University of Victoria
Faculty of Engineering

ENGR 446 Co-op Report

ECO-RECORDING STUDIO DESIGN: I.

Proposed Architectural Acoustics and Photovoltaic System

Tim Perry
Acoustic Designer at Arqen Sonic
Electrical Engineering & School of Music Student
timperry@uvic.ca

May 6, 2011

In partial fulfillment of the requirements of the
B.Eng. Degree

#3-1002 Bay Street
Victoria, B.C. V8T 1R9

Jonathan Foweraker
Faculty of Engineering
University of Victoria
P.O. Box 1700
Victoria, B.C. V8W 2Y2

May 6, 2011

Dear Dr. Foweraker:

The attached ENGR 446 report, titled "Eco-Recording Studio Design: I. Proposed Architectural Acoustics and Photovoltaic System", documents the preliminary design work of a greater, ongoing project.

Having spent the last four years learning about digital signal processing, audio production and acoustics, I have developed a fascination for the fields of acoustics and architectural design. This project ambitiously convolves those passions with another personal interest: sustainable development.

The result is an exploratory design of both recording studio acoustics and photovoltaics. Parameters obtained from acoustical design are used to approximately size a facility; I then estimate the requirements of a photovoltaic system needed to power that facility. As my engineering specialization is digital signal processing, I've gone through the computer music option, and my past employment has involved recording, audio signal processing and physical modeling sound synthesis; I am well grounded for conceptual acoustic design. However, I had no previous experience with solar power system design.

A larger purpose of this report is to reveal conflicts between acoustical design and eco-building design. The objective was not to resolve these conflicts—at least not yet. That would be premature optimization. It is my hope to continue this work in the future.

I would like to thank Peter Driessen, Kirk McNally, Ryan Boc, Artur Galiullin, Gina Brown, my parents, and many others who have provided support, feedback and inspiration.

Sincerely,

Tim Perry

CONTENTS

LIST OF TABLES AND FIGURES

TABLES

FIGURES

SUMMARY

This paper provides preliminary acoustical design results for a proposed eco-recording studio; in addition, an off-grid photovoltaic (PV) power system is specified for the studio, catered to the region surrounding Vancouver, British Columbia, Canada.

Green goals present challenges to acoustical design. The purpose of acoustical design was to determine optimal parameters for a recording studio control room and live room, identify architectural dimensions to achieve those parameters, and derive electrical appliance loads from the architectural dimensions. An acoustically optimized design places constraints on structural form, building materials, passive heating, ventilation and natural lighting; thus it may conflict with green building practices. Also, recording studios have high power demands and may be operated for extended hours, consuming large amounts of energy. The purpose of photovoltaic system sizing was to estimate the portion of that energy need that may be satisfied by building-integrated photovoltaics. It is hoped these findings may eventually be used as constraints to help guide a more rigorous design effort by architects, engineers, acousticians and designers.

The conceptual control room is a 'live-end-dead-end' room with splayed walls. The design facilitates critical listening in an environment that is not acoustically dead (An alternative is a Non-Environment room, offering superior critical listening at the expense of liveliness). An "equivalent volume rectangular room" was used to simulate rudimentary acoustics. By adjusting room parameters the reverberation time and initial time delay gap can be tuned to near-optimal values, determined to be 0.345 seconds and about 20 milliseconds, respectively. Investigations into live room design conclude that a 20200 ft3 room with a reverberation time of 0.67 seconds is an optimal recording space for this studio.

Peak demand for the studio is expected to be 23.2 kW, based on known equipment loads and the dimensions specified by acoustical design. 102 kW of photovoltaic module capacity with 30 kW of inverter capacity is the minimum PV system for the facility to be net-zero on a day with 3.7 peak sun hours (the annual mean for Vancouver). Further investigations reveal that up to 56% of the required modules will fit on the expected roof of the facility, placing a limit on the building-integrated PV potential. This result draws attention to conflicting design objectives: the studio requires more power than the off-grid building-integrated photovoltaics can provide.

It is recommended that remote photovoltaic arrays utilizing 2-axis sun tracking be investigated as a method to meet the excess power demand; moreover, future eco-building design should focus on minimizing energy consumption. It is also recommended that feasibility analysis, cost-benefit-analysis and detailed assessment of PV potential be conducted with input from experts. Detailed design requires an architectural firm and feedback from engineers and green building experts

GLOSSARY

Acoustician	A physicist who specializes in the science of sound.
Control Room	An acoustic space designed for the critical assessment of sound that is played over speakers.
Diffuser, Acoustic	A device used to treat unwanted echoes and reflections. Unlike absorption, diffusers preserve the liveliness of a room because they do not absorb much sound energy. Instead, they disperse it, spreading the energy around the room.
Diffusion (Acoustics)	The re-radiation (or scattering) of an incident sound wave over a wide area. Ideal diffusion refers to a uniform spread of energy in an environment.
Early Reflections	The first reflections that we hear within about 100 ms of hearing the direct sound of the source. These give important cues about our location in a room relative to the walls, floor and ceiling.
Impulse Response (IR)	The impulse response of the room is its response to a delta function. Important acoustical properties like frequency response and reverberation are largely characterized by the impulse response. One can essentially listen to the impulse response of a room by standing inside it and clapping.
Initial Time Delay Gap (ITDG)	The time gap between the arrival of the direct sound that we hear, and the first early reflection. This gives an impression of intimacy in relation to walls in a room, helping a listener sense their relative position within that room.
'Live Room'	A room with lush reverberation, used for musical performance or tracking musicians. A live room in a recording studio is typically located next to the control room. These rooms should be acoustically isolated from each other.
'Live-End, Dead-End' control room (LEDE)	A control room intended to allow critical listening without creating an acoustically dead environment. The front of the control room, or 'dead-end', relies on high absorption to prevent early reflections from interfering with the direct source during the ITDG. The back end of the control room, or 'live-end', is covered with broadband diffusers to scatter reflections back toward the listening position with a dense, non-uniform texture.

Late Reverberation	The reverberant sound field after about 100 ms, until it fully decays. Late reverb is characterized by a dense texture of diffused reflections that reach our ears from many different paths. These diffused reflections are out of phase with one another, causing us to hear the comb filtering effect. We perceive this as ambience.
'Non-Environment' control room.	A room designed with a live front wall and a dead rear end (the sidewalls and ceiling are also absorptive, and the floor is reflective). Non-Environment rooms offer a better critical listening environment than a 'Live-End, Dead-End' room, at the expense of liveliness. Some people find these rooms sound uncomfortably sterile when performing tasks other than critical listening. (After Newell [2]).
Resonant Room Modes (or Eigenmodes)	Resonances in a room, largely determined by its geometry. Because a control room is relatively small, widely spaced resonant modes will occupy the lower region of the audible spectrum. A listener positioned in a high pressure region for particular modal frequency will hear an exaggerated volume at that frequency (a 'modal peak'), and a de-emphasized volume when positioned in a low pressure region.
Reverberation (Reverb)	The indirect sound that reaches a listener from a source. If this indirect sound is well-diffused, reverberation is said to have a rich texture and is perceived as a pleasant ambience.
RT60 (Reverberation Time)	The time it takes for the acoustic signal to decay by 60 dB. The reverb time varies throughout the frequency spectrum.
Studio Monitors	Accurate speakers with a neutral response, designed for critical listening.
Texture, Reverb	Texture is a measure of acoustical quality that is characterized by the number and distribution of reflections that arrive at the listener during the first 100 ms, after the perception of the direct source.

.

1. BACKGROUND

1.1. Green Goals Present Challenges to Acoustical Design

Recording studios are commercial music production facilities that have high operating costs, potentially leaving large ecological footprints. The construction and operation of recording studios places special challenges on sustainable development:

- Architectural acoustics may conflict with common green-building practices such as natural lighting, natural ventilation, and radiant heating and cooling. Windows for natural lighting may produce undesirable reflections for certain applications, while radiant heating and natural ventilation conflict with acoustic isolation (sound-proofing).

- Studios are constructed using specialized materials and procedures. Commonly used green building materials have resulted in structures with offensive acoustics; fortunately, eco-friendly acoustic products do exist and continue to emerge [1].

- Studios use equipment that draws a lot of power, often day and night.

- Studios are used day and night by a small group of people who work long hours and may temporarily live on-site.

- World class studios have a global client base; long-distance travel contributes to global pollution.

1.2. British Columbians Shy Away from Solar

Energy is cheap in British Columbia compared with most of Canada. While many residents of the Vancouver region are concerned with the environment, they are reluctant to adopt alternative energy solutions such as photovoltaics (solar panels) because of high installation costs and low return on investments. The return on investment for a typical photovoltaic (PV) installation in British Columbia is between 60 and 80 years [2], while the equivalent system in Ontario might pay for itself in less than 10 years due to the higher cost of energy. Electricity in Vancouver is mainly supplied by hydroelectric, a near zero-emission technology; however, hydroelectric dams are not sustainable developments—they alter the landscape and destroy river ecosystems. Additionally, significant losses are incurred by transmitting electricity over long distances from centralized power stations.

Ecologically sustainable development calls for small scale power solutions that harvest renewable energy resources on-site. In the Vancouver region, building-integrated photovoltaic (BIPV) systems tend to be the most feasible approach to harvesting renewable energy on-site for basic electrical needs.

2. DESIGN OBJECTIVES

The core objective of the greater project is *to design a sustainable recording studio with excellent acoustics, using eco-building design considerations catered to the Vancouver region.*

This paper covers the first phase of the project, and has four high-level objectives:

1. To design a recording studio control room—a room where recorded music will be critically assessed. While conceptual, the design should produce realistic dimensions and acoustic parameters where feasible.

2. To specify desired architectural acoustics for a live room—a room where music will be recorded.

3. To propose an off-grid photovoltaic power system that will satisfy a portion (to be approximately determined) of the power needs for a recording studio in the Vancouver region.

4. To find constraints and conflicting objectives that could help guide future project planning and eco-building design.

The high-level objectives are interrelated; mainly, objective 3 depends on the results of 1 and 2, and objective 4 seeks to consolidate the previous three.

2.1. Harmonizing Acoustical Objectives and Green Objectives

Eco-building design will involve balancing possible conflicts between sustainable design and the special demands of recording studio design. The fourth high-level objective is to reveal some of these conflicts—to present findings which could aid a more rigorous design effort by an architectural firm, acoustical engineers and environmental designers and engineers.

This section examines the relationships between the high level objectives, and the more intimate goals of design. Each element of studio design has its own primary objective; the primary objectives may be universally summarized using three words: *form follows function*. The foremost goal is to define forms that cater to the primary function.

The primary function of a recording studio is to provide an environment for recording and producing music. The primary function of a photovoltaic system is to collect energy from the sun. Clearly, the form will have to do some bending if it is to satisfy both of these primary functions. To help guide design, these two primary functions will be assigned the following priorities:

1. To provide an environment for recording and producing music.
2. To collect energy from the sun (or in a broader sense, to harvest renewable energy).

Primary Objectives of Acoustical Design

The primary objective of studio control room design is to specify the ultimate room for listening to sound through speakers, with the purpose of critically assessing that sound. Acoustically speaking, the goal is *to propose a recording studio control room for optimal stereo reproduction of sound, such that the original acoustic signal can be perceived with clarity*. Ideally, the room acoustics should not colour or add anything new to that signal.

The primary objective of live room design is *to specify desirable acoustic parameters for a room where microphones are placed and sound is recorded.* These parameters are necessary to help guide future architectural design.

Secondary Objectives of Acoustical Design

Solar power system design and eco-building design must harmonize with acoustical design. Therefore, the secondary objective of acoustical design is to produce results that can be used to parametrically design the rest of the facility. Of greatest interest are parameters that will restrict the design of a sustainable facility: *design constraints*. The proposed studio is a fully operational music production facility; it will:

- Consume a lot of energy.
- Require a lot of specialized material to build.
- Place restrictions on passive heating, cooling and ventilation.
- Place restrictions on natural lighting.

The above are expected constraints for eco-building design. In this paper, an objective is to quantify the first constraint: i.e., *determine the connected load and energy consumption of the facility.*

In the context of the larger project, an objective is *to specify the dimensions of the control room and live room so that the facility can be sized appropriately*. The size of the control room plays a role in choosing equipment for the studio, thus it is a prerequisite for determining peak power demands and energy consumption in the facility. Finally, the floor area and interior volume of the control room and live room must be determined to help assess lighting and heating needs.

Objectives of Solar Power System Design

The objective of solar power system design is to estimate the portion of the recording studio's electrical needs that can be supplied by photovoltaics, and to estimate the size of the system required. The intention is to provide data that could be used for a future feasibility study and cost-benefit-analysis to assess the potential of such an instalment in the Vancouver region.

2.2. Scope

This paper documents the preliminary design of architectural acoustics and photovoltaic power systems.

The first part of this paper documents the conceptual (but analytical) design of a recording studio control room. The conceptual elements of the control room were drafted for a previous non-technical project, and they have been revised and documented with an updated technical analysis for this paper. Next, the desired acoustic properties of a live recording room are specified and used to determine the volume of the structure.

The later parts of this paper focus on solar power system design. Recording studio equipment is specified, followed by demand load calculations. After assessing the photovoltaic potential and insolation in the Vancouver region, an off grid photovoltaic system is approximately sized. Future work will use the basic acoustic and PV system requirements as parameters for eco-building design (sustainable architecture).

While other design considerations may be mentioned, the following are beyond the official scope of this paper:

- Detailed design of solar power systems.
- Detailed acoustical design and physical modeling.
- Eco-building design considerations such as heating, ventilation and air conditioning (HVAC), building material selection and rainwater water collection.
- Full-facility architectural design and structural elements.
- Feasibility analysis.
- Cost estimates and return on investment.

This paper assumes that the reader is familiar with basic principles of electrical power, and has at least a conceptual understanding of acoustics. Acoustical parameters are defined and explained where appropriate. It is also assumed that the reader can grasp digital signal processing (DSP) concepts such as frequency response. DSP terms such as *fast Fourier transform* (FFT) and *finite impulse response* (FIR) are mentioned; however, the reader does not necessary need to understand them to grasp the larger concepts.

3. ACOUSTICS PRIMER: REVERBERATION AND THE IMPULSE RESPONSE

Clap your hands in a large room. The clapping sound is an impulse of broadband noise that resembles a *delta function*—a burst of energy at all frequencies. The resulting reflections and ambience that you hear after exciting the room, is reverb. Reverberation is the indirect sound that reaches a listener from a source. From any source there is sound that reaches the listener in a direct path, as well as sound that reaches the listener indirectly through reflections in the acoustic space. This reflected sound travels further than the direct sounds before reaching the listener, thus it is delayed. It has also been diffused by certain surfaces, and lost energy due to propagation through the air and absorption in the room. The reflected/diffused sound continues to interact with its surroundings, until it has been fully absorbed.

The *impulse response* (IR) of the room is its response to a delta function. Important acoustical properties like frequency response and reverberation are largely characterized by the impulse response. One can essentially listen to the impulse response of a room by standing inside it and clapping.

3.1. Early Reflections and Late Reverb

Reverb can be separated into two main components, which can be viewed when looking at the impulse response representation of a particular location in a room:

1. Early Reflections – the first reflections that we hear within about 100ms of hearing the direct sound of the source. These give important cues about our location in a room relative to the walls, floor and ceiling.

2. Late Reverberation – the reverberant sound field after about 100ms, until it fully decays. Late reverb is characterized by a dense texture of diffused reflections that reach our ears from many different paths. These diffused reflections are out of phase with one another, causing us to hear the comb filtering effect. We perceive this as ambience.

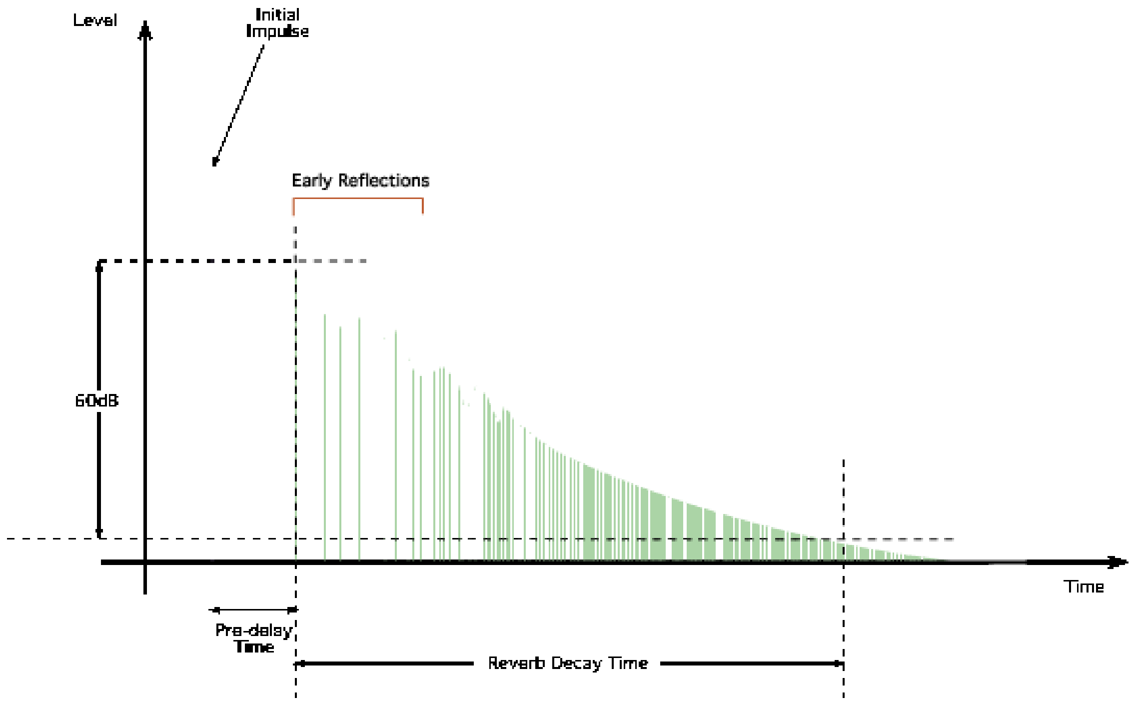


Figure 1 Typical impulse response of a room, showing the ITDG, early reflections and RT60. ***Source: Sound on Sound, 2000*** **[3].**

By viewing a typical impulse response in the time domain, one can establish parameters to measure the early reflections/late reverberation. Two quantitative acoustic parameters for characterizing reverb will be frequently discussed:

> Initial Time Delay Gap (ITDG) – the time gap between the arrival of the direct sound that we hear, and the first early reflection. This gives an impression of intimacy in relation to walls in a room, helping a listener sense their relative position within that room.
>
> RT60 - the *reverberation time, RT60,* is the time it takes for the acoustic signal to decay by 60dB. The reverb time varies throughout the spectrum, and can be measured at discrete frequency values. For practical applications, averaging schemes are used to define the reverb time in the portion of the spectrum where human hearing is most sensitive (between about 125 Hz and 4000 Hz is where we perceive the most significant sound colouration by reverb). RT60 is a function of the volume of a room and the absorption of sound energy inside that room, defined according to the *Sabine* and *Eyring* equations.

4. CONTROL ROOM ACOUSTICS

The recording studio control room is an environment where critical assessment of an acoustic signal must be possible. High demands are placed on the acoustical engineers and architects who are responsible for the design. Even with modern simulation tools, the acoustics of complex control rooms can be difficult to predict.

This section documents the conceptual design of a recording studio control room, placing emphasis on optimizing acoustics for stereo reproduction. In order to work with realistic parameters toward a well-defined goal, design criteria will be established and adhered to wherever possible. The impression of sound is subjective; however, there are a number of key characteristics that define a control room with quality acoustics. The following ideal control room characteristics will be viewed as design guidelines:

Ideal Control Room Characteristics

- The acoustic balance of a source signal is clearly perceived, and phantom images map to recorded sources.

- The listening position receives no significant acoustic distortions such as those caused by early reflection comb filtering, flutter echo, and modal ringing.

- The ideal control room will exhibit a flat frequency response in the listening position, such that the frequency balance of an acoustic signal is reproduced perfectly. In other words, the control room should not add a noticeable impression to the sound through colouration. In small rooms, modal resonances play a big role in obscuring the frequency balance of acoustic signals, and must be addressed.

- The acoustics of the original recorded space should be clearly perceived during playback. This means that the first reflection heard by the listener in the playback space should be from the recorded space. Since most recorded spaces are larger than control rooms, realizing this is goal will require special design considerations to suppress early reflections.

- The control room should exhibit a well-defined initial time delay gap, such that exponential decay and the impression of a larger room may be perceived.

- A controlled, diffuse reverb texture should be present, and RT60 should be optimized for the volume of the room in order to facilitate a natural sounding acoustic environment. To maintain the source frequency balance, RT60 should be similar throughout the audible spectrum. Reverb should allow for controlled liveliness without compromising the clarity of the direct sound source.

- The control room interior should be acoustically isolated from all sources of undesirable noise.

4.1. Control Room Dimensions

The control room acoustics must allow the engineer to accurately assess the material being heard. This does not mean that the room should be acoustically dead. An anechoic room will not allow the listener to hear a natural impression, and will inhibit the interpretation of decay products that will exist in other listening environments. The goal is to avoid coloration and acoustic distortion added by the listening environment. The ultimate goal is a control room with a flat frequency response, such that the frequency balance of an acoustic signal can be reproduced in the listening position. In a small live room, the dimensions will play a huge role in defining the frequency response.

Resonant Room Mode Considerations

Minimizing the effects of resonant room modes in the listening position is the first goal that will influence the selection of dimensions and the shape of the control room. The control room, designed for critical listening, will be smaller than typical live rooms in order to facilitate a relatively short reverb time. Because the room is relatively small, widely spaced resonant modes will occupy the lower region of the audible spectrum. A listener will hear an exaggerated volume at the particular modal frequency in high pressure regions (peaks for standing waves at the modal frequency), and a de-emphasized volume in low pressure regions.

To obtain desirable acoustics, one goal is to find room proportions that allow for an even distribution of sound across the frequency spectrum (a relatively flat frequency response). However, modal resonances will exist, regardless of the shape of the room. An approach will be taken to create many modal resonances, and to spread them as evenly as possible across the frequency spectrum [4]. Later, ensuing modal problems will be controlled with low frequency absorption techniques.

Room modes will present the greatest problems in rooms with dimensions that are divisible by the same number (Figure 1), resulting in degenerate axial modes. However, a ratio based approach to selecting proportions should take into account not only the relative size of each dimension, but the quantity of each dimension. Ratios for length, width, and height that are optimal in a large room may not be ideal in a smaller room, as different modes will be excited. To select appropriate starting dimensions for this conceptual design, a sampling of measured ideal room dimensions based on the Louden (Figure 1) and Bonello criterion (involving Axial mode distribution) could be use (Figure. 2) [4].

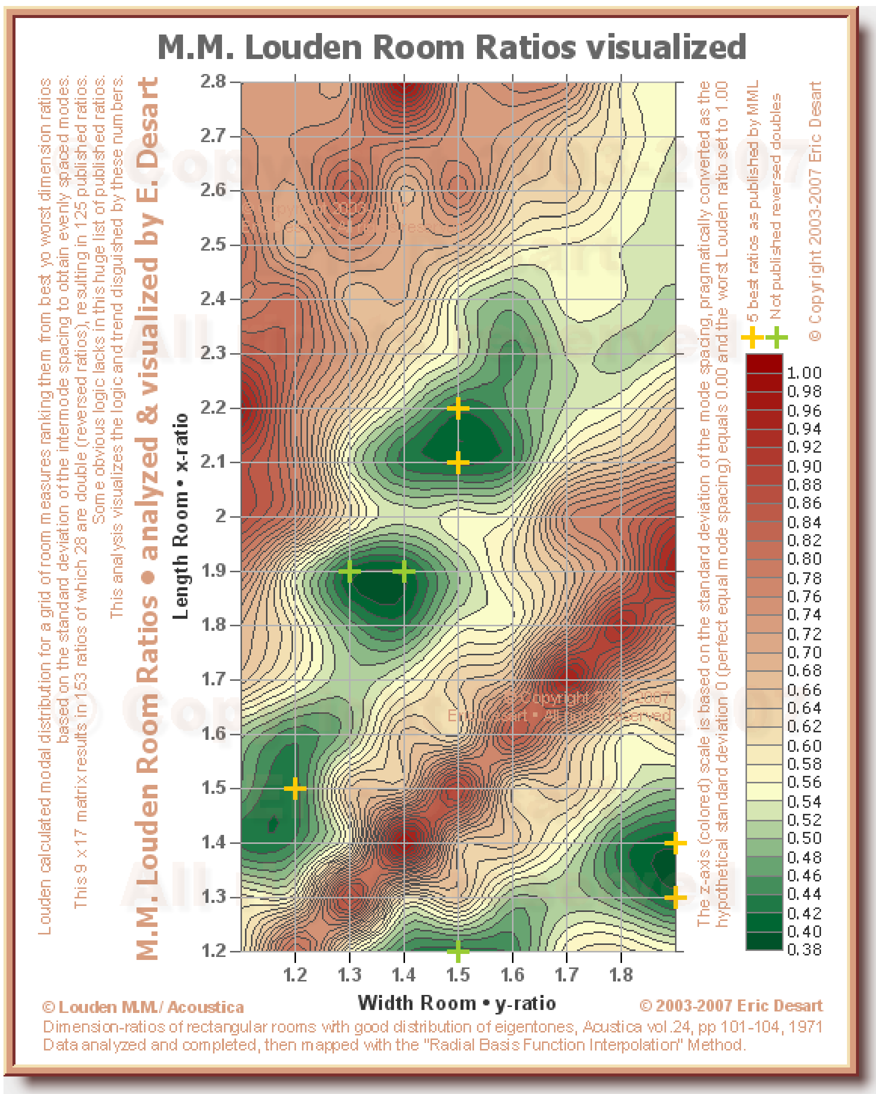


Figure 2 Louden ideal room ratios as determined by the analysis of axial modes. Clearly, there is not a fixed ideal ratio [4].

Table 1 Rectangular room dimensions with "ideal" spreading of axial resonant modes [4].

Eleven Studio Room Dimension Suggestions (Courtesy of *Auralex*)						
	L	W	H	L	W	H
A	226.00 in	162.00 in	84.00 in	574cm	411cm	213cm
B	218.75 in	182.75 in	90.00 in	556cm	464cm	229cm
C	253.50 in	182.50 in	96.00 in	644cm	464cm	244cm
D	252.00 in	209.00 in	102.00 in	640cm	531cm	259cm
E	293.75 in	206.25 in	108.00 in	746cm	524cm	274cm
F	301.00 in	217.75 in	114.00 in	765cm	553cm	290cm
G	302.50 in	218.50 in	120.00 in	768cm	555cm	305cm
H	342.75 in	243.25 in	126.00 in	871cm	618cm	320cm
J	359.00 in	257.50 in	132.00 in	912cm	654cm	335cm
K	343.50 in	285.75 in	138.00 in	872cm	726cm	351cm
L	354.25 in	296.75 in	144.00 in	900cm	754cm	366cm

Five Vocal Booth Room Dimension Suggestions (Courtesy of *Auralex*)						
	L	W	H	L	W	H
A	79.75 in	66.25 in	84.00 in	203cm	168cm	213cm
B	84.50 in	72.25 in	87.00 in	215cm	184cm	221cm
C	87.25 in	68.50 in	90.00 in	222cm	174cm	229cm
D	88.25 in	69.75 in	93.00 in	224cm	177cm	236cm
E	94.00 in	74.00 in	96.00 in	239cm	188cm	244cm

Note: Dimensions are not ranked - they are in order according to increasing ceiling height.

Note: Ratios are deliberately omitted since a good ratio for one set of dimensions does not necessarily constitute a universally "ideal" ratio.

Before jumping to conclusions based on these parameters, additional factors must be recognized:

- In order to reduce unwanted reflections in the listening position (to be discussed in more detail later), a splayed ceiling concept will be employed [1]. Also, parallelism between the floor and the ceiling will be avoided in order to prevent monitor response problems caused by vertical axial room modes [4].

- Following the above point, the control room will need height. Planning ahead to use a floating floor and acoustic treatments on the ceiling, additional height will be required. With a height much less than 4 m to work with, achieving the acoustics of a high quality control room will be very difficult [4].

- In order to reduce flutter echo (discussed later), the room will be designed with splayed side walls. Nonparallel walls will also have the effect of eliminating axial modes in one direction; however, this will not necessarily result in a more desirable model response [5].

The above details complicate matters, as clearly we are no longer dealing with a rectangular room. Also, given the height requirement, some minimum size restrictions have become apparent. With angled walls, room modes still exist, but they are more difficult to predict without the use of simulation software. There will be many high order oblique and tangential modes that can still create problems; however, when approached properly, non-parallel walls can provide an advantage by distributing room modes more evenly throughout the frequency spectrum [6].

To obtain an approximation of the modal response of the room, an analysis of the equivalent rectangular room having the same volume as the control room will be conducted in the next section. Since the concern is primarily tangential and oblique modes, Figure 2 will not be used to obtain starting dimensions. In the case of a rectangular room, ratios would be selected based on the European Broadcasting Union recommendations [2] (Figure 3). Ultimately, however, the decision will be based on a non-rectangular existing control room layout that has proven to exhibit desirable modal response [5].

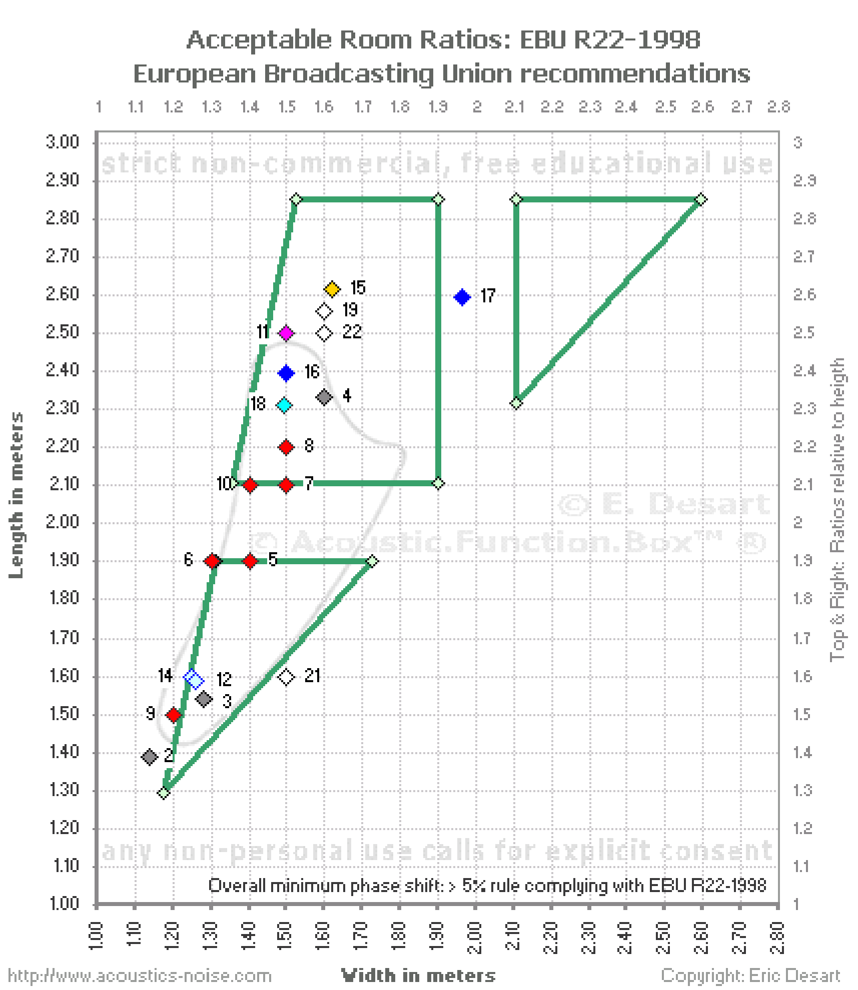


Figure 3 Acceptable room ratios for desirable eigenmode distribution based on [7].
Source: Acoustics Forum, 2005.

In Figure 3:

- Points 5-10 represent ideal axial mode spacing (the top 5 Louden analysis ratios), where 5 represents the ratio 1:1.4:1.9.
- Point 15 represents the "golden rule ratio" - 1.236:2:3.236.
- Point 17 represents the IEC 60268-13 recommendation for a listening room: 2.7:5.3:7.
- Point 18 represents Dolby's optimum ratios for Film & Music Rooms - 0.67:1:1.55.
- Point 24 represents the *worst case scenario*, as calculated by RPG diffusors - 1:1.075:1.868.
- Points 2-4 represent ratios, neglecting axial modes, as published by L. W. Sepmeyer in 1965. The most common one (very widely used) is 1:1.14:1.39.

Assigning a height of 12′ in order to exceed the minimum height requirement [3], and using Dolby's optimum ratio for film and music rooms:

Mean Height = 12′ = 365.76 cm
Mean Width = 17.91′ = 545.90 cm
Mean Length = 27.76′ = 846.12 cm

The above dimensions calculated using Dolby's ratio should be well suited for a rectangular control room, and it could be verified by plotting the distribution of axial, tangential, and oblique modes.

When judging the Sepmeyer ratios based on purely axial mode distribution, the results are not favourable [5]. However, since these ratios were optimized for tangential and oblique modes, they may be suitable as guideline for a non-rectangular room. Realistically, without advanced calculation tools and acoustic expertise, the selection of ratios for a non-rectangular room based on an analytical approach is beyond the scope of this conceptual design. Instead, an existing design will be partially adopted, modified based on research and reason, and then the equivalent rectangular room will analyzed.

Control Room Shape and Size

The selection of room dimensions will be derived from on an existing control room concept by Aurlex acoustics [5]. "*The Acoustics 101 Room*" (Figure 4). This design is based on the shape of many modern control rooms in top studios; it is intended to produce a controlled listening environment, without being acoustically dead.

The Acoustics 101 control room is designed for use with a ceiling height of 8-10′ (with higher ceilings being acceptable). However, considering the height above the floor of a listener's ears (usually in the region of 4'), they will be located at roughly half the vertical distance from floor to ceiling in an 8′ high room. This will create a predictable vertical axial mode problem at 71.5 Hz, as the listener's ears will be positioned at that mode's minima. For proper imaging, the listener must be located at the half way point widthwise, but effort will be made to avoid symmetry in the other dimensions.

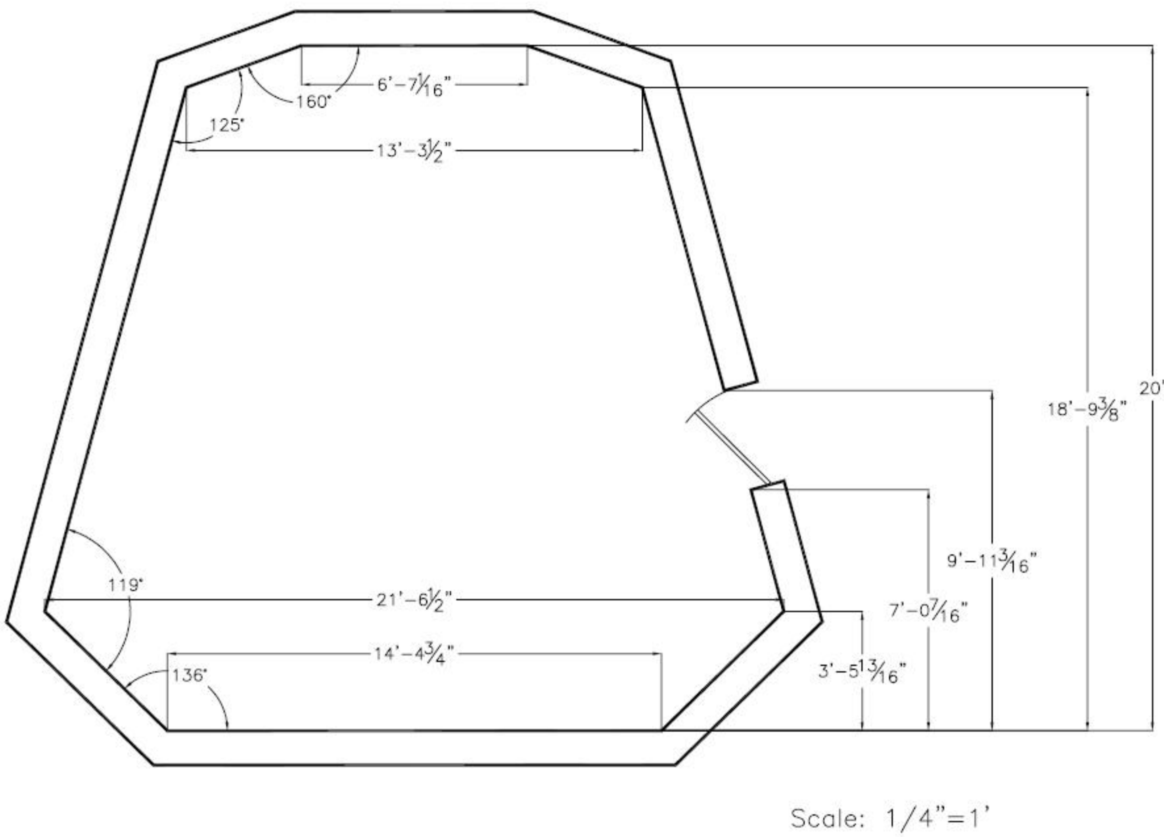


Figure 4 "The Acoustics 101 Room" is one approach to a near-optimal control room shape. ***Source: Auralex Acoustics, 2010*** **[5].**

Our design will make use of a splayed ceiling in order to avoid parallelism between the floor and ceiling [3], and according to the recommendations in [5], additional height will be needed. The room will consist of an inner shell for controlling reflections (Figure 5), and an outer shell which will define the modal contributions to the low frequency response.

To facilitate an average ceiling height of over 4m, the rest of the acoustics 101 room will be scaled up in size. Scaling the wall shape of Figure 4 up by a factor of 1.35 results in a ceiling height of 13′-6′′. This will be the target average ceiling height after a floating floor, splayed ceiling, and acoustic treatments have been added. This means that if the control room is being constructed in an existing building (a room inside a room) 16′ of vertical space will be needed for construction.

However, based on the Acoustics 101 control room proportions, a 13′-6′′ ceiling corresponds to a room length of 27′, exactly half the height. To reduce the apparent degenerate axial mode problem with these proportions, the room length will be kept at 27′, the average inner shell height (for broadband diffusion) will be kept at 13′-6″, but the average outer shell height (which will define the low frequency modal response) will be further increased.

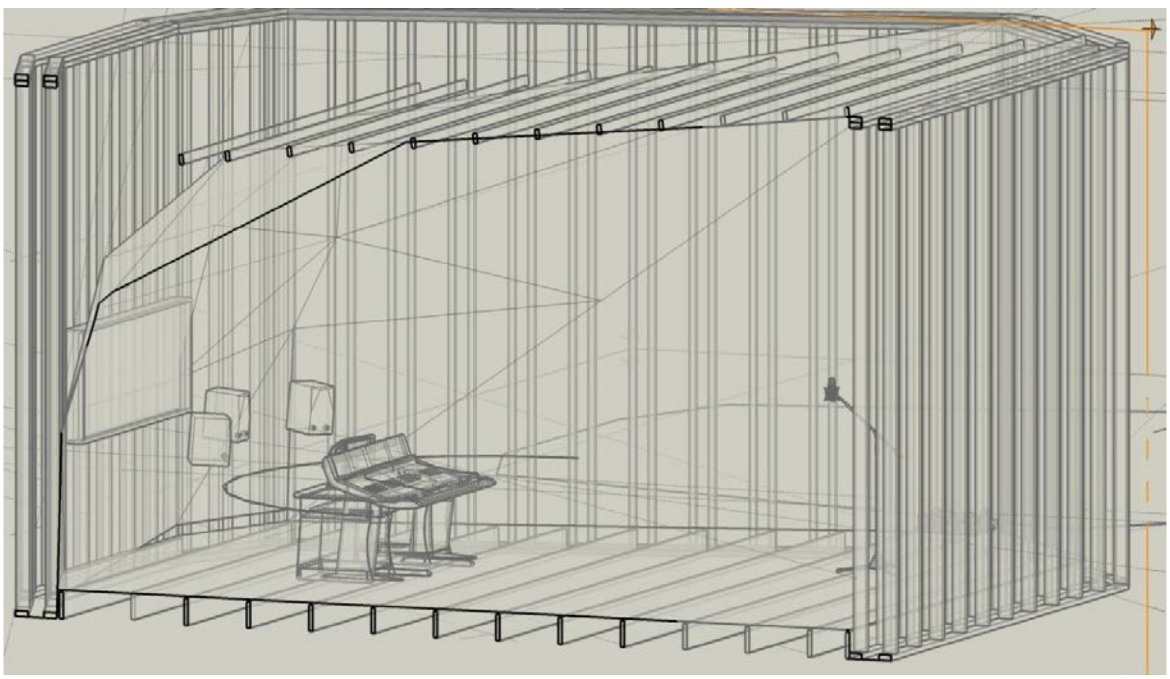


Figure 5 Side section for proposed control room shape, utilizing an inner and outer shell.

Many simulations were conducted in attempt to determine the average outer shell height of the control room. The goal was to a find a dimension that theoretically allows for an even distribution of tightly spaced modes within the human hearing range. Widely spaced modal spikes in the lower frequency range of our hearing are problematic, preventing a balanced frequency response in the listening position. Figure 6 displays the simulated modal response of the equivalent rectangular room with a similar volume to the splayed surface control room. The estimated average dimensions that were used for length and width are:

- Effective Length = 27′= 8.229 m (since the front and rear walls are parallel, the full interior length was used, rather than an average).

- Average Effective Width = 23′ – 7 $^{1}/_{16}$″ = 7.187 m (calculated based on the difference between the maximum and minimum interior width)

A simulated test microphone was oriented at the estimated listening position: 4′-3′′ high, centered widthwise at 38% of the length dimension [6]. A damping coefficient of 0.02 was used to simulate a controlled environment with moderate liveliness, and the first 40 axial, tangential, and oblique modes were modeled. Assigning a maximum height of 15 and a half feet (for construction feasibility) and working down in increments of tenths of a foot, the best modal response was initially found to be with a ceiling height 14′–7″ (4.45 m). This height results in a fairly flat response; the peaks are for the most part accumulating near each other (Figure 6.). For comparison, the data was also plotted with a ceiling height of 8′. A clear improvement is apparent with the additional height (this is considering only modal response).

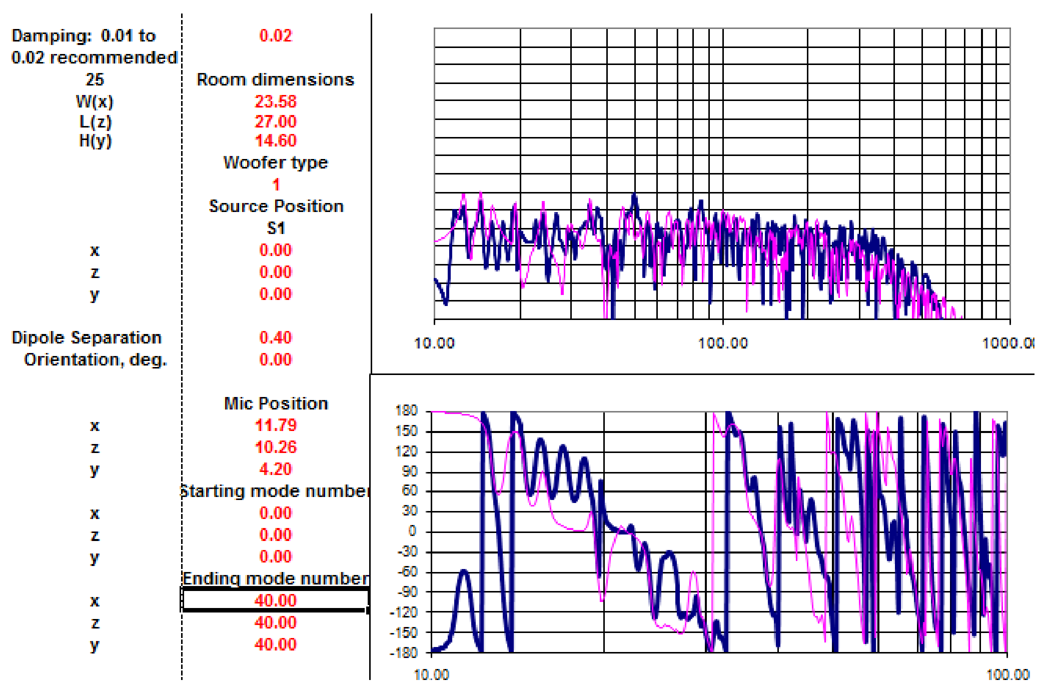


Figure 6 Modal response of the ~equivalent rectangular room (top) from 0 to 1000 Hz. The thick line represents a 14'-7" ceiling height, while the thin line represents an 8' ceiling height. The simulation modeled the effect of a subwoofer in one corner of the room, exciting all resonant modes with broadband (pink) noise. The bottom plot displays the phase versus frequency response from 0 to 100 Hz. Program used: Room Response
Source: Room Response Simulator by John Kreskovskt, 2008.

The simulation was later carried out using the original proposed ceiling height of 13′-6″. Interestingly, good modal response was observed at this height (half of the room length) when all modes are taken into consideration, not just axial modes. It appears that the effect of higher order oblique and tangential modes lead to a fairly even distribution of peaks. As a result, 13′-6″ may indeed be an appropriate average outer shell height in an equivalent volume room with splayed surfaces. Assuming a splayed ceiling on the outer shell to break up modal patterns, a 13′-6″ average height will allow for more ceiling slope than a 14′–7″ average height if restricted to 16 feet of vertical construction space. The alternative is to stick with a more predictable flat ceiling for the outer shell, and reserve the splayed ceiling for the inner shell.

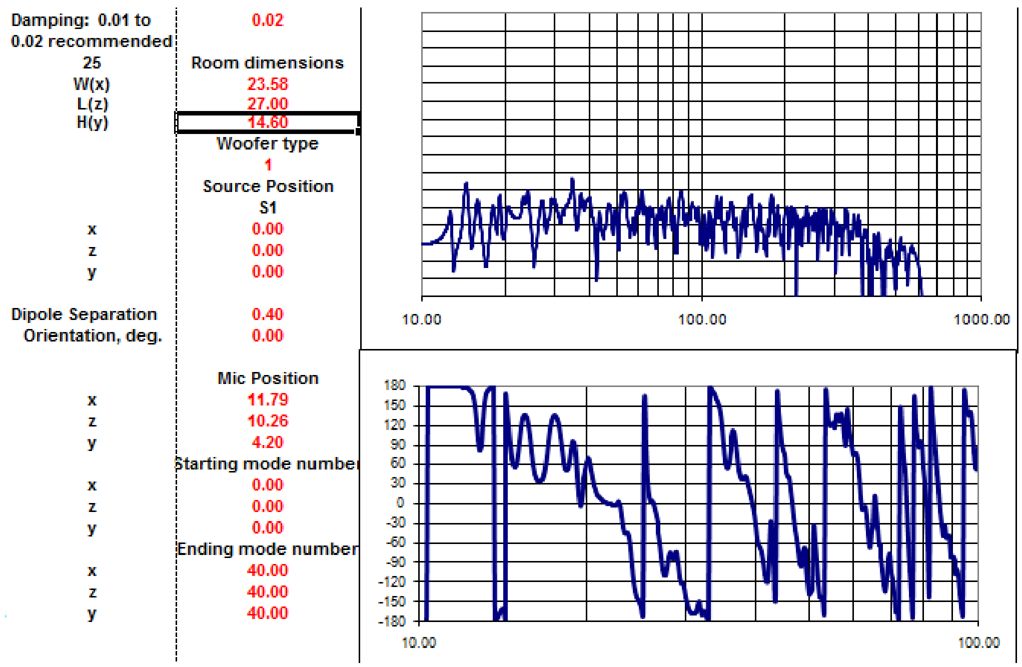


Figure 7 Modal response of ~equivalent rect. room using 13'-6" average ceiling height. Plots depict magnitude versus frequency (top) and phase versus frequency (bottom) for broadband excitation using a subwoofer in a front corner of the room. Program used: *Source: Room Response Simulator by John Kreskovskt, 2008.*

It is important to note that the above modal response curves will in fact be different in a room with splayed walls and ceiling. However, there is at least one similarity that will exist: the length axial modes between the parallel front and back surfaces of the control room. As a result, we can predict modal resonances at integer multiples of 20.9 Hz (20.9 Hz, 41.8 Hz, 62.7 Hz, 83.6 Hz, etc.). Low frequency absorption and other bass management tools will be discussed in Section 4.4.

Imaging and Reflections

To obtain a proper acoustic balance for imaging in the control room, horizontal symmetry is essential about the mixing position. However, an addition problem surfaces in rectangular rooms without proper acoustic treatment. Early reflections, in particular the first reflections from the sidewalls, will cause an obscured stereo image and effect clarity and the perception of detail. Additionally, repetitive high frequency reflections around the listener, if they are spaced apart in time by less than 20 ms [4], will cause flutter/slap echo. This further harms the ability to localize sounds, and creates distracting effects such as ringing and obvious phase related acoustic distortion. Early reflections cause comb filtering due to phantom images of the source arriving at the ears at different times. This can distort the timbre of the perceived sound. If a reflection free zone is created around the listening position, constructive and destructive interference during the initial perception of the source can be avoided.

Figures 8 to 10 display the symmetrical distribution of phantom sources for the rectangular room with equivalent volume to the proposed control room (from this point onward, the equivalent volume rectangular room will be abbreviated as EVRR where appropriate). A three-monitor playback configuration was used, with two simulated omnidirectional testing microphones at the listening position, separated by 14.5 cm. Simulations were carried out in MATLAB by writing scripts for an acoustic toolbox called RoomSim, created by D. R. Campbell. Relative amplitude data was obtained through impulse response and RT60 simulations of the room, which will be described in Section 4.3.

The following plots illustrate that in the equivalent volume rectangular room, first reflections will follow the direct source closely in time. Additionally, these first reflections will have retained much of the original signal power, and will have a negative effect on imaging.

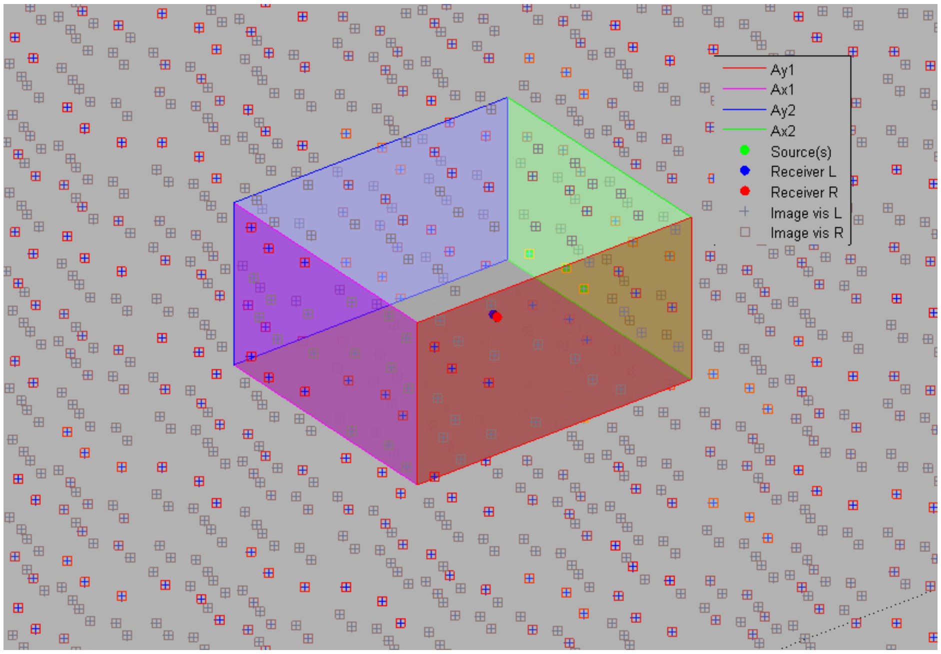


Figure 8 3D plot of image sources for rectangular room of equivalent volume.

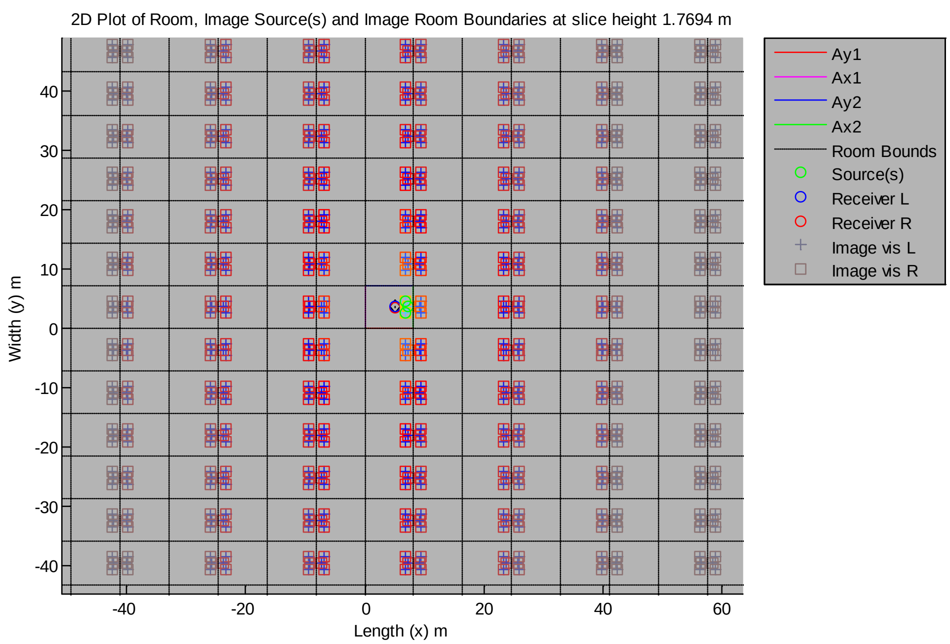


Figure 9 2D plot of image sources for rectangular room of equivalent volume.
The plot represents a top view of a slice of the 3D distribution, cut in the horizontal plane.

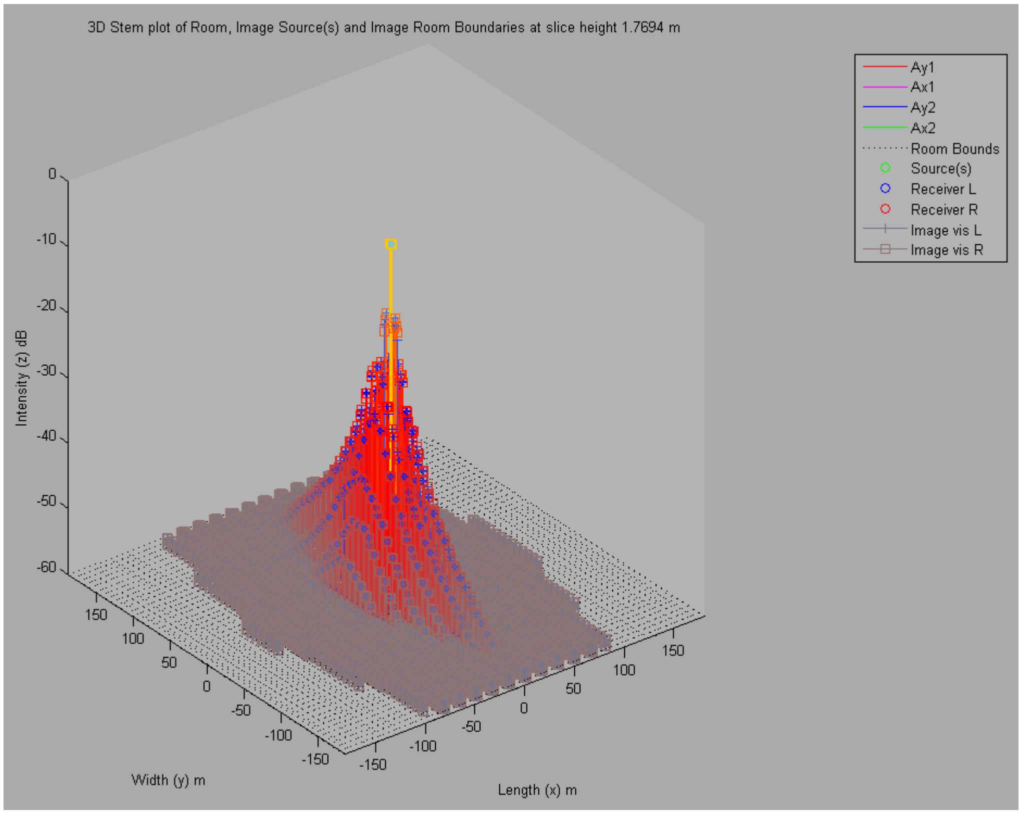


Figure 10 2D distribution of image sources; stem height shows relative amplitude. Symmetrical imaging is apparent.

This brings us back to the main purpose of splayed sidewalls. A reflection free zone can be created by using anechoic absorption on the front and sidewalls in a rectangular room; however, this can result in an unnaturally dead sound. In order to perceive a source realistically, the human ear needs to perceive an element of exponential decay. By angling the walls so that early reflections are deflected toward the back of the control room Figure 11), a reflection free zone can be created around the listening position, and liveliness may be preserved.

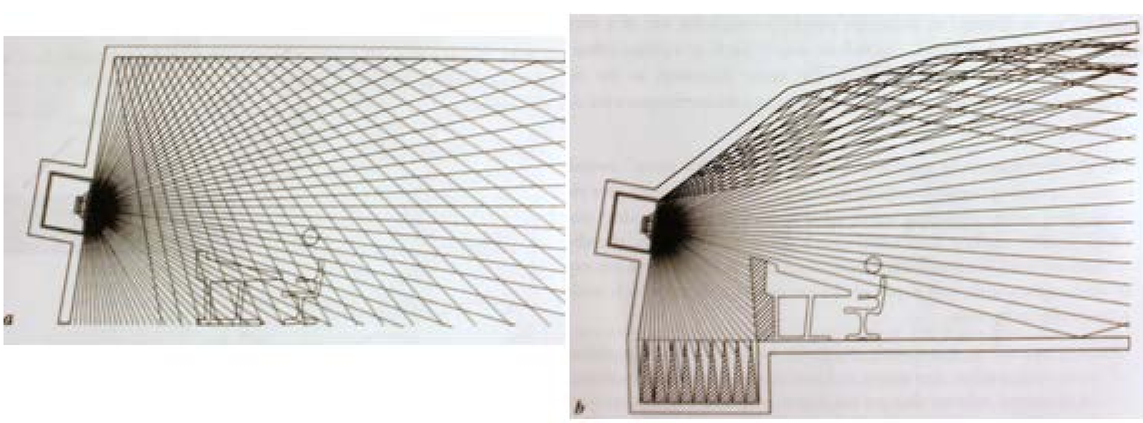


Figure 11 Effect of a splayed ceiling (right) to reduce interfering early reflections [4].

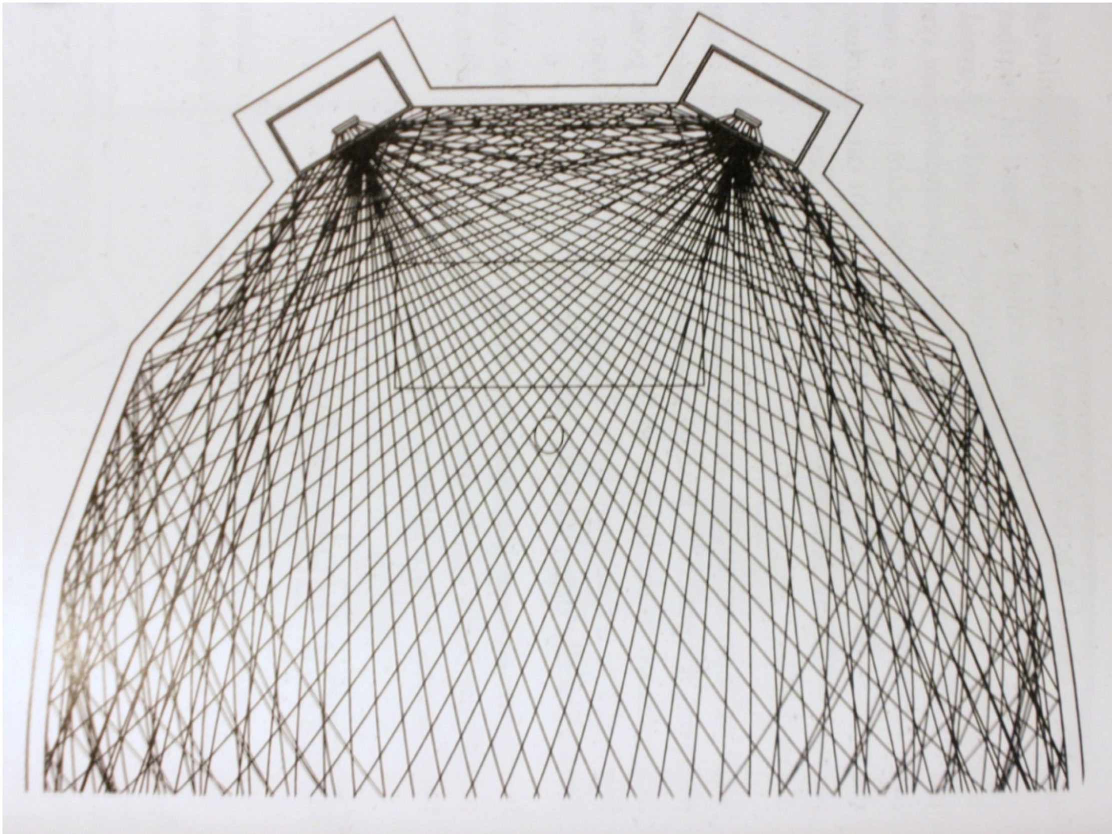


Figure 12 Symmetrical splayed sidewalls about the listening position.
Splayed sidewalls are used to prevent phase combing from early reflections [4].

In the quest to facilitate accurate imaging without sacrificing liveliness, splayed sidewalls and ceiling are key components of the design. This leads to an interesting concept for optimizing control room acoustics: the live-end dead-end design.

Revealing the Initial Time Delay Gap

The initial time delay gap (ITDG) is the one measure of acoustical quality that is almost impossible to optimize in a small room [2] without radical design conventions. Ideally the listener will hear the uninterrupted direct source, and after an initial time delay, hear scattered reflections from distant surfaces (with decaying energy). Without the reflection free zone, the ITGD is masked by early reflections; as a result, the listener is deprived of an important environmental parameter when evaluating the sound. In a concert call, these early reflections are critically important – but in the highest rated halls they arrive at the listener after an ITDG of about 20 milliseconds. How can a smaller room, such as a control room, be built with an ITDG that gives the impression of a larger (but still controlled) room?

By creating a reflection free zone (for early reflections), we will instead rely on later reflections to give a well-defined ITDG. Early reflections that were deflected toward the back of the room will be diffused and scattered back toward the front of the room with a balanced texture (as late reflections). In this way, both the natural exponential decay of sound and a diffuse sound field (controlled revered) can be perceived. The front of the control room will rely on heavy absorption to be relatively "dead" acoustically, ensuring an accurate portrayal of the direct sound. The back end of the room will contain broadband diffusors, creating a controlled liveliness. Hence, we will have the live-end dead-end design. Using this method, small rooms with genuine high quality acoustics are possible [2].

With the dimensions used in this conceptual design, an ITDG of up to 30 ms can be achieved using the live-end dead end design. By adjusting the listening position, the distance traveled by the first reflections from the back wall before reaching the listener can be optimized. Providing about 7m of travel distance after the direct sound was heard, an ITDG of 20 ms can be achieved. For a shorter ITDG in this control room (12-20 ms), a ceiling diffusor can be placed above and behind the listening position. Ultimately, it is important that the ITDG is well defined.

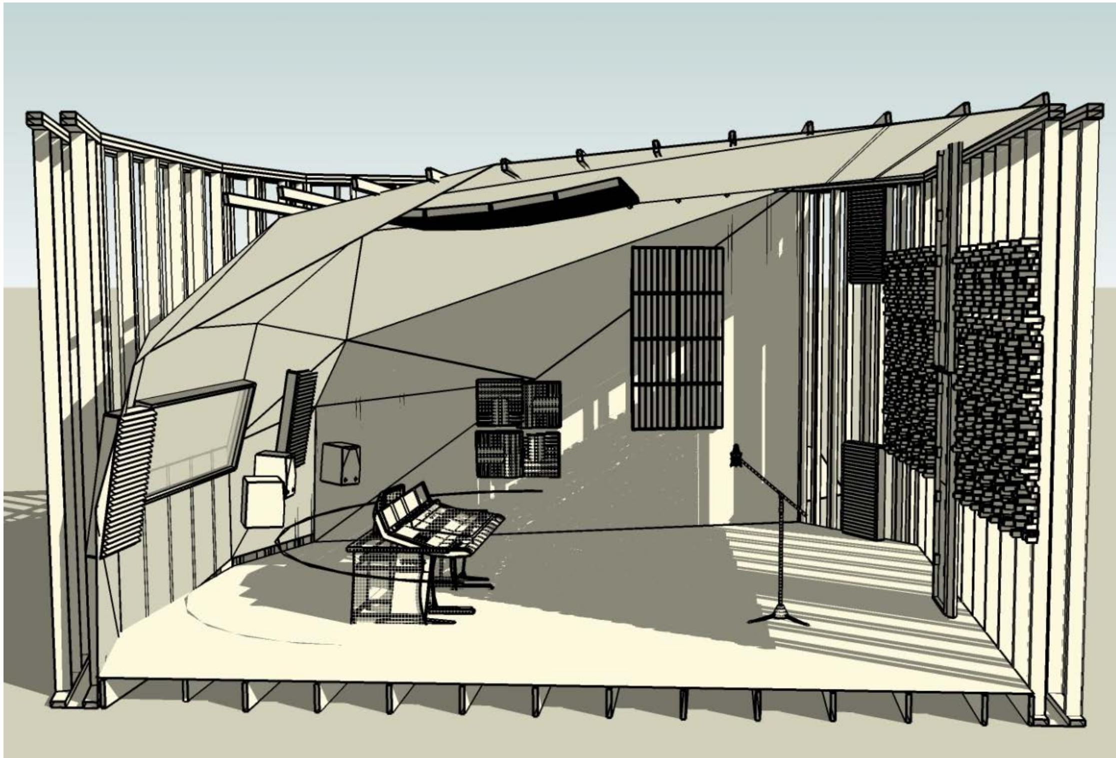


Figure 13 Side section of proposed control room design, illustrating diffusor placement. Diffusers are located the on the back wall, ceiling, and sidewalls. For a longer ITDG, the ceiling and sidewall diffusors may be moved back from the listening position. The front end contains heavy absorption to create a reflection free zone around the listener.

4.2. Acoustic Isolation and Noise Reduction

Acoustic isolation is an important concern in control room design, and will have a huge impact on the constriction methods used. During critical listening, disturbance from unwanted noise sources both outside and inside the control room needs to be avoided. Since the focus of this conceptual design is on internal acoustics, acoustic isolation will not be explored in detail. Instead, standardized construction techniques for studio sound proofing will be briefly overviewed.

Walls

Attenuation caused by transmission loss through walls depends on a number of factors: notably, thickness and density of the material used. Standard wall construction permits excessive transmission, as sound has a resonant pathway from one side of the wall to the other along the wall studs. Staggered stud construction can reduce this problem by decoupling the inner and outer wall surfaces from each other. For even better sound attenuation, a change of medium such as an insulated air gap is helpful, followed by another dense obstacle. Additionally, vibration dampening structures can be added to walls to reduce the transmission at problem frequencies.

The “room within a room” concept employs double walls, spaced apart and treated with material that adds mass and provides extra attenuation. In the conceptual design, 2x4 studs were used, with a spacing of 6” between the inner and outer walls (Figure 15). Proper double wall construction can yield high STC ratings in the range of STC70, which is the goal for acoustic isolation in certain demanding critical listening environments. As a general rule of the thumb, the control room should achieve STC > 45 for any given barrier (including windows and doors).

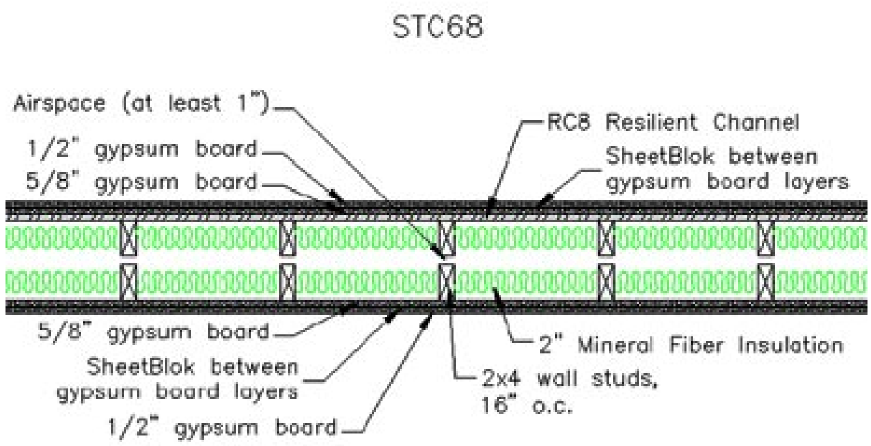


Figure 14 Typical double wall construction [4].

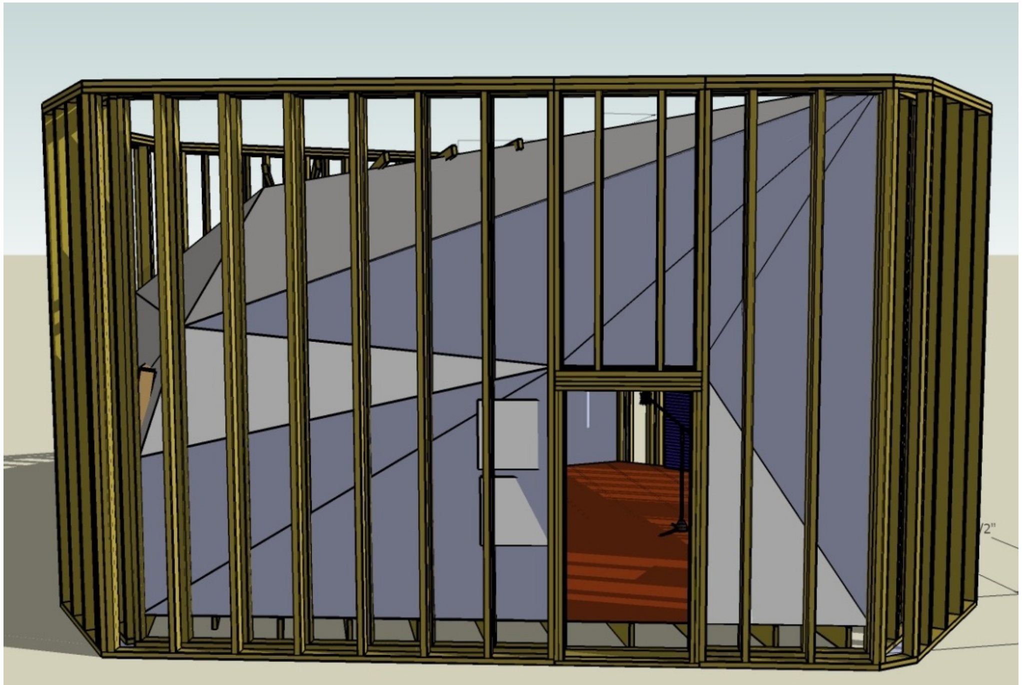


Figure 15 Spaced double wall construction used on the outer shell of the control room.

Floor and Ceiling

A floating floor is helpful for acoustic isolation from low frequency sounds, such as drums or terrestrial rumble (for example, from nearby heavy vehicles or machines). The floor can be largely decoupled from the foundation or existing floor beams by using narrow channel supports that have difficulty transmitting low frequencies. In the conceptual design the intended floor structure is similar Figure 16, with a top surface of floating cork floor tiles.

A similar concept can be used to decouple the ceiling from the supporting structure. The inner shell ceiling may be suspended using "Z" suspension channels. These channels will allow some high frequency transmission; however, high frequencies are easier to attenuate using insulation than low frequencies.

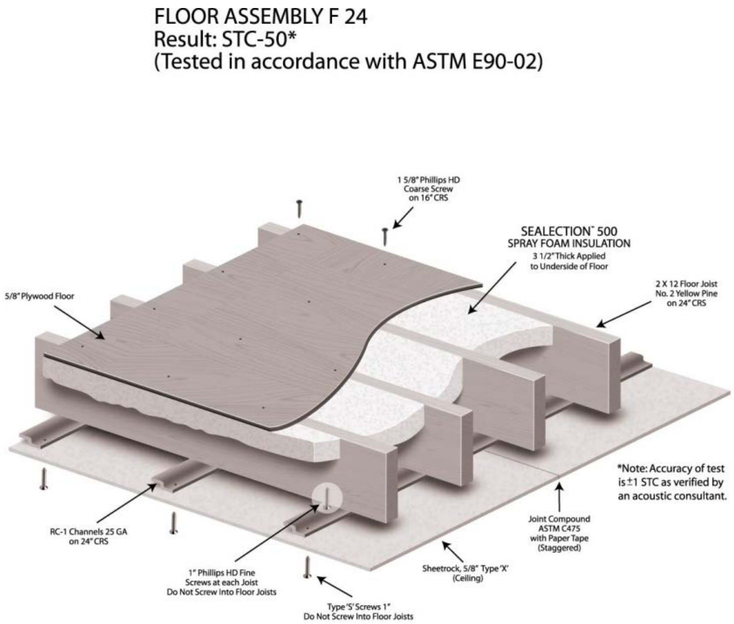


Figure 16 Floating floor assembly on decoupling rails.

HVAC and Electrical Noise

There are many sources of noise that cause acoustic isolation concerns in control rooms, including:

- noise from HVAC units (another reason to maximise passive heating and cooling)
- noise from computers and hardware that is not in soundproofed enclosures
- other electrical noises (caused by improper grounding, lack of cable isolation, lights, poor voltage regulation and general AC hum)

While it is beyond the scope of this paper, electrical noise must be addressed as part of any thorough sound proofing scheme.

4.3. Desired Reverberation Time and Frequency Response

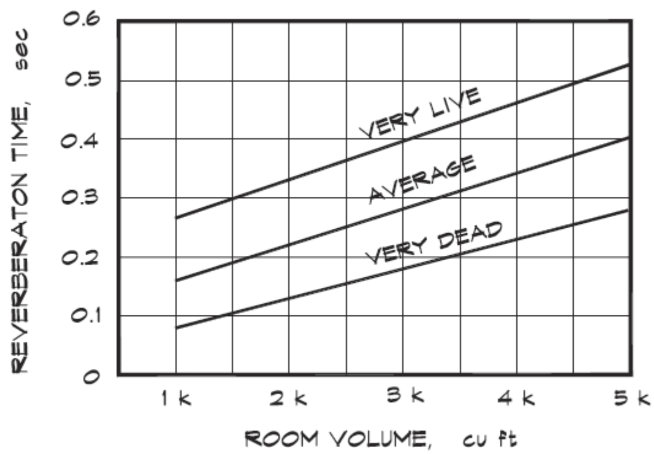


Figure 17 Suggested Reverberation Times for Control Rooms.
***Source: Architectural Acoustics, 2006* [8].**

Optimal reverb time for a control room is somewhat subjective, and depends on the size of the room. The goal is to allow a natural spatial impression that does not colour the sound. Too little reverb and the control room will sound unnaturally dead; too much reverb and we compromise the clarity of the direct sound—and with it our ability to critically assess recordings. Additionally, RT60 will be slightly different at each frequency. Several sources recommend an RT60 average between 0.3 and 0.5 seconds in the 500 Hz and 1 kHz frequency bands. Others recommend a reverberation time between 0.2 and 0.4 seconds as an average in the one-third-octave bands from 200 Hz to 4 kHz. A tighter guideline prefers reverberation times in the 0.3 to 0.4 second range for average control room volumes [8].The Audio Engineering Society recommends the following formula to calculate T_m, the nominal reflected sound reverberation time between 200 Hz and 4 kHz [8]:

$$T_m \approx 0.25\,(V/V_0)^{1/3} \qquad (1)$$

Where V is the volume of the listening room, and V_0 is the reference room volume (V_0 = 100 m^3).

A target T_m is estimated using the equivalent volume rectangular room:

$$V = 263.18\ m^3$$

$T_m \approx 0.345$ s

RT_{60} and Absorption Coefficients

To simulate the soundfield in the equivalent volume rectangular room, absorption coefficients for the wall materials first needed to be assigned. RT60 is a function of the room volume and the average absorption of each surface, as described by the Sabine (left) and Eyring (right) equations [9]:

$$\frac{0.161V}{S_{tot}\alpha_{sab} + 4\,\mathrm{mV}} = T_{60} = \frac{0.161V}{S_{tot}[-2.3\log(1-\alpha_{ey})] + 4\,\mathrm{mV}} \quad (2)$$

where V is the volume of the room, S_{tot} is the total surface area, and α_{sab} and α_{ey} are coefficients that represent the average absorption of all surfaces.

The EVRR was simulated using a custom MATLAB script for RoomSim. The script takes into consideration many test and environmental parameters; some parameters are well defined, several have been estimated. The volume of the EVRR is 263.18 m^3, based on the average dimensions of the control room as specified in Section 4.1.

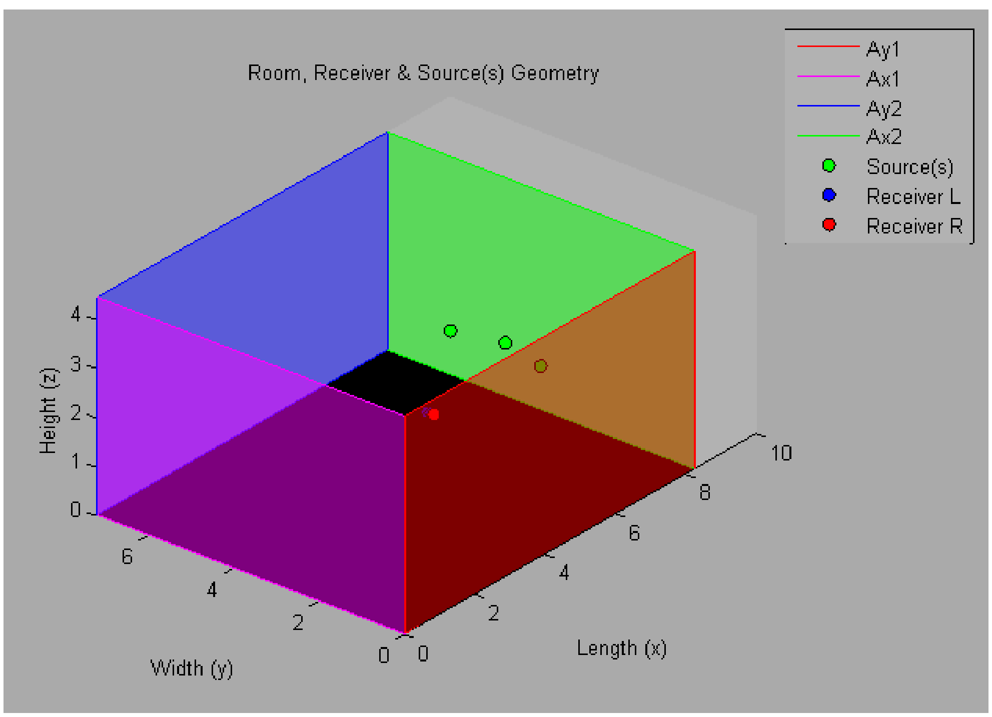


Figure 18 EVRR simulation layout with 3 studio monitors (30° angle between pairs) at a 2.2m radial distance, angled 10 degrees down toward the listening position for sources. Two simulated omnidirectional test microphones separated by 14.5 cm are located

in the listening position as sensors (listening position used is at 38% of the length dimension back from the front wall, centered widthwise at a height of 1.2m).

In attempt to estimate the acoustics of the partially treated EVRR, the absorption coefficients in Table 1 (plotted in Figure 19) were used in the simulation. The goal was to approximate untreated sidewalls, but some acoustic treatment on surfaces that have already been partially defined. The partially defined surfaces are the back wall (the "live end", a diffusive surface) and the front wall (the "dead end", a surface with high absorption in most places, but also containing a window).

Table 2 Absorption coefficients used for Control Room Simulation

Surface	Main Surface Material Simulated	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
Back Wall (Ax1)	RPG Skyline diffusor (attenuation at 125 Hz added)	0.15	0.34	0.28	0.29	0.19	0.16
Front Wall (Ax2)	hypothetical 50% broadband attenuation (acoustic foam and glass)	0.75	0.75	0.75	0.75	0.75	0.75
Side Wall 1 (Ay1)	gypsum wallboard	0.3	0.1	0.05	0.04	0.07	0.1
Side Wall 2 (Ay2)	gypsum wallboard	0.3	0.1	0.05	0.04	0.07	0.1
Floor (Az1)	varnished cork parquet on joists (floating)	0.15	0.11	0.10	0.07	.0.06	0.7
Ceiling (Az2)	acoustic tile (suspended)	0.5	0.7	0.6	0.7	0.7	0.5

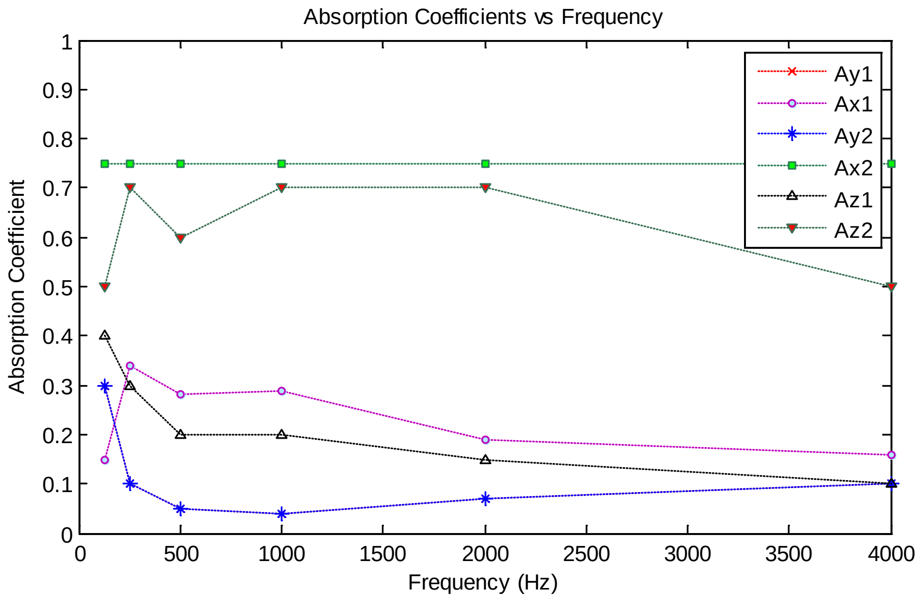


Figure 19 Absorption coefficients versus frequency for simulated surface materials.

The RT60 simulation was run using a generalized version of the Eyring equation at six frequency bands, taking into account environmental parameters such as room temperature, humidity and air density (typical values were used). The results are displayed in Figure 20.

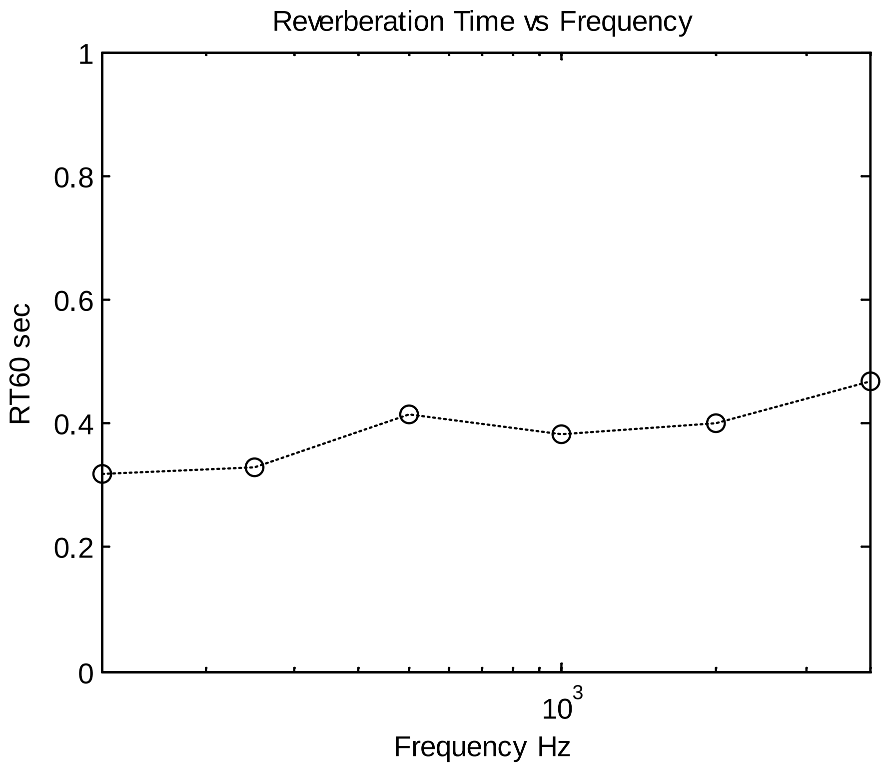


Figure 20 RT60 versus frequency for EVRR with estimated absorption coefficients.

The estimated RT60 results for the partially treated control room are encouraging. The values are certainly between 0.3 and 0.5 seconds throughout the hearing spectrum. However, additional absorption will need to be added in order to get closer to the goal $T_m \approx 0.345$ s. This absorption will also have a secondary purpose: to adjust the frequency balance of the room.

Impulse Response Results

The impulse response and its FFT, the frequency response, provide valuble data regarding the acoustics of the room, and reveal some problem areas. An IR simulation was performed on the EVRR for each of the three sound sources (monitors), with test microphones simulated at the listening position (as depicted in the layout of Figure 18). The EVRR was modeled as a19th order FIR filter using RoomSim and MATLAB.

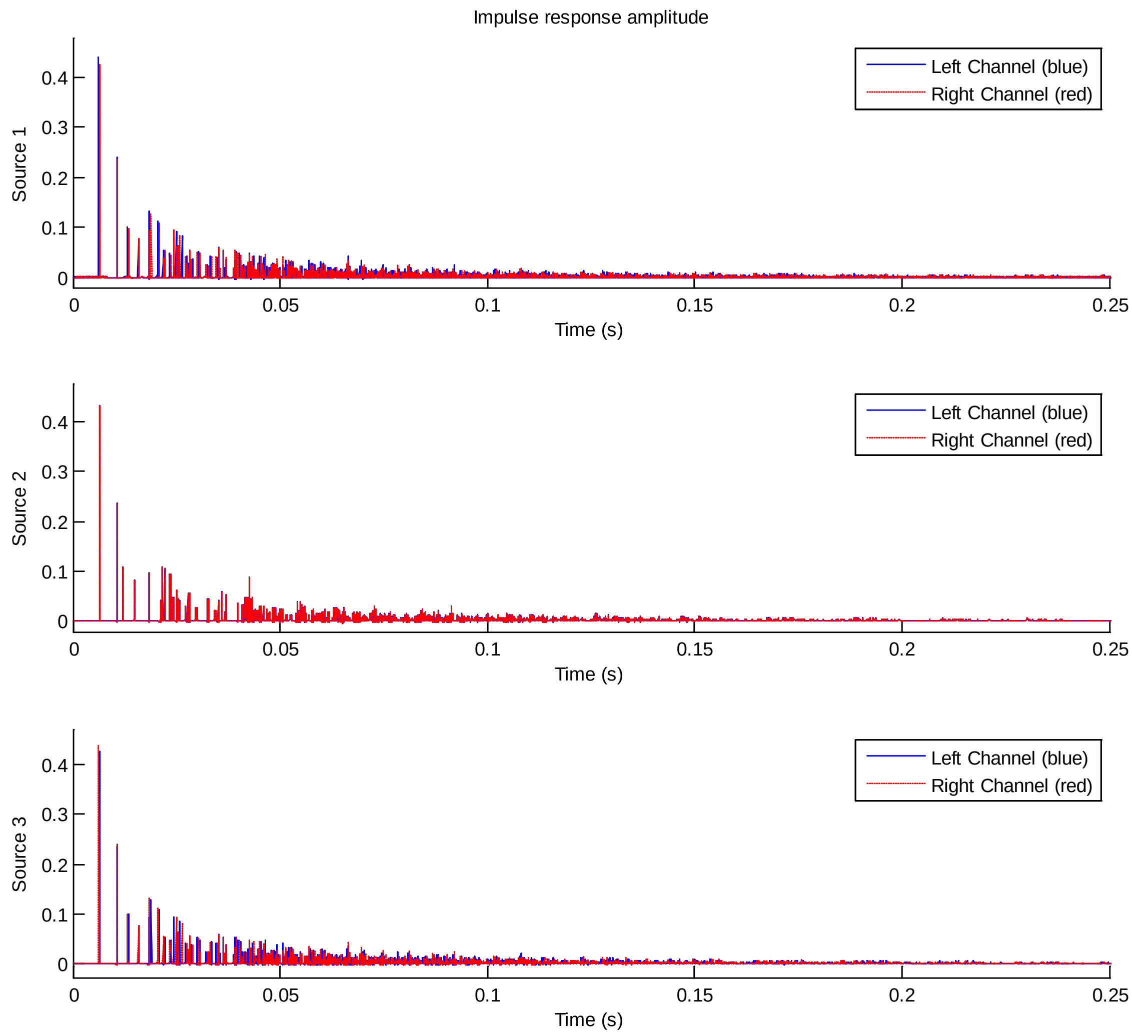


Figure 21 Impulse response at the listening position for three sound sources (monitors).

Impulse response characteristics look quite promising. As expected, the direct sound arrives from source 2—the center monitor—to both test microphones at the same time. Timing delay between the test microphones is visible for the direct sound from sources 1 and 3. This is consistent with balanced stereo imaging. After the direct sound, first reflections are observed:

- The first of these reflections (and largest in magnitude) arrives at both microphones with less relative timing difference than observed with the direct sound image. This first reflection is almost certainly from the reflective cork floor. Here we have obtained a big hint: when a console or mixing desk is placed in the room, there should be a barrier behind it to block the first reflection. This also serves as fair warning for reflections off of the console or desk (which was not simulated in the

EVRR). These will occur even closer in time to the direct source image, and should be dealt with by minimizing the workspace surface area and sloping the console on axis with the speakers (this is displayed in Figure 11).

- The second and third reflections are significantly damped, and are therefore from the absorbent front wall and the ceiling acoustic tiles. In fact, the ceiling will have a diffusor above/ behind the mixing position, so reflections from this point will be exposed to less damping. However, these ceiling reflections from the EVRR simulation should not be problematic, as a splayed ceiling is being used in the design to reflect much of this energy toward the back wall. The reflection from the front wall is a cause for concern, considering that it if there is a window the reflection will have higher energy than the IR plot depicts. To work around this problem, the window must be properly tilted downward so that the offending reflection may be trapped. An alternative is to instead orient the window on one of the splayed sidewalls.

- The fourth reflections are more spaced out in time, and have a greater amplitude than the second and third. These seem to be from sidewall surfaces in the EVRR, which were simply untreated gypsum wallboard in the simulation. With splayed sidewalls to create a reflection free zone, these early reflections will be instead deflected toward the live end of the room.

After these very first reflections, exponential decay is the primary trend (with a few stray reflections jumping out), ending in a stationary sound field. Application of diffusers should improve the texture of the early reverberant sound field by scattering amplitude spikes in different directions based on frequency. Also, additional absorption will be needed on the front wall (the dead end).

Due to the reflection free zone created by the splayed inner room shell and dead front end, the first four early reflections depicted above can be mostly avoided in the listening position. This leaves us with a well-defined ITDG after the direct source image.

Frequency Response

Maintaining the frequency balance of the original signal is fundamentally important in control room design. In this respect, the frequency response simulation results for the EVRR are not so encouraging. The 8192 point FFT magnitude spectrum is plotted in Figure 22; a flat frequency response is certainly not depicted. While the general trend may be relatively flat, there are many sharp changes in the magnitude response by as much as 40 dB. Using shorter FFT windows revealed that many of these sharp deviations are due to resonant room modes. A harmonic relationship is apparent with many of the dips, which is expected. However, the magnitude of the deviations is disconcerting. Clearly, a lot of acoustic interference is present within the EVRR.

Considering the large influence of resonant modes on the frequency response, it is difficult to predict what the response will look like within the splayed double-shell control room. What this data does reveal is that a lot of acoustic treatment will be necessary at targeted frequencies, in particular, modal resonant frequencies.

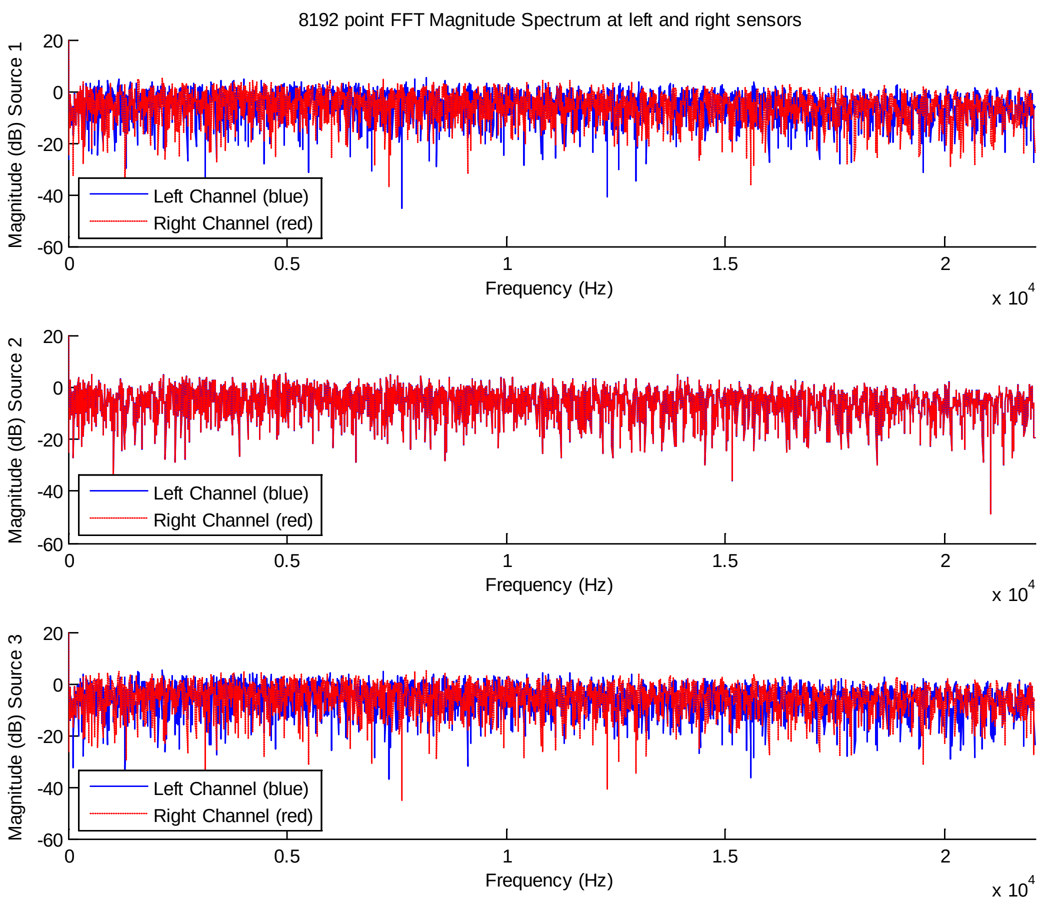


Figure 22 Frequency response from each source (monitor) in the partially treated EVRR. Data is received at the listening position and plotted on a linear frequency scale.

4.4. Tuning the Control Room with Acoustic Treatments

A perfectly proportioned and shaped control room still requires acoustic treatments to optimize the frequency balance, adjust the modal bandwidth, diffuse broadband reflections, and control reverb time throughout the spectrum.

Low Frequency Absorption

Bass traps are necessary to dissipate modal energy in the control room, even if a splayed outer shell is used. The modal response characteristics from Section 4.1and the frequency response plot indicates that special attention will be needed for treating room modes. For this conceptual design, specific solutions cannot be practically specified for the splayed wall control room. However, the control room will share at least one train of modal resonances with the tested equivalent volume rectangular room: axial modes in the central portion of the length dimension, occurring at integer multiples of 20.9 Hz. This first targeted mode is just in the very bottom edge of our hearing, but higher order axial modes may be more perceivable (41.8 Hz, 62.7 Hz, 83.6 Hz, etc.).

To target the fundamental known length axial mode, a Helmholtz resonator will be installed centrally, at the rear of the room. The Helmholtz resonator cavity can be accurately tuned to a particular resonance, and the bandwidth may be widened by adding fiberglass absorption inside the resonant chamber [1]. However, the Helmholtz resonator is limited in that it will only work over a relatively narrow frequency range. Another attractive option is the use of membrane absorbers, which vibrates in sympathy with sound waves within an effective frequency range, causing attenuation by absorbing energy at those frequencies. Membrane absorbers will also be useful in back of the control room, as they reflect higher frequencies.

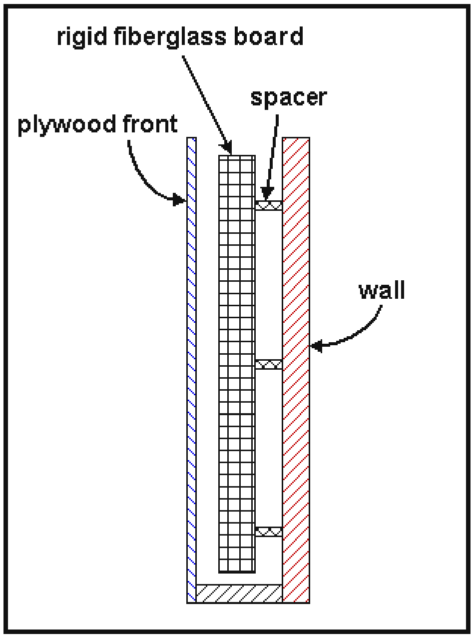


Figure 23 Basic membrane absorber bass trap structure.
Low frequency sound striking the plywood panel causes vibrations, which are damped by the fiberglass. [7]

In general, bass traps will be used to widen the modal bandwidth of resonant modes by decreasing the Q of modal peaks. This is an important step toward evening out the low end frequency response of the room. Additionally, a side effect of standing waves is modal ringing, where certain low frequencies have significantly longer decay times compared with others. Increasing the modal bandwidth will reduce the average reverb decay time in the low frequencies, revealing additional clarity [7].

Low frequency absorption will be installed throughout the control room in attempt to dissipate as much modal energy as possible. In rectangular rooms, corners are typically the first to be treated with bass traps. With the splayed wall design, however, specific modal problems are more difficult to predict. An overall balance of low frequency absorption and diffusion coverage in the control room can be installed underneath broadband acoustic treatments, and should improve the room frequency response. The specific choices that will lead to a marked improvement in bass management will require professional evaluation and detailed simulations.

Broadband Absorption

Large amounts of broadband absorption will be installed on the front ("dead end") of the control room. To achieve a reflection free zone about the listening position, the front end should absorb early reflections and return as little as possible to the listener. The splayed wall design should alleviate slap and flutter echo problems; however, the front portion of the sidewalls may require broadband absorption to make the reflection free zone possible.

To effectively bring RT60 down across the spectrum, with the goal Tm□0.345 s, absorption at all frequencies will need to be installed in patches onto the bare gypsum walls. These patches should be applied symmetrically on both sidewalls. The amount of coverage will determine the broadband reduction of RT60. However, there must not be so much absorption coverage as to prevent the splayed walls from doing their job: transferring early reflections to the back ("live-end") of the control room. This also holds true for the ceiling, which will be partly surfaced with absorptive acoustic tile, complemented by diffusers.

Diffusion and Soundfield Texture

The role of the splayed inner room shell has already been discussed: it serves the purpose of deflecting early reflections away from the listener, toward the back wall. This describes specular reflection, where the acoustical energy at all frequencies is reflected along the same path. To create a desirable reverb texture, energy scattered back toward the listening position should be spread out in space and time using diffusers. Texture is a measure of acoustical quality that is characterized by the number and distribution of reflections that arrive at the listener during the first 100 ms, after the perception of the direct source [9]. Diffusion creates a scattered distribution of reflected energy, resulting in non-uniform comb filtering that is perceived as a rich texture - a pleasant reverb [2].

Diffusors will be used to create a controlled ambience in the control room. In addition, the frequency balance in the listening position will most likely be improved, as it will be represented by a more even blend of the original acoustic signal spectra.

The first diffusers that interact with the sound will be reflection phase-grating diffusers, located at on the sidewalls and ceiling. These will serve the purpose of scattering the first reflections while angling them toward the back wall.

Additional improvements to modal ringing are possible through the use of low-frequency diffusers (Figure 25). For example, a low-frequency primitive root-sequence diffusor at the extreme rear of control room can be used to clean up modal interference. Certain diffusers are able to obtain wide-band diffusion through use of the Diffractal™ [7] principle, which involves diffusers within diffusors.

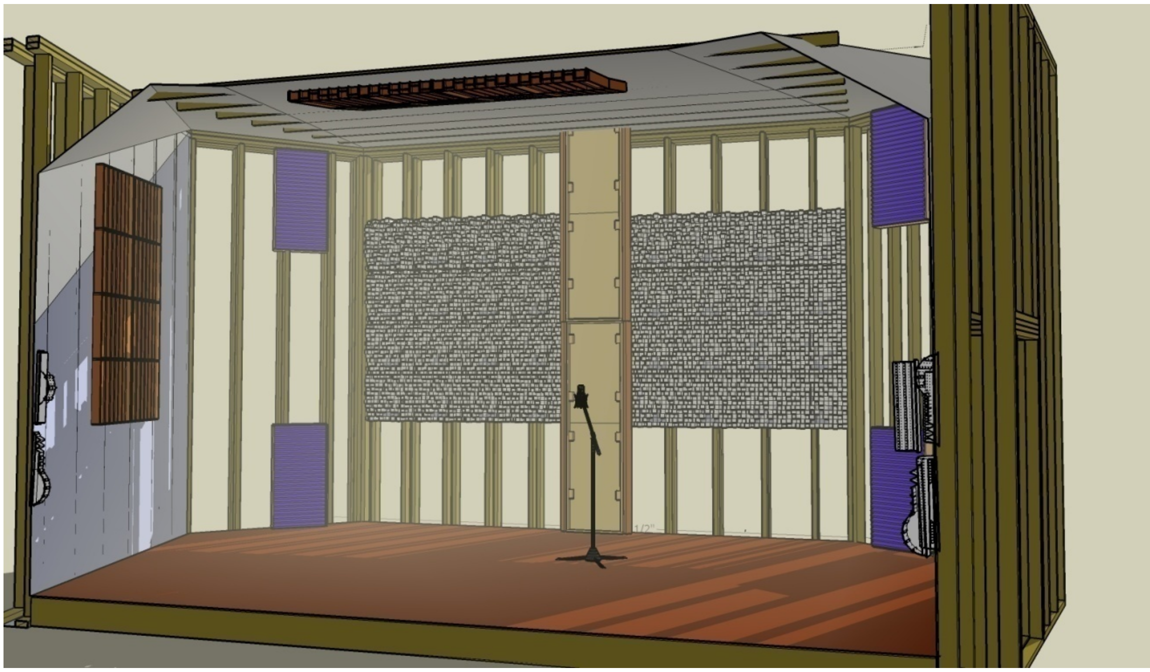


Figure 24 The back ("live end") of the control room is a diffusive environment for sound. Broadband diffusers and bass traps are displayed. In a completed control room, additional coverage is likely.

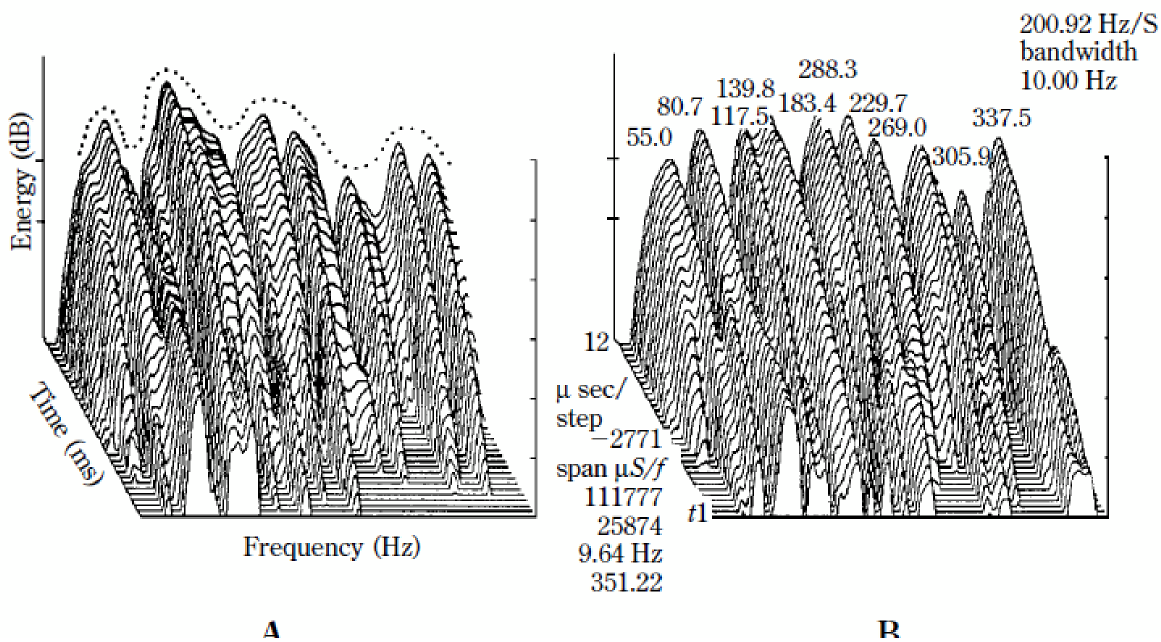


Figure 25 3D energy-time-frequency plot displaying low frequency modal decay. Display A represents an un-treated room, revealing problematic room modes; display B represents the addition of a low-frequency diffusor at the rear end of the room [2].

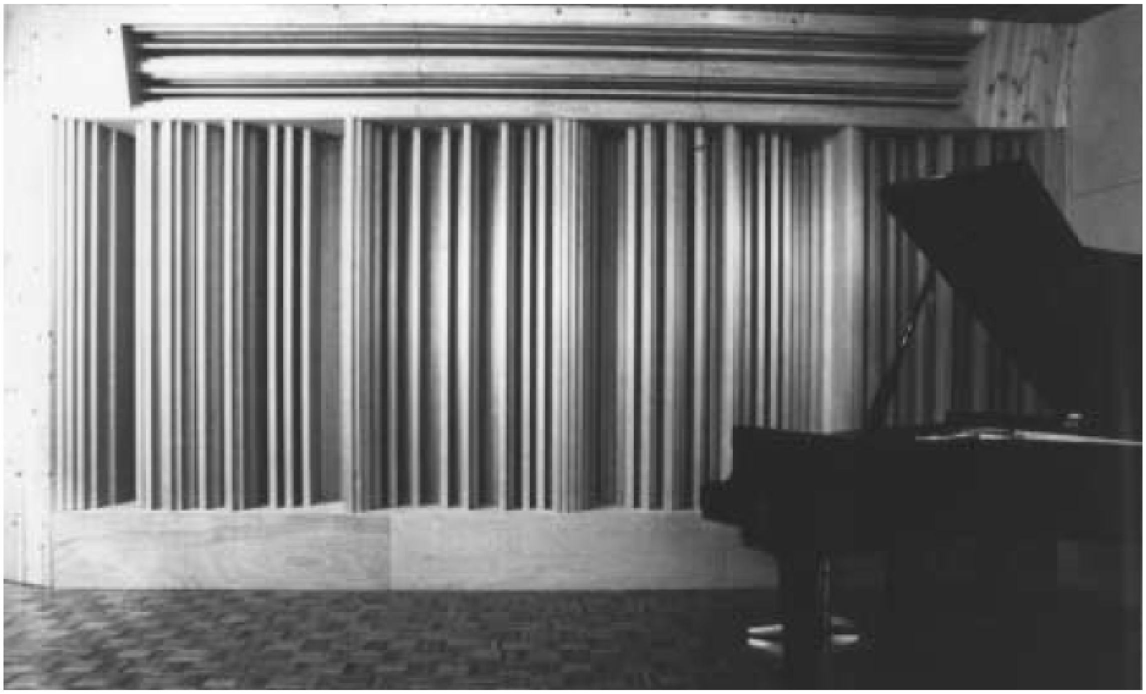


Figure 26 Large tower low-frequency diffuser based on the primitive root sequence. The smaller upper diffuser is based on the quadratic-residue sequence. Location: the recording studio of Studio Sixty, Lausanne, Switzerland [2].

The most important diffusion will take place on the back wall, where a dense texture of reflections will be scattered back toward the listener. For the conceptual control room design, most of the back wall will be covered with *RPG Skyline*® diffusers. These are omnidirectional diffusers that are based on primitive root number theory. The Skyline diffusors exhibit a near-uniform diffusion capability across the hearing spectrum [11]; as a result, they should prove excellent for broadband diffusion.

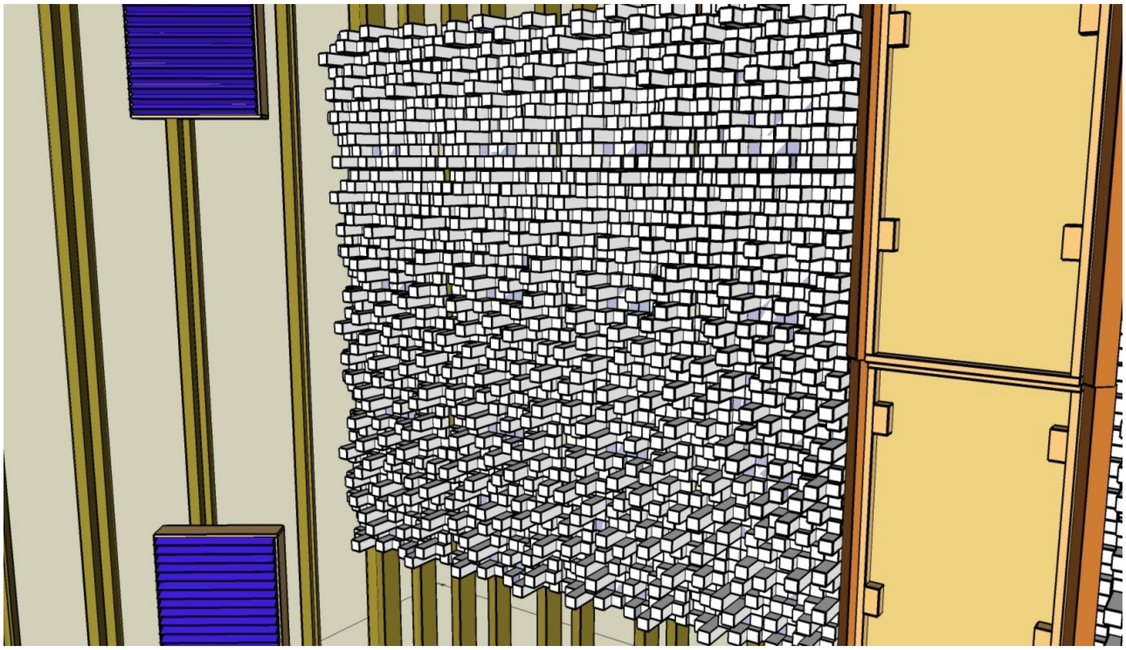


Figure 27 RPG Skyline diffusors [11] on the back wall provide for broadband diffusion. Bass traps are also depicted.

4.5. Control Room Conceptual Design Overview

The following figures visually document the key elements of the conceptual control room design and recap some of the decisions that were made.

After initially considering some ratios to minimize resonant mode problems in rectangular rooms, a splayed wall design was chosen instead. The floor section (Figure 28) shape was borrowed from the Auralex "Acoustics 101 Room" [5], and scaled up 1.35 times in size to facilitate a high splayed ceiling. The splayed surface room shape is intended to prevent flutter echo, prevent uniform buildup of resonant modes, and create a reflection free zone about the listener when proper acoustic treatment is applied.

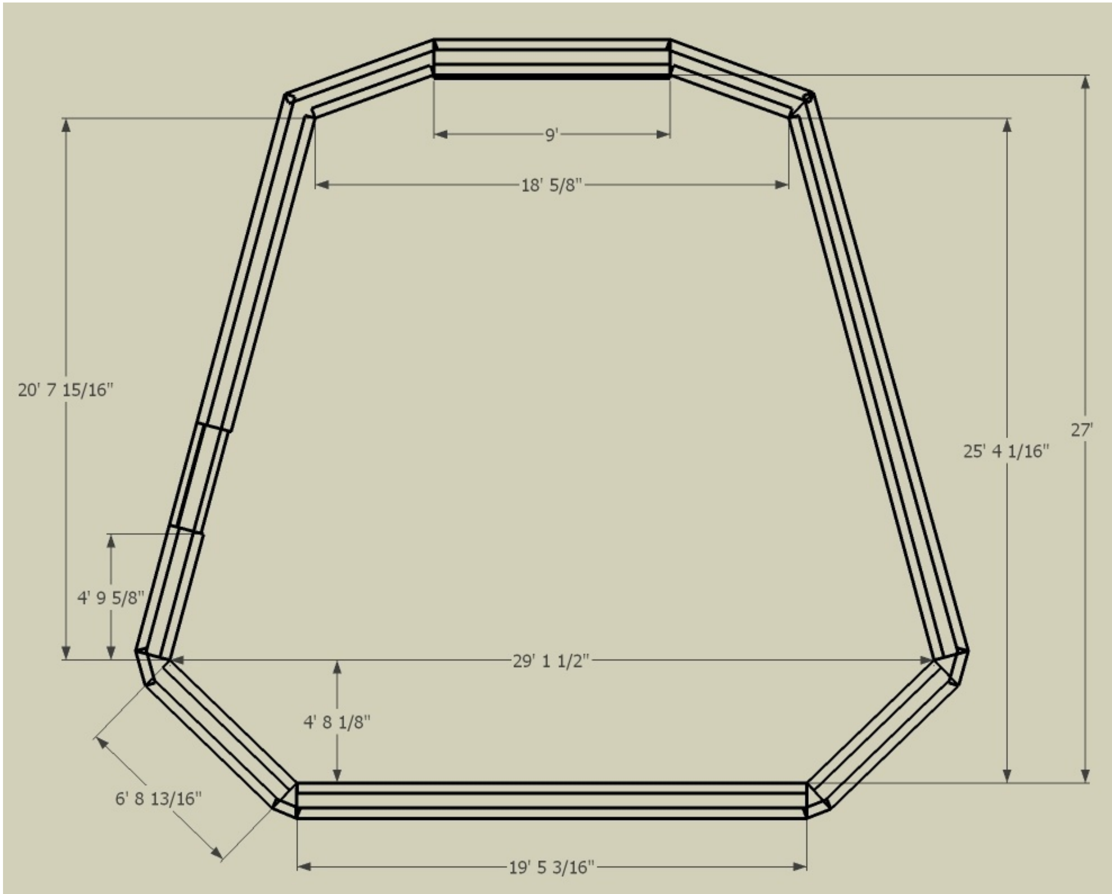


Figure 28 Floor section dimensions of the conceptual control room.
Dimensions are based on the "Acoustics 101 Room", but scaled up by a factor of 1.35.

A live-end dead-end concept was applied, with the goal of creating a well-defined initial time delay gap. The front of the control room, or "dead-end", relies on high absorption to prevent early reflections from interfering with the direct source during the ITDG. The back end of the control room, or "live-end", is covered with broadband diffusers to scatter reflections back toward the listening position with a dense, non-uniform texture. These diffused reflections will be spread out in space and time, creating a pleasant ambience, and will reach the listener after a well-defined ITDG. An appropriate ITDG will allow the listener to perceive the first reflection of an acoustic signal that was recorded in a larger space, as it can be heard before the control room's ITDG. This makes an accurate spatial impression possible.

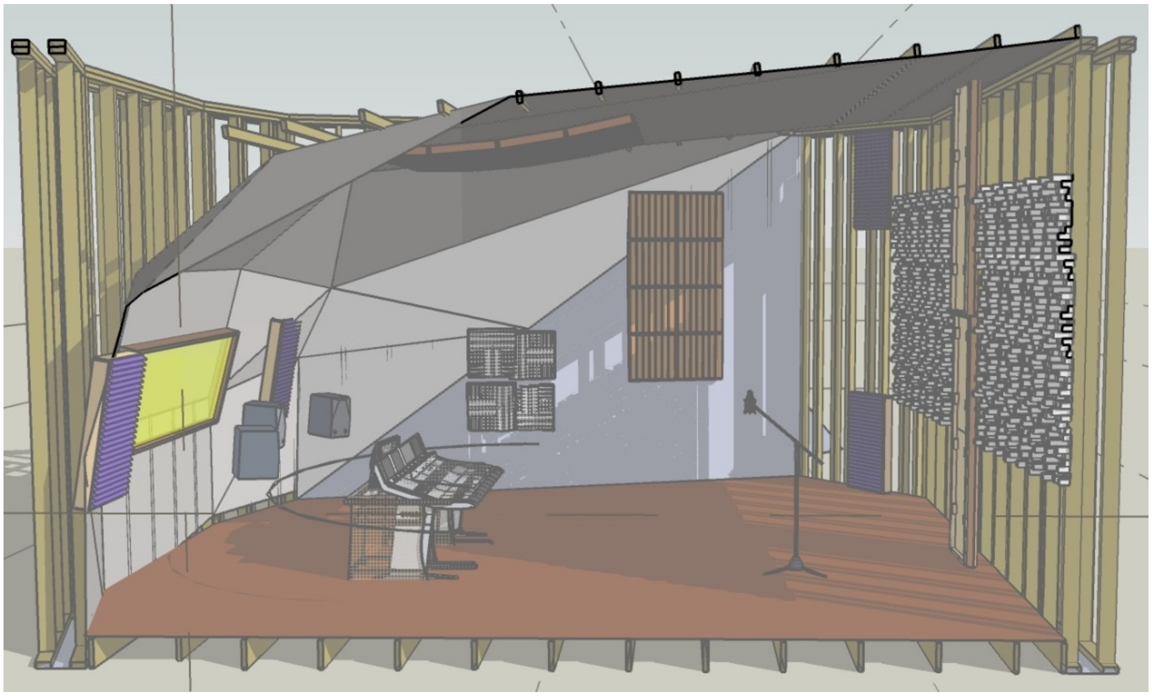


Figure 29 Control room side profile: splayed inner shell and 'Live-End, Dead-End' design. Double wall construction is used on the outer shell to provide acoustic isolation. The front end of the room is surfaced with heavy broadband absorption (not explicitly shown) to create a reflection free zone around the listener. The back end contains low frequency absorbtion (Auralex venus bass traps and a Helholtz resonator or membrane absorbers) and broadband RPG Skyline® diffusers. The ceiling and sidewalls are treated with a combination of insulation and reflection phase-grating diffusers. In practice, the Auralex T-Fusers® (displayed beside the mixing position) will probably be moved back to create a larger ITDG, or be replaced with 1-dimensional diffusers that only scatter reflections toward the back wall.

Figure 30 A diffused reflection's perspective, on a trajectory toward the mixing position.

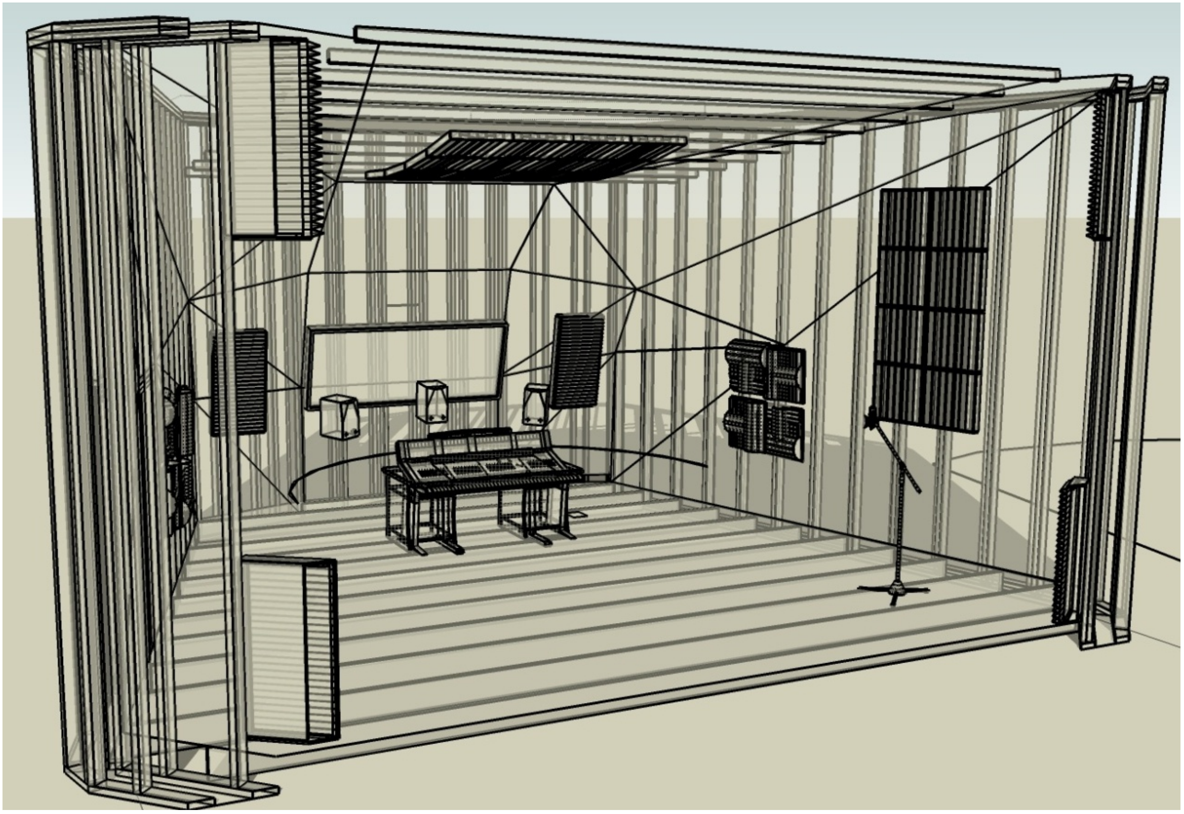


Figure 31 X-ray perspective through the live end of the control room (sectioned view), looking forward through the reverberant sound field. Full acoustic treatment is not shown.

Simulations were performed on a rectangular room with the approximate equivalent average volume to the control room above. The dimensions of the EVRR were estimated to be:

- Effective Length = 27′= 8.229 m
- Average Effective Width = 23′ – 7 $^{1}/_{16}$″ = 7.187 m
- Average Outer Shell Height = 14′ – 7″ = 4.45 m

The simulation results did provide some useful feedback that can be used to modify the room characteristics. However, it was difficult to map many of the parameters to the splayed wall control room. As a result, many decisions for the conceptual design were based on research and intuition, while keeping the design criteria in mind.

5. LIVE ROOM ARCHITECTURAL ACOUSTICS

The acoustic requirements of the live room, or "tracking room", will have a huge impact on architectural and environmental design choices. While the control room is an environment for critical listening through speakers, the live room is a more lush acoustic space where music is performed and recorded. It is typically situated next to the control room—but the two rooms should to be acoustically isolated from one another.

The size of the live room is largely determined by the type of music that will be tracked there. As this recording studio will also include a smaller isolation room (e.g., a vocal booth), the live room will cater to a variety of recording and live sound activities such as:

- Recording solo acoustic instruments such as acoustic/classical guitar, orchestral strings, woodwinds, brass.
- Recording small ensembles such as string quartets, very small chamber orchestras, groups of vocalists.
- Recording piano.
- Recording drum kits.
- Film scoring.
- Band rehearsals with acoustic and electric instruments, from jazz to folk metal.
- Small ensemble rehearsals.
- Special events such as recitals and clinics.
- Acoustic research.

A decent sized space is necessary to provide lush reverb for orchestral instruments; however, there must be a method to quickly reduce the reverb time for applications that require a more subtle ambience, such as band rehearsals and intimate recordings.

As design guidelines, the live room must have:

- Excellent acoustic isolation.
- Natural lighting.
- A high ceiling.
- A diffuse soundfield.
- Reverberation properties that can be altered, likely using absorptive curtains and adjustable height "clouds" (overhead reflection control; see Figure 32).

Figure 32 Adjustable height acoustic clouds for early reflection control and scattering. This photograph shows the stage in the University of Victoria's Phillip T. Young Recital Hall. The 5 channel surround sound microphone array in the foreground was used for impulse response measurements in the hall.

Examples of recording studio tracking rooms are shown in the following figures. See Appendix B for additional examples and floor plans. There are many design possibilities, but ultimately the live room must be designed as an acoustic volume integrated with a piece of sustainable architecture. A region-specific example of eco-acoustic-design can be found inside the First People's House in Victoria, BC (Figure 36).

Figure 33 World-class NY studios. Allaire Studios: the Great Hall (L), Neve Room (R). These tracking rooms were not originally designed for musical acoustics, but the tall, peaked, intricate ceilings likely contribute to an acceptable modal response and diffuse reflections. The Neve Room is basically a large home studio with million-dollar equipment. *Sources: Studio Expresso, 2010* [9].

Figure 34 World-class NY studios. Allaire Studios: Sunset Porch (L); Avatar Studio A (R). Studio A is considered one of the world's greatest recording rooms, particularly for drums. The large 2496 Sq. ft. live room has a ceiling height that peaks at 35'.
***Sources: Studio Expresso, 2010* [9]*; Avatar Studios, 2011* [10].**

Figure 35 Avatar Studio C: mid-sized live room, 980 Sq. ft., 24' high ceiling at peak.
***Source: Avatar Studios (2011)* [10].**

The University of Victoria's First Peoples received LEED Gold certification, is registered with the CaGBC, and was recognized as one of the best Western Red Cedar architectural designs in the world. The design features rammed earth walls and a cedar plank exterior [11].

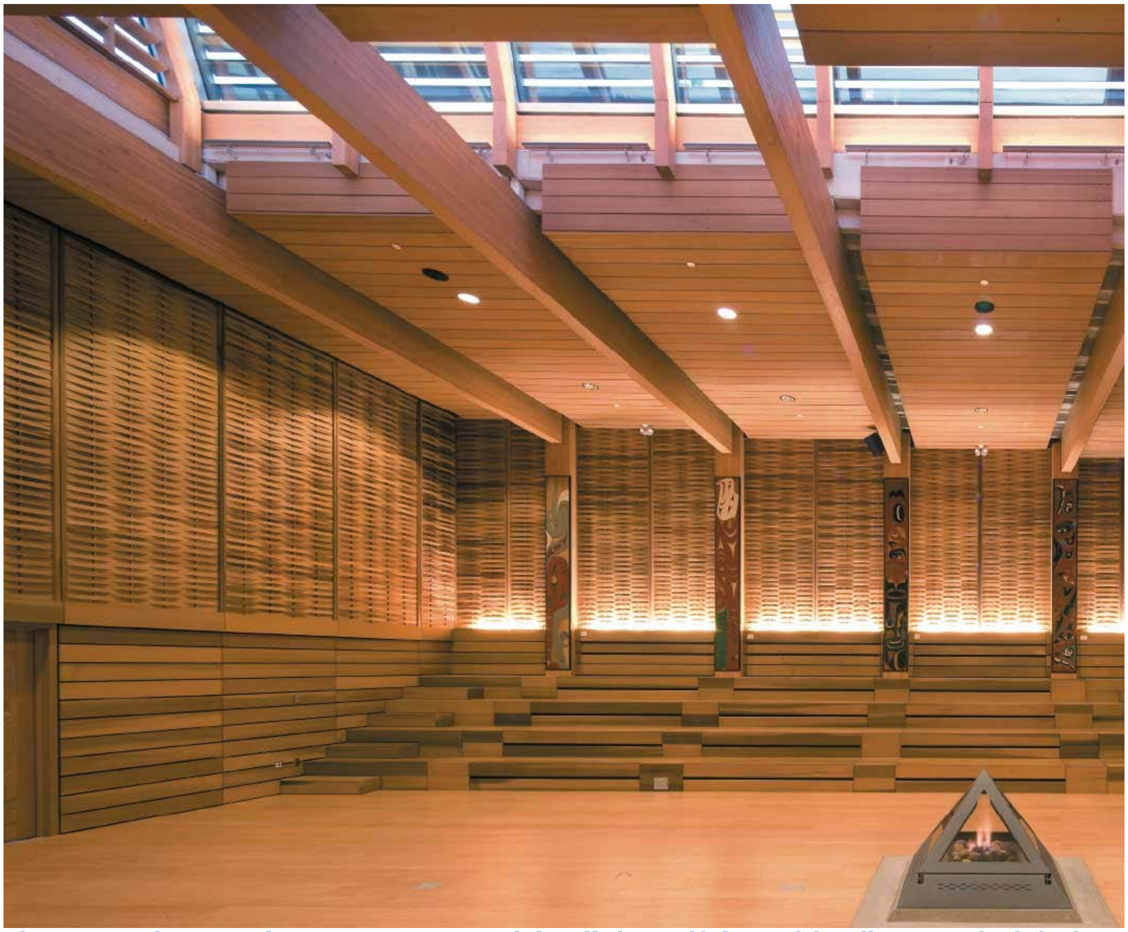


Figure 36 First People's House Ceremonial Hall: beautiful eco-friendly acoustical design. Custom milled beach and salvaged (pine-beetle damaged) Western red cedar is used for the wall cladding. *Source: SAB Magazine, 2011* [11].

5.1. Dimensions of the Live Room

The live room should be designed by architects and acoustical engineers; however, in order to determine the expected power consumption of the studio it was first necessary to estimate the size of the facility. An estimate of the live room dimensions will help establish the lighting and HVAC power consumption demands. (While these demands should be reduced through eco-building design, in the present paper they are parameters that will be used in photovoltaic system design.)

Potential live room sizes were calculated for three different ceiling heights (Table 3) using Dolby's optimum ratios for Film & Music Rooms:

0.67:1:1.55 (from Figure 5)

Table 3 Dimensions of Live Sound Rooms Using Dolby's Optimal Ratios

0.67	Mean Height (ft)	16	17	18
1	Mean Width (ft)	23.88	25.37	**26.87**
1.55	Mean Length (ft)	37.01	39.33	**41.64**
	Floor Area (Sq. ft)	883.9	997.9	**1118.7**
	Volume (Cu. Ft)	14143	16963	**20119.25**

5.2. Desired Impulse Response Characteristics

The live room may benefit from a more intricate design—as the floor plans in Appendix B suggest—rather than a basic shoebox shape. The desired impulse response (IR) characteristics will help guide a more rigorous acoustic design. Surround sound impulse response data from the Philip T. Young (PTY) recital hall was analyzed to provide design insight for the live room. The main data of interest is the initial time delay gap (ITDG) and reverberation time (RT60) throughout the spectrum. These impulse responses were measured for a previous project which focussed on reproducing spatial acoustics using surround sound *convolution reverb* [12].

Desired Early Reflection Characteristics

Figure 37 is an example of acceptable early reflection characteristics for recording an instrumentalist in a small ensemble (specifically, the example shows early reflection data based on where a cellist would sit in a string quartet). In this case, the early reflections are characterized by the placement of the sound source and microphones in relation to:

- The wood floor.
- The three walls of the stage.
- The clouds above the stage.

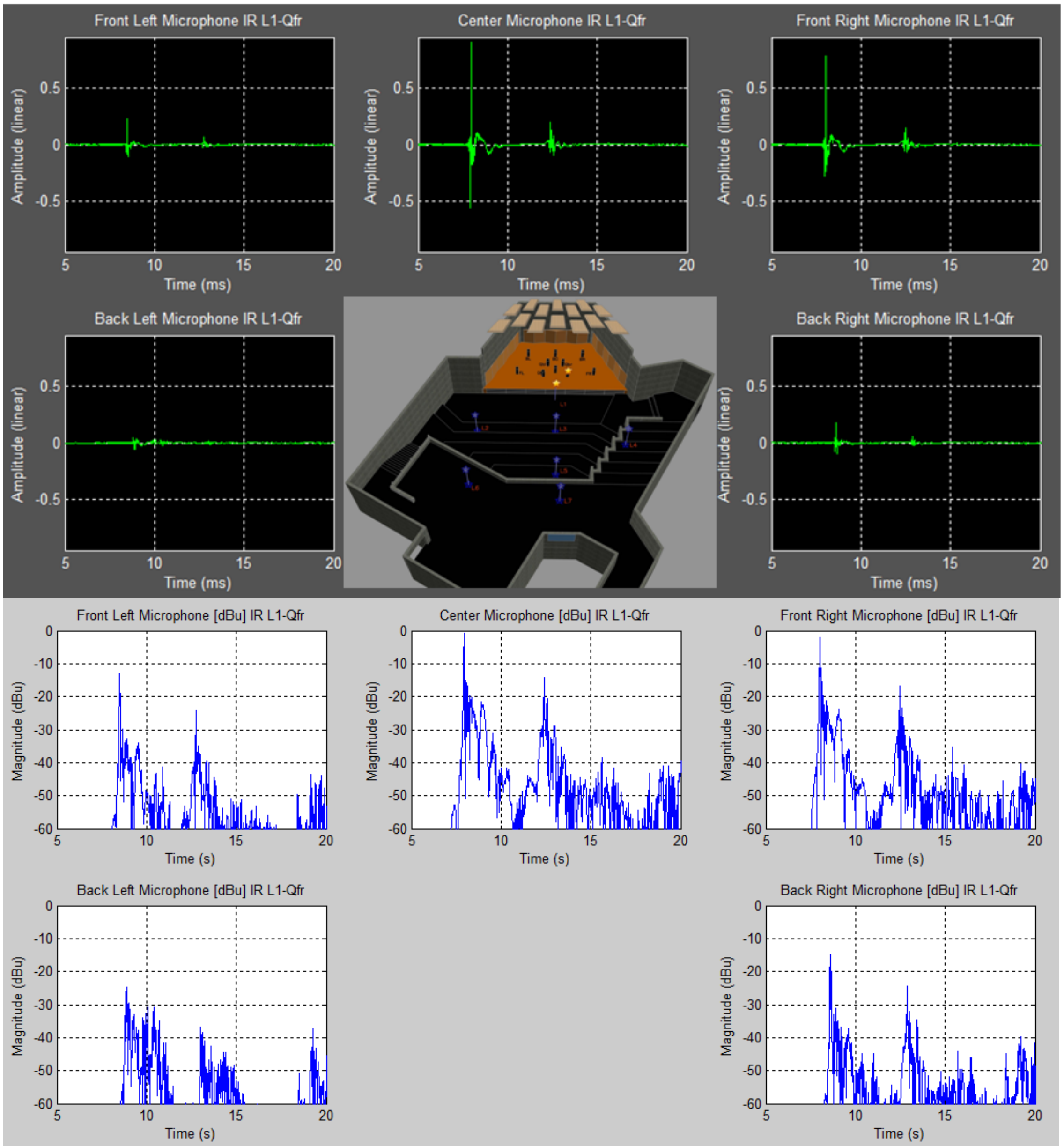


Figure 37 5-channel surround IR showing first reflection for a typical recording setup. The sound source is located where a cellist would sit when performing in a string quartet. The 5-channel microphone array is located in front of stage center, 6'-9" above the stage in the PTY recital hall about 7' (as the crow flies) from the sound source [12]. Amplitude is plotted on a linear scale (top) and in dBu (bottom). The ITDG = 5.24 ms for the center microphone and 6.38 ms for the front right microphone. The first reflection is 13.42 dB below the direct source magnitude for the center channel.

Reverberation Times throughout the Spectrum

Insight on volume and materials for live room design can be gained by analyzing the late reverberation in PTY recital hall. The reverberation at each frequency can be visualized using the time-frequency representation (or *waterfall* plot) of an impulse response. Figure 38 shows reverberation time measurements for PTY hall using the waterfall plot of an IR that was measured near the back of the hall. Measurements were taken at various locations in the hall, but the IR-based RT60 measurements are only accurate if the impulse response was measured sufficiently far from the sound source, beyond the *critical distance* [12]. RT60 is a function of the volume and absorption in the room, and is independent of location.

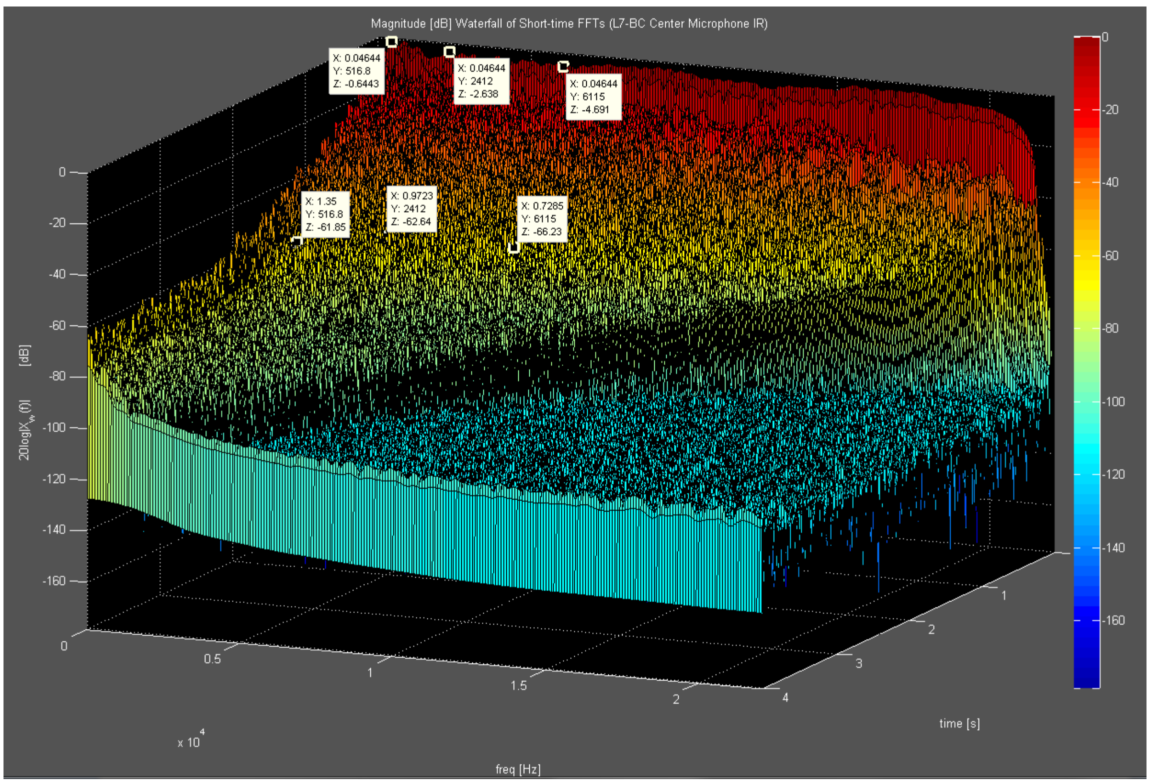


Figure 38 Waterfall plot and RT60 of an IR measured near the back of PTY recital hall. This plot uses a linear frequency scale over the audio spectrum, 0-20kHz. Details on measurement locations are given in [12].

$$RT60 \sim \begin{cases} \textbf{1.3 seconds at 516Hz} \\ \textbf{0.9 seconds at 2412 } Hz \\ \textbf{0.7 seconds 6115 } Hz \end{cases}$$

The waterfall plots represent the spectrum as is changes with time (successive FFT frames) and provide a great visual representation of how sound decays in the room. The plots show that energy decays more quickly in the high frequencies, and that the reverb tail is characterized primarily by the response in the lower frequencies.

We are most interested in the reverberation in the lower end of the spectrum—between about 125 Hz and 4 KHz—where humans perceive the greatest effects of sound colouration provided by reverb, To visualize this data as it applies to human hearing, a logarithmic frequency scale (Figure 39) is most appropriate when viewing the time-frequency representation.

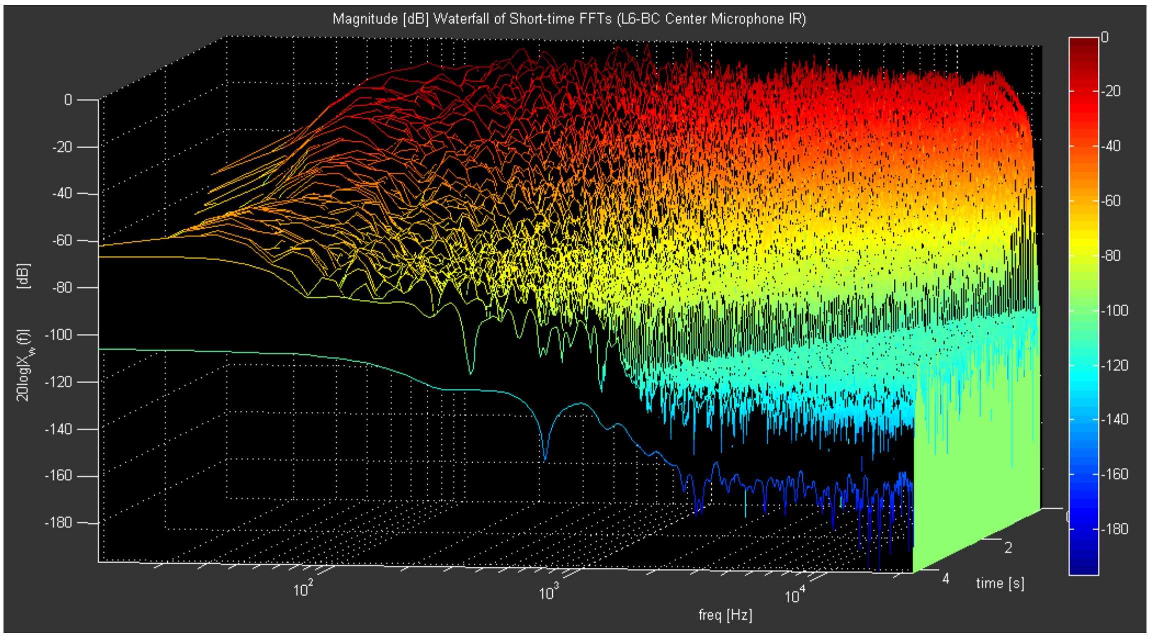


Figure 39 Waterfall representation of an IR measured near the back of PTY recital hall. This plot uses a logarithmic frequency scale over the audio spectrum, 0-20kHz. Details on measurement locations are given in [12].

Figure 39 also reveals a discrepancy between the IR measurement and the true room response below about 20Hz: since this frequency range was not excited, it is not represented by the IR. However, the noise floor is higher in the very low end of the spectrum. Luckily, human hearing is relatively insensitive in this frequency range. A slight increase in the noise floor below 40 Hz will not have a pronounced effect on the dynamic range that we perceive. In music production, highpass filtering is typically performed to remove most of the low end energy below about 30-40 Hz—intended to improve the clarity of the signal. To compensate for the loss in low end energy, equalization is applied to emphasize selected low frequencies that contribute to a muddy sounding signal (*muddy* describes a signal lacking clarity).

Additional reverberation data can be obtained by using more accurate measurement methods such as a) measuring the *early decay time (EDT)* or b) using an algorithm to calculate the "optimal" RT60 decay time at one-third octave band increments, according to the *Topt* method.

As an additional reference for live room design, the frequency response can be mapped throughout the PTY recital hall. This simply involves taking the Fourier Transform of each measured multi-channel IR.

Desired RT60

The average reverb time (measured in the time domain) in PTY recital hall is about 0.75 seconds Figure 40, but acoustic drapes can be raised or lowered to make the room sound more wet (higher RT 60) or more dry (lower RT 60).

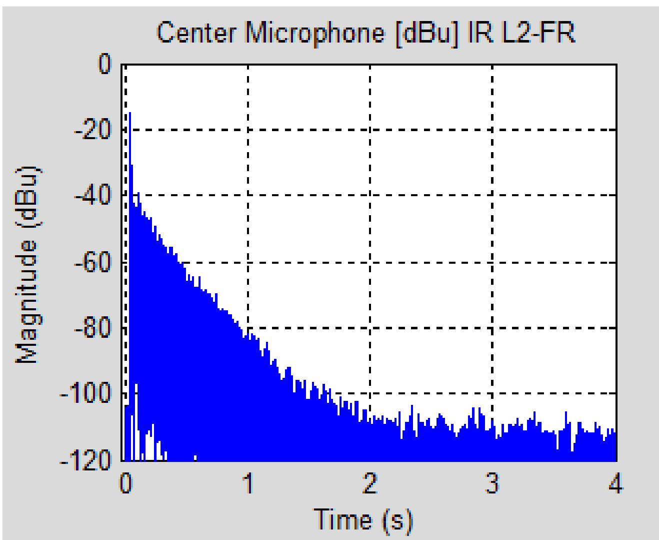


Figure 40 Center channel IR plotted in dBu near the critical distance in PTY recital hall. -RT60 estimation is about ~ 0.75 seconds.

As the proposed live room will be smaller than PTY recital hall, Figure 41 is helpful for determining a target RT60. Using 20000 ft^3 as the desired live room volume (from Table 3) and referencing Figure 41, suitable reverb times for the 500-1000 Hz frequency range are determined:

- 0.67 seconds—for jazz and chamber music.
- 1.02 seconds—for symphonic music such as small orchestras and string quartets.

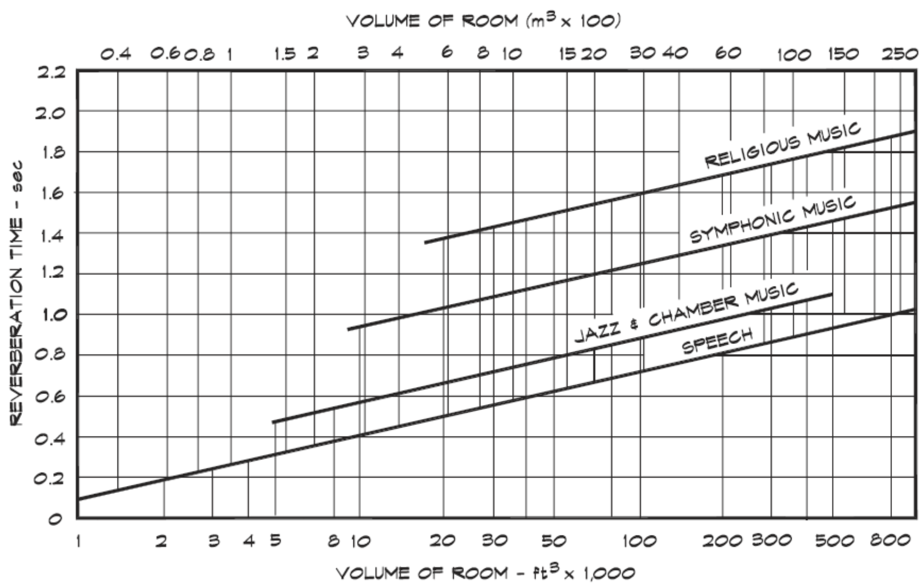


Figure 41 Reverberation Times for Studios in the 500-1000 Hz Range.
***Reprinted Source: Architectural Acoustics, 2006* [8]. *Original Source: Environmental Acoustics,1972* [13].**

5.3. Reverberation Time Calculations

Reverberation times were calculated for the18′ ceiling shoebox shaped room specified in Table 3. Wall materials and the estimated surface area of glass windows (which are highly reflective) are given in Table 4.

Table 4 Estimated RT 60 for live room using the SAE institute RT60 calculator [5].

Width 26.8657 Length 41.6418 Height 18

(•) feet ( ) meters

Walls	Material	Windows,Doors and other Surfaces Material	Size		How Many
Front	Gypsum board	Glass-windows	8	x 4	1
Back	Gypsum board	Glass-windows	4	x 3	6
Left	Gypsum board	Wood floor	2	x 0	0
Right	Gypsum board	Glass-windows	0	x 0	0
Ceiling	Ac. tile suspended	Glass-windows	0	x 0	0
Floor	Wood floor	Wood floor	0	x 0	0

( ) 125 Hz ( ) 250 Hz ( ) 500 Hz (•) 1000 Hz ( ) 2000 Hz ( ) 4000 Hz

Estimated RT60 of your room is 0.77 **seconds**

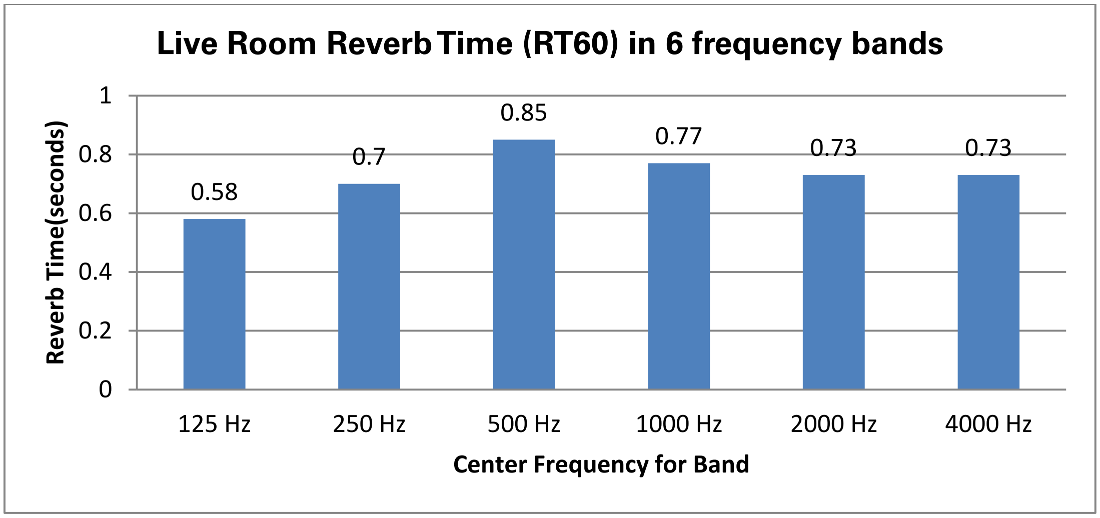


Figure 42 Live room broadband reverb calculated with dimensions/materials in Table 4.

Resulting broadband reverberation times (Figure 42) suggest a fairly even broadband modal decay thanks to Dolby's Optimal Ratios. RT60 between 500 Hz and 1000Hz is within the target range of 0.67 to 1.02 seconds. This would be a reasonable room for musical activities that require a medium sized space with a lively response, such as tracking classical guitar, string quartets, chamber orchestras, piano and wet drum tracks.

For other applications, RT60 can be tamed using acoustic drapes (Table 5). With acoustic drapes on two walls, the resulting RT60 matches our desired reverb time for jazz and chamber recordings, 0.67s.

Table 5 Live room broadband reverb adjusted using acoustic drapes. Calculations were performed using the SAE institute RT60 calculator [14].

Width 26.8657 Length 41.6418 Height 18

(•) feet ( ) meters

Walls	Material	Windows,Doors and other Surfaces Material	Size		How Many
Front	Gypsum board	Glass-windows	8	x 4	1
Back	Gypsum board	Glass-windows	4	x 3	6
Left	Drapery-lightwt	Glass-windows	0	x 0	0
Right	Drapery-lightwt	Glass-windows	0	x 0	0
Ceiling	Ac. tile suspended	Glass-windows	0	x 0	0
Floor	Wood floor	Wood floor	0	x 0	0

( ) 125 Hz ( ) 250 Hz ( ) 500 Hz (•) 1000 Hz ( ) 2000 Hz ( ) 4000 Hz

Estimated RT60 of your room is 0.67 **seconds**

6. POWER REQUIREMENTS

Power requirements for the full recording studio facility can be estimated based on the size of the structure, the local climate and seasonal daylight, the electrical loads from equipment and appliances and the expected hours of operation. These early estimations are made prior to eco-building design, therefore special considerations for natural lighting and passive HVAC cannot be declared yet.

6.1. Estimated Floor Area and Interior Volume

The studio will be occupied full time. Living quarters for 2 to 4 full time occupants and several guests (e.g., 4 visiting musicians) should be incorporated into the design, adding approximately 2000 ft^2. to the studio footprint. The combined floor space of the musical facilities (control room, live room, and a smaller tracking room or isolation booth), storage facilities and living space is expected to be in the range of 4000+ ft^2. The total interior volume was roughly estimated to be 57500+ ft^3.

Table 6 Estimated Dimensions, Floor Area and Interior Volume

Space	Mean Length (ft)	Mean Width (ft)	Mean Height (ft)	Floor Area (ft^2)	Volume (ft^3)
Control Room	27.0	23.6	14.6	636	9290
Live Room	41.6	26.9	18.0	1120	20200
Other studio space (small tracking rooms, vocal booth, storage)			16.0	450	6400
Living Quarters (may be partly lofted)			12.0	1800+	21600+
Totals (approximate)				**4000+**	**57500+**

6.2. Estimated Heating, Lighting and HVAC Requirements

Lighting requirements were estimated using the expected floor area and the expected hours of operation. The expected availability of natural daylight was also taken into consideration. While energy efficient lighting was not assumed, the lighting load can be reduced by using compact fluorescent or LED lights where feasible. Additionally, DC lighting can be run from the photovoltaic system, avoiding the losses that occur when inverting DC to 120 VAC.

Heating requirements were calculated using the average winter temperature in Vancouver, the expected interior volume of the structure, plausible exterior dimensions and plausible *R-values* (thermal resistance) for the construction materials. See Appendix D for heat loss and heating demand calculations.

Photovoltaics will not be used for heating and cooling

While photovoltaic systems are planned as the primary source of electrical power, solar electric is very inefficient for heating. A huge photovoltaic array would be necessary to meet winter heating needs, and battery capacity would have to be massive to power electrical heaters at night and on cloudy days.

By using solar thermal panels instead, one can potentially harvest almost 3 times as much BTU for either hot air or hot water. In the summertime, passive cooling methods may be sufficient for a facility in the Vancouver region; for hot days, a central fans and swamp cooling could be used avoid air conditioning. Eco-building design should incorporate sustainable heating, cooling and ventilation solutions where feasible. Possibilities include:

- Solar thermal panels (i.e., solar hot water or “wet” solar panels).
- Solar radiation with thermal mass[1] heating and cooling.
- Natural convection driven ventilation using underground cooling tubes, windows and skylights.
- Geothermal heat pump heating and/or cooling.
- Wood pellet heaters.
- Biomass boilers.

---

[1] Thermal mass heating: the sun heats a mass—e.g., it shines through a south-facing window onto dense surfaces such as rammed-earth walls, a brick floor, etc. When the temperature of the room drops below the temperature of the walls, heat is released from the walls into the space.

6.3. Connected Loads and Peak Power Demand

Connected loads in the recording facilities and living quarters are tallied in Table 8. Using this data, the peak demand is estimated to be 23.3 kW (neglecting HVAC). The residential appliance load will vary, and can be reduced by using low power and DC appliances (Table 7). Care was used when establishing the recording equipment requirements; while these loads are less flexible, energy consumption may be reduced by limiting their hours of use and using power management. Energy consumption (kWh) calculations are performed in Section 7: Solar Power System Design.

Table 7 Appliance Comparisons: Solar and Alternatives vs. Propane and Conventional [2]

SOLAR AND ALTERNATIVES				PROPANE AND CONVENTIONAL			
Services	Type of power	Approx. cost	Power required	Type	Approx. cost	Operating cost	Power required
Domestic hot water	Complete solar system	$ 4,000	PV panel with package	Propane on demand, tankless	$ 1,500	Fuel cost	Small amount for controls
Water pump	Soft start	$ 1,500	yes	Conventional	$ 600 + power supply	0	Use 40% more power
Compositng toilet	Non-powered	$1,750	no	Dual flush toilet	$ 350 + plumbing	0	power for pumped water supply
Freezer	DC	$ 1,200	yes	Propane	$ 2,000	Fuel cost	no
Fridge	DC & AC	$ 3,000	yes	Propane	$ 2,000	Fuel cost	no
Dish washer	AC - 120v	$ 1,400	yes	same			
Cook stove	Wood approx. 10 chords/year	$ 2,600 + fuel cost	no	Propane	$ 500	Fuel cost	no
Clothes washer	AC - 120v	$ 1,400	yes	same			
Clothes dryer	Not available	Not available	Not available	Propane	$ 800	Fuel cost	yes
HRV	AC	$ 2,600	Yes	Same			

Table 8 Power Demand Load Calculation[2]

Floor Area 4000 Sq. ft

STEP 1: LIGHTING LOAD				
	Floor Sqft x 3 W/sqrft =		12000	
STEP 2: LAUNDRY LOAD				
	1500 W per washer-dryer set =		1500	
STEP 3: SMALL APPLIANCE LOAD				
	Kichen appliance loads rated 1500 W, multiplied by 2 =		3000	
STEP 4: TOTAL LIGHTING LOAD				
	Sum of the loads in Steps 1 to 3 =		16500	
STEP 5: LIGHTING LOAD DERATING				
	3000 W of the total lighting load + 35% of the balance			
	3000 + 4725 =			7725 W
STEP 6: KITCHEN APPLIANCE LOADS				
	Dishwasher	1200		
	Microwave oven	1200		
	Refrigerator	1000		
	Kitchen hood	400		
	Sink garbage disposer	800		
	Total kitchen appliance load	4600		
	If there are > 4 appliances, multiply appliance load by 75%:			3450 W
STEP 7a: RECORDING STUDIO EQUIPMENT LOADS				
	Console (Yamaha DM-2000 x2 or SSL AWS 900)		600	
	Computers and DAW			
	2 x high power PCs		900	
	6 x 27" LED displays		600	
	3 x single display home/office computers		450	
	Network Storage (8 bay RAID NAS Server)		300	
	Rack-Mounted Gear on 2x 15A power conditioners			
	2 full racks each drawing 9 A @ 120V		2200	
	Studio Monitoring Systems			
	Nearfield 7.1: 7x(120W LF/60W HF) + 400W sub			
	7x(120W/2) + 7x(60W/2) + (400W/2)		850	
	Main Monitoring System: 3x In-Wall Mains			
	3x(LF 800W/2 + MF 350W/2 + HF 120W/2)		1900	
	Instrument Amplification			
	2 x 150W guitar amps, 4 x 250W cabinets		1300	
	750W bass amp, 1200W bass cabinet		2000	
	PA System			
	600W live sound PA, 100W mixer, rack FX		1000	
			12100	
	Total Studio Equipment Load			12100 W
STEP 7b: WINTER HEATING DEMAND. 2° C outside, 20° C inside				
	Prior to passive heating and cooling systems design		26000	
	Use more efficient technologies, e.g. solar thermal panels, heat pump, thermal mass. Allocate 0% of heating load to PV system:			0 W
	Total Power Consumption Demand Load, Excluding HVAC:			23275 W

[2] Load calculation procedure from [15]. See Appendix D for heating demand calculations.

7. SOLAR POWER SYSTEM DESIGN

Detailed solar power system design requires site-specific evaluations:

- Insolation—the amount of solar energy that strikes the location—must be calculated.

- A shading analysis must be performed to assess the year round shadows cast on the site by nearby buildings, terrain, trees and other objects. An instrument called a *Solar Pathfinder* is typically used to conduct the field survey and shading evaluation.

- A photovoltaic mapping or configuration analysis is necessary to determine the optimal arrangement of the solar power arrays, allowing the maximum harvest of solar energy.

- Photovoltaic array tilt angle loss needs to be considered based on seasonal power needs. For example, an increased tilt angle above the latitude will increase winter power production but decrease summer power production.

- The photovoltaic array azimuth angle—the angle between true north and the direction that the array faces—should be optimized for arrays that do not employ automatic sun tracking.

Lacking architectural blueprints and construction site field data, a formal solar power system design is not possible. However, a photovoltaic (PV) system catered to the Vancouver region can be roughly sized with the aid of regional solar insolation data and simplifying assumptions.

7.1. Photovoltaic Potential and Insolation in British Columbia

In British Columbia, residential building installed PV (BIPV) systems have the potential to supply 53% of household electrical needs [15]. The calculations in [15] are based on the ground floor area and yearly electrical use of a typical BC household (see Appendix E); a mean daily insolation for latitude tilt of 3.8 kWh/m^2, or 3.8 *peak sun hours,* is assumed. *Peak sun hours* are the equivalent number of hours when solar energy averages 1000 W/m^2. Detailed PV potential and solar insolation data for Vancouver was obtained from Natural Resources Canada [16], summarized in Table 9, Table 10, and Appendix E.

Using the average peak sun hours in January, 1.6, a PV system can be designed to meet the power demand year round. Extra power will be produced in the summer, which can be fed back to the grid for profits.

Another option is to use the annual mean of 3.7 peak sun hours as a design parameter, with the intention of using the excess summer energy harvest to produce hydrogen using electrolysis. In the winter, the extra power demand can be fulfilled by stored hydrogen fed to a fuel cell[3]. While this option allows a smaller PV system, it would require additional expensive equipment, a more complex system design and large hydrogen storage tanks.

Table 9 Annual PV Potential for Vancouver Region, South-Facing Array, Tilt=Latitude

Subregion	**Annual PV Potential** (kWh/kW)
Surrey, Richmond	1000-1100
Vancouver	1000-1100
Burnaby, Port Moody, North Vancouver, Coquitlam	900-1000
Abbotsford	900-1000
Greater Victoria	1000-1100
Resulting Design Parameter: Annual PV potential = **900-1000 kWh/kW**	

Table 10 Mean Daily Insolation for Vancouver, South-Facing Array, Tilt=Latitude

Design Parameter	**Peak Sun Hours** (kWh/m^2)
Annual Mean Daily Insolation	3.7
Minimum Monthly Mean Daily Insolation (January)	1.6

[3] During the winter, Michael Strizki uses a 6 kW plug power hydrogen fuel cell to augment his 10kW PV system in Hopewell New Jersey (a 2kW fuel cell would have been sufficient). These fuel cells are typically used to power cell phone sites [16].

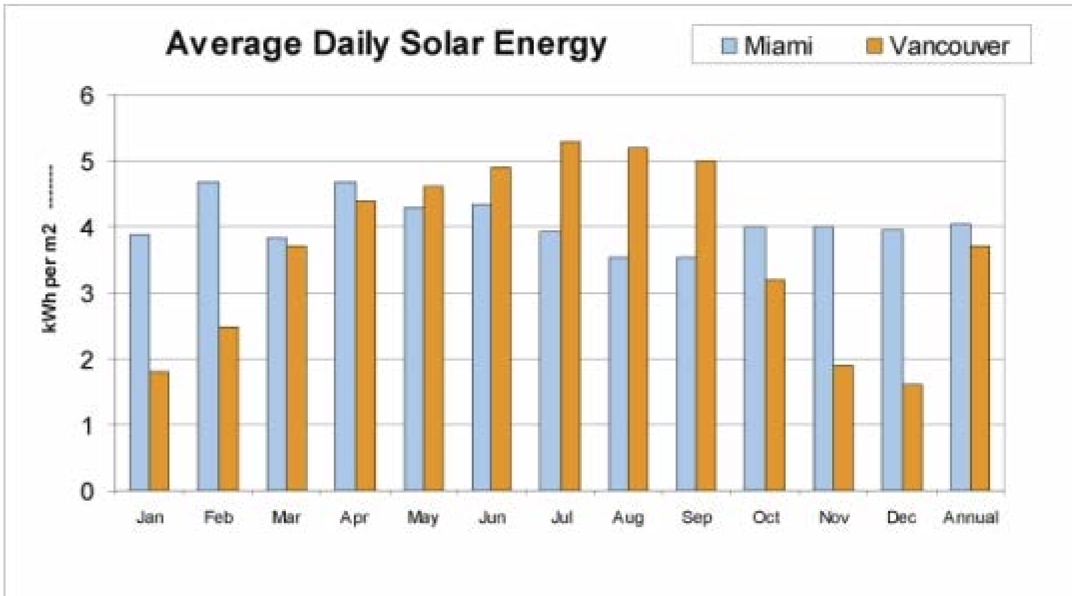


Figure 43 Mean daily solar energy for Vancouver and Miami, compared month-by-month. Vancouver receives an annual mean of 3.7 peak sun hours. *Source: SolarBC, 2011* [17].

The peak sun hour value does not take into account the shading at a specific site. A formal site evaluation would need to factor in decreased solar insolation due to buildings, trees and other obstructions. Additionally, an accurate analysis of insolation should factor in any deviation from optimum tilt angle. Mean daily insulation maps for typical tilt angles are included in Appendix E to highlight the effect of tilt angle on seasonal solar energy harvest potential. To maximize the harvesting potential of an array year-round, two-axis sun tracking can be used (Figure 45).

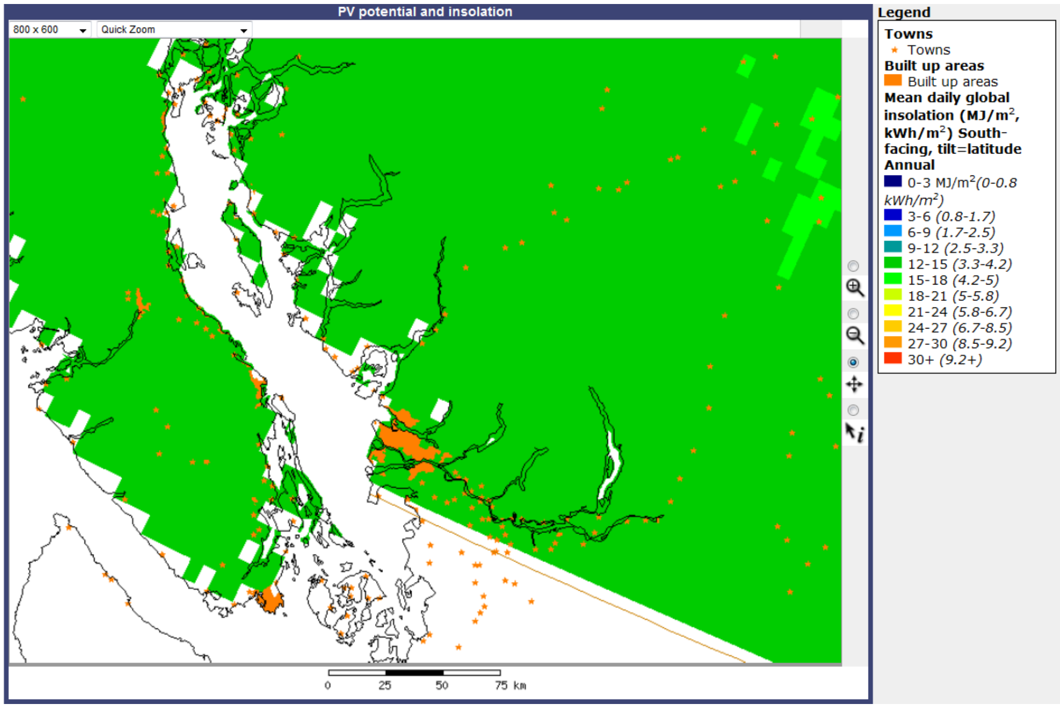


Figure 44 Mean daily global insolation. PV panel orientation: South-facing, tilt=latitude. Period: Annual. Units: MJ/m^2, kWh/m^2. *Source: National Resources Canada, 2011* [16].

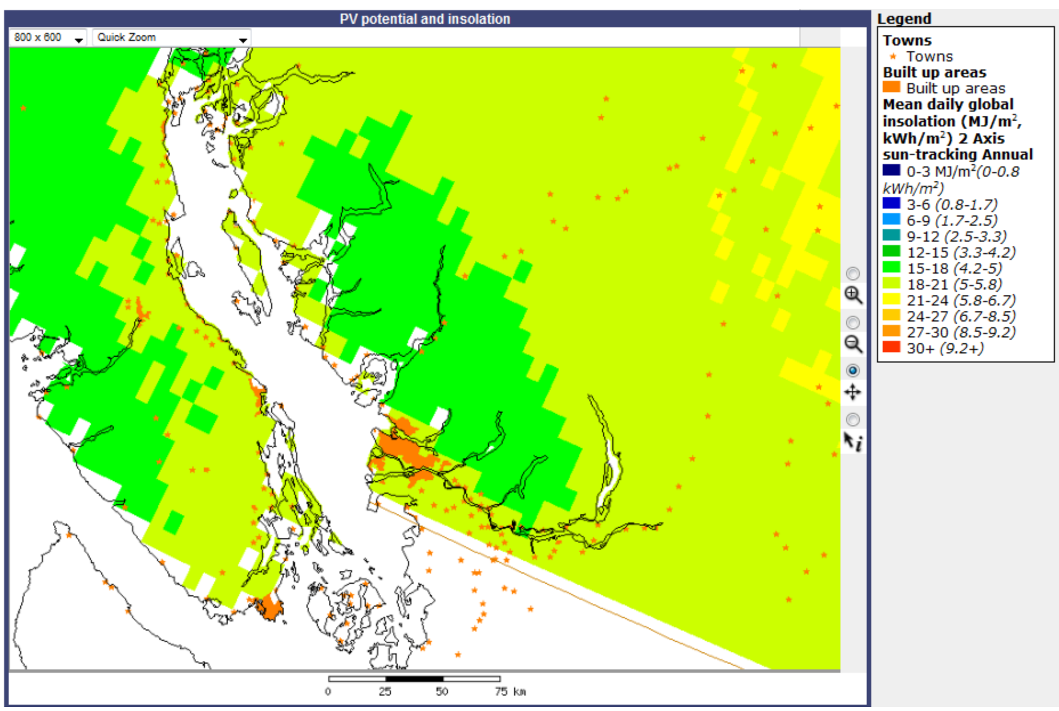


Figure 45 Mean daily global insolation. PV panel South-facing, 2 Axis sun-tracking. Period: Annual. Units: MJ/m^2, kWh/m^2. *Source: National Resources Canada, 2011* [16].

7.2. Off-Grid Photovoltaic System Sizing Worksheets, 24 VDC

Initial photovoltaic system sizing attempts assumed a system voltage of 24 VDC. Later research revealed that given the large connected load, a higher voltage system should be used (see Section 7.3).

The energy consumption of the facility was first calculated assuming liberal use of the recording equipment. In addition to the essential studio equipment, the main monitoring system (wall mounted speakers) in the control room was assumed to be running 12 hours per day. Additionally, two fully loaded racks of studio equipment were assumed to be drawing over 2000 W, for 12 hours per day.

Revised estimations of equipment use are more conservative, and assume that the studio operators turn off rarely used equipment when it is not needed. The revised energy consumption was calculated by assuming the following:

- The main monitoring system would only be used for 3 hours per day, mainly reserved for when multiple listeners are present in the control room. The nearfield/midfield 7.1 monitoring system (surround sound reference speakers) would still be operated for 12 hours per day.

- One of the two racks of equipment would be contain mainly analog effects and mastering equipment, and would be used rarely.

The following pages show the systematic calculation of expected energy consumption for both the liberal use and revised use conditions. HVAC requirements are not included, as discussed in Section 6.2. Connected loads are based on the power demand calculations in Table 8, Section 6.3.

PV Sizing Worksheets, Liberal Use of Studio Gear

Electric Load Worksheets

Table 11 240 VAC Loads and Consumption

240 VAC LOADS				
Load	**Qty.**	**Watts**	**Hours**	**Watt Hours**
Dishwasher	1	1200	0.3	360
Refrigerator	1	1000	1.5	1500
Oven	1	1800	0.7	1260
Laundry	1	1500	0.5	750

Average 240 VAC Demand: 161.25 W

AVERAGE 120 VAC POWER DEMAND BASED ON 2006 BC DATA
(excluding studio loads)

using residential data from SESCI, 2006:
1311.9 W for 1205.6 Sq. ft house = 1.08 W/ Sq. ft

4000 Sq. ft x 1.08 W/Sq. ft = 4320 W

Subtract Average 240 VAC Demand: 4158.75 W

Table 12 Liberal Use 120 VAC Recording Equipment Loads

Console (Yamaha DM-2000 x2 or SSL AWS 900)	600
Computers and DAW	
2 x high power PCs	900
6 x 27" LED displays	600
3 x single display home/office computers	450
Network Storage (8 bay RAID NAS Server)	300
Rack-Mounted Gear on 2x 15A power conditioners	
2 full racks each drawing 9 A @ 120V	2200
Studio Monitoring Systems	
Nearfield 7.1: 7x(120W LF/60W HF) + 400W sub	
7x(120W/2) + 7x(60W/2) + (400W/2)	850
Main Monitoring System: 3x In-Wall Mains	
3x(LF 800W/2 + MF 350W/2 + HF 120W/2)	1900
	7800 (frequent load)
Instrument Amplification	
2 x 150W guitar amps, 4 x 250W cabinets	1300
750W bass amp, 1200W bass cabinet	2000
PA System	
600W live sound PA, 100W mixer, rack FX	1000
	4300 (infrequent load)

Table 13 Liberal Use 120 VAC Loads and Consumption, Full Facility

120 VAC LOADS				
Load	**Qty.**	**Watts**	**Hours**	**Watt Hours**
120V Residential Ave, 4000 Sq. ft	1	4159	24	99816
Recording Equipment (high use)	1	7800	12	93600
Amps and PA System (low use)	1	4300	1	4300

EXTRA LIGHTING ALLOWANCE, 24 VDC

Assume fluorescent, 1000 Sq. ft coverage, 8 hrs/day

1000 *Sq.ft x 0.9 W/Sq.ft* = 900 W

Table 14 24 VDC Loads and Consumption

24 VDC LOADS				
Load	**Qty.**	**Watts**	**Hours**	**Watt Hours**
Extra Lighting Allowance, Fluorescent	1	900	8	7200

Table 15 Total Liberal Use Electrical Loads and Consumption

LOAD SUMMARY				
	24 VDC	**120 VAC**	**240 VAC**	**System Total**
Connected Watts	900	16259	5500	22659
Watt Hours	7200	197716	3870	208786
Peak DC Amps	37.5	677.46	229.17	944.13
DC Amp Hours	300	8238.17	161.25	8699.42

From Table 15Table 18, the daily electrical energy consumption (neglecting HVAC) would be approximately209 kWh/day under the "liberal use" condition.

PV Sizing Worksheets, Smart Use of Studio Gear

Electric Load Worksheets

Table 16 Revised 120 VAC Recording Equipment Loads

Console (Yamaha DM-2000 x2 or SSL AWS 900)	600	
Computers and DAW		
2 x high power PCs	900	
6 x 27" LED displays	600	
3 x single display home/office computers	450	
Network Storage (8 bay RAID NAS Server)	300	
Rack-Mounted Gear on 15A power conditioners		
1 full rack drawing 9 A @ 120V	1100	
Studio Monitoring Systems (used heavily)		
Nearfield 7.1: 7x(120W LF/60W HF) + 400W sub		
7x(120W/2) + 7x(60W/2) + (400W/2)	850	
	4800	(baseline load)
Studio Monitoring Systems (used conservatively)		
Main Monitoring System: 3x In-Wall Mains		
3x(LF 800W/2 + MF 350W/2 + HF 120W/2)	1900	
	1900	(extra load 1)
Instrument Amplification (used rarely)		
2 x 150W guitar amps, 4 x 250W cabinets	1300	
750W bass amp, 1200W bass cabinet	2000	
PA System (used rarely)		
600W live PA, 100W mixer, rack FX	1000	
	4300	(extra load 2)

Table 17 Revised 120 VAC Loads and Consumption

120 VAC LOADS

Load	Qty.	Watts	Hours	Watt Hours
120V Residential Ave, 4000 Sq. ft	1	4159	24	99816
Recording Equipment (high use)	1	4800	12	57600
In-Wall Main Monitors (low use)	1	1900	4	7600
Amps and PA System (low use)	1	4300	1	4300

Table 18 Total Electrical Loads and Consumption, Revised

	24 VDC	120 VAC	240 VAC	System Total
Connected Watts	900	15159	5500	21559
Watt Hours	7200	169316	3870	180386
Peak DC Amps	37.5	631.63	229.17	898.3
DC Amp Hours	300	7054.83	161.25	7516.08

From Table 18, the expected daily electrical energy consumption (neglecting HVAC) is approximately180.5 kWh/day. This result assumes the revised use of equipment conditions discussed at the beginning of this section.

Battery Bank Sizing Worksheet

The battery bank sized in Table 19 assumes the revised use of equipment conditions and uses 24 volts as the DC system voltage. An equivalent higher voltage system will require a much lower amp hour capacity, as demonstrated by the manually sized PV system calculated in Section 7.3.

Table 19 Battery Bank Sizing[4]

BATTERY BANK SIZING

Manufacturer	Interstate	Model	L - 16
Amp Hour Capacity	380	Nominal Voltage	6.0
Battery Efficiency	0.85	Depth of Discharge	0.40
Temperature Derate	1.0	Wire Efficiency	0.96
Days of Storage	1	Inverter Efficiency	0.90
Daily Amp Hour Load	7516.08	DC System Voltage	24
Adjusted Daily AH Load	10193.47	Number of Batteries	272
Cycled Amp Hours	10193.47	Number in Series	4
Optimum AH Capacity	25483.67	Number of Parallel	68
Actual AH Capacity	25840	Critical Application?	Yes

COMMENT: Actual AH Capacity is 356.33 AH more than Optimum.

PV Array Sizing Worksheets

PV array sizing worksheets for a 24 VDC photovoltaic system are included in Appendix F. The calculations conclude that a 114.5 kW photovoltaic array is necessary to meet the revised total daily electrical energy consumption of180.5 kWh/day. This result is not well founded, as the DC system voltage was selected based on standards for much smaller PV systems. A more valid result is calculated in the next section.

---

[4] The battery bank was sized using worksheets available at www.advancepower.net/advcalc.htm [17].

7.3. System Voltage Considerations

The DC output of the photovoltaic arrays needs to be converted to 120 VAC to power the studio equipment and most of the appliances in the facility, and 240 VAC for certain large draw appliances[5]. The voltage across each PV module (photovoltaic panel) is typically 12V or 24V; for a monocrystalline module at maximum this may be closer to 18.5 V [18]. By connecting *N* 24-volt PV modules in series, a PV array can be built with an output voltage of *N x 24* volts. While a system voltage of 24 VDC was used in Section 7.2, PV modules are typically connected so that each array produces a higher voltage, with the optimal voltage depending on the system specifications. Standard system voltages for small residential off-grid PV systems are 12 V, 24 V and 48 V. In contrast, the voltage for building-integrated PV systems occupies a broader range, from 50V to over 700V. A 2kWp array might have a nominal output of 96 VDC, while a 74kWp array might have a nominal output of 350 VDC [18].

Higher voltage offer lower power losses, the ability to use a smaller wire gauge and enable transition over further distances with less voltage drop. Lower voltage systems use cheaper components and typically present less risk to public safety.

7.4. Off-Grid Photovoltaic System Manual Sizing, 264 VDC

An off grid photovoltaic power system was manually sized using design guidelines from [19], [18] and [20]. The calculations apply to the revised energy consumption conditions outlined in at the beginning of Section 7.

---

[5] Photovoltaics are typically not used to power HVAC, electric hot water heaters, dryers, ovens, large pumps large draw appliances. While powering large appliances becomes more realistic for higher voltage PV power systems, a more rigorous design would consider alternate power solutions for these appliances. For a grid connected (or "*grid tie*") PV system, large draw appliances could simply draw from the electrical grid. However, one of the goals of the present small scale power system design is to gain independence from grid infrastructure where possible. Backup power (in this case, battery backup) is essential for a reliable recording studio—and an off-grid PV system is at the very least a permanent, sustainable backup power solution.

Step 1: Average Power Consumption Demands

From Table 18, the total appliance/ studio equipment use is 180386 Wh/day.

To account for energy lost in the system when using battery backup, a 30 percent derating must be applied. The total Watt-hours per day needed from the panels can by calculated by multiplying the total appliance Watt-hours per day by 1.3:

$$\begin{aligned}\text{Total PV panels energy needed} &= 180386 \cdot 1.3 \\ &= \mathbf{234502\ Wh\ /\ day}\end{aligned}$$

Step 2: Sizing the PV Modules

<u>Chosen PV Module:</u> *SolarWorld AG SW 175 mono* (see Appendix G for specifications)

Calculating the total peak watt (Wp) rating needed for PV modules by dividing the total Watt-hours per day needed by the *"panel generation factor"* (PGF, the daily sun hours times 0.62):

$$\text{PGF} = 3.7 \cdot 0.62 = 2.29$$

$$\begin{aligned}\text{Total Wp of PV panel capacity needed} &= 234502 / 2.29 \\ &= \mathbf{102224\ Wp}\end{aligned}$$

Calculating the number of PV panels needed for the system by dividing the total Watt-peak rating by the rated output Watt-peak of the PV modules:

$$\begin{aligned}\text{Number of PV modules needed} &= 102224 / 175 \\ &= \mathbf{584}\end{aligned}$$

Step 3: Inverter Sizing

The input rating of the inverter should be 25-30% higher than the total connected load, and *must have the same nominal voltage as the battery bank*. For motor or compressor loads the inverter should be at least 3 times the capacity of those appliances [19]. This must be added to the inverter input rating to handle surge current.

Total connected load = 23275 W (from Table 8)
Sizing the inverter to be 25-35% larger for safety:
The inverter should be about 30 kW or greater.

Table 20 Possible Inverters for Off-Grid System

Inverter Model	PMI INV-3/30 (3-phase)	GN30KF (monophase)
Output Power	30 kVA	30 kVA
Power Factor	0.8	0.8
Output Voltage	380 VAC, 400 VAC, ±1%	220 VAC
Input DC Voltage	264 VDC	220 VDC
DC Voltage Operating Range	220-330 VDC	194-300 VDC
Efficiency (Full Load)	95%	≥ 92%
Operating Topology	Microcontrolled Hig Frequency IGBT PWM with Output Isolation Transformer	Intel microprocessor & TI DSP control. Imbedded IPM from Mitsubishi Japan.
Protection	Short Circuit, Overload, Over Temperature, Over Voltage	Short Circuit, Overload, Low Voltage, Overvoltage, Reverse-Polarity
Operating Temperature	-10 °C / +50 °C	-20°C ~60 °C

Step 4: Battery Bank Sizing

Deep cycle batteries are well suited for photovoltaic systems: they are designed to be discharged to low energy levels and rapidly recharged daily (cycle charged) for many years. The bank will be sized to meet the power demand on cloudy days and at night.

The required deep-cycle battery Ampere-hour capacity is calculated using

$$\text{Battery Capacity } (\text{Ah}) = \frac{(\text{Total Watt-hours per day used by appliances}) \cdot (\text{Days of autonomy})}{(0.85) \cdot (0.6) \cdot (\text{nominal battery voltage})}$$

where division by 0.85 accounts for battery loss and division by 0.6 accounts for depth of discharge.

Total appliance use = 180386 Wh/day
Nominal battery voltage = 264 VDC
Days of autonomy = 1 day

$$\text{Battery Capacity } (\text{Ah}) = \frac{180386 \cdot 1}{0.85 \cdot 0.6 \cdot 264} = 1339.76 \text{ Ah}$$

For 1 day of autonomy, the battery bank should be rated 264 V, 1500 Ah.

Step 5: Solar Change Controller Sizing

PV module specification:

Pmax = 175 Wp

Vmp = 35.8

Imp = 4.89 A

Voc = 44.4 V

Isc = 5.30 A

Solar charge controller rating = (Total short circuit current of PV array) · (1.3)
= (11 strings) · (5.30 A) · (1.3)
= 75.79 A

The solar charge controller should be rated 76 A at 264 V or greater.[6]

Summary of 264 VDC Photovoltaic System

The resulting photovoltaic system specifications are summarized in Table 21.

Table 21 Photovoltaic System Specifications

Parameter	Quantity
Total connected load:	23.28 kW
Total peak watts of PV module capacity:	102.2 kWp
Number of 175 W PV modules needed:	584
Inverter Capacity:	30 kW or greater
Battery bank rating for 1 day of autonomy:	264 V, 1500 Ah
Solar charge controller rating:	76 A at 264 V or greater

[6] Sizing is different for an MPPT (maximum power point tracking) charge controller. MPPT is an optimization algorithm used to extract the maximum available power from a PV module.

7.5. Available Roof Space for Building-Integrated Photovoltaics

Using the ground floor space estimate from Section 6.1, and assigning a roof slope angle of 30 degrees, the roof area of the facility would be approximately 4600 ft^2. If the structure has a peaked room, then only half of this surface area will be south facing. To maximize south-facing surfaces, roof shapes similar to those shown in Figure 46 and Figure 47 may be employed.

A rough, experimental assessment of building-integrated PV potential is carried out below, assuming that the entire roof has a 30 degree slope, facing south:

Surface Area of *Kyocera KD135GX-LP* module (135W panel):		10.79 ft^2
Surface Area of *SolarWorld AG SW 175* module (175W panel):		14.04 ft^2
No. of 135W panels that can fit on roof:	4600 ft^2/10.79 ft^2 =	426.3
No. of 175W panels that can fit on roof:	4600 ft^2/14.04 ft^2 =	327.7

A 30 degree sloped roof over 4000 ft^2ground floor can fit 426 135-Watt modules or 327 modules 175-Watt modules. This falls short of the 584 175-Watt panels necessary to satisfy the energy consumption on a day that receives 3.7 peak sun hours (the annual average sun hours for Vancouver, assuming no shadows cast on the site by terrestrial objects such as trees and buildings). In January, when Vancouver averages 1.6 peak sun hours, over twice as many PV modules would be necessary to provide the total electrical consumption needs (neglecting HVAC).

The above results indicate that on a day with 3.7 peak sun hours, building-integrated (roof mounted) photovoltaics can provide up to 56% of the electrical energy consumed by the facility (neglecting HVAC). To meet the additional power demand, a remote array that employs 2-axis sun tracking can be located on site. Furthermore, extra PV modules may be mounted on or built into the siding of the structure.

A smart architectural design might take advantage of the structure height, and extend the rooftop on the south side so that the slope continues to near ground level, similar to the structure in Figure 46. Additionally, an overhanging roof (e.g., a large eastern overhang) could be used to accommodate additional modules. A southern overhang might be designed with two purposes: to house PV modules and to provide shade to windows in the summertime. As the winter sun is lower in the sky, such an overhang could be designed to allow direct sunlight to enter through windows during winter, facilitating passive heating.

Figure 46 Beddington Zero Energy Development (BedZED), London, England [2].

Figure 47 Kingspan Lighthouse at BRE Innovation Park. Achieved CSH level 6 [21].

1. **Wind catcher, for summer ventilation**
2. **Solar array at back of house for hot water and electricity**
3. **High-level of wall insulation**
4. **Biomass boiler**

8. CONCLUSIONS

Green goals present challenges to acoustical design. An acoustically optimized architectural design places constraints on structural form, building materials, passive HVAC and natural lighting, and may conflict with eco-building design and construction practices. Additionally, a recording studio has a high peak power demand and may be operated for extended hours, consuming large amounts of energy. For true environmental sustainability, this energy would be harvested entirely from renewable resources, presenting an ideal that may not be cost effective or feasible.

This project had four high-level objectives: to design a recording studio control room, conceptually optimized for stereo reproduction of sound; to specify acoustical parameters for a live room; to size an off-grid photovoltaic system based on the power requirements of the studio; and to reveal conflicts between design objectives, which could be used to help guide a more rigorous design effort by architectural and engineering firms.

8.1. Acoustical Design Conclusions

The conceptual conclusions from control room design are visually documented in Section 4.5: Control Room Conceptual Design Overview. The present section will review the analytical conclusions.

Primary Conclusions: Acoustic Parameters and Behaviour

Control Room

A splayed surface room shape was used to prevent flutter echo, prevent uniform buildup of resonant modes, and create a reflection free zone about the listener. A live-end-dead-end design was used to provide controlled ambience in the room, with an initial time delay delay gap (ITDG) resembling that of a larger room. Results from the equivalent volume rectangular room (EVRR) simulation lead to the following conclusions about the proposed control room:

- The resonant mode simulations revealed relatively closely spaced modal distribution in the EVRR; however, most of this data cannot be used to judge the splayed wall control room design. Without a detailed simulation of the room geometry, most modal behaviour is unclear.

- The phantom image simulation illustrated the need to move toward a splayed inner shell, and to create a reflection free zone about the listening position. Otherwise first reflections will affect imaging, cause excessive comb filtering and obscure the initial time delay gap.

- The RT60 simulation with estimated absorption coefficients for partially treated surfaces provided a fairly even reverb time throughout the spectrum. Additional broadband absorption can be added to bring the average RT60 closer to the calculated target: $T_m \approx 0.345$ s. Given that RT60 depends on room volume and absorption, these results are likely quite consistent with the splayed wall control room RT60.

- The impulse response simulation revealed the potential for a well-defined initial time delay gap, which can be achieved by removing the first reflections arriving at the listening position in the EVRR. The splayed shell control room is designed specifically for this purpose. Theoretically, the initial time delay gap in this room can be varied between 0 and 30ms by shifting the listening position. The default listening position can achieve an ITDG of 20 ms with proper live-end-dead-end acoustic treatment. For a shorter ITDG in the control room (e.g., 12-20 ms), a ceiling diffusor can be placed above and behind the listening position.

- The frequency (magnitude) response plot revealed obvious modal problems in the EVRR that will negatively affect the acoustic balance. Since the frequency response was so characterized by resonant room modes, it is difficult to compare this data with the splayed wall design (which shares only the length dimension with the EVRR). What is evident is that lots of low frequency absorption and diffusion will be needed in order to widen the model bandwidths in each dimension, and therefore distribute modal energy to neighbouring frequencies.

The design criteria for an ideal control room were not satisfied; however, these criteria were meant as guidelines for the conceptual design, not as realistic goals. Although the modal response results may be invalid for a splayed surface control room, the design processes produced useful data on broadband reverberation times, early reflections, interior surface materials and acoustic treatments.

Live Room

The primary design parameter resulting from the live room investigation is the desired reverberation times for the 500-1000 Hz frequency range:

- 0.67 seconds—for jazz and chamber music.
- 1.02 seconds—for symphonic music such as small orchestras and string quartets.

An RT60 simulation was conducted for a 20200 ft^3 room (from Table 3) using Dolby's Optimal Ratios for film and music rooms. With the surface materials properties indicated in Figure 42, RT60 was measured to be 0.77 seconds at 1000 Hz. Adding acoustic drapes to the simulation, RT60 at 1000 Hz was tuned to 0.67 seconds—the "optimal" reverb time for jazz and chamber music in the proposed 20200 ft^3.

Using typical room dimensions and selecting materials based mainly on acoustic intuition, simulation results were consistent with ideals presented in literature. In conclusion, the chosen room volume is a fairly robust constraint that can be used to help size the facility, even in the absence of formal acoustic design.

Secondary Conclusions: Room Volumes and Power Requirements

The secondary objectives of acoustical design were satisfied. Approximate dimensions were obtained for the control room and live room to assist with sizing the rest of the facility. The results are reproduced in Table 22.

Based on the dimensions of the facility and the appliances, the total connected load, or peak power demand, was determined to be 23.28 kW.

Table 22 Estimated Dimensions, Floor Area and Interior Volume

Space	Mean Length (ft)	Mean Width (ft)	Mean Height (ft)	Floor Area (ft^2)	Volume (ft^3)
Control Room	27.0	23.6	14.6	636	9290
Live Room	41.6	26.9	18.0	1120	20200
Other studio space (small tracking rooms, vocal booth, storage)			16.0	450	6400
Living Quarters (may be partly lofted)			12.0	1800+	21600+
Totals (approximate)				4000+	57500+

8.2. Solar Power System Conclusions

Using the mean annual average of 3.7 peak sun hours for Vancouver, 12 VDC and 264 VDC photovoltaic systems were sized. The most realistic system was sized using 264 VDC as the system voltage and assumes that the studio operators turn off rarely used equipment when it is not needed.

The resulting photovoltaic system specifications summarized below (from Table 21)

Total connected load:	23.28 kW
Total peak watts of PV module capacity:	102.2 kWp
Number of 175 W PV modules needed:	584
Inverter Capacity:	30 kW or greater
Battery bank rating for 1 day of autonomy:	264 V, 1500 Ah
Solar charge controller rating:	76 A at 264 V or greater

A rough analysis of roof-mounting potential for PV modules revealed that on a day with 3.7 peak sun hours (the annual average for Vancouver), building-integrated photovoltaics can provide up to 56% of the electrical energy consumed by the facility, omitting heating, ventilation and cooling needs. This finding is useful, as it highlights a conflict of design objectives: the studio requires a generous power supply to operate, while off-grid building-integrated photovoltaics are typically intended for buildings that use energy conservatively.

There is insufficient photovoltaic potential for a net-zero building unless extra PV arrays are installed remotely, likely using 2-axis sun tracking. Detailed solar power system design with a site-specific shading analysis is required to fully assess the photovoltaic potential. Eco-building design is required to minimize the energy needs that cannot be met by off-grid photovoltaics or other renewable energy solutions.

9. EXTENSIONS AND RECOMMENDATIONS

The design work conducted to date has been exploratory. Future work is planned, and will involve more formal design efforts, feasibility investigations, networking and project management.

Detailed design of solar power systems

Site selection and evaluation is essential to formally assess the photovoltaic potential of the facility. Sustainable development requires that the design conforms to the site—not vice-versa.
Shading Analysis of the site is necessary to determine the true insolation and photovoltaic potential, accounting for shadows cast on the site by nearby obstacles such as buildings and trees.
Formal photovoltaic system design must be conducted, and should include investigating the potential of 2-axis sun tracking arrays to satisfy the unmet power demand.
Solar power system modeling will involve the transient simulation of the specified system to test its expected year round operation. Simulations are a simple, low-cost way to assess a system before building it.

Detailed acoustical design and physical modeling

Assistance from an acoustical consulting engineer is recommended to make optimal control room design decisions. Also, noise and vibration assessment/control must be considered when forming a complete model of the room's acoustics.

Methods of computationally modeling acoustical systems include ray-tracing, beam tracing, boundary element predictions and finite element vibro-acoustic simulations. A future objective is to analyze the control room and live room using finite element analysis to simulate the geometry (as a finite element mesh), and model the eigenmodes and nonlinearities in the room. Ray-tracing, beam tracing or boundary element predictions can be used to assess the behaviour of the early reflections, with the goal of designing a reflection-free-zone at the front of the control room.

Eco-building design

Eco-building design considerations are currently being researched. Designing a sustainable recording studio will require a competent architectural firm and feedback from engineers, acousticians and environmental designers. Acoustical design will constrain eco-building designers, and eco-building design will constrain acoustical designers. There are many elements of sustainable architecture to be considered, including natural acoustic insulation provided by green roofs, rainwater collection, modular prefabricated construction. Significant design decisions will have to consider the items listed below.

Heating, cooling and ventilation:

- Solar thermal panels (i.e., solar hot water or "wet" solar panels).
- Solar radiation with thermal mass[7] heating and cooling.
- Natural convection driven ventilation using underground cooling tubes, windows and skylights.
- Geothermal heat pump heating and/or cooling.
- Wood pellet heaters.
- Biomass boilers.

Choosing local materials and construction methods:

- Round earth walls.
- Insulating concrete form.
- Pine beetle damaged wood.
- Recycled materials.
- Design for safety in seismic events.

Feasibility study and economics analysis

Feasibility questions are expected to emerge periodically during the design of an ecologically friendly recording studio. Economic considerations are currently under investigation. Items to consider include

- Upfront costs and funding.
- Return on investments.
- Cost-benefit-analysis.
- Global economic trends.

[7] Thermal mass heating: the sun heats a mass—e.g., it shines through a south-facing window onto dense surfaces such as rammed-earth walls, a brick floor, etc. When the temperature of the room drops below the temperature of the walls, heat is released from the walls into the space.

REFERENCES

CITED REFERENCES

[1] M. Noble, D. Kennedy. (2008, July) "Acoustic Design Performance in Green Buildings", Sustainable Architecture & Building Magazine (SABMag). [Online]. http://www.sabmagazine.com/blog/2008/07/21/acoustic-design/

[2] Sustainable Architecture & Building Magazine (SABMag). (2011, April) 2008-2010 SABAwards Winning Projects. [Online]. http://www.sabmagazine.com

[3] Sound on Sound. (2000, May) Reverb FAQ. [Online]. http://www.soundonsound.com/sos/may00/articles/reverb.htm

[4] P.R. Newell, *Recording Studio Design*, 2nd ed. New York: Focal Press, 2007.

[5] Auralex Acoustics. (2003) Acoustics 101 Room. [Online]. http://www.acoustics101.com/room_dimensions.asp

[6] D.M. Thompson, *Understanding Audio: Getting the Most Out of Your Project or Professional Recording Studio*. Boston: Berklee Press, 2005.

[7] Eric Desart. (2007) Acoustics Forum. [Online]. http://forum.studiotips.com/viewtopic.php?t=1414

[8] M. Long, "Design of Studios and Listening Rooms," in *Architectural Acoustics*. Burlington, MA: Elsevier Academic Press, 2006, ch. 21, pp. 741-779.

[9] Allaire Studios. (2010, November) Studio Expresso. [Online]. http://www.studioexpresso.com/Spotlight%20Archive/SpotlightAllaire.htm

[10] Avatar Studios. (2011, April) Avatar Studios. [Online]. http://www.avatarstudios.net/

[11] A. Waugh. (2011, April) Sustainable Architecture & Building Magazine (SABMag). [Online]. http://www.sabmagazine.com/blog/2011/04/13/first-peoples-house/

[12] H. Giesbrecht, T. Perry, M. Carson, "Surround Sound Impulse Response: Measurement with the Exponential Sine Sweep; Application in Convolution Reverb," University of Victoria, Victoria, 4th Year Engineering Design Project 2009.

[13] L.L. Doelle, *Environmental Acoustics*. New York, NY: McGraw-Hill, 1972.

[14] SAE Institute. (2008) Reverberation Time Calculator. [Online]. http://www.sae.edu/reference_material/audio

[15] Y. Poissant, S. Pelland, "An evaluation of the potential of building integrated photovoltaics in Canada," in *31st Annual Conference of the Solar Energy Society of Canada (SESCI)*, Montréal, 2006.

[16] National Resources Canada. (2011, March) Photovoltaic potential and solar resource maps

of Canada. [Online]. https://glfc.cfsnet.nfis.org/mapserver/pv/index.php?lang=e

[17] SolarBC. (2011, March) Average Daily Solar Energy in Vancouver. [Online]. http://www.solarbc.ca/sites/default/files/images/solarenergy.jpg

[18] M. Fordham, *Photovoltaics and Architecture*, R. Thomas, Ed. London, UK: Spon Press, 2001.

[19] LEONICS Co. Ltd. (2009) Solar PV System Sizing. [Online]. http://www.leonics.com/support/article2_12j/articles2_12j_en.php

[20] P. Gevorkian, *Solar Power in Building Design, the Engineer's Complete Design Resource*, 1st ed. New York, NY: McGraw-Hill Professional, 2007.

[21] Kingspan Group, BRE Group. (2009) Kingspan Lighthouse at BRE Innovation Park. [Online]. http://www.kingspanlighthouse.com/

[22] A. Farina, "Advancements in impulse response measurements by sine sweeps”," in *122ed AES Convention*, 122ed AES Convention, 2007.

[23] J. Kreskovskt, Single woofer Room Response Simulator (Excel Spreadsheet), 2008.

[24] D. Campbell, RoomSim acoustic toolbox for MatLab, 06 June 2007.

[25] M. Striski. (2008) Strizki Systems. [Online]. http://www.renewableenergyinternational.com/release/mike-strizki-and-renewable-energy-international-receive-award

[26] Advance Power Inc. (2011, March) PV Off Grid System Design On-Line Calculator. [Online]. http://www.advancepower.net/advcalc.htm

GENERAL REFERENCES

U. Zölzer, *Digital Audio Signal Processing*, 2nd ed., West Sussex: John Wiley & Sons, 2008.

F. Everest, *The Master Handbook of Acoustics*, 4th ed. , New York: McGraw-Hill, 2001.

L. Beranek, " Concert Hall Acoustics—2008*," *J. Audio Eng. Soc.*, vol. 56, no. 7/8, pp. 532-544, 2008 July/August.

T. Hughes, *The Finite Element Method, Linear Static and Dynamic Finite Element Analysis*, 2nd ed., Mineola: Dover Publications, Inc., 2000.

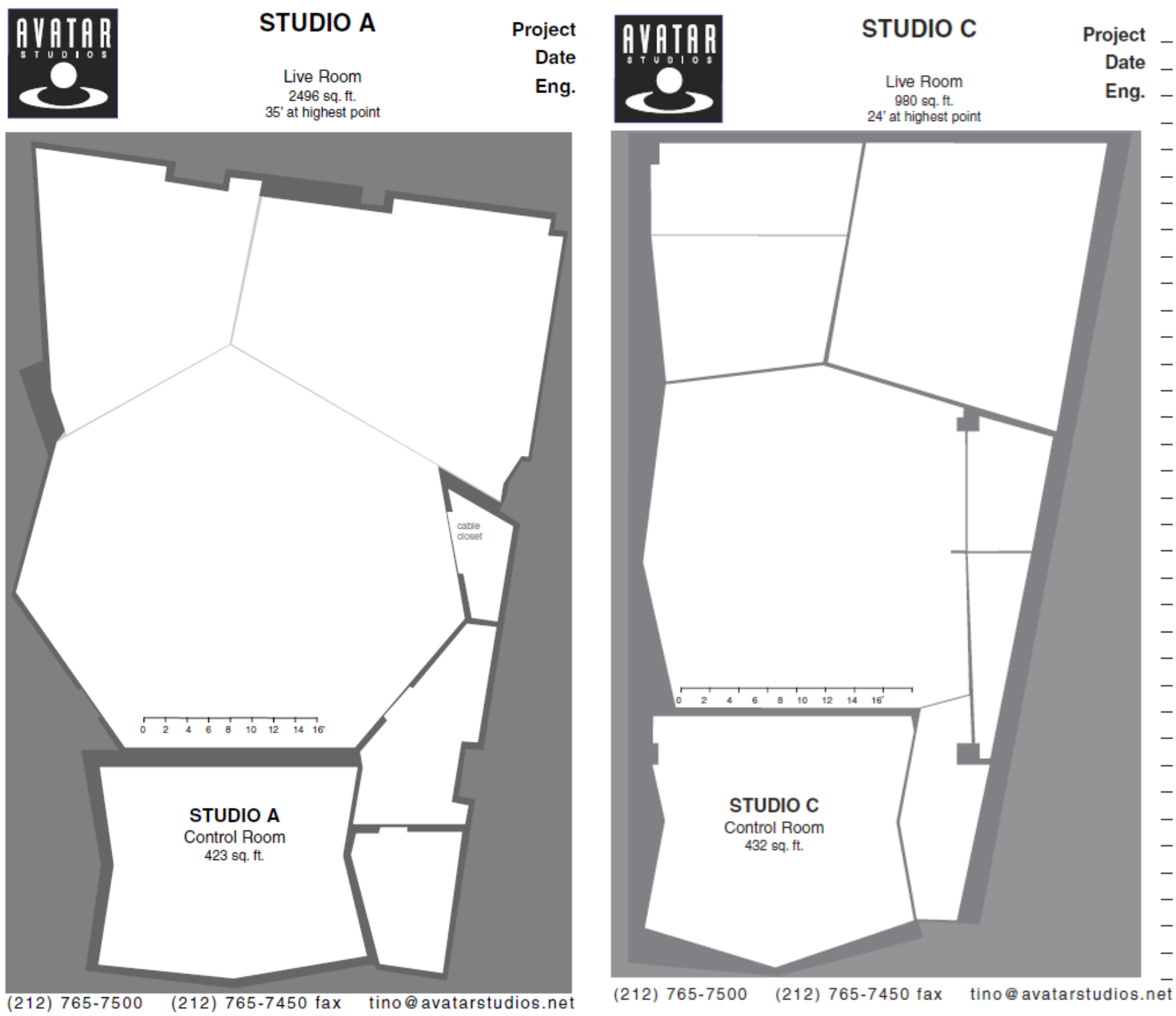
Appendix A Control Room Simulation Parameters

Simulation Parameters used with RoomSim

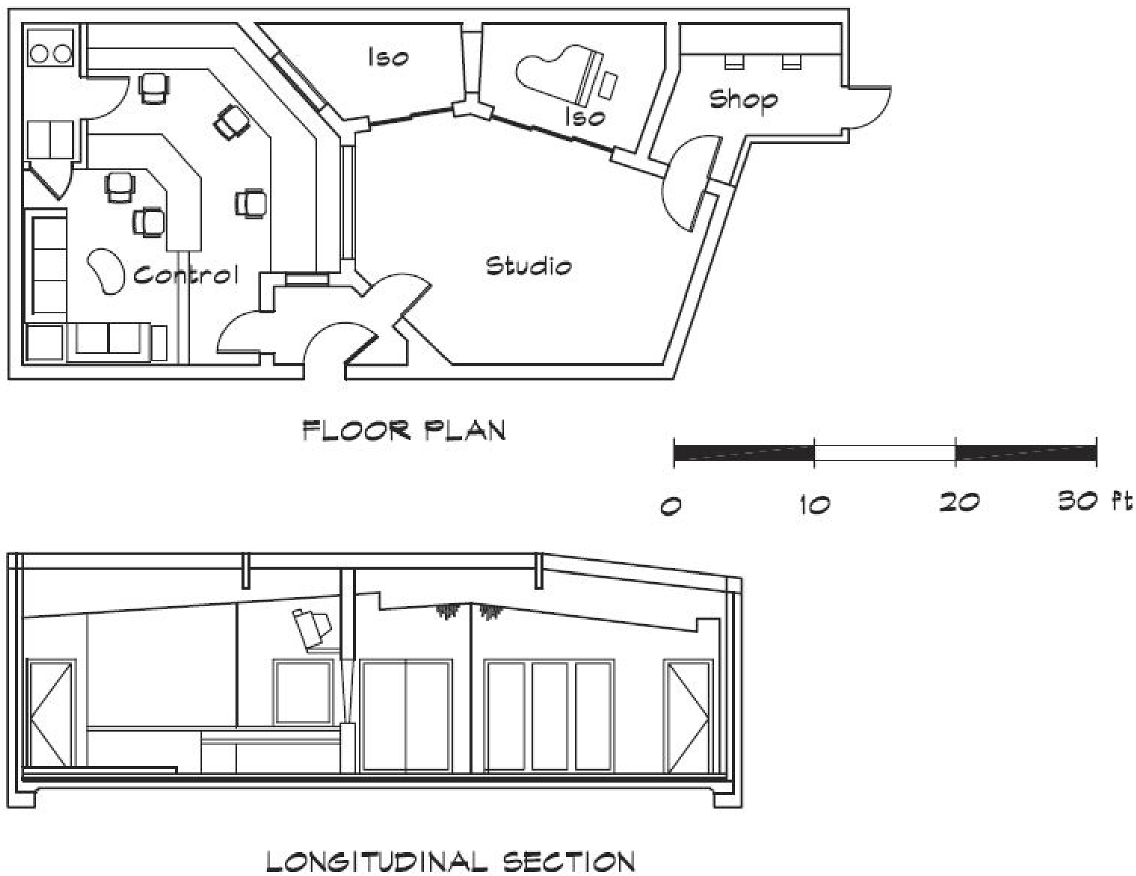
```
TEMP            20                      % Temperature of air (deg C) (Used to calculate speed of sound c (m/s))
order           -1                      % If -ve then a value will be computed, else value supplied here is used (limits order of reflections computed)
H_length        -1                      % Length of impulse Response. If -ve then a value will be is computed, else value supplied here is used"
H_filename      CTRLROOM_IMPULSE        % Filename for impulse response.
air_F           1                       % 0 = no absorption due to air, 1 = air absorption is present.
dist_F          1                       % 0 = no distance attenuation applied (ie no 1/R effect), 1= distance attenuation applied
Fc_HP           0                       % 0 = no high-pass filter. If scalar value supplied for cut-off frequency Fc_HP then high-pass filter applied.
smooth_F        0                       % 0 = no smoothing filter applied, 1= smoothing filter used. (Not used for MIT or CIPIC)
plot_F2         1                       % 0 = no plot, 1 = 2D-plan, shows image rooms and sources on constant z plane."
plot_F3         1                       % 0 = no plot, 1 = 3D-plot, shows image sources. Rotatable in MATLAB"
alpha_F         0                       % 0 = fixed transparent surfaces for Room Geometry plot, 1 = (surface opacity = reflectivity)
Lx              8.229                   % Room Length (m) x direction
Ly              7.187                   % Room Width (m) y direction
Lz              4.45                    % Room Height (m) z direction
xp              5.102                   % Receiver x co-ordinate (m)
yp              3.59                    % Receiver y co-ordinate (m)
zp              1.2                     % Receiver z co-ordinate (m) e.g. 1.2m is a typical height above floor of ears of seated human subject
Receiver        two_mic                 % Receiver, copy one of these:  one_mic two_mic mithrir cipicir NB all strings must be same length for later logical tests.
sensor_space    0.145                   % Sensor separation in 'two_mic' case (0.145 m is CIPIC average)
MIT_root        MIT_HRTF                % The root of MIT Kemar data base file
subdir1         Kemar                   % MIT sub-directory1 name
subdir2         compact                 % MIT sub-directory2 name
filename        hrir_final.mat          % MIT filename for HRIR
CIPIC_root      CIPIC_HRTF              % The root of the CIPIC data base files
subdir1         standard_hrir_database  % CIPIC sub-directory1 name
subdir2         subject_                % CIPIC sub-directory2 name (program combines this with subject number)
S_No            021                     % CIPIC subject number, format '&&&' (e.g. '021' is the Kemar with small pinnae)
filename        hrir_final.mat          % CIPIC filename for HRIR
receiver_yaw    0                       % Yaw (Azimuth) offset of receiver system (degrees) +ve slew left
receiver_pitch  0                       % Pitch (Elevation) offset of receiver system (degrees) +ve nose up
receiver_roll   0                       % Roll offset of receiver system (degrees) +ve right wing down
%-------------------------------------------------------------------------------------
        Set the room surface absorptions
F_abs   125     250     500     1000    2000    4000    %Standard measurement frequencies (Hz)
AX1     0.3     0.1     0.05    0.04    0.07    0.1     %Absorption of wall in x=0 plane (behind Receiver in plan)
AX2     0.3     0.1     0.05    0.04    0.07    0.1     %Absorption of wall in x=Lx plane (front in plan)
Ay1     0.75    0.75    0.75    0.75    0.75    0.75    %Absorption of wall in y=0 plane (right in plan)
Ay2     0.04    0.04    0.07    0.06    0.06    0.07    %Absorption of wall in y=Ly plane (left in plan)
Az1     0.15    0.11    0.10    0.07    .0.06   0.7     %Absorption of floor i.e. z=0 plane
Az2     0.5     0.7     0.6     0.7     0.7     0.5     %Absorption of ceiling i.e. z=Lz plane
%-------------------------------------------------------------------------------------
Directionality  Single/Left             Right_(if present)
azim_off        0                       0                       % ]azimuth offset for sensor (degrees)
elev_off        0                       0                       % ]elevation offset for sensor
roll_off        0                       0                       % ]roll offset for sensor
SENSOR_root     SENSOR                  SENSOR                  % The root of the SENSOR data base file
subdir1         Types                   Types                   % SENSOR sub-directory1 name
filename        omnidirectional.mat     omnidirectional.mat     % Sensor filenames for Impulse Response
%-------------------------------------------------------------------------------------
Directionality          Single/Left                 Right_(if present)

azim_off                 0                                  0                                      % ]azimuth offset for sensor (degrees)

elev_off                 0                                  0                                     % ]elevation offset for sensor

roll_off                  0                                 0                                       % ]roll offset for sensor

SENSOR_root         SENSOR                           SENSOR                           % The root of the SENSOR data base file

subdir1                    Types                             Types                                     % SENSOR sub-directory1 name

filename                 bidirectional.mat                 unidirectional.mat               % Sensor filenames for Impulse Response

%-------------------------------------------------------------------------------------

SOURCES  R_s (m)     alpha (deg)              beta (deg)  % R_s = Radial distance(s) of source(s) from head (m).

1                        2.2          30                    15          % alpha = Azimuth(s) of sources -180< alpha < 180 (deg) NB +ve is ACW on xy plane.

2                        2.2         0                      15         % beta = Elevation(s) of sources -90< beta < 90 (deg).

3                        2.2          -30                   15         %

                                                                        % To add a source

                                                                        % 1)Add an entry row (Source Number TAB R_s TAB alpha TAB beta) below the existing values list above

                                                                        % 2)Save the file

                                                                        % To change/remove a source:

                                                                        % 1) Clear or change any inappropriate existing values, OR

                                                                        % 2) Remove the complete row (Source Number, R_s, alpha, beta)

                                                                        %    NB there must be NO blank rows within the table.

                                                                        % 3) Save the file.
```

Appendix B Floor Plans: Various Recording Studios

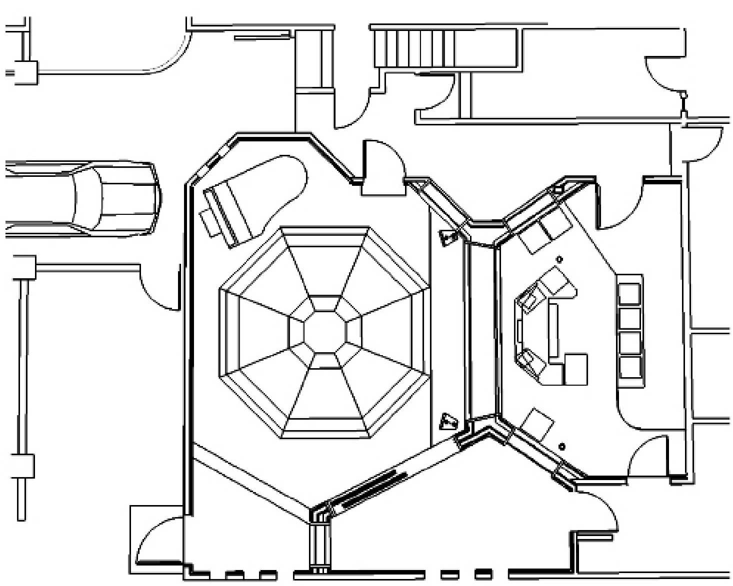
The following floor plans show possible shapes and configurations of live rooms, control rooms, iscolation booths and other studio facilities.



Floor plans for Avatar Studios A and C, New York [10]. Additional images available at http://www.avatarstudios.net/.



Hum Studio A, Santa Monica, CA (Acoustician: Marshall Long Acoustics).
(Architect: Walter Meyer Associates). ***Source: chapter 21 of Architectural Acoustics, 2008*** **[8]**



Floor plan for a small studio in Woodland Hills, CA. Additional images available at
http://www.gearslutz.com/board/high-end/58112-show-me-your-studio-ground-plan.html

Appendix C MATLAB code for impulse response plots

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% waterfall_Plot.m                                       Author: Tim Perry
%                                                                 2011-04-08
%
% Function to perform time-frequency representation plots (waterfall plots)
% from the phase and moduli data provided by a phase vocoder.
% Plots the following:
%          - Amplitude & Phase Waterfalls
%          - Magnitude Waterfall (dB scale)
%          - Phase vs. Time plot of Freq Bins near max amplitude
%              (in the case of a single tone sinusoid, will be centered
%              around pitch)
%
% FIG = WATERFALL_PLOT(Moduli,Phases,nPlotIndices,fs,WLen,Ra,Rs,N,nameTAG)
%
%           Moduli = amplitude matrix
%           Phases = phase matrix (input or output phases)
%           nPlotIndices =  sample indexes for FFT frame plots
%           fs = sampling frequency
%           WLen = analysis and synthesis window size
%           Ra = analysis hop size
%           Rs = synthesis hop size
%           N = length of time axis in samples (signal length, typically)
%           nameTAG = 'String-For-Naming-Plots'
%
%           P = plot handle
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function [waterAmpFIG waterPhaseFIG] =
waterfall(Moduli,Phases,nPlotIndices,fs,WLen,Ra,Rs,N,plotTAG)

figNumStart = get(0,'CurrentFigure');
%clear figure(figNumStart);
figNum = figNumStart + 1;

waterAmpFIG = figure('Colormap',jet(128),'Name','Waterfall Amplitude Plot', ...
    'Position',[10,20,1800,950]);
clear figure(figNum);
figNum = figNum + 1;

waterPhaseFIG = figure('Colormap',jet(128),'Name','Waterfall Phase Plot', ...
    'Position',[20,20,1800,950]);
clear figure(figNum);
figNum = figNum + 1;


%==============================================================
% Time-Frequency Plots
%==============================================================

Amp_norm = Moduli/Ra;                % Amp spectrum in quantity peak
Mag_dB = 20*log10(Moduli/max(max(Moduli)));

f0 = fs/WLen;                        % frequency resolution
numBins = WLen;                      % # of frequency bins
kBins = linspace(0,fs/2,numBins/2 + 1); % lin spaced freq bins up to Nyquist
```

```
[n, k] = meshgrid(nPlotIndices,kBins);    % rectangular domain

set(0,'CurrentFigure',waterAmpFIG)
%=================================================================
% Amplitude Waterfall
%=================================================================
hold on
waterAmp = surf(n,k,Amp_norm(1:(numBins/2 + 1), :));  %plot input amps
colorbar
axis([0,N,0,fs/2,0,max(max(Amp_norm))])
title(['Amplitude Waterfall of Short-time FFTs (', plotTAG, ')']);
grid on
ylabel('f [Hz]')
xlabel('n [samples]')
zlabel('|X_w(f)|')
hold off
view(viewmtx(-55,25,25));              % set viewpoint


%=================================================================
% Phase Waterfall
%=================================================================
set(0,'CurrentFigure',waterPhaseFIG)
hold on
waterPhase = surf(n,k,Phases(1:(numBins/2 + 1), :));  %plot  phases
colormap('jet')
colorbar
axis([0,N,0,fs/2,-3.2,3.2])
title(['Phase Waterfall of Short-time FFTs (', plotTAG, ')']);
grid on
ylabel('f [Hz]')
xlabel('n [samples]')
zlabel('Arg{X_w_(f)}  [rad]')
hold off
view(viewmtx(-55,75,25));              % set viewpoint


%=================================================================
% Amplitude Waterfall (dB)
%=================================================================
figure('Name','Magnitude Waterfall [dB]','Position',[50,100,1700,800]);
clear figure(figNum);
figNum = figNum + 1;

hold on
waterMag = surf(n,k,Mag_dB(1:(numBins/2 + 1), :));  %plot mag
colormap('jet')
colorbar
axis([0,N,0,fs/2,1.2*min(min(Mag_dB)),0])
title(['Magnitude [dB] Waterfall of Short-time FFTs (', plotTAG, ')']);
grid on
ylabel('f [Hz]')
xlabel('n [samples]')
zlabel('20log|X_w(f)|        [dB]')
hold off
view(viewmtx(-55,25,25));              % set viewpoint
```

Appendix D Heating Demand Calculations

The studio heating demand was estimated using the Chrimalox Room Heat Calculator, available at http://www.chromalox.com/resource-center/calculators/comfort-heater.aspx.

1. Room Size & Specs

Length: 100 ft. Width: 40 ft. Height: 16 ft.

Total Sq. Footage: 4000 ft. Room Cu. Footage: 64000 ft.

Item	Area	R-Factor	= BTU/Hr/Degrees F
Windows	168 Sq. ft.	x 2	= 84
Doors	84 Sq. ft.	x 10	= 8.4
Net Walls	4160 Sq. ft.	x 26	= 160
Roof	4500 Sq. ft.	x 50	= 90
Floor Perimeter*	4000 Sq. ft.	x 26	= 153.8461
		Transmission Losses Total	= 496.2461

*Use the R-Factor Reference to lookup common material R-Factor values. Important: R-Factor values are additive. For example, 2" of softwood results in an R-Factor of 2 x 1.25 = 2.5.

*For floor perimeter use U-factor of 1.2 for 1" insulation or 0.7 for 2" insulation.

2. Design Information

Air Changes per hour: 3.7

Outside Design Temp: 2

Inside Design Temp: 20

Temperature Difference: 18

Design Temperature Reference

3. Calculations

Air Changes Loss: 236800 Cu. Ft / hr x0.019 BTU / Cu. Ft = 4499.2

Total Losses Transmission Losses + Air Change Loss = 4995.446

TOTAL HEATING REQUIREMENT

Total Losses	x Temperature Difference	= Total BTU / Hr
4995.446 BTU/Hr/Degrees F	x 18 Degrees F	= 89918.03 BTU / Hr

CONVERSION TO WATTS

Total BTU / Hr / 3.412 BTU per watt = 26353.4(Total Watts per hour

Table 23 Parameters used for Heat Loss Calculations

Item	Specifications
14 3'x4' windows = 168 Sq. ft	Double pane glazed with an R-factor of 2
4 7'x3' doors = 84 Sq. ft	R-10, energy efficient doors, likely double doors
Wall insulation	R-26, assuming effective R-value of Insulating Concrete Form, IRC
Roof (30° slope, 4600 Sq. ft)	R-50 attic insulation
Average dimensions of interior perimeter	50'x80'x16'
Average outside temp (winter)	2° C
Average air changes/hr	3.7, the average for Sweden (likely close to the winter average in Vancouver). Canada's annual average is 4.4, with less statistical support.

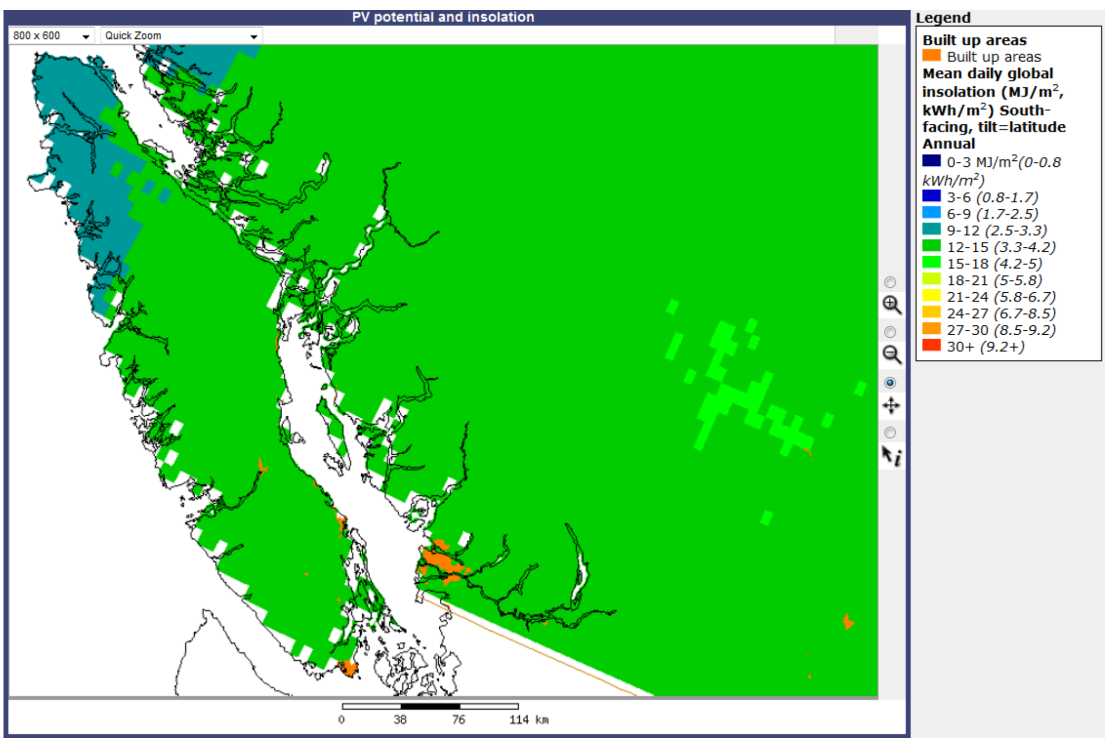
Appendix E PV Potential and Solar Insolation Maps

Residential Building Installed PV potential per household for Canada and the provinces [15]

Region	Mean daily insolation for latitude tilt (kWh/m2)	Ground floor area (m2)	Yearly electricity production (MWh)	Yearly electricity use (MWh)	Electricity production/ Electricity use (%)	GHG emissions intensity (kg/kWh)	Yearly GHG emissions reductions (tonnes)
Alberta	4.73	105	7.2	7.0	103	0.911	6.6
Saskatchewan	4.99	98	7.1	8.0	88	0.84	6.0
Québec	4.33	102	6.4	22.3	29	0.0088	0.056
Ontario	4.22	102	6.2	11.8	53	0.272	1.7
Manitoba	4.55	100	6.5	15.1	43	0.0305	0.20
PEI	4.06	100	5.9	3.2	181	1.12	6.6
Newfoundland/ Labrador	3.39	97	4.8	17.9	27	0.0211	0.10
Nova Scotia	3.92	97	5.5	11.8	46	0.759	4.2
New Brunswick	4.19	93	5.6	19.3	29	0.433	2.4
British Columbia	3.80	112	6.1	11.5	53	0.0209	0.13
Territories	3.67	107	5.7	10.7	53	0.255	1.5
Canada		103	6.3	13.6	46		1.9

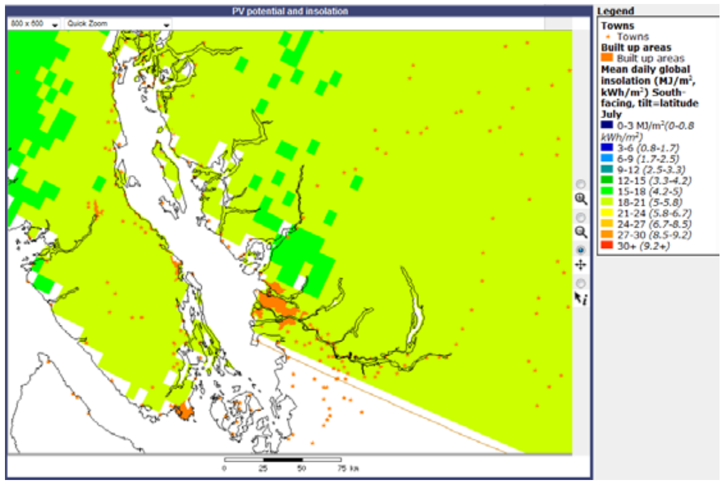
The following information was obtained from the Natural Resources Canada website: https://glfc.cfsnet.nfis.org/mapserver/pv/index.php?lang=e

Mean Daily Global Insolation, Annual

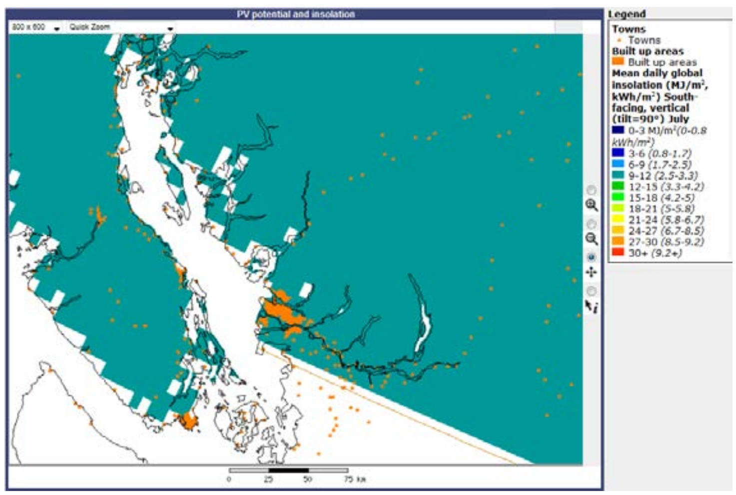


Period: Annual. PV panel orientation: South-facing, tilt=latitude.

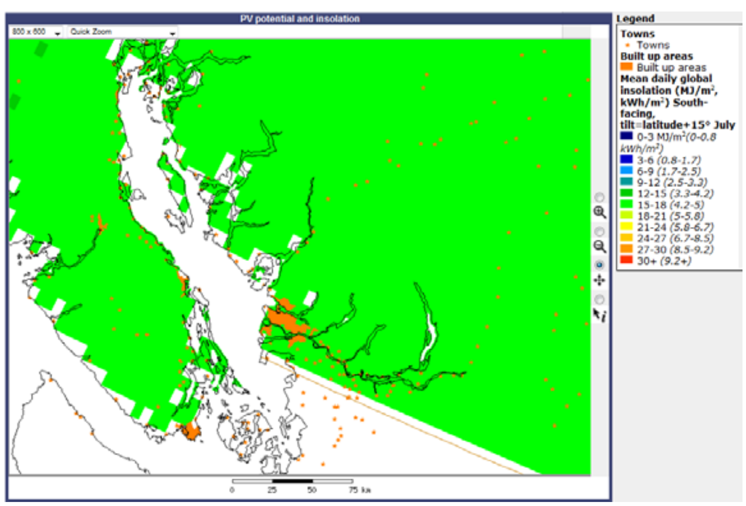
Mean Daily Global Insolation, July



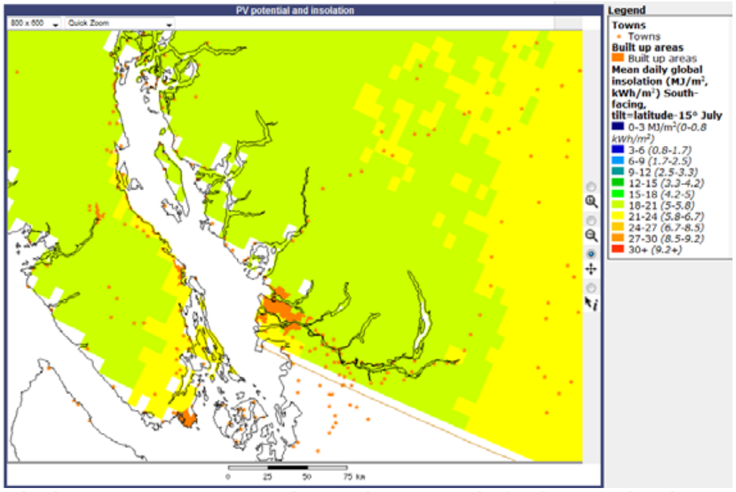
Period: July. PV panel orientation: South-facing, tilt=latitude.



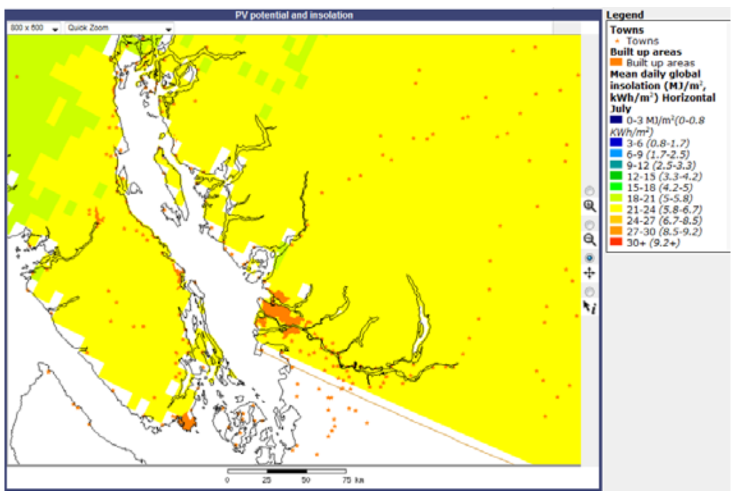
Period: July. PV panel orientation: South-facing, vertical (tilt=90°).



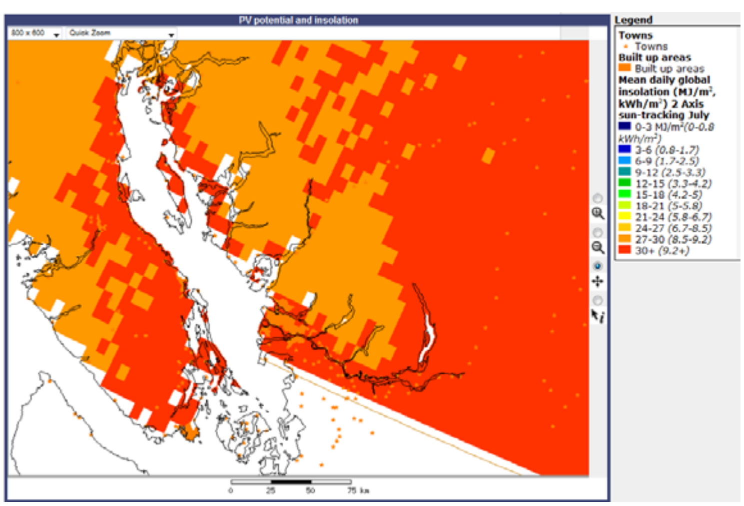
Period: July. PV panel orientation: South-facing, latitude+15°.



Period: July. PV panel orientation: South-facing, latitude-15°.

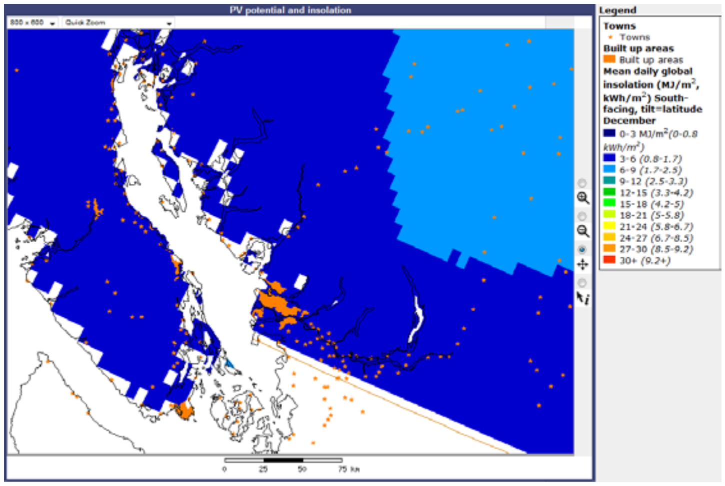


Period: July. PV panel orientation: Horizontal.

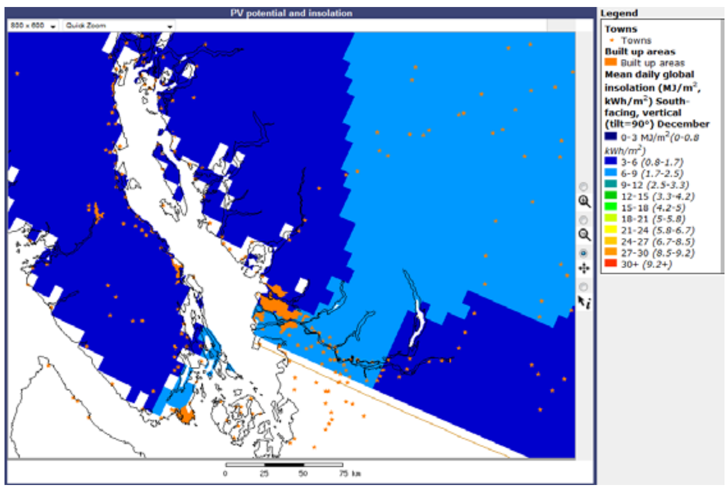


Period: July. PV panel orientation: 2 Axis sun-tracking.

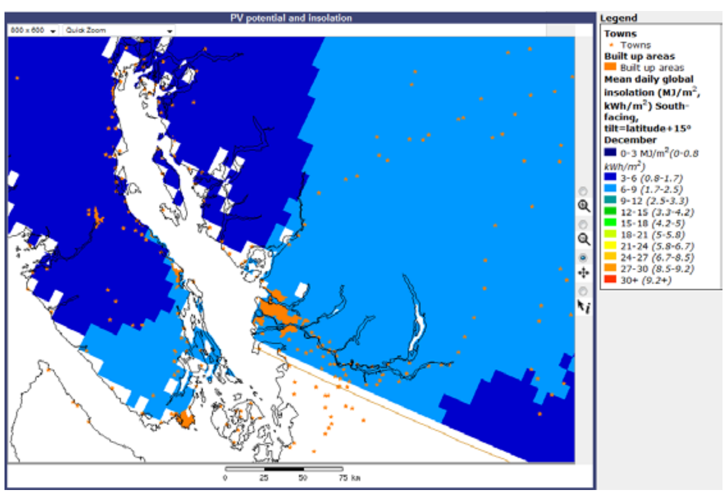
Mean Daily Global Insolation, December



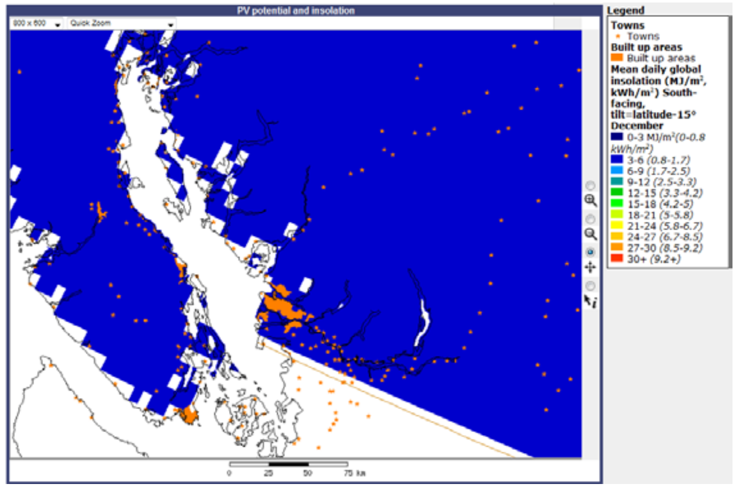
Period: December. PV panel orientation: South-facing, tilt=latitude.



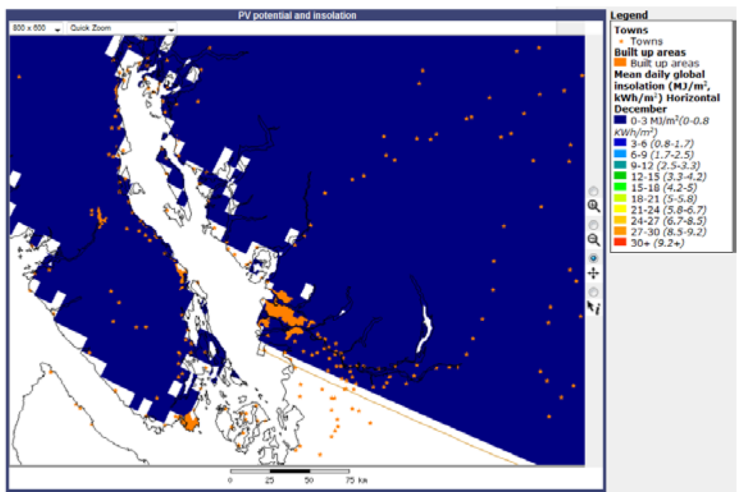
Period: December. PV panel orientation: South-facing, vertical (tilt=90°).



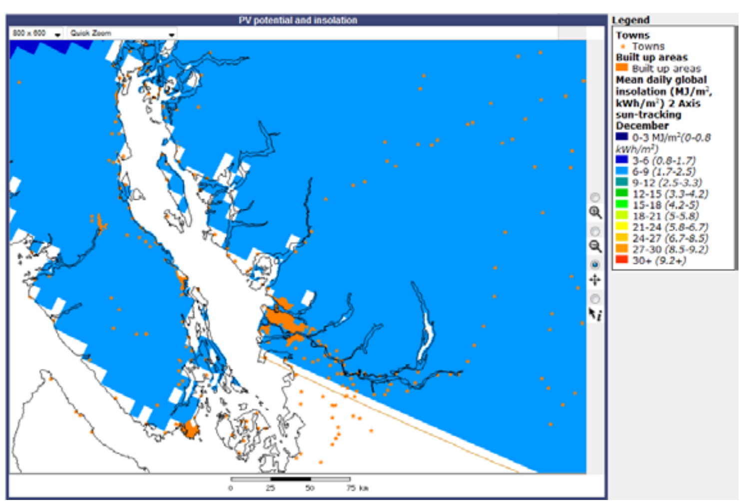
Period: December. PV panel orientation: South-facing, tilt=latitude +15°.



Period: December. PV panel orientation: South-facing, latitude-15°.



Period: December. PV panel orientation: Horizontal.



Period: December. PV panel orientation: 2 Axis sun-tracking.

Appendix F PV Array Sizing for Various PV Modules

PV Array Sizing for 24 VDC System, Trial 1

Basic sing sizing calculator available at: http://www.webcalc.net/calc/0317_solar.php:

Inputs

Daily amp hours: 7,516
Average sun hours: 3.7
Peak amps produced by solar panel (Imp): 7.63
Battery Voltage: 24 VDC

Outputs

Total number of solar panels: **640**
Panels in each series string: 2
Panels in each parallel string: 320

(135 W /panel)x(640 panels)= **86400 W array**

PV Array Sizing for 24 VDC System, Trial 2[8]

Sizing calculator available at: http://www.advancepower.net/advcalc.htm

Manufacturer	Kyocera	Model	KD135GX-LP
Rated Current (Imp)	7.63	Rated Voltage (Vmp)	17.7
Short Circuit Current (Isc)	8.37	Open Circuit Voltage (Voc)	22.1
Module Derate	0.89	Nominal Voltage	12
Peak Sun Hours	3.7	Target Solar to Load Ratio	1.0
Adjusted Daily AH Load	3000	DC System Voltage	24
Array Current	814.88	Number of Modules	240
Short Circuit Current	1004.4	Number in Series	2
Array Voltage (Vmp)	35.4	Number of Parallel	120
Open Circuit Voltage	44.2	Critical Application Option	Yes
Array AH per Day	3015.06		

COMMENT: Actual Solar to Load Ratio is 1.01

[8] The adjusted daily amp hour load, indicated in the battery bank sizing worksheet, is greater than 3000 AH. The array size must be scaled appropriately to meet the full system daily amp hour load: 10590AH/3000AH = 3.53.
3.53 x 240panels = 847.2 ➔ 848 panels
848 panels x 135W/panel = 114 480 W array

Array Sizing Worksheet 2 (600 VDC System)

* Sized for only 3000 AH of Total Daily AH Load

Sizing calculator available at: http://www.advancepower.net/advcalc.htm

Photovoltaic Array: Inputs

Manufacturer	SolarWorld	**Model**	AG SW 175 m
Rated Current (Imp)	4.90	**Rated Voltage (Vmp)**	35.7
Short Circuit Current (Isc)	5.30	**Open Circuit Voltage (Voc)**	44.4
Module Derate	0.89	**Nominal Voltage**	387
Peak Sun Hours	3.5	**Solar to Load Ratio Target**	1.0
Adjusted Daily AH Load	3000	**DC System Voltage**	600

Photovoltaic Array: Outputs

Array Current	859.12	**Number of Modules**	305.42635658!
Short Circuit Current	1044.1	**Number in Series**	1.5503875968!
Array Voltage	55.35	**Number of Parallel**	197
Open Circuit Voltage	68.84	www.AdvancePower.net	
Array AH per Day	3006.92	**Critical Application?**	☑ Yes
Array Amp Hours:	Actual Solar to Load Ratio is 1		

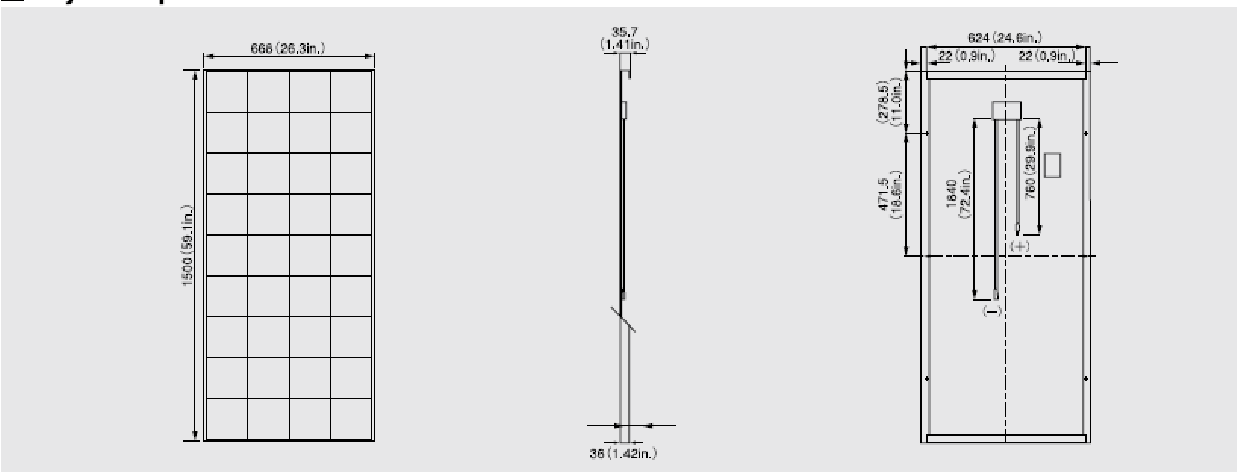
Appendix G Photovoltaic Module Specifications

SPECIFICATIONS

KD135GX-LP

Physical Specifications

Unit : mm (in.)



Specifications

Electrical Performance under Standard Test Conditions (*STC)	
Maximum Power (Pmax)	135W (+5%／−5%)
Maximum Power Voltage (Vmpp)	17.7V
Maximum Power Current (Impp)	7.63A
Open Circuit Voltage (Voc)	22.1V
Short Circuit Current (Isc)	8.37A
Max System Voltage	600V
Temperature Coefficient of Voc	−.080 V/℃
Temperature Coefficient of Isc	5.02×10^{-3} A/℃

*STC : Irradiance 1000W/m², AM1.5 spectrum, cell temperature 25℃

Electrical Performance at 800W/m², *NOCT, AM1.5	
Maximum Power (Pmax)	95W
Maximum Power Voltage (Vmpp)	15.6V
Maximum Power Current (Impp)	6.10A
Open Circuit Voltage (Voc)	19.9V
Short Circuit Current (Isc)	6.82A

*NOCT (Nominal Operating Cell Temperature) : 49℃

Cells	
Number per Module	36

Module Characteristics	
Length × Width × Depth	1500mm(59.1in)x668mm(26.3in)x36mm(1.4in)
Weight	13.0kg(28.7lbs.)
Cable	(+)760mm(29.9in),(-)1840mm(72.4in)

Junction Box Characteristics	
Length × Width × Depth	100mm(3.9in)X108mm(4.3in)X15mm(0.6in)
IP Code	IP65

Others	
*Operating Temperature	−40℃~90℃
Maximum Fuse	15A

*This temperature is based on cell temperature.

Please contact our office for further information

KYOCERA

Sunmodule
SW 155/165/175 mono

Performance under standard test conditions

		SW 155	SW 165	SW 175
Maximum power	P_{max}	155 Wp	165 Wp	175 Wp
Open circuit voltage	V_{oc}	43.6 V	44.0 V	44.4 V
Maximum power point voltage	V_{mpp}	34.8 V	35.3 V	35.8 V
Short circuit current	I_{sc}	4.90 A	5.10 A	5.30 A
Maximum power point current	I_{mpp}	4.46 A	4.68 A	4.89 A

Performance at 800 W/m², NOCT, AM 1.5

		SW 155	SW 165	SW 175
Maximum power	P_{max}	110.8 Wp	118.0 Wp	125.1 Wp
Open circuit voltage	V_{oc}	39.4 V	39.8 V	40.2 V
Maximum power point voltage	V_{mpp}	31.2 V	31.6 V	32.1 V
Short circuit current	I_{sc}	4.05 A	4.22 A	4.38 A
Maximum power point current	I_{mpp}	3.55 A	3.73 A	3.90 A

Minor reduction in efficiency under partial load conditions at 25°C: at 200 W/m², 95% (+/- 3%) of the STC efficiency (1000 W/m²) is achieved.

Component materials

Cells per module	72
Cell type	monocrystalline silicon
Cell dimensions	125 x 125 mm²

System integration parameters

Maximum system voltage SC II	1,000 V_{DC}
Maximum system voltage USA NEC	600 V_{DC}
Maximum series fuse rating	15 A

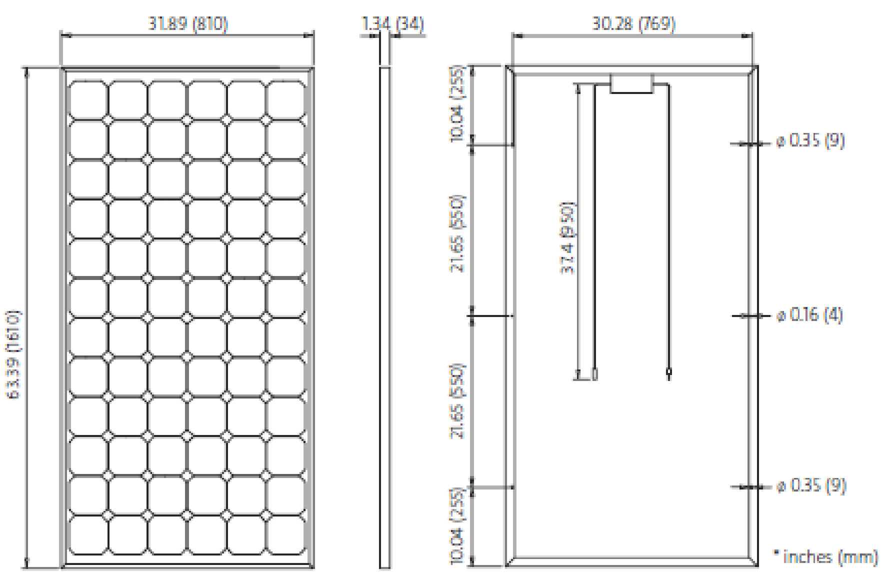
Thermal characteristics

NOCT	46°C
TC I_{sc}	0.036 %/K
TC V_{oc}	-0.33 %/K

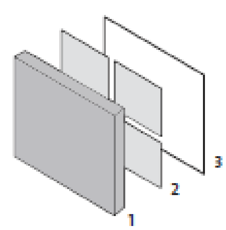
Additional data

Power tolerance	+/- 3 %
Junction box	IP 65
Connector	MC type 4

Front **Side** **Rear**



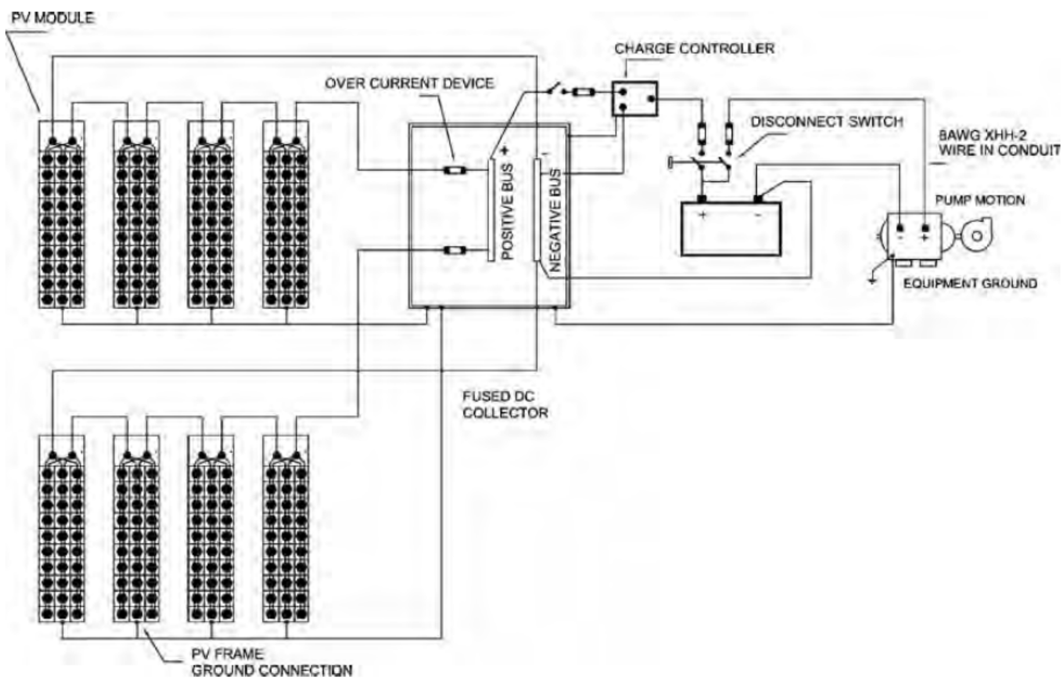
Construction



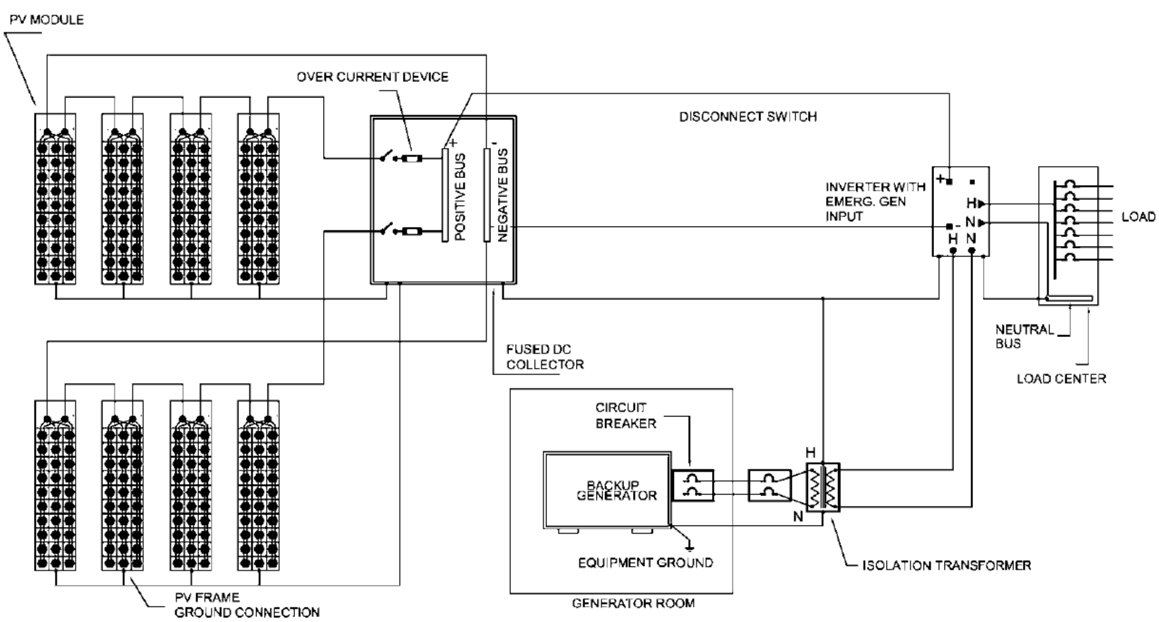
1] Front: tempered glass
2] crystalline solar cells embedded in EVA (ethylene-vinyl-acetate)
3] Rear: Tedlar

Appendix H Off-Grid Solar Power System Schematics

The following schematics were obtained from Solar Power in Building Design, 2007 [20]



Battery-backed solar power—driven dc pump (above) [20].



Stand-alone hybrid solar power system with standby generator (above) [20].

Appendix I   Specifications for Off–Grid Inverters

The following specifications for PMI off-grid inverters were obtained from the Power Management Instruments website: http://www.pmienergy.com/pro6-eng.php

MONOPHASE INVERTER (DC/AC CONVERTER) SYSTEMS								
	INV-1000	INV-2000	INV-3000	INV-4000	INV-5000	INV-7500	INV-10000	INV-15000
Output Power	1000 VA	2000 VA	3000 VA	4000 VA	5000 VA	7500 VA	10 KVA	15 KVA
Power Factor	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Output Voltage	220 VAC/ 230 VAC ±1%	220 VAC/ 230 VAC ±1%	220 VAC/ 230 VAC ±1%	220 VAC/ 230 VAC ±1%	220 VAC/ 230 VAC ±1%	220 VAC/ 230 VAC ±1%	220 VAC/ 230 VAC ±1%	220 VAC/ 230 VAC ±1%
Input DC Voltage	24 VDC	48 VDC	120 VDC	120 VDC	144 VDC	144 VDC	144 VDC	144 VDC
DC Voltage Operating Range	20-30 VDC	40-60 VDC	100-150 VDC	100-150 VDC	120-180 VDC	120-180 VDC	120-180 VDC	120-180 VDC
Efficiency (Full Load)	90%	92%	94%	95%	95%	95%	95%	95%
Operating Topology	Microcontrolled Hig Frequency IGBT PWM with Output Isolation Transformer							
Protection	Short Circuit, Overload, Over Temperature, Over Voltage							
Dimension (HxWxD) in mm	810x355x485	810x355x485	810x355x485	1020x490x590	1020x490x590	1020x490x590	1020x490x590	1220x495x600
Weight in kg	71	110	110	120	177	200	238	286
Operating Temperature	-10 °C / +50 C	-10 °C / +50 C	-10 °C / +50 C	-10 °C / +50 C	-10 °C / +50 C	-10 °C / +50 C	-10 °C / +50 C	-10 °C / +50 C

THREEPHASE INVERTER (DC/AC CONVERTER) SYSTEMS								
	INV-3/10	INV-3/15	INV-3/20	INV-3/30	INV-3/40	INV-3/80	INV-3/120	INV-3/150
Output Power	10 KVA	15 KVA	20 KVA	30 KVA	40 KVA	80 KVA	120 KVA	150 KVA
Power Factor	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Output Voltage	380 VAC 400 VAC ±1%	380 VAC 400 VAC ±1%	380 VAC 400 VAC ±1%	380 VAC 400 VAC ±1%	380 VAC 400 VAC ±1%	380 VAC 400 VAC ±1%	380 VAC 400 VAC ±1%	380 VAC 400 VAC ±1%
Input DC Voltage	264 VDC	264 VDC	264 VDC	264 VDC	264 VDC	360 VDC	360 VDC	360 VDC
DC Voltage Operating Range	220-330 VDC	220-330VDC	220-330VDC	220-330VDC	220-330VDC	300-450 VDC	300-450VDC	300-450VDC
Efficiency (Full Load)	90%	92%	94%	95%	95%	95%	95%	95%
Operating Topology	Microcontrolled Hig Frequency IGBT PWM with Output Isolation Transformer							
Protection	Short Circuit, Overload, Over Temperature, Over Voltage							
Dimension (HxWxD) in mm	1230x510x715	1230x510x715	1430x600x810	1430x600x810	1550x660x910	1700x780x960	1900x1350x800	1900x1350x800
Weight in kg	240	298	392	425	470	600	1110	1300
Operating Temperature	-10 °C / +50 °C	-10 °C / +50 °CC	-10 °C / +50 °C	-10 °C / +50 °C	-10 °C / +50 °C	-10 °C / +50 °C	-10 °C / +50 °C	-10 °C / +50 °C

Appendix J Grid-Tie PV System Performance Data for Vancouver

The following performance data for grid connected photovoltaic systems in Vancouver was calculated using PVWatts, available at http://rredc.nrel.gov/solar/calculators/PVWATTS

Station Identification	
City:	Vancouver
Country/Province:	BC
Latitude:	49.18° N
Longitude:	123.17° W
Elevation:	3 m
Weather Data:	CWEC
PV System Specifications	
DC Rating:	4.00 kW
DC to AC Derate Factor:	0.770
AC Rating:	3.08 kW
Array Type:	Fixed Tilt
Array Tilt:	49.2°
Array Azimuth:	180.0°
Energy Specifications	
Energy Cost:	0.0862 CanB/kWh

Results			
Month	Solar Radiation ($kWh/m^2/day$)	AC Energy (kWh)	Energy Value (CanB)
1	1.41	121	10.43
2	2.69	219	18.88
3	3.44	307	26.46
4	5.13	446	38.45
5	5.43	484	41.72
6	5.25	441	38.01
7	6.03	517	44.57
8	5.60	486	41.89
9	5.04	431	37.15
10	2.72	238	20.52
11	1.68	143	12.33
12	1.32	116	10.00
Year	3.82	3950	340.49