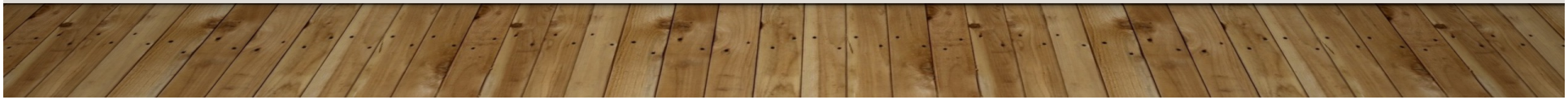
FINAL PROJECT: MMI606 - ACOUSTICS

BY THOMAS BAKER

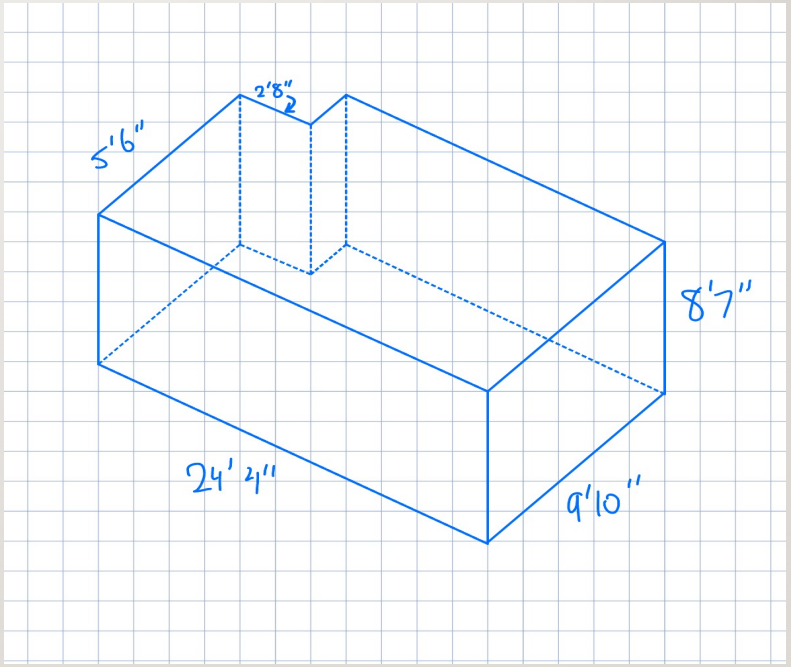


OVERVIEW

- Acoustic Analysis of a Room – MuE Grad Lab
  - Calculations – Bolt's Area, Modal Analysis, Schroeder Frequency, etc.
  - Measurements – Room EQ Wizard
- Propose the following:
  - Speaker and listener placement
  - an acoustic treatment based on analysis

DIMENSIONS

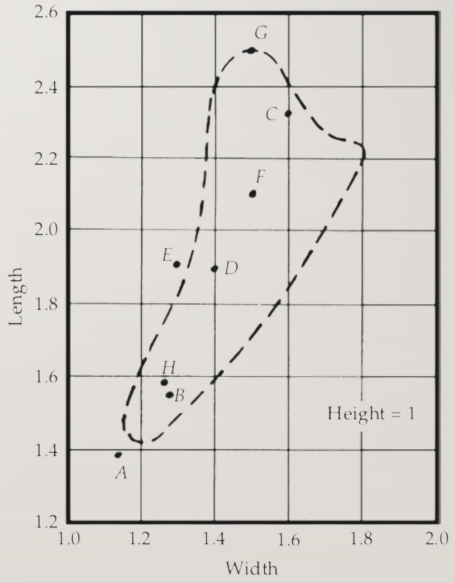
- Consider the room as a rectangular parallelepiped for the purpose of this project
  - Disregard indented corner
  - Use longest length and width measurements
  - Length – 24 feet, 4 inches
  - Width – 9 feet, 10 inches
  - Height – 8 feet, 7 inches



Drawing by Nicolas Adler

DIMENSIONS (CONT.)

- Length x Width x Height
  - 24’ 4” x 9’ 10” x 8’ 7” (feet, inches)
  - 741.6 x 299.7 x 261.6 (cm)
- Ratio of Room Dimensions (Height normalized to 1)
  - 2.835, 1.146, 1.000 (Length, Width, Height)
- Fit within Bolt’s Area? – No
  - Closest Ratio: Point G, Volkmann (5:3:2)
  - Normalized: 2.5, 1.5, 1



PICTURES OF SURFACES

Wall

Floor (Carpet)

Door

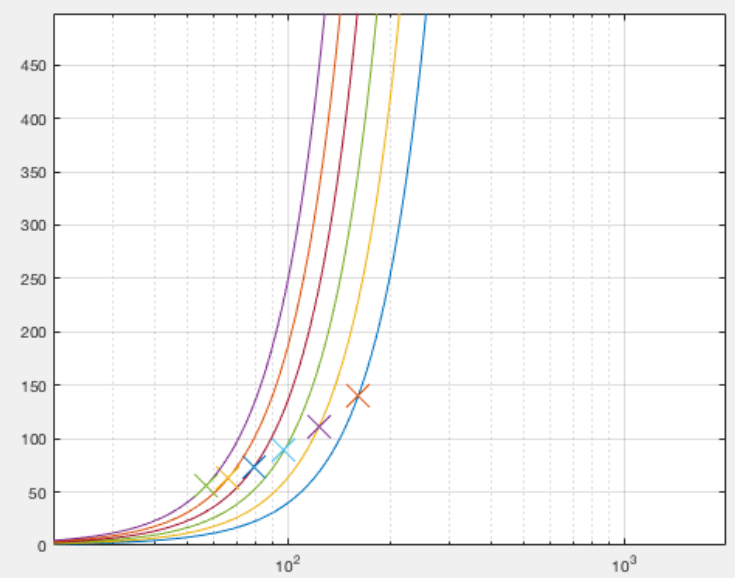
Whiteboard

Speaker

TV

SCHROEDER FREQUENCY CALCULATION

- RT_{60} taken from measurements in REW, average all 30 measurements at 500Hz
  - T20 method - 350.1 ms
  - T30 method - 354.6 ms
- Volume of room: 2053.8 ft^3
  - 24' 4" x 9' 10" x 8' 7"
- f_c = 11885 * sqrt(RT_{60}/ V)
  - T20 - 155.17 Hz
  - T30 - 156.17 Hz



From class notes

AXIAL MODES

- Axial Modes up to Schroeder Frequency ≈ 156 Hz
- "Mode" is mode order with Length-Width-Height
  - 1-0-0 is first-order axial mode across the length of the room
- Areas of Concern
  - Gap between #1-2, 5-6
  - Modes #7 and 8 are extremely close

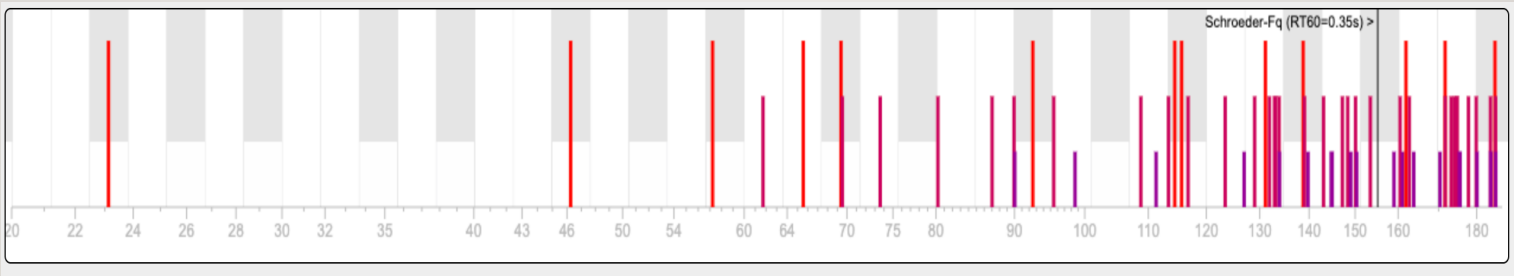
#	Freq (Hz)	Mode
1	23.13	1-0-0
2	46.25	2-0-0
3	57.22	0-1-0
4	65.56	0-0-1
5	69.38	3-0-0
6	92.50	4-0-0
7	114.45	0-2-0
8	115.63	5-0-0
9	131.12	0-0-2
10	138.75	6-0-0

ALL MODES

- Full list of modes with axial, tangential, and oblique can be calculated with amcoustics.com
  - All 3 contribute to modal density, so should be considered
- 42 modes up until Schroeder Frequency (156 Hz)

1	23.13 Hz	F0#	1-0-0	ax
2	46.25 Hz	F1#	2-0-0	ax
3	57.22 Hz	A1#	0-1-0	ax
4	61.72 Hz	B1	1-1-0	tan
5	65.56 Hz	C2	0-0-1	ax
6	69.38 Hz	C2#	3-0-0	ax
7	69.52 Hz	C2#	1-0-1	tan
8	73.58 Hz	D2	2-1-0	tan
9	80.23 Hz	E2	2-0-1	tan
10	87.02 Hz	F2	0-1-1	tan
11	89.93 Hz	F2#	3-1-0	tan
12	90.04 Hz	F2#	1-1-1	obl
13	92.51 Hz	F2#	4-0-0	ax
14	95.45 Hz	G2	3-0-1	tan
15	98.55 Hz	G2	2-1-1	obl
16	108.77 Hz	A2	4-1-0	tan
17	111.29 Hz	A2	3-1-1	obl
18	113.38 Hz	A2#	4-0-1	tan
19	114.44 Hz	A2#	0-2-0	ax
20	115.63 Hz	A2#	5-0-0	ax
21	116.76 Hz	A2#	1-2-0	tan
22	123.44 Hz	B2	2-2-0	tan
23	127 Hz	B2	4-1-1	obl
24	129.02 Hz	C3	5-1-0	tan
25	131.11 Hz	C3	0-0-2	ax
26	131.89 Hz	C3	0-2-1	tan
27	132.92 Hz	C3	5-0-1	tan
28	133.14 Hz	C3	1-0-2	tan
29	133.83 Hz	C3	3-2-0	tan
30	133.9 Hz	C3	1-2-1	obl
31	138.76 Hz	C3#	6-0-0	ax
32	139.03 Hz	C3#	2-0-2	tan
33	139.77 Hz	C3#	2-2-1	obl
34	143.05 Hz	D3	0-1-2	tan
35	144.72 Hz	D3	5-1-1	obl
36	144.91 Hz	D3	1-1-2	obl
37	147.16 Hz	D3	4-2-0	tan
38	148.34 Hz	D3	3-0-2	tan
39	149.02 Hz	D3	3-2-1	obl
40	150.09 Hz	D3	6-1-0	tan
41	150.35 Hz	D3	2-1-2	obl
42	153.46 Hz	D3#	6-0-1	tan
43	158.99 Hz	D3#	3-1-2	obl
44	160.46 Hz	E3	4-0-2	tan
45	161.1 Hz	E3	4-2-1	obl
46	161.88 Hz	E3	7-0-0	ax
47	162.69 Hz	E3	5-2-0	tan
48	163.79 Hz	E3	6-1-1	obl

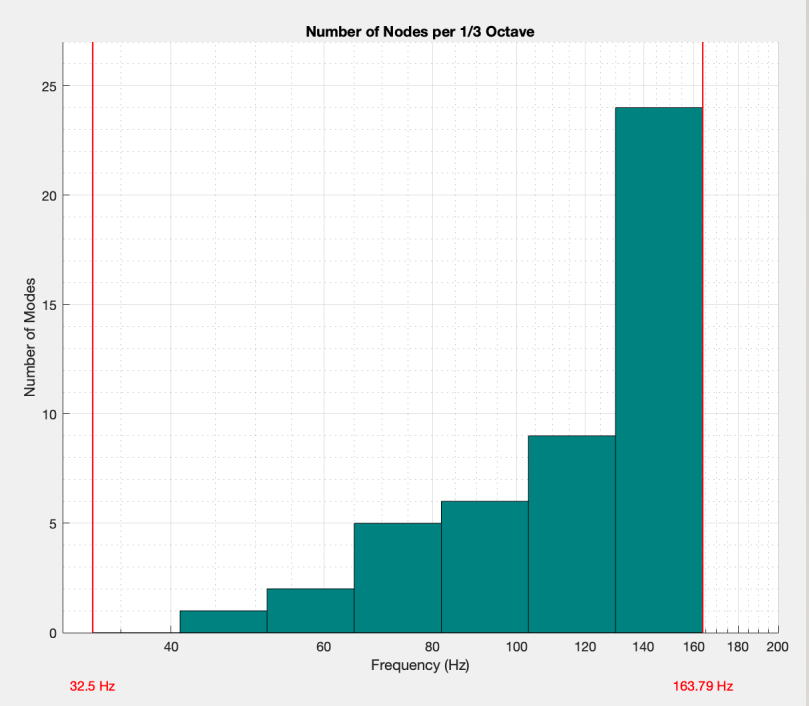
MODAL SPACING



- Longest lines represent axial modes
- Shorter lines represent tangential modes
- Shortest lines represent oblique nodes

MODAL DENSITY

- Using full list of Modes
- 1/3 Octave Bands, starting from 32.5Hz
  - 32.5Hz to 40.95Hz – 0 modes
  - 40.95Hz to 51.59Hz – 1 mode
  - 51.59Hz to 65Hz – 2 modes
  - 65Hz to 81.89Hz – 5 modes
  - 81.89Hz to 103.18Hz – 6 modes
  - 103.18Hz to 130Hz – 9 modes
  - 130Hz to 163.79Hz – 24 modes
- Meets Bonello's Criterion for this range
  - Number of modes increases every band
  - However, keep in mind the mode at 23.13Hz. Most likely doesn't meet criterion for all modes



MODAL DENSITY ESTIMATION

- Modal Density can be calculated with the following equation:
- Volume (V): 2053.8 ft^3
- Surface Area (S): 1065.08 ft^2
- L = 171 ft

$$\Delta N = \left[\frac{4\pi V f^2}{c^3} + \frac{\pi S f}{2c^2} + \frac{L}{8c}\right]\Delta f$$

ΔN = number of modes
Δf = bandwidth, Hz
f = center frequency, Hz
$V = (l_x l_y l_z)$ = room volume, ft^3
$S = 2(l_x l_y + l_y l_z + l_x l_z)$ = room surface area, ft^2
$L = 4(l_x + l_y + l_z)$ = lengths of all edges in room, ft
c = speed of sound = 1,130 ft/sec

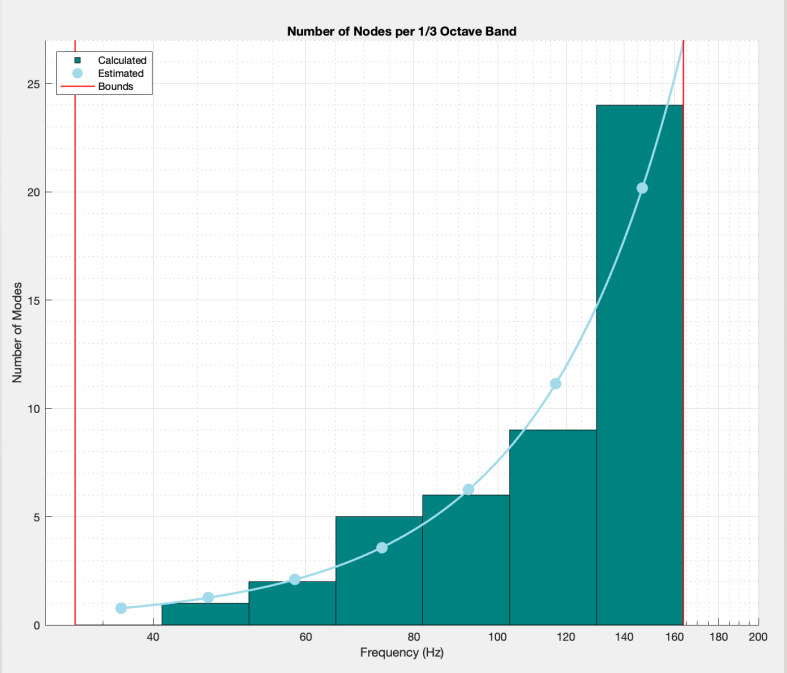
MODAL DENSITY ESTIMATION

- 1/3 Octave Bands, starting from 32.5Hz
  - 32.5Hz to 40.95Hz – 0.7703 modes
  - 40.95Hz to 51.59Hz – 1.2538 modes
  - 51.59Hz to 65Hz – 2.0930 modes
  - 65Hz to 81.89Hz – 3.5744 modes
  - 81.89Hz to 103.18Hz – 6.2447 modes
  - 103.18Hz to 130Hz – 11.1253 modes
  - 130Hz to 163.79Hz – 20.1843 modes
- Change values of freqLow and freqHigh in MatLab Script for the different bands

```
pi = 3.14159265358979323846264338327950288419716939937510;
c = 1130;

freqLow = 32.5;
freqHigh = 40.95;


bandwidth = freqHigh - freqLow;
centerFreq = (freqHigh + freqLow)/2;

length = 24.3333333;
width = 9.83333333;
height = 8.58333333;

volume = length * width * height;
surfaceArea = 2 * (length*width + length*height + width*height);
totalLength = 4 * (length + width + height);


numNodes = (((4*pi*volume*centerFreq^2)/(c^3))+ ...
    ((pi*surfaceArea*centerFreq)/(2*c^2))+ ...
    (totalLength/(8*c))) * bandwidth;

disp(numNodes);
```

MODAL DENSITY ESTIMATION

- Estimation overlayed on previous graph
  - Estimation in light blue



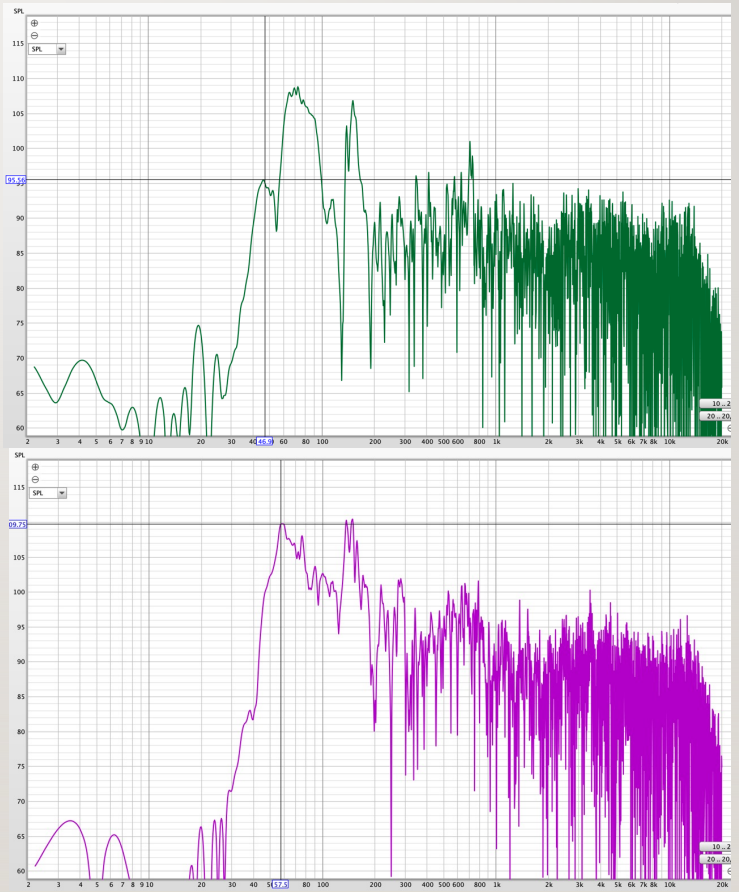
REAL MODES

- List of modes for the actual room, with the indented corner
- Amroc Pro room mode calculator for non-rectangular rooms
- Compare with measurements!

id	Hz	Note
1	24.19	G0
2	47.01	F1#
3	57.27	A1#
4	61.56	B1
5	65.94	C2
6	70.33	C2#
7	70.83	C2#
8	78.68	D2#
9	81.32	E2
10	87.83	F2
11	90.72	F2#
12	91.14	F2#
13	97.44	G2
14	101.04	G2#
15	103.38	G2#
16	113.32	A2#
17	113.47	A2#
18	114.35	A2#
19	117.84	A2#
20	121.64	B2
21	123.78	B2
22	126.44	B2
23	132.27	C3
24	133.09	C3
25	134.43	C3
26	136.13	C3#
27	136.25	C3#
28	136.71	C3#
29	138.47	C3#
30	141.50	C3#
31	143.10	D3
32	143.86	D3
33	147.25	D3
34	147.66	D3
35	149.07	D3
36	152.11	D3#
37	152.63	D3#
38	153.75	D3#
39	154.70	D3#
40	157.75	D3#
41	163.09	E3
42	164.60	E3
43	165.00	E3
44	165.70	E3
45	167.23	E3
46	171.29	F3
47	175.81	F3
48	178.90	F3

COMPARISON WITH MEASUREMENTS

- SPL graphs from different room locations
- 24.19 Hz mode too low for frequency response of speaker
- 47.01 Hz mode visible in graph 1
- 57.27 Hz mode visible in graph 2
- Modes from 61.56-81.32 Hz explain peak in both graphs

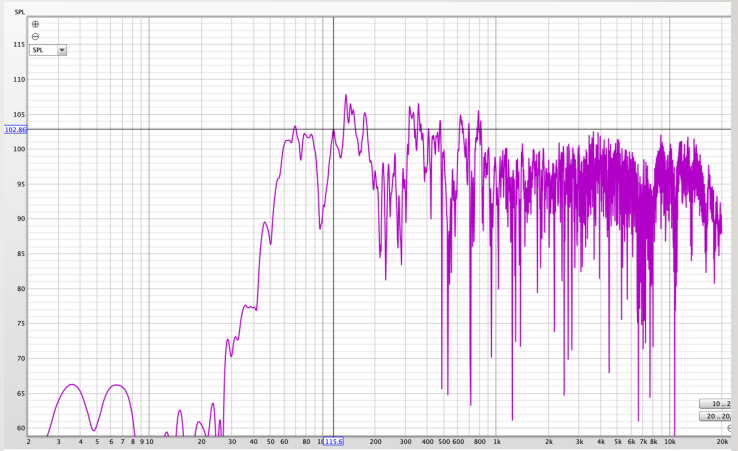


Location 1

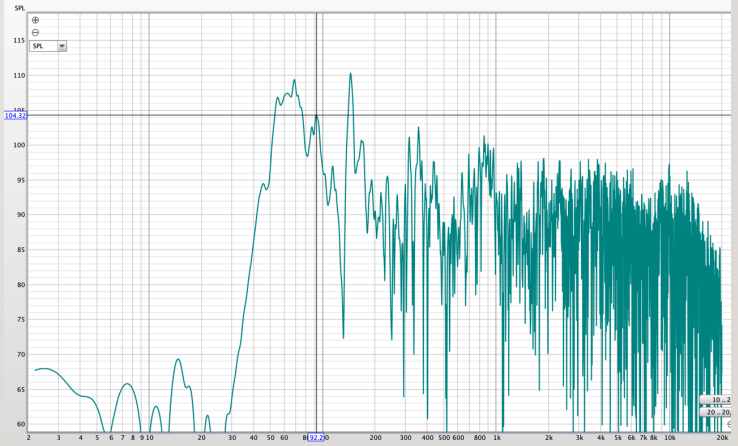
Location 2

COMPARISON WITH MEASUREMENTS

- 87.83-91.14 Modes shown in graph 4
- Not much evidence of modes 97.44-126.44Hz except in location 3
- Modes 132.27-157.75Hz can be explained by second major peak in graph 2, previous slide
- Overall, measurements match pretty well!

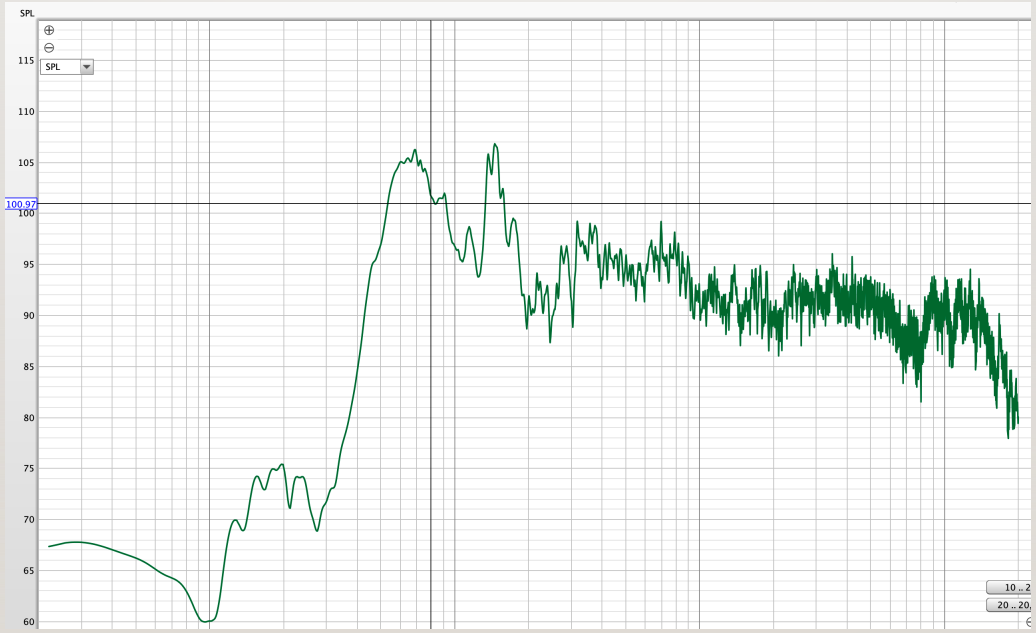


Location 3



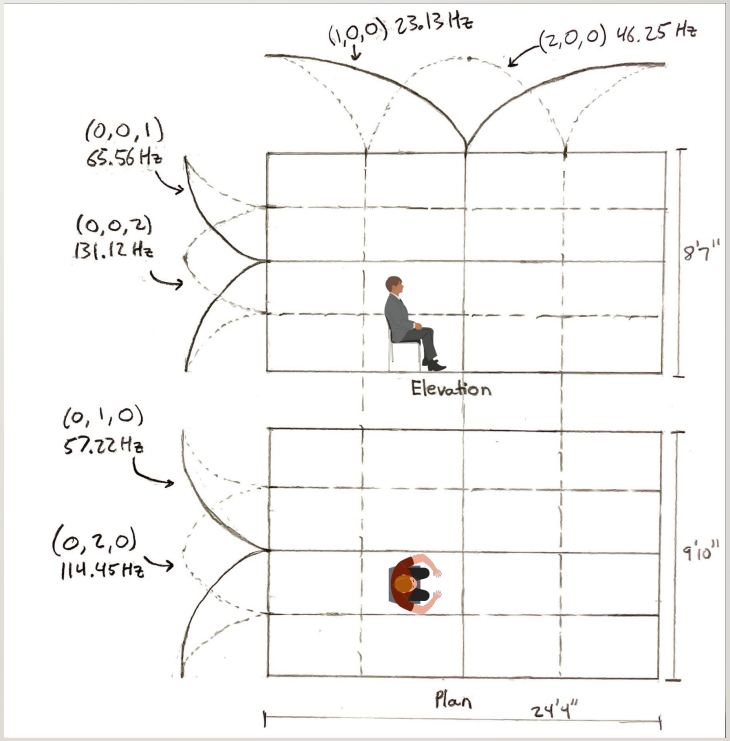
Location 4

AVERAGE OF ALL SPL MEASUREMENTS



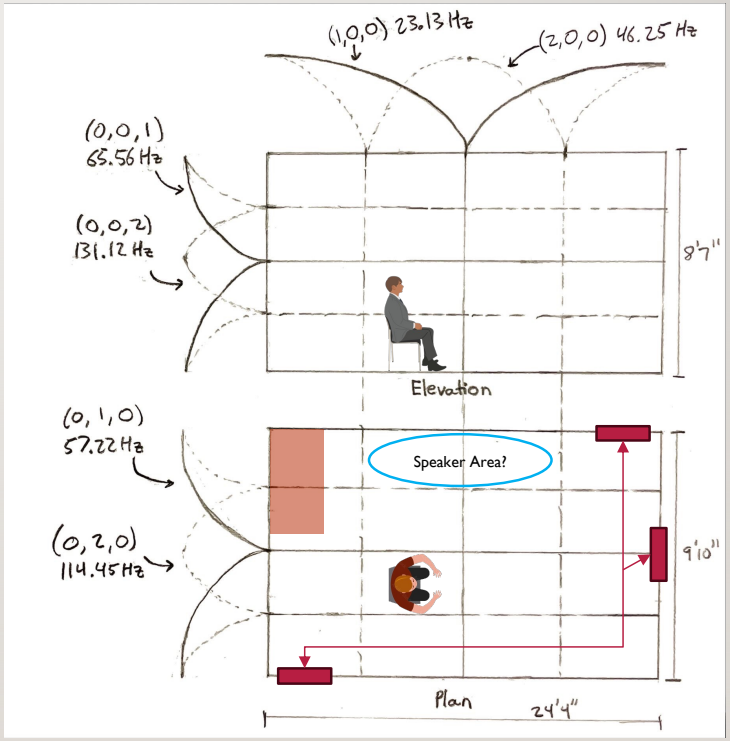
ROOM MODE DIAGRAM

- First and second order axial modes shown in the drawing
  - Man in chair shown for perspective
- Solid lines represent first-order nodes
- Dotted lines represent second-order nodes
- Straight lines represent nulls
  - Both the sound sources and listener should avoid these locations



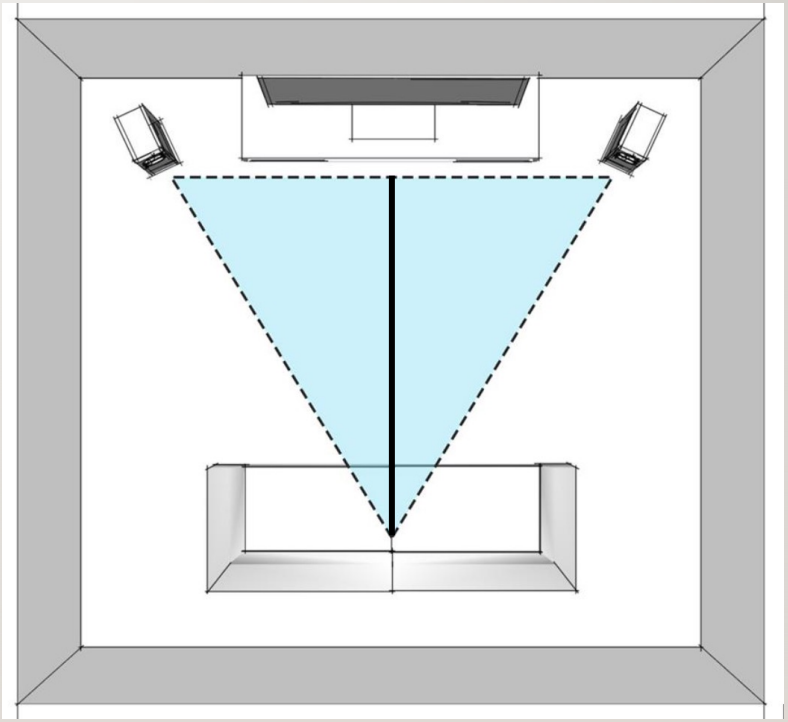
ROOM MODE DIAGRAM

- Where do we put the speakers and listening position?
- Practical considerations
  - Door placement
  - Will still have to serve as a walkway between the other rooms
  - Indented corner
- Only practical configuration is to put speakers near the back wall



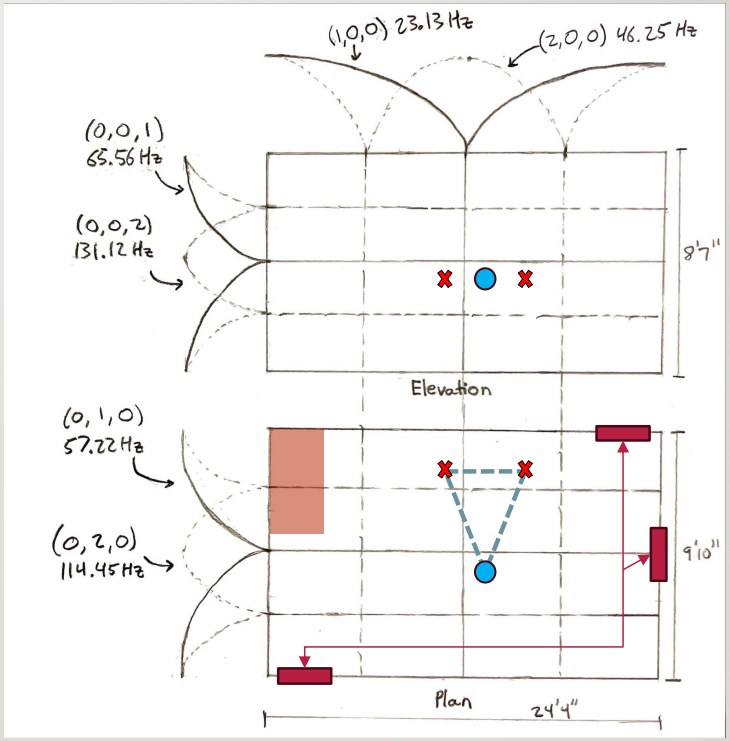
SPEAKER AND LISTENER LOCATIONS

- Average sitting ear height: 36-38 inches
- Speaker Spacing
  - Recommended 8 feet from each other, but room is too small!
  - About 4’ 8” feels more appropriate
  - Form equilateral triangle with listening position



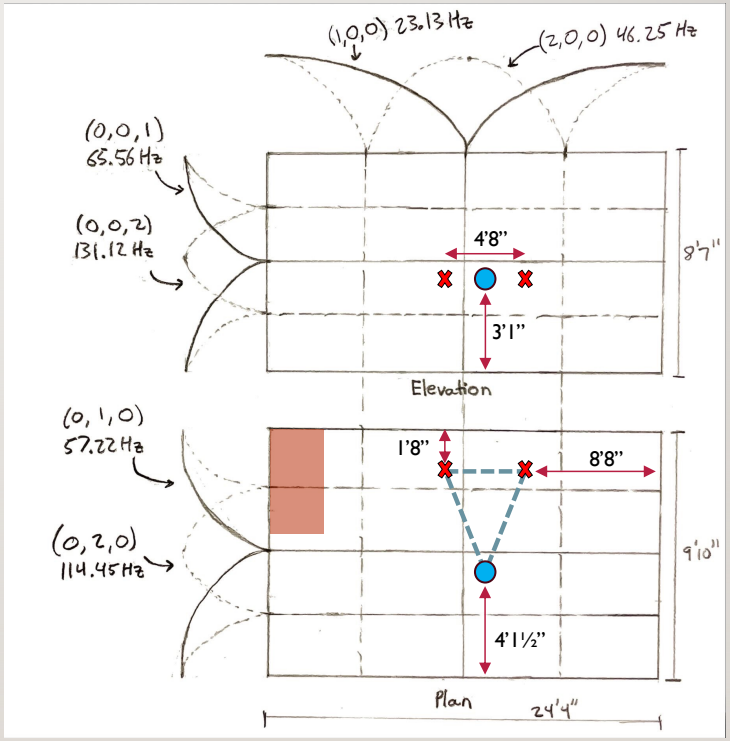
SPEAKER AND LISTENER LOCATIONS

- Practical Considerations
- Crosses represent speaker placement
  - 37 inches from floor – sitting ear height
  - 4’ 8” away from each-other
- Circle represents listener location
  - 4’ 8” away from each speaker
- Blue triangle is equilateral – room not drawn to dimensions, so graphic is stretched



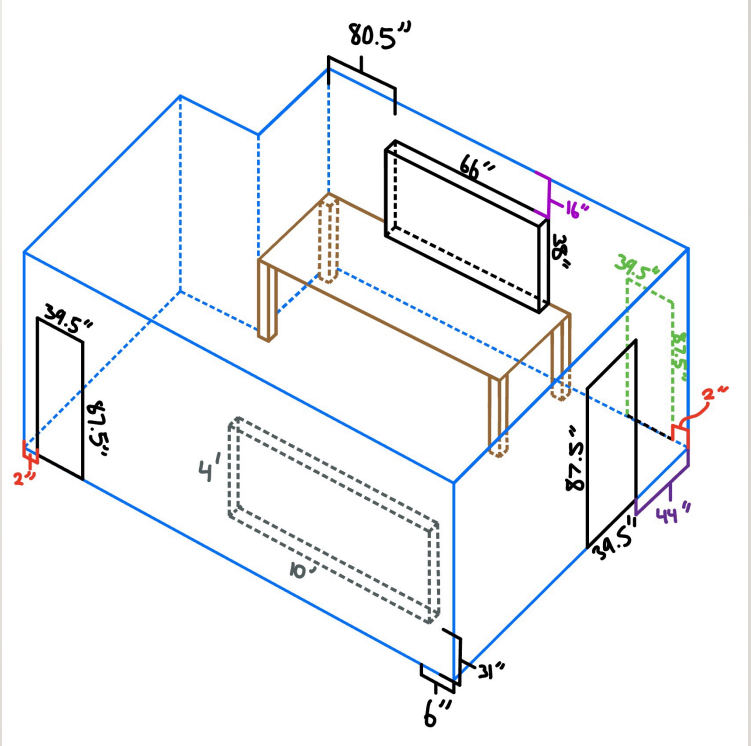
SPEAKER AND LISTENER LOCATIONS

- Speakers
  - 3’ 1” up from floor
  - Around 1’ 8” away from front wall
  - Right speaker 8’ 8” away from right wall
  - Left speaker 4’ 8” away from right speaker
- Listener
  - 4’ 1½” from back wall
  - Centered between the two speakers
    - 11’ from right wall



ROOM DIAGRAM

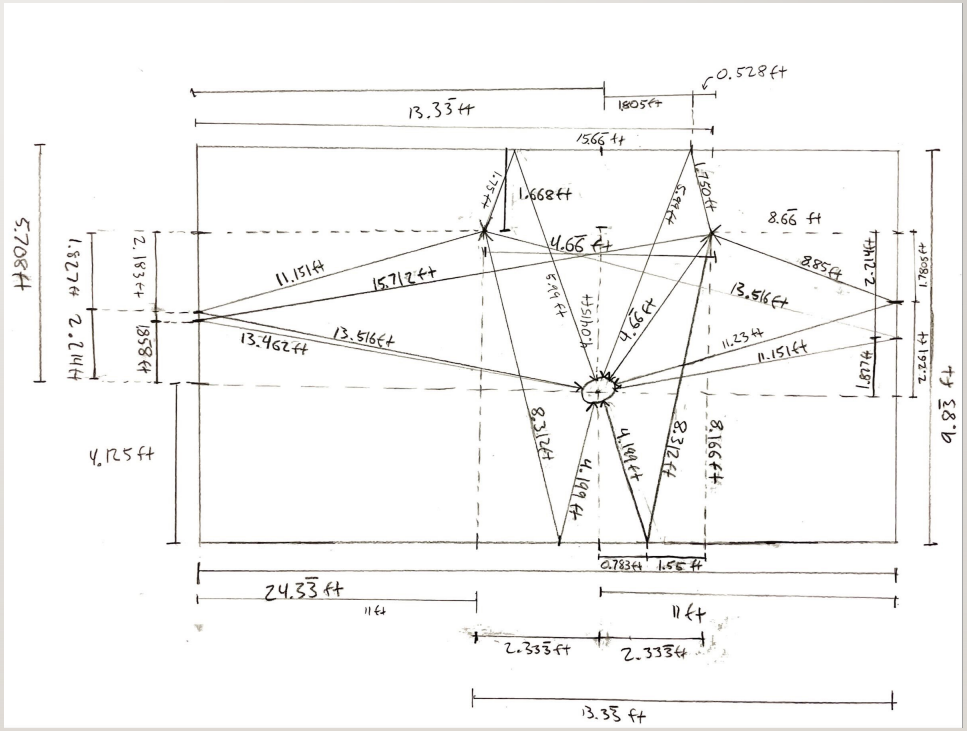
- Other considerations
  - Remove the whiteboard – reflective surface behind listener location
  - Remove big panel speakers
  - Get new table that is small enough to center between the two speakers
  - Move the TV to be centered with speakers



Drawing by Nicolas Adler

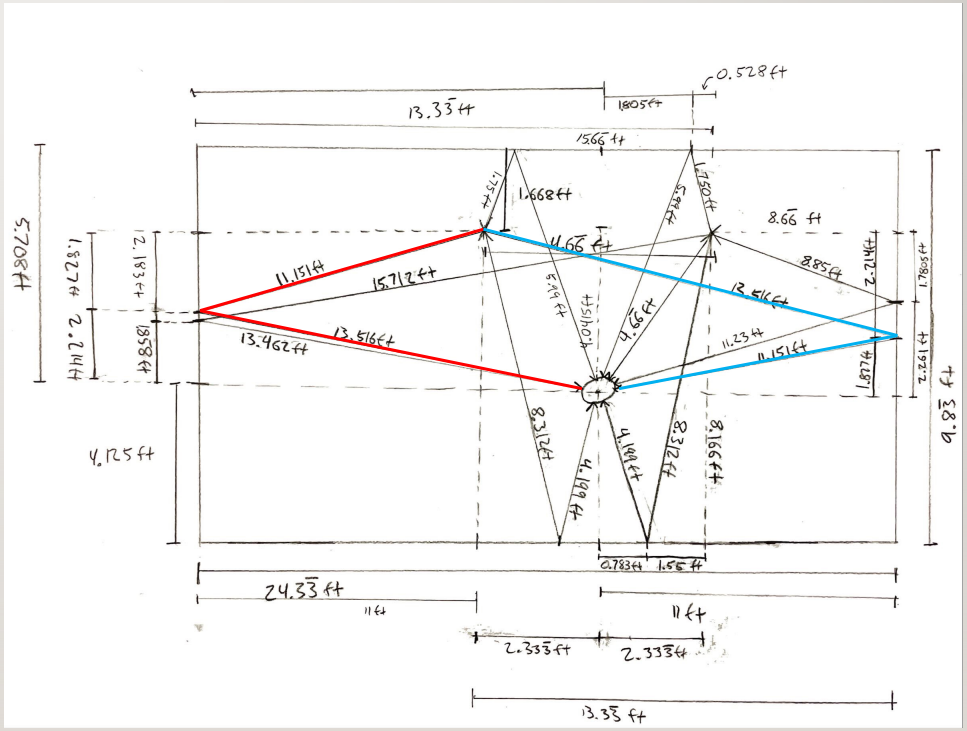
FIRST REFLECTIONS

- Floorplan – Length x Width
- Reflections off left, right, front, and back walls
- Left Speaker
  - Left Wall Reflection: 24’ 8”
  - Right Wall Reflection: 24’ 8” (whaaa??)
  - Front Wall Reflection: 7’ 9”
  - Back Wall Reflection: 12’ 6”
- Right Speaker
  - Left Wall Reflection: 29’ 2”
  - Right Wall Reflection: 20’ 1”
  - Front Wall Reflection: 7’ 9”
  - Back Wall Reflection: 12’ 6”



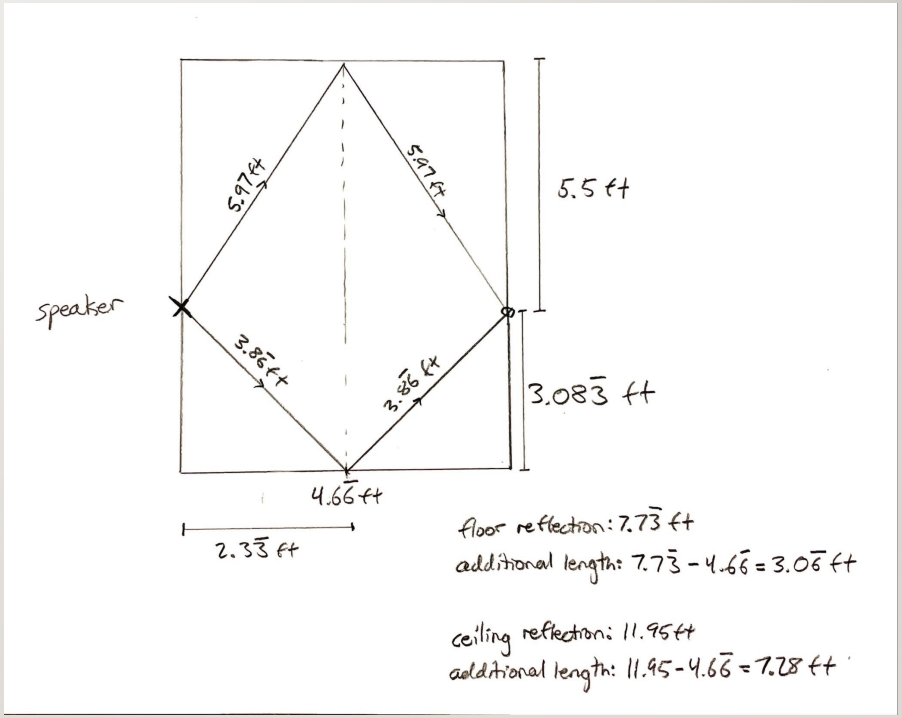
FIRST REFLECTIONS

- Floorplan – Length x Width
- Reflections off left, right, front, and back walls
- Left Speaker
  - Left Wall Reflection: 24’ 8”
  - Right Wall Reflection: 24’ 8” (whaaa??)
  - Front Wall Reflection: 7’ 9”
  - Back Wall Reflection: 12’ 6”
- Right Speaker
  - Left Wall Reflection: 29’ 2”
  - Right Wall Reflection: 20’ 1”
  - Front Wall Reflection: 7’ 9”
  - Back Wall Reflection: 12’ 6”



FIRST REFLECTIONS

- Additional distance from direct path
- Floor, ceiling, and back wall reflections will be the same for left and right speakers
  - They are both the same distances for each
- Floor reflection: 3'1" additional length
- Ceiling reflection: 7'3½" additional length
- Back wall reflection: 7'10" additional length



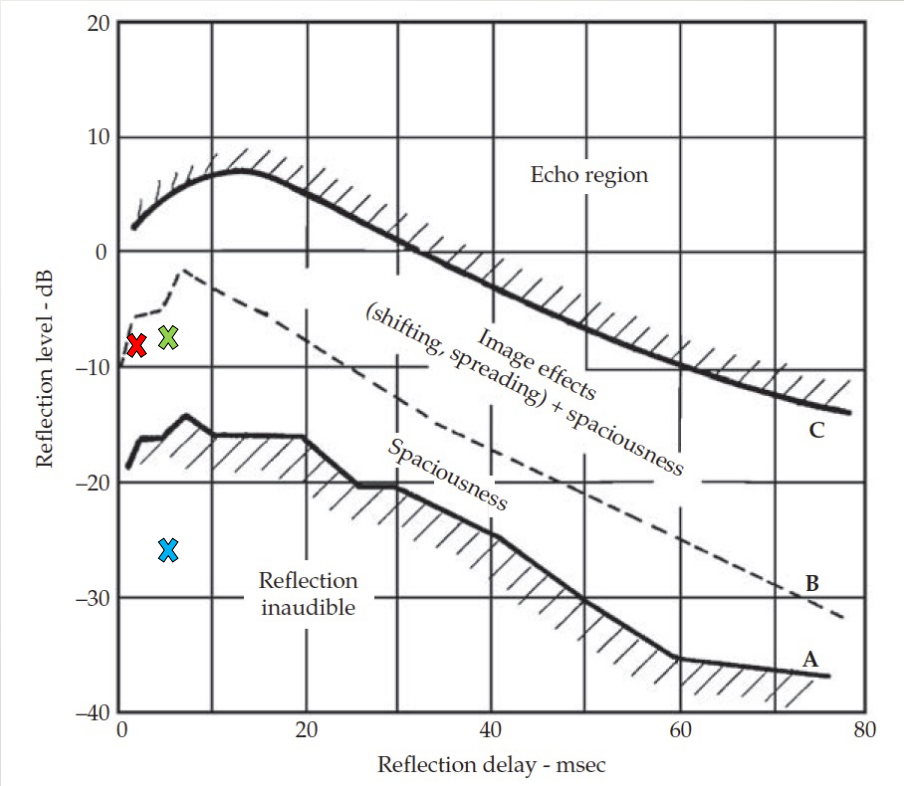
FIRST REFLECTIONS CALCULATIONS

- Calculations for level
  - $Loss\ from\ distance = 20\log\left(\frac{r_1}{r_2}\right)$
  - $Loss\ from\ absorption = 20\log(1-\alpha)$
  - $Total\ Loss = 20\log\left(\frac{r_1}{r_2}\right) + 20\log(1-\alpha)$
- Calculations for delay
  - $\frac{Additional\ Time}{Speed\ of\ Sound}$

	Floor	**Ceiling**	**Back wall**
Additional Length	3'1"	7'3½"	7'10"
Reflection material	Carpet tiles	Mineral Wool Tiles	Plaster on studs
α at 1kHz	0.43	0.88	0.05
Level	-9.27dB	-26.58dB	-4.96dB
Delay	+2.7ms	+6.45ms	+6.56ms

FIRST REFLECTIONS

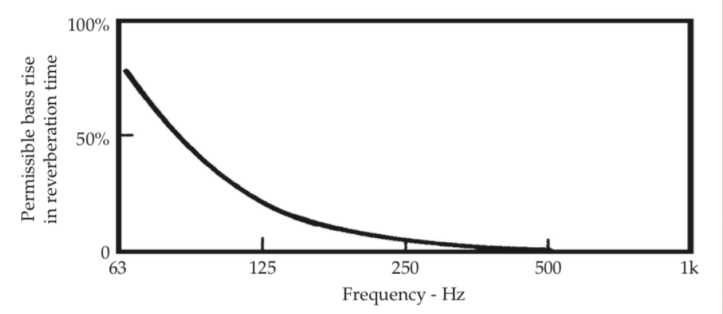
- Red Marks represent first reflection points
  - Red – floor reflection
  - Blue – ceiling reflection
  - Green – back wall reflection
- Floor and back wall reflections add to the spaciousness, ceiling reflection inaudible



BASS RISE

- Use the equation to the right for calculation
- Values from Room EQ Wizard: RT_{60} tab
- Average of two T30 measurements per location, so 10 measurements total for each
  - 125Hz – 0.5155 seconds
  - 250 Hz – 0.4001 seconds
  - 500 Hz – 0.3529 seconds
  - 1000 Hz – 0.3046 seconds

$$BR = \frac{(RT60_{125} + RT60_{250})}{RT60_{500} + RT60_{1,000}}$$



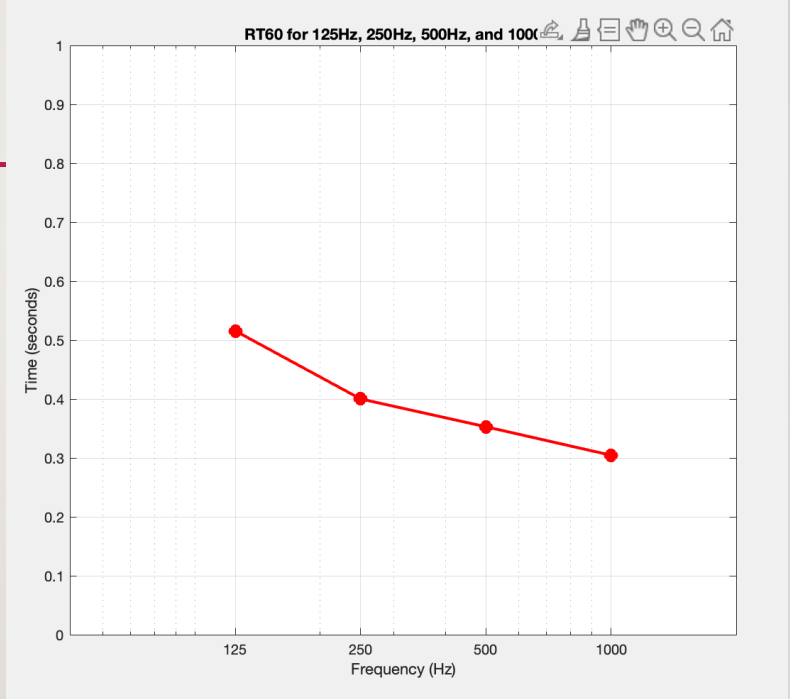
BASS RISE

$$BR = \frac{(RT60_{125} + RT60_{250})}{RT60_{500} + RT60_{1,000}}$$

$$BR = \frac{(0.5155 \ + \ 0.4001)}{0.3529 \ + 0.3046}$$

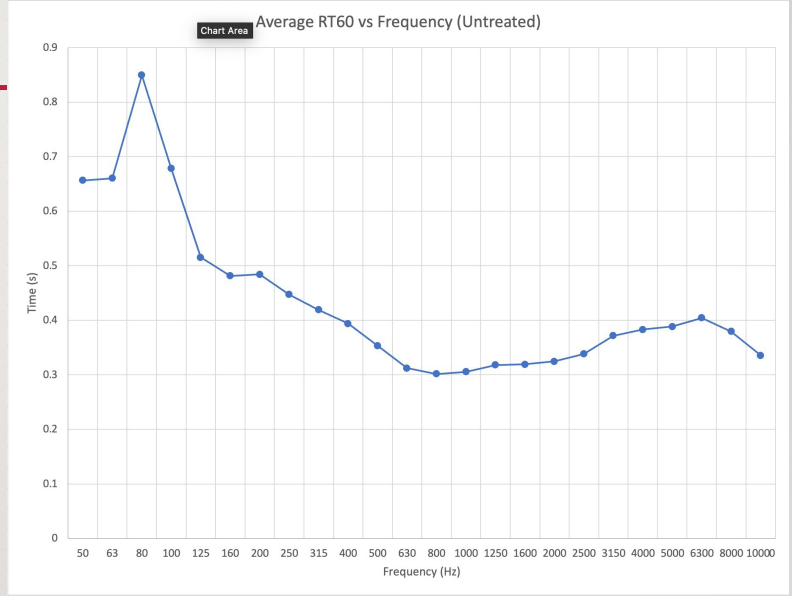
$$BR = 1.39$$

- A calculated value of 1.1 to 1.45 is considered permissible. 1.39 is within range, but a bit high



FULL RT_{60} PLOT

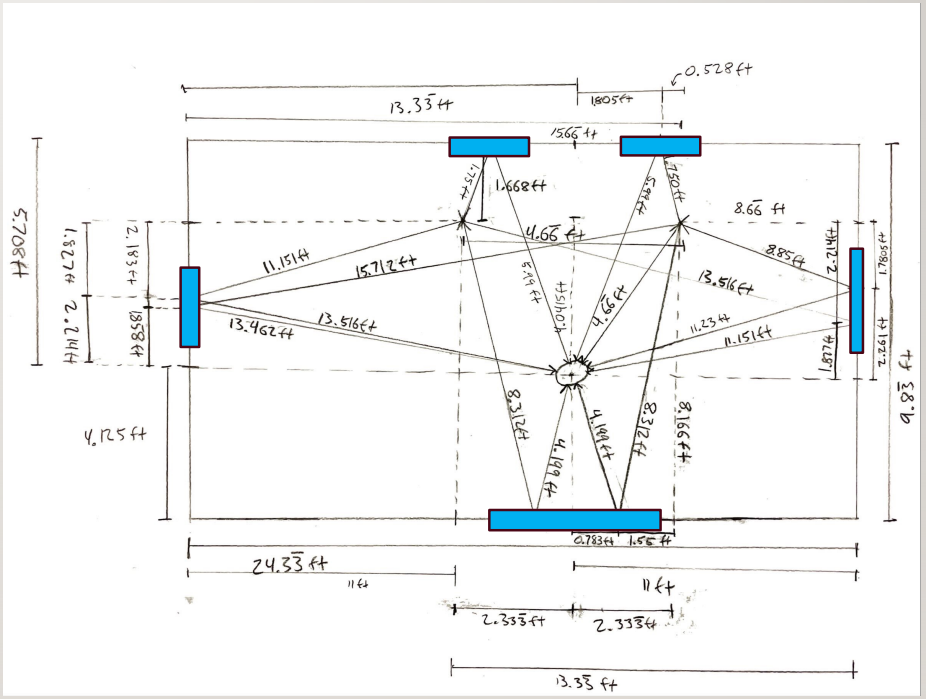
- All 30 RT_{60} graphs from REW, averaged
  - X axis – Frequency (Hz)
  - Y axis – Time (seconds)
- Unacceptable peak centered at 80Hz due to room modes, take it down as much as possible



Graph by Spencer Soule

POTENTIAL ROOM TREATMENT: DIFFUSION

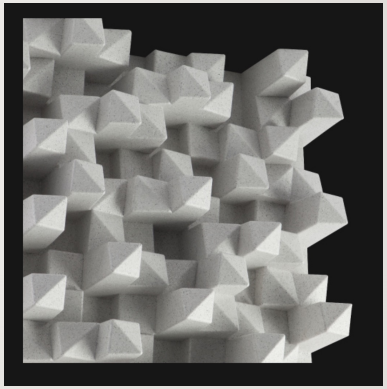
- Put diffusers at first reflection points in the room
  - Wall directly behind listener
  - No need to treat ceiling reflection, as it is inaudible
  - Floor reflection impractical to treat, so we will ignore
  - Reflection happening right on the door on the right-hand side!
    - Put diffusion panel on the door

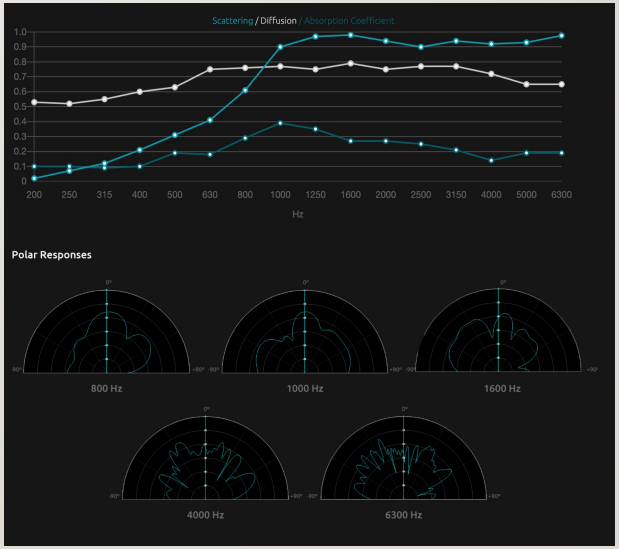


POTENTIAL ROOM TREATMENT: DIFFUSION

- Myron E Diffuser - Artnovion
  - 1'11½" x 1'11½"
  - 630Hz to 6300Hz
  - 3 for the back wall, one for each side wall, two for front wall
  - 7 in total

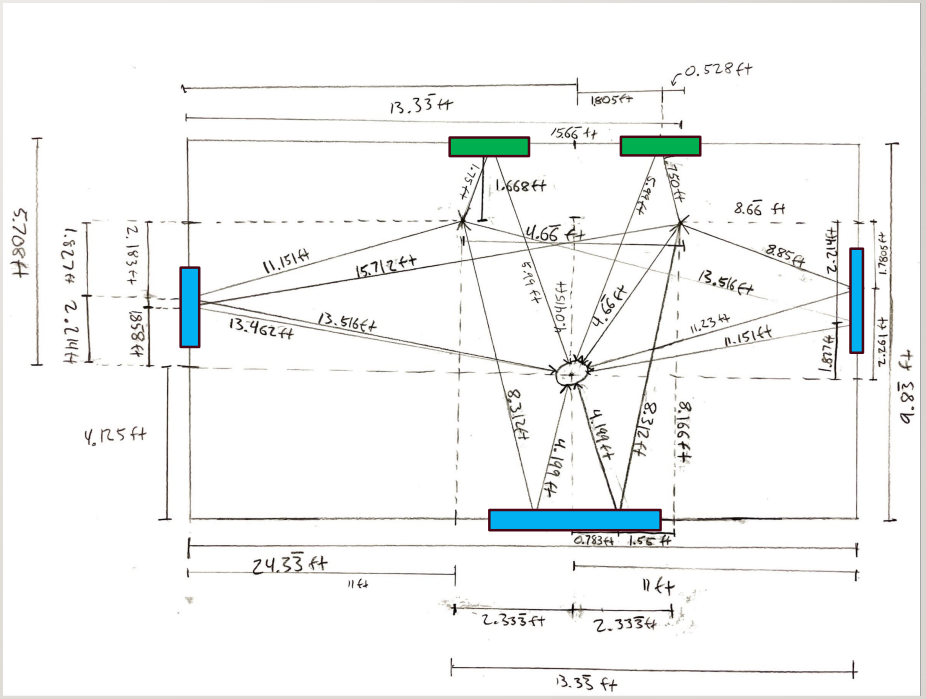
https://www.artnovion.com/product-categories/4-diffusion/products/10-myron-e-diffuser





POTENTIAL ROOM TREATMENT: ABSORPTION

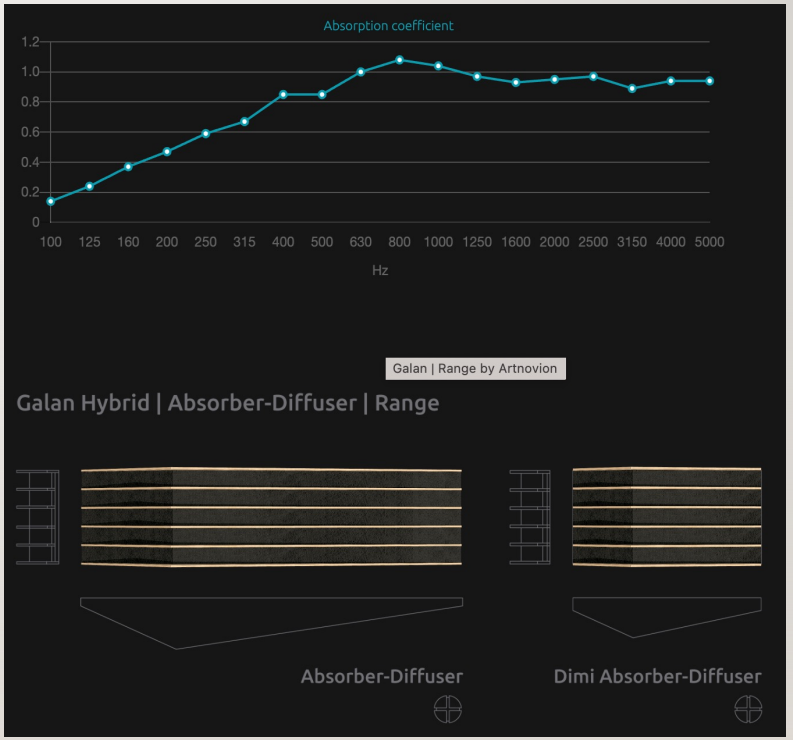
- No traditional absorbers needed
  - Most seem to target the 500Hz-2kHz range, which is not an issue for this room
  - Potentially use two absorbers not to change characteristic of the room, but to reduce energy in reflection off wall behind speaker
    - Alternative to diffusers in these positions
    - Reduce cone filtering



POTENTIAL ROOM TREATMENT: HYBRID

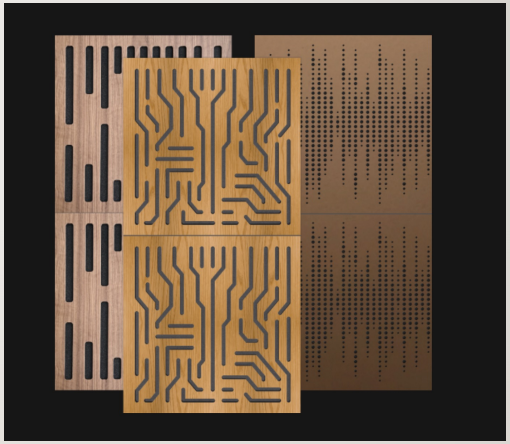
- Galan Dimi Hybrid Absorber-Diffuser
  - 3’11” x 1’
  - 2 for the front wall for first reflections

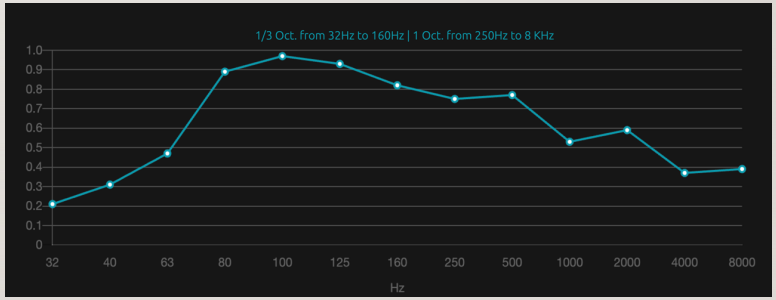
https://www.artnovion.com/product-categories/1-absorption/products/1062-galan-range



POTENTIAL ROOM TREATMENT: BASS TRAPS

- Bass Traps are most important in our case
  - Meant to target 80Hz reverb time in our room
  - Peak absorption at 90Hz, nearly the same at 80Hz
  - Gradual roll-off will help us reduce the bass rise as well
    - Hit two stones with one bird!
  - 3’ 11” tall, so buy two units per corner
    - 8 units in total
    - Re-do room measurements to see how they interact with modes





https://www.artnovion.com/product-categories/3-bass-trap/products/392-bass-trap-wall-range

DIMENSIONS FOR NEW RT_{60} CALCULATION

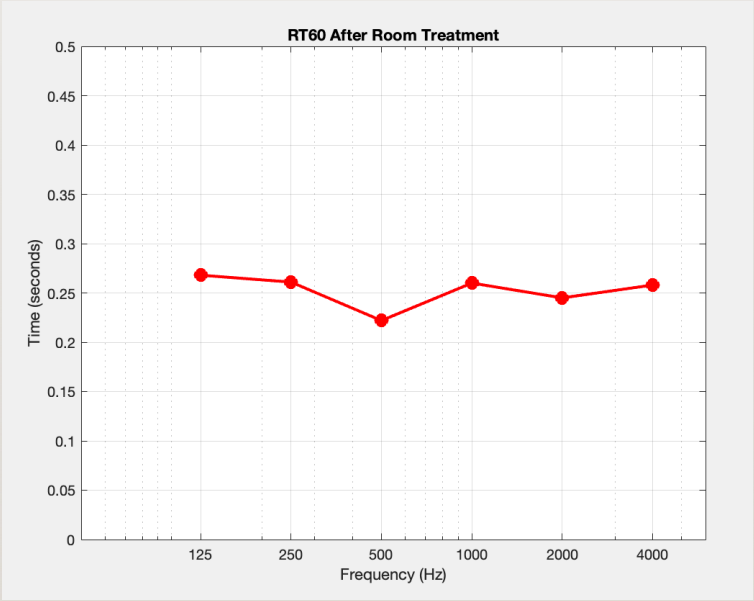
- 5 diffusers: 19 ft^2 total
- 2 absorber/diffuser hybrid: 3.8 ft^2
- Bass Traps: 61 ft^2
- Doors: 72 ft^2 – 3.8 ft^2 = 68.2 (one door with diffuser)
- TV: 17.42 ft^2
- Carpet: 239.28 ft^2
- Ceiling Material: 239.28 ft^2
- Wall material: 1065.1 ft^2 – 19 – 3.8 – 61 – (72 – 3.8) – 17.42 – 239.28 – 239.28 = 417 ft^2
- No more whiteboard!

DIMENSIONS FOR NEW RT_{60} CALCULATION

Material	Sq ft.	125Hz	125Hz	250Hz	250Hz	500Hz	500Hz	1kHz	1kHz	2kHz	2kHz	4kHz	4kHz
		α	Sα	α	Sα	α	Sα	α	Sα	α	Sα	α	Sα
Diffusers	19	0.1	1.9	0.1	1.9	0.19	3.61	0.39	7.41	0.27	5.13	0.14	2.66
Hybrid	3.8	0.24	9.12	0.59	2.24	0.85	3.23	1.08	4.10	0.95	3.61	0.94	3.57
Bass Trap	61	0.93	56.73	0.75	45.75	0.77	46.97	0.53	32.33	0.59	35.99	0.37	22.57
Metal Doors	68.2	0.2	13.64	0.2	13.64	0.15	10.23	0.05	3.41	0.05	3.41	0.05	3.41
TV	17.42	0.2	3.48	0.2	3.48	0.2	3.48	0.35	6.10	0.35	6.10	0.35	6.10
Carpet	239.28	0.27	64.61	0.26	62.21	0.52	124.43	0.43	102.89	0.51	122.03	0.58	138.78
Mineral Wool Tiles	239.28	0.42	100.50	0.72	172.28	0.83	198.60	0.88	210.57	0.89	212.96	0.80	191.42
Plaster on studs	417	0.3	125.1	0.2	83.4	0.15	62.55	0.05	20.85	0.05	20.85	0.05	20.85
Total absorption (sabins)			375.08		384.9		453.1		387.66		410.08		389.36
RT_{60} (seconds)			0.268		0.261		0.222		0.260		0.245		0.258

$$RT_{60} = \frac{0.049V}{A}$$

RT_{60} AFTER ROOM TREATMENT



THANK YOU FOR LISTENING!

Questions?