0.65 | 0.35 | 2.00 | 2.20 | 1.76 | 1.77 | 1.73 | 1.64 | 1.76 | 1.19 |
| 15 | 0.6 | 0.4 | 2.07 | 2.26 | 1.79 | 1.78 | 1.75 | 1.65 | 1.79 | 1.21 |
| 15 | 0.55 | 0.45 | 2.14 | 2.33 | 1.82 | 1.79 | 1.76 | 1.67 | 1.82 | 1.24 |
| 15 | 0.5 | 0.5 | 2.22 | 2.40 | 1.85 | 1.81 | 1.78 | 1.69 | 1.85 | 1.26 |
| 15 | 0.45 | 0.55 | 2.30 | 2.47 | 1.88 | 1.82 | 1.80 | 1.70 | 1.88 | 1.29 |
| 15 | 0.4 | 0.6 | 2.39 | 2.55 | 1.92 | 1.83 | 1.82 | 1.72 | 1.92 | 1.32 |
| 15 | 0.35 | 0.65 | 2.49 | 2.63 | 1.96 | 1.85 | 1.83 | 1.74 | 1.96 | 1.35 |
| 15 | 0.3 | 0.7 | 2.59 | 2.71 | 1.99 | 1.86 | 1.85 | 1.76 | 1.99 | 1.38 |
| 15 | 0.25 | 0.75 | 2.71 | 2.81 | 2.03 | 1.87 | 1.87 | 1.78 | 2.03 | 1.41 |
| 15 | 0.2 | 0.8 | 2.84 | 2.91 | 2.07 | 1.89 | 1.89 | 1.80 | 2.07 | 1.45 |
| 15 | 0.15 | 0.85 | 2.97 | 3.02 | 2.11 | 1.90 | 1.91 | 1.82 | 2.11 | 1.49 |
| 15 | 0.1 | 0.9 | 3.12 | 3.13 | 2.16 | 1.92 | 1.93 | 1.84 | 2.16 | 1.54 |
| 15 | 0.05 | 0.95 | 3.29 | 3.26 | 2.20 | 1.93 | 1.95 | 1.86 | 2.20 | 1.58 |
| 15 | 0 | 1 | 3.48 | 3.39 | 2.25 | 1.95 | 1.97 | 1.88 | 2.25 | 1.64 |
| 20 | 1 | 0 | 1.98 | 2.22 | 1.81 | 1.84 | 1.78 | 1.69 | 1.81 | 1.15 |
| 20 | 0.95 | 0.05 | 2.03 | 2.26 | 1.83 | 1.85 | 1.79 | 1.70 | 1.83 | 1.17 |
| 20 | 0.9 | 0.1 | 2.08 | 2.31 | 1.85 | 1.86 | 1.81 | 1.71 | 1.85 | 1.18 |
| 20 | 0.85 | 0.15 | 2.14 | 2.36 | 1.88 | 1.87 | 1.82 | 1.73 | 1.88 | 1.20 |
| 20 | 0.8 | 0.2 | 2.19 | 2.41 | 1.90 | 1.88 | 1.83 | 1.74 | 1.90 | 1.22 |
| 20 | 0.75 | 0.25 | 2.25 | 2.47 | 1.93 | 1.89 | 1.85 | 1.75 | 1.93 | 1.23 |
| 20 | 0.7 | 0.3 | 2.32 | 2.52 | 1.96 | 1.90 | 1.86 | 1.77 | 1.96 | 1.25 |
| 20 | 0.65 | 0.35 | 2.38 | 2.58 | 1.99 | 1.91 | 1.88 | 1.78 | 1.99 | 1.27 |
| 20 | 0.6 | 0.4 | 2.46 | 2.65 | 2.01 | 1.93 | 1.89 | 1.80 | 2.01 | 1.30 |
| 20 | 0.55 | 0.45 | 2.53 | 2.71 | 2.04 | 1.94 | 1.91 | 1.81 | 2.04 | 1.32 |
| 20 | 0.5 | 0.5 | 2.61 | 2.78 | 2.07 | 1.95 | 1.92 | 1.83 | 2.07 | 1.34 |
| 20 | 0.45 | 0.55 | 2.70 | 2.85 | 2.10 | 1.96 | 1.94 | 1.84 | 2.10 | 1.37 |
| 20 | 0.4 | 0.6 | 2.79 | 2.93 | 2.14 | 1.97 | 1.95 | 1.86 | 2.14 | 1.39 |
| 20 | 0.35 | 0.65 | 2.89 | 3.01 | 2.17 | 1.98 | 1.97 | 1.88 | 2.17 | 1.42 |
| 20 | 0.3 | 0.7 | 3.00 | 3.10 | 2.20 | 2.00 | 1.98 | 1.89 | 2.20 | 1.45 |
| 20 | 0.25 | 0.75 | 3.11 | 3.19 | 2.24 | 2.01 | 2.00 | 1.91 | 2.24 | 1.48 |
| 20 | 0.2 | 0.8 | 3.23 | 3.29 | 2.28 | 2.02 | 2.02 | 1.93 | 2.28 | 1.52 |
| 20 | 0.15 | 0.85 | 3.37 | 3.39 | 2.31 | 2.03 | 2.03 | 1.94 | 2.31 | 1.55 |
| 20 | 0.1 | 0.9 | 3.51 | 3.50 | 2.35 | 2.05 | 2.05 | 1.96 | 2.35 | 1.59 |
| 20 | 0.05 | 0.95 | 3.67 | 3.61 | 2.39 | 2.06 | 2.07 | 1.98 | 2.39 | 1.64 |
| 20 | 0 | 1 | 3.84 | 3.74 | 2.43 | 2.07 | 2.08 | 2.00 | 2.43 | 1.68 |
| 25 | 1 | 0 | 2.27 | 2.51 | 1.98 | 1.95 | 1.89 | 1.80 | 1.98 | 1.22 |
| 25 | 0.95 | 0.05 | 2.33 | 2.56 | 2.00 | 1.96 | 1.90 | 1.81 | 2.00 | 1.23 |
| 25 | 0.9 | 0.1 | 2.38 | 2.61 | 2.03 | 1.97 | 1.92 | 1.82 | 2.03 | 1.25 |
| 25 | 0.85 | 0.15 | 2.44 | 2.66 | 2.05 | 1.98 | 1.93 | 1.83 | 2.05 | 1.26 |
| 25 | 0.8 | 0.2 | 2.50 | 2.71 | 2.08 | 1.99 | 1.94 | 1.85 | 2.08 | 1.28 |
| 25 | 0.75 | 0.25 | 2.56 | 2.77 | 2.10 | 2.00 | 1.95 | 1.86 | 2.10 | 1.30 |
| 25 | 0.7 | 0.3 | 2.62 | 2.82 | 2.13 | 2.01 | 1.96 | 1.87 | 2.13 | 1.32 |
| 25 | 0.65 | 0.35 | 2.69 | 2.88 | 2.15 | 2.02 | 1.98 | 1.89 | 2.15 | 1.34 |
| 25 | 0.6 | 0.4 | 2.77 | 2.95 | 2.18 | 2.03 | 1.99 | 1.90 | 2.18 | 1.36 |
| 25 | 0.55 | 0.45 | 2.84 | 3.01 | 2.21 | 2.04 | 2.00 | 1.91 | 2.21 | 1.38 |
| 25 | 0.5 | 0.5 | 2.93 | 3.08 | 2.23 | 2.05 | 2.02 | 1.93 | 2.23 | 1.40 |
| 25 | 0.45 | 0.55 | 3.01 | 3.15 | 2.26 | 2.06 | 2.03 | 1.94 | 2.26 | 1.43 |
| 25 | 0.4 | 0.6 | 3.10 | 3.22 | 2.29 | 2.07 | 2.04 | 1.95 | 2.29 | 1.45 |
| 25 | 0.35 | 0.65 | 3.20 | 3.30 | 2.32 | 2.08 | 2.06 | 1.97 | 2.32 | 1.48 |
| 25 | 0.3 | 0.7 | 3.30 | 3.39 | 2.35 | 2.09 | 2.07 | 1.98 | 2.35 | 1.51 |
| 25 | 0.25 | 0.75 | 3.41 | 3.47 | 2.39 | 2.10 | 2.08 | 2.00 | 2.39 | 1.54 |
| 25 | 0.2 | 0.8 | 3.53 | 3.56 | 2.42 | 2.11 | 2.10 | 2.01 | 2.42 | 1.57 |
| 25 | 0.15 | 0.85 | 3.66 | 3.66 | 2.45 | 2.12 | 2.11 | 2.03 | 2.45 | 1.60 |
| 25 | 0.1 | 0.9 | 3.80 | 3.76 | 2.49 | 2.13 | 2.13 | 2.04 | 2.49 | 1.63 |
| 25 | 0.05 | 0.95 | 3.94 | 3.87 | 2.52 | 2.14 | 2.14 | 2.06 | 2.52 | 1.67 |
| 25 | 0 | 1 | 4.10 | 3.98 | 2.56 | 2.15 | 2.16 | 2.07 | 2.56 | 1.71 |
| 30 | 1 | 0 | 2.52 | 2.76 | 2.12 | 2.03 | 1.97 | 1.88 | 2.12 | 1.27 |
| 30 | 0.95 | 0.05 | 2.58 | 2.80 | 2.14 | 2.04 | 1.98 | 1.89 | 2.14 | 1.29 |
| 30 | 0.9 | 0.1 | 2.63 | 2.85 | 2.16 | 2.05 | 1.99 | 1.90 | 2.16 | 1.30 |
| 30 | 0.85 | 0.15 | 2.69 | 2.90 | 2.18 | 2.06 | 2.01 | 1.91 | 2.18 | 1.32 |
| 30 | 0.8 | 0.2 | 2.75 | 2.96 | 2.21 | 2.06 | 2.02 | 1.93 | 2.21 | 1.34 |
| 30 | 0.75 | 0.25 | 2.81 | 3.01 | 2.23 | 2.07 | 2.03 | 1.94 | 2.23 | 1.35 |
| 30 | 0.7 | 0.3 | 2.88 | 3.07 | 2.25 | 2.08 | 2.04 | 1.95 | 2.25 | 1.37 |
| 30 | 0.65 | 0.35 | 2.95 | 3.12 | 2.28 | 2.09 | 2.05 | 1.96 | 2.28 | 1.39 |
| 30 | 0.6 | 0.4 | 3.02 | 3.19 | 2.30 | 2.10 | 2.06 | 1.97 | 2.30 | 1.41 |
| 30 | 0.55 | 0.45 | 3.10 | 3.25 | 2.33 | 2.11 | 2.07 | 1.98 | 2.33 | 1.43 |
| 30 | 0.5 | 0.5 | 3.18 | 3.32 | 2.36 | 2.12 | 2.08 | 2.00 | 2.36 | 1.45 |
| 30 | 0.45 | 0.55 | 3.26 | 3.38 | 2.38 | 2.13 | 2.10 | 2.01 | 2.38 | 1.47 |
| 30 | 0.4 | 0.6 | 3.35 | 3.46 | 2.41 | 2.14 | 2.11 | 2.02 | 2.41 | 1.50 |
| 30 | 0.35 | 0.65 | 3.45 | 3.53 | 2.44 | 2.15 | 2.12 | 2.03 | 2.44 | 1.52 |
| 30 | 0.3 | 0.7 | 3.55 | 3.61 | 2.47 | 2.15 | 2.13 | 2.05 | 2.47 | 1.55 |
| 30 | 0.25 | 0.75 | 3.65 | 3.69 | 2.50 | 2.16 | 2.15 | 2.06 | 2.50 | 1.58 |
| 30 | 0.2 | 0.8 | 3.76 | 3.77 | 2.53 | 2.17 | 2.16 | 2.07 | 2.53 | 1.60 |
| 30 | 0.15 | 0.85 | 3.88 | 3.86 | 2.56 | 2.18 | 2.17 | 2.08 | 2.56 | 1.63 |
| 30 | 0.1 | 0.9 | 4.01 | 3.96 | 2.59 | 2.19 | 2.18 | 2.10 | 2.59 | 1.67 |
| 30 | 0.05 | 0.95 | 4.15 | 4.06 | 2.62 | 2.20 | 2.20 | 2.11 | 2.62 | 1.70 |
| 30 | 0 | 1 | 4.29 | 4.16 | 2.65 | 2.21 | 2.21 | 2.13 | 2.65 | 1.74 |

| | 125 Hz | 250 Hz | 500 Hz | 1 kHz | 2 kHz | 4 kHz |
|---|---|---|---|---|---|---|
| Plywood | 0.28 | 0.22 | 0.17 | 0.09 | 0.1 | 0.11 |
| Glass | 0.04 | 0.04 | 0.03 | 0.03 | 0.02 | 0.02 |
| Walls | 0.12 | 0.13 | 0.21 | 0.26 | 0.27 | 0.28 |
| Floor | 0.04 | 0.04 | 0.07 | 0.06 | 0.06 | 0.07 |


Plywood and Glass
Bass Ratio
RT60 (sec)
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
0.00
0.50
1.00
1.50
2.00
2.50
3.00
15 Feet
20 Feet
25 Feet
30 Feet