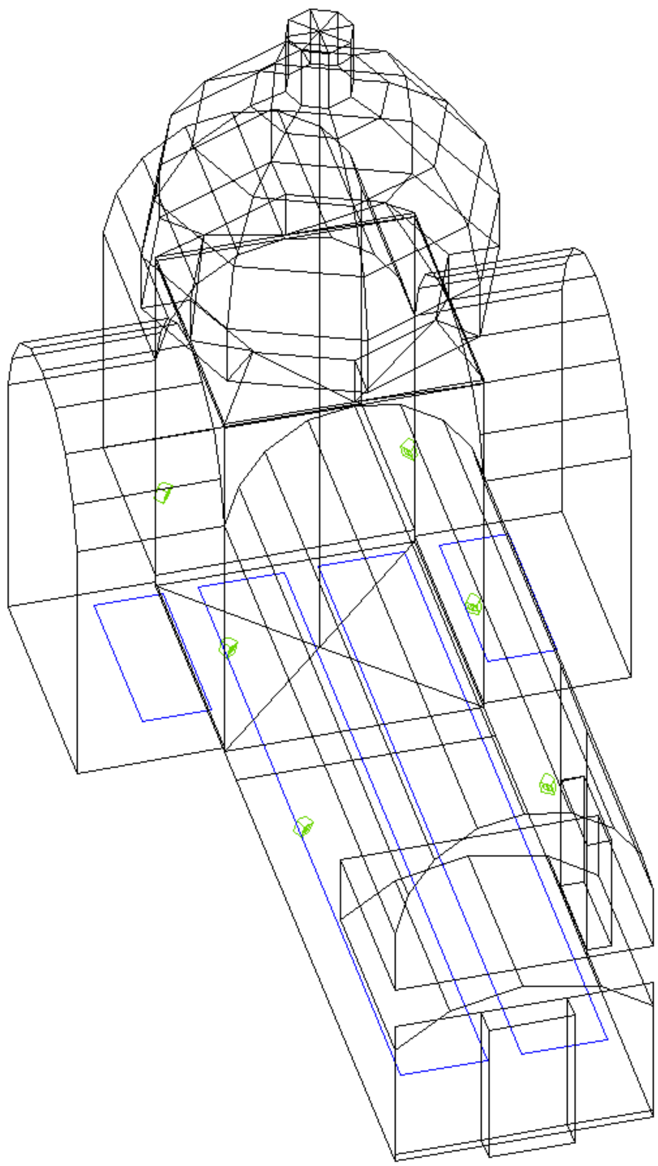
San Juan de Dios Sound System
Part 1
Acoustic Analysis



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Preface

San Juan de Dios in San Miguel de Allende is a colonial era church build around 1760. Like almost all such structures in Mexico it has terrible acoustic characteristics. The interior structure is almost entirely plaster or stone having virtually no acoustic absorption. The original sound system used non-directive loudspeakers. This caused the sound to be echoed and reverberated through the inside of the church making speech extremely difficult to understand.

This report describes the analyses, tests and changes that were made to improve the sound system.

Two software programs were used.

Ulysses is an acoustic simulation program where the interior of the church is modeled in three dimensions. The absorptive properties of all the interior surfaces can be independently specified. A data base is provided that includes the acoustic absorption values of hundreds of common construction materials. A speaker system can then be modeled, and each speaker independently located and aimed. The directional and frequency properties of each speaker are based on manufacturer's data measured in an anechoic (non-reflective) chamber and provided in another data base. The audience seating area can be defined, and sound calculations displayed over that area. These include the total sound level, the direct sound level, the difference between direct and reverberant sound levels and other properties, all of which vary with the frequency. Using this program, alternative wall treatments and speaker systems can be evaluated rapidly and without incurring any cost. Like any modeling program, however, it must be verified by test.

The second program used is called Smaart8, and it is an acoustic test data analysis program. It provides an excitation source that is fed into the sound system, and data is collected through a measurement microphone. The program then processes both data streams to calculate direct and reflected sound levels and many other acoustic properties, all of which again vary with the frequency. Smaart8's results can be used to update and verify the Ulysses model and to optimize the performance of the sound system through equalization, level adjustment, delay adjustment, etc.

The report is divided into parts. Part 1 documents the physical dimensions of the interior of the church and the development of the Ulysses acoustic model. Part 1 also analyzes the predicted performance of the existing sound system and the improvements possible using alterative loudspeaker configurations and wall treatments. Part 2 describes the implementation of the new sound system for the English Mass where the audience is limited to the front half of the church. It presents test data that allows comparison between the original system and the new one. It also compares predicted and measured data to confirm the acoustic model used in Ulysses. Changes required to expand the system to improve the performance in the back half of the church used for the Spanish Mass are also discussed. Part 3 explains a modification to the way clarity and direct sound is calculated and reanalyzes the measurements made in Part 2. It then presents four changes to the sound system to improve the performance at the back – replacement of the original loudspeakers with two additional HS1200's, delay compensation, level adjustment, and acoustic treatment of the rear wall. It also contains an expanded Summary and Conclusions that covers the results from all 3 parts.

This project has been successful based on both measured results and the opinions expressed by the church attendees. It is hoped that these results may be useful in making sound system improvements to other similar churches in Mexico.

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Introduction

This report evaluates the acoustic performance of San Juan de Dios church using the model described in Appendix A using the Ulysses acoustic analysis program.

The existing sound system is first described with its measured and calculated performance. Succeeding sections describe alternative sound system designs and their calculated performance in an empty church. Then the best of the alternate sound system designs is analyzed with different audiences (Spanish and English Masses) which make a significant difference. The new amplifier and wiring required is presented. Also discussed are the addition of sound absorption panels (which are not recommended at this time). Finally, the predicted performance improvement is summarized and a cost is estimated for the recommended system.

Current Sound System – 2 CS212's at Front, 4 KR1's at Center & Back

Creation of the 3-dimensional model of the church interior includes all interior walls, barrel ceilings over the nave, sanctuary and transepts, and a dome over the crossing. The nomenclature used for these areas is summarized in Figure 1. The notation [SJD33] in the caption refers to the specific Ulysses file that corresponds to the model shown.

Acoustic properties used are:

- Walls and ceilings were initially modeled as *Plaster – Gypsum or Lime over Masonry*. However, this was changed to *10% Absorption Linear* after measuring the reverberation time of the interior as discussed below.
- The two doors are modeled as *Doors Solid Wood Panel*
- The floor in the sanctuary is modeled as *Carpet ¼" Ply Glued Down*
- The floors in the crossing, nave and transepts are modeled as *Seating Hard Empty*

There are three seating areas shown by blue rectangles in Figure 1. The nave seating is along either side of a center aisle which begins at the center of the crossing, directly below the center of the dome. Seating is used for calculating and displaying the sound measurements in the program. By default, it is located 1.2 meters above the floor which corresponds to the normal head height of a seated person. No seating is shown in the left transept but there is seating in the right transept as shown.

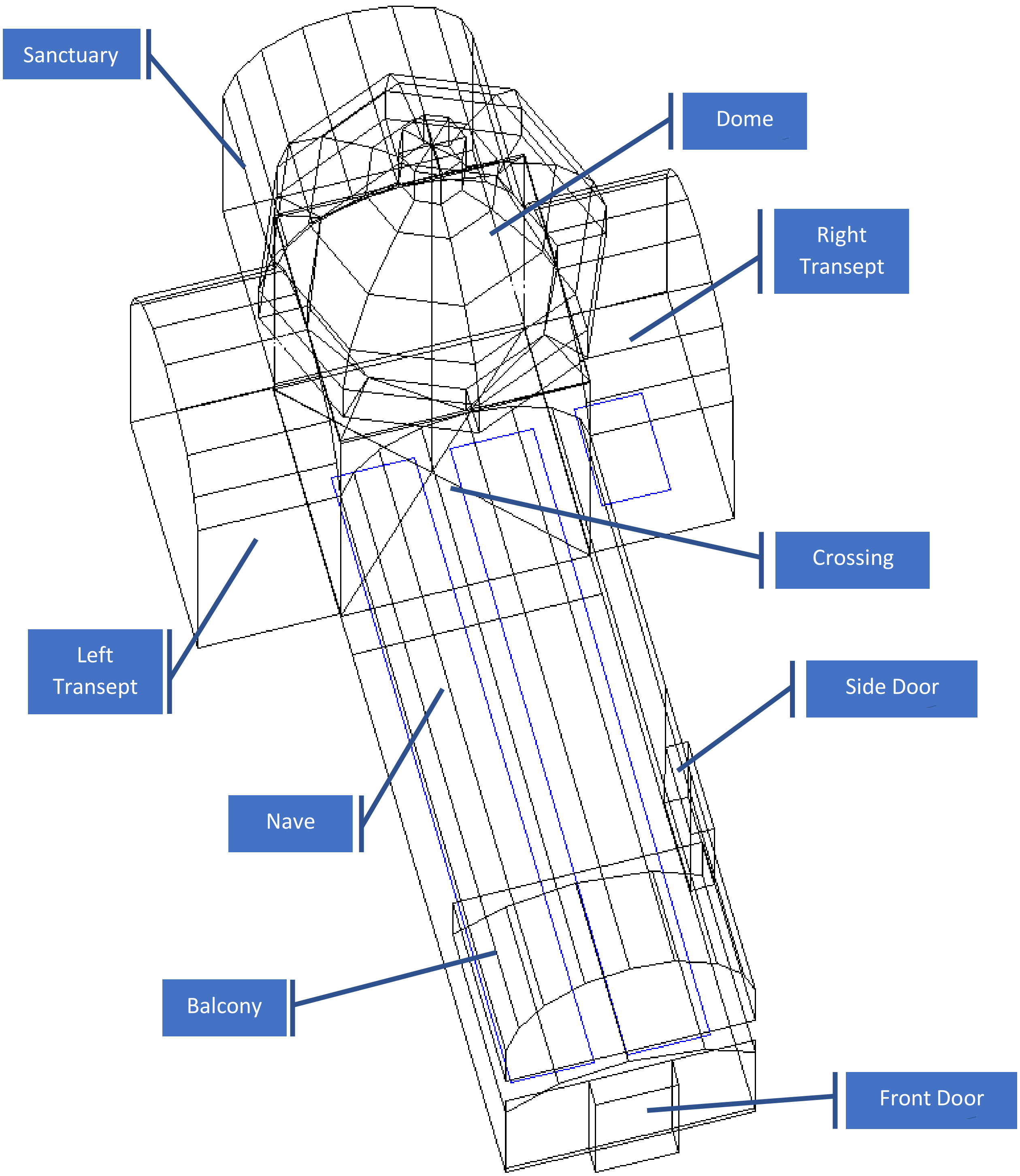

Figure 1 Three-Dimensional Model of Church Interior (SJD33)

The original loudspeaker configuration that was present in the church (and is described in Appendix A model SJD14) performed so poorly that no sensible measurement data could be obtained for it. The speakers were rearranged and re-aimed as shown in Figure 2.

The existing sound system comprises four Celestion model KR1-T box style loudspeakers along the sides of the nave and two Steren model CS212 loudspeakers mounted on the columns at the front of the crossing. All six speakers contain line level transformers which are connected to a single 70V output from the Radio Shack model MPA125 Public Address Amplifier. The Celestion speakers are approximately 30 years old and the Radio Shack amplifier is about 20 years old. The Steren speakers are only about 5 years old.

The Steren speakers are rated at 25 watts peak each and the Celestions at 75 watts peak. Average power is rated at half of that. However, the taps used are 12 watts for the Sterens and 8 watts for the Celestions, so the total load is about 75 watts. There is also an outside horn loudspeaker that is normally disconnected. The amplifier is rated at 100 watts.

Very little is known about the characteristics of these loudspeakers. The Celestion KR1T contains a 5-3/4 inch speaker with a smaller tweeter mounted coaxially. For the model, I used a Tannoy V6 which is a similarly sized speaker that is in the Ulysses data base. The V6 has a beam width of +/- 60 degrees in both vertical and horizontal planes. (This is normally referred to as a 120-degree beam width).

The Steren is what is known as a column or line array loudspeaker. It consists of several smaller loudspeakers arranged in a line such that the vertical beam width is reduced (at high frequency) and the horizontal beam width is the same as the individual loudspeakers. Since no beam width is specified, a generic line array speaker provided by Ulysses was used.

The loudspeakers are mounted in the locations shown in Figure 2 and are aimed as indicated by the magenta lines. The Sterens are located at a height of 3.5 meters (about 12 feet) and the Celestions are 2.5 meters (about 8 feet) above the floor.

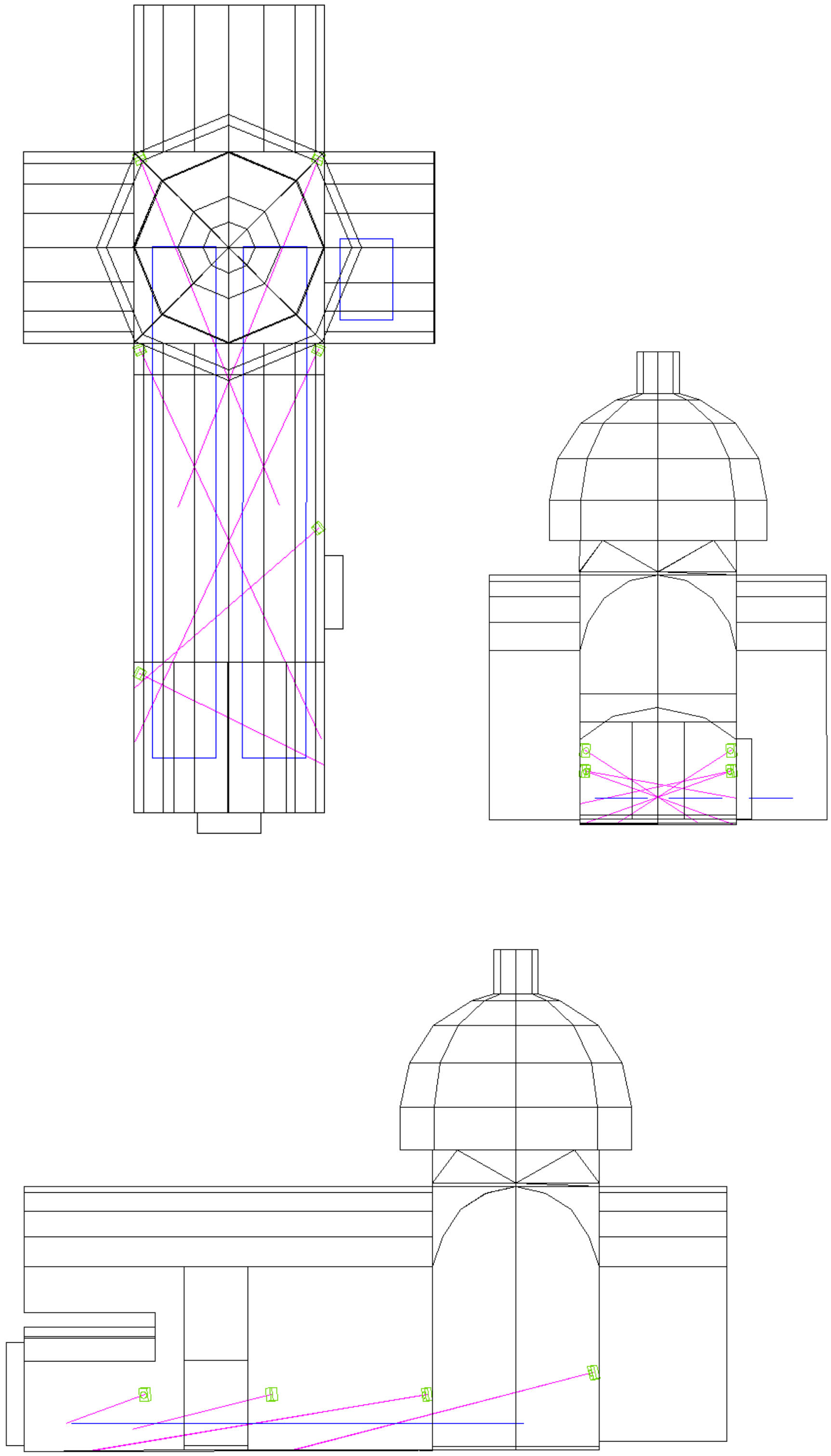

Figure 2 Original Sound System Showing Speaker Aim Points (SJD34)

The first calculation to make is the reverberation time. This is a property of the building itself and is independent of the speaker system. It depends on the total volume, the surface area and the acoustic absorption of the various surfaces. Ulysses calculates the interior volume to be 3773 cubic meters and the surface area to be 1967 square meters. The reverberation time with the walls and ceilings plastered was 5.5 seconds at 1 KHz. However, when measured by SMAART8, this was only 2.9 seconds. The reverberation time varies with frequency, so the surface absorption should be modified to match the measurements across the audio frequency range. A number of materials were substituted for the plaster including brick, concrete block, etc. but it was found that simply using an absorption of 10% at all frequencies provided the best match. See Table 1. (Note that the plywood semicircular structure mentioned in Appendix A for the North wall was also replaced with the 10% absorption).

Table 1 Calculated and Measured Reverberation Time RT60

Frequency	250	500	1KHz	2KHz	4KHz	8KHz
Calculated	3.2	3.1	2.9	2.6	1.8	0.9
Measured	4.5	3.4	2.9	2.5	2.2	1.5

The measured data above is the average of measurements made in the center aisle at rows 1, 6, 12 and 18 using only the front two loudspeakers to excite the room. The agreement is pretty good, and from this point forward 10% absorption was used for the walls and ceilings.

The reverberation time known as RT60 is the time required for a loud sound to decrease 60 dB. (The decibel or dB is a logarithmic measurement of intensity or power). RT60 was originally measured by striking a note with an organ then measuring the time for the reverberation to die out. The human ear has a dynamic range of about 60 dB (1000 to 1 intensity), so it was possible to do this using a stopwatch.

The preferred reverberation time depends on the room size and type of material (speech or music) being presented. For speech only, 0.4 to 0.5 seconds is best in smaller rooms and 0.8 to 1.2 seconds is good for larger rooms. For music, the preferred range is from 1.8 to 3 seconds. The recommended value for a church is between 1 and 2.5 seconds. So, San Juan de Dios is at the upper end of this range - poor for speech but good for music. Remember, however, that this is for empty seating. If all the seats are full, the absorption will increase and RT60 will decrease. Wall treatment can help also. These will be discussed later, but the seating will remain empty for evaluating (and measuring) alternative sound systems in the following sections.

Intelligibility of sound, especially speech, depends on receiving a good direct sound compared to the reflected or reverberant sound. Early reflections, within the first 35 msec or so of the direct sound, are actually helpful. Later reflections - certainly anything greater than 95 msec - can destroy speech intelligibility. Unless the speaker talks very slowly, the reflections or echoes from one syllable will interfere with the direct sound of the next one and make comprehension difficult. Improving the ratio of direct to reflected sound can be accomplished by reducing the reflections (RT60) or by designing a sound system that provide a uniform direct sound field where it is wanted (the listening areas) and minimizing the sound field elsewhere that simply adds to the reverberation. This is why using highly directive, properly aimed loudspeakers is important. It is also why using more speakers, located closer to the audience is beneficial.

Ulysses calculates the direct sound pressure level (Ld) over the listening area and the ratio of the direct to reflected sound pressure (Ld-Lr) in addition to many other acoustic characteristics. Ld is the sound level that arrives soonest. It includes both initial sound and the first reflection received. This first reflection is generally the floor bounce, and it arrives very soon after the initial sound. The reflected sound level, Lr, includes all echoes and reverberations that occur afterward. (The ratio of direct to reflected sound is listed as Ld-Lr because it is given in dB where a ratio becomes a subtraction).

As a general rule, the variation in the direct sound (ΔLd) is considered good if it is less than 3 dB, fair if it is between 3 and 6 dB and poor if it is greater than 6 dB. The direct to reflected sound level is considered good if it greater than +3 dB, fair if it is between -3 and +3 dB and poor if it is less than -3 dB. These are summarized in Table 2 below with the color coding that will be used to make comparison easier.

Table 2 Acoustic Performance Criteria

Acoustic Performance	Good	Fair	Poor
ΔLd (dB)	<3	3 to 6	>6
Ld-Lr (dB)	>+3	-3 to +3	<-3

To verify the model, the direct sound field and the direct to reflected sound ratio were calculated and measured with just the front two speakers energized. In these tables, the measured Ld was arbitrarily increased a fixed amount at all locations so as to compare it more closely to the Ulysses calculation. Remember that the absolute value of Ld is not so important as the variation over the listening area since it can always be adjusted with the volume control. The comparison between measurement and model is listed in Table 3 and Table 4.

Table 3 Measured and Calculated Ld, Current Sound System, Only Front Speakers On

Row	Measurement			Calculation		
	Left	Center	Right	Left	Center	Right
1	97.2	98.9	100.5	104.5	102.5	103.9
6	101.2	103.2	100.3	98.7	101.5	98.5
12	95.4	94.2	90.7	96.2	96.0	95.5
18	86.4	86.4	87.8	92.7	92.2	92.7

Table 4 Measured and Calculated (Ld – Lr), Current Sound System, Front Speakers On

Row	Measurement			Calculation		
	Left	Center	Right	Left	Center	Right
1	1.9	3.0	1.3	1.5	-0.9	0.7
6	3.5	4.4	2.0	-4.7	-0.9	-4.9
12	-0.4	-1.2	-1.9	-6.6	-7.1	-7.6
18	-4.1	-3.3	-3.3	-10.1	-11.6	-10.2

The model agrees with the measured data within about 6 dB which is not great but is probably due to the difference in the directional characteristics of the actual and modeled loudspeakers.

A second check is to compare the direct sound and direct to reflected sound levels with all speakers turned on. This comparison is listed in Table 5 and Table 6.

Table 5 Measured and Calculated Ld, Current Sound System, All Speakers On

Row	Measurement	Calculation

	Left	Center	Right	Left	Center	Right
1	95.5	101.5	100.7	104.5	102.4	103.9
6	109.9	103.2	112.7	106.3	102.7	106.3
12	96.3	103.1	97.0	99.4	102.8	105.8
18	98.4	97.7	93.6	102.2	99.7	97.4

Table 6 Measured and Calculated (Ld – Lr), Current Sound System, Front Speakers On

Row	Measurement			Calculation		
	Left	Center	Right	Left	Center	Right
1	-0.4	-0.1	-2.0	0.8	-1.7	-0.1
6	6.5	4.4	7.3	0.5	-1.4	0.4
12	-1.0	-0.1	-1.0	-6.0	-2.4	0.1
18	-5.3	-2.6	-3.5	-4.9	-5.5	-7.5

Again, the model agrees with the measurements within about 6 dB.

The above tables are for specific locations in the nave. A better idea of the best and worst case Ld and Ld-Lr are shown in Figure 3. These are Ulysses predictions, not measurements.

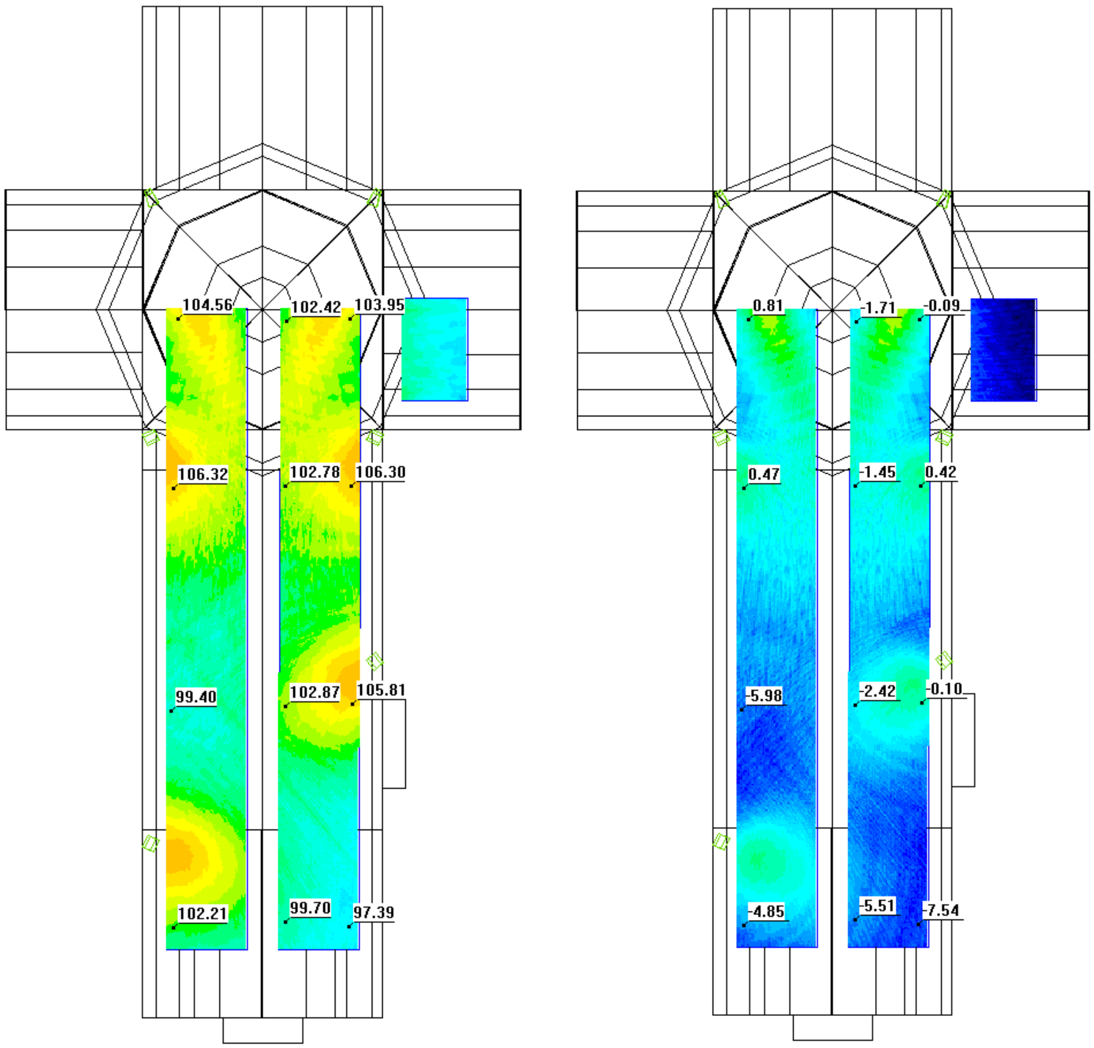

Figure 3 Current Sound System, Ld (left) and Ld-Lr (right)

Calculated values of the Ld variation and worse case Ld-Lr are 8.9 and -7.6 dB respectively (both poor).

In this section, and in the following, the performance is calculated only for the listening areas in the nave and crossing. The small seating area in the right transept will be considered separately. (It may be covered with a separate loudspeaker if the main speaker systems do not provide sufficient coverage).

Figure 4 shows the Celestion and Steren loudspeakers along with the Tannoy speaker used to model the Celestion.

Figure 4 Celestion KR1 (left), Steren CS-212 (center) and Tannoy V6 (right)

Single Overhead HX-5 Line Array Loudspeaker

The array shown in Figure 5 is a smaller version of the HX-7 which is widely used in larger churches. It consists of 4 separate modules that can be adjusted so as to produce a vertical beam width of 60, 45, 30 or 15 degrees. The horizontal beam width is 100 degrees. Cost is about $538 but that does not include the transformer ($136) or mounting bracket ($60). Ulysses includes models for this speaker at each of the adjustment angles.

Figure 5 TOA HX-5 Array Speaker

The best location for mounting this speaker is along the center line at the front of the crossing. Both the mounting height and the beam width angle can be varied. Figure 6 summarizes the results.

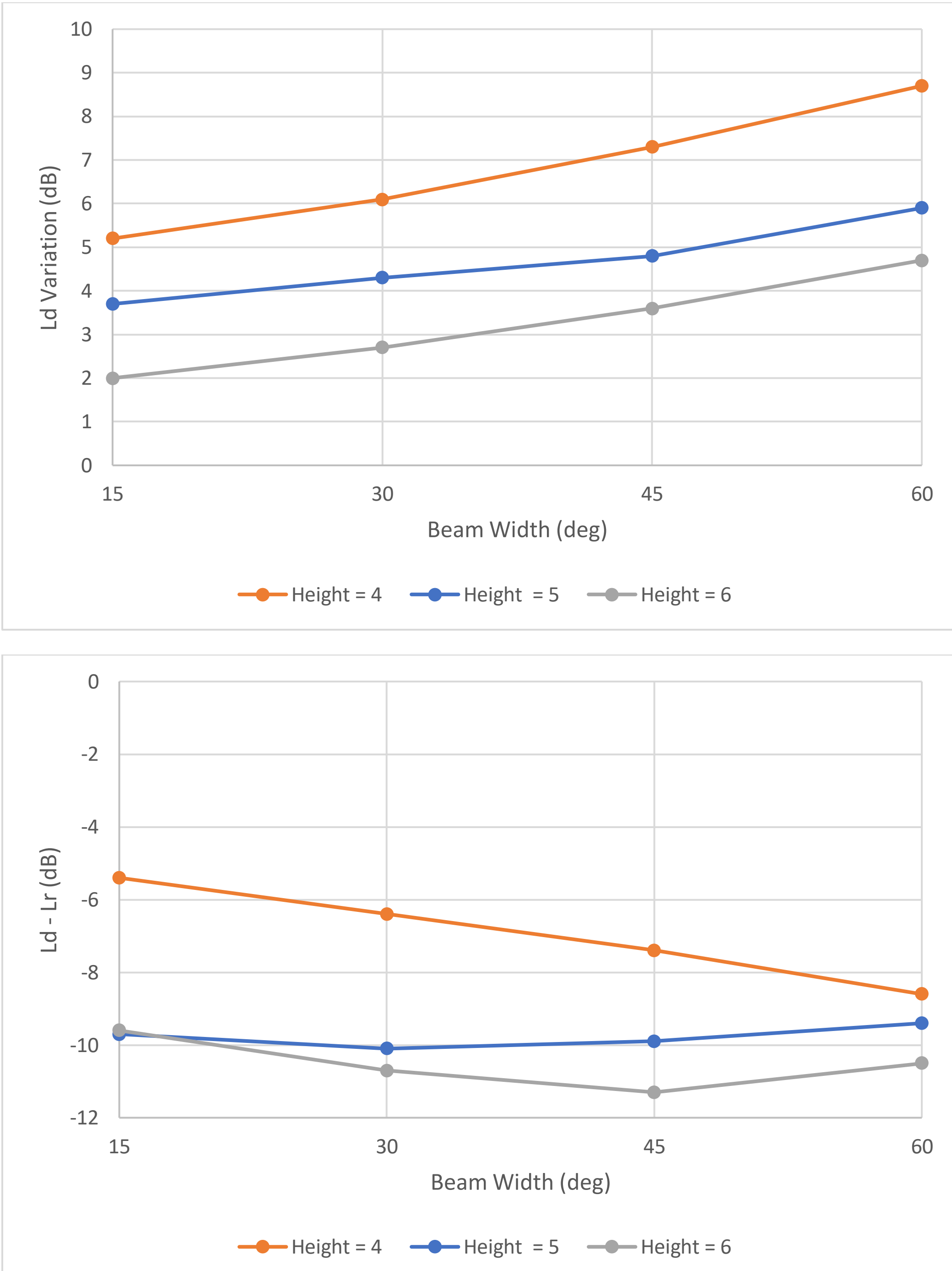

Figure 6 ΔLd (top) and Ld-Lr (bottom) for a single HS-5 line array mounted at front of crossing

The results shown above indicate the lowest height and narrowest beam width produce the best (largest) Ld-Lr. However, any height below 6 m will interfere with the visual line of sight to the sanctuary and is objectionable for that reason. Figure 7 shows the geometry and Figure 8 shows the results for the 6 m height with 15 deg beamwidth.

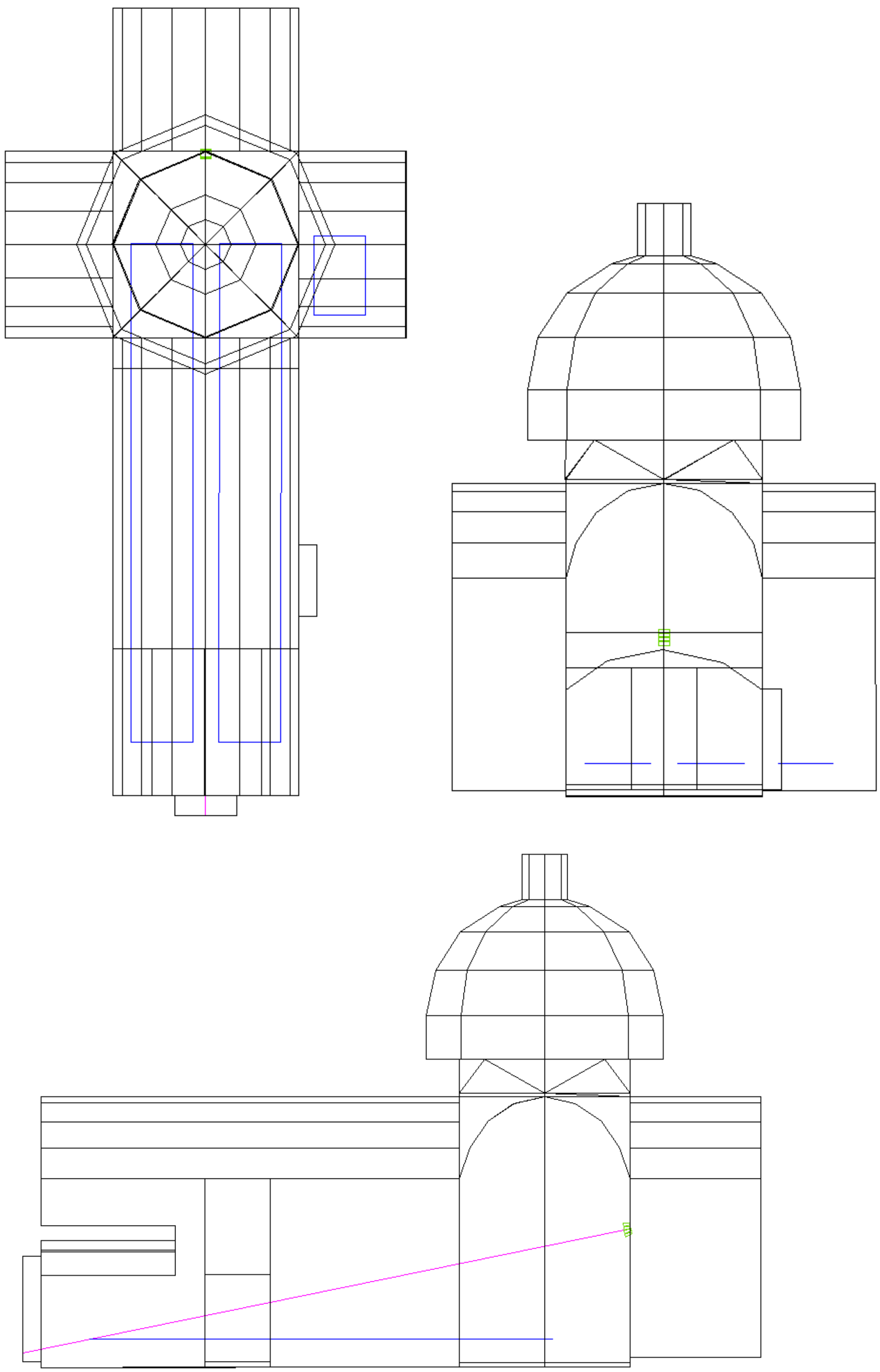

Figure 7 Single HX-5 with 15 deg beam width mounted at front of crossing at 6 m height (SJD35)

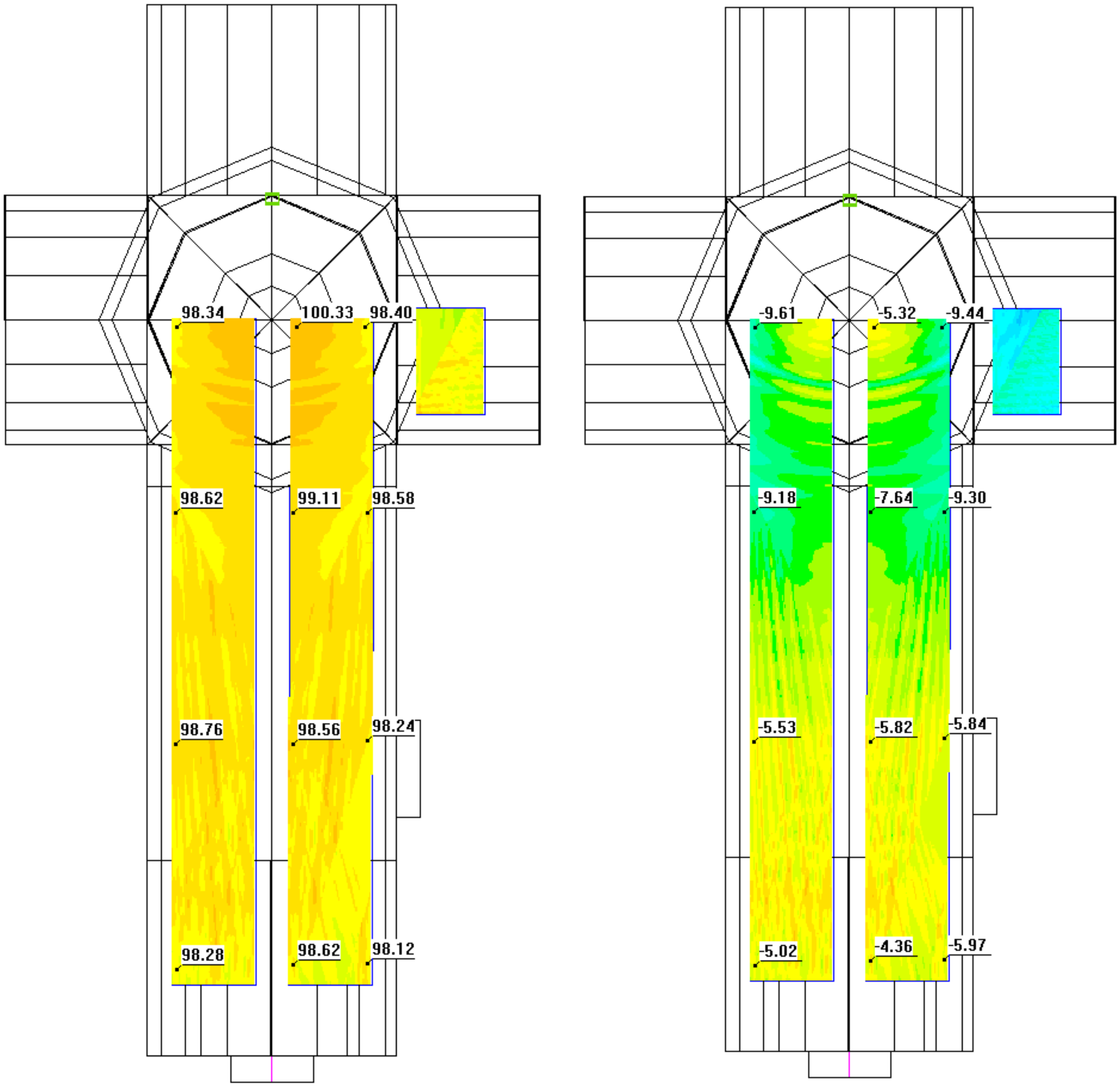

Figure 8 Single HX5 with 15 deg beam width mounted at 6 m high , Ld (left) and Ld-Lr (right)

Calculated values of the Ld variation and worse case Ld-Lr are 2.0 (good) and -9.6 dB (poor).

(2) HS1200 Front Speakers and (6) HS1200 Side Speakers

This configuration is a variation of one suggested by TOA who offers a free consultation for projects of this sort. Their arrangement used SR-H2S loudspeakers. The SR-H2S is a column line array with a 90 deg horizontal by 20 deg vertical pattern. Unfortunately, its directional properties are not included in the Ulysses data base. It costs about $677 with the accessory transformer and mounting bracket. Instead, I evaluated the HS1200 speaker which has a similar pattern and is in the data base. The HS1200 is called a coaxial speaker and consists of a 12-inch diameter woofer with a line array of (6) 1-inch tweeters mounted directly in front (coaxially). It has a pattern of 90 deg horizontal by 40 deg vertical. It has a built-in transformer and costs about $399 with a locally fabricated mounting bracket. See Figure 9.

Figure 9 TOA HS1200 Coaxial Array Loudspeaker

All eight speakers are mounted at a height of 2.5 m (8 ft) above the floor. I looked at higher mounting of the front speakers, but performance was worse. Lowering the height below 2.5 m is not a good idea because of head clearance.

Positioning of the speakers is based on dividing the listening area into more or less equal square areas, 4 on the left and 4 on the right. Each speaker is then located in the outside front corner of each square and aimed at the inside back corner (i.e., the center aisle). The speakers are aimed down to the height of the seated audience at this point. This works out to be 8 deg for the front speakers and 11 deg for the others.

The front two speakers are mounted to the columns at the front of the crossing. The nave speakers are mounted on the side walls at distances of 4.5, 10, and 15.5 m from the center of the crossing. This avoids the Cantera arches and the side door. Figure 10 shows the arrangement.

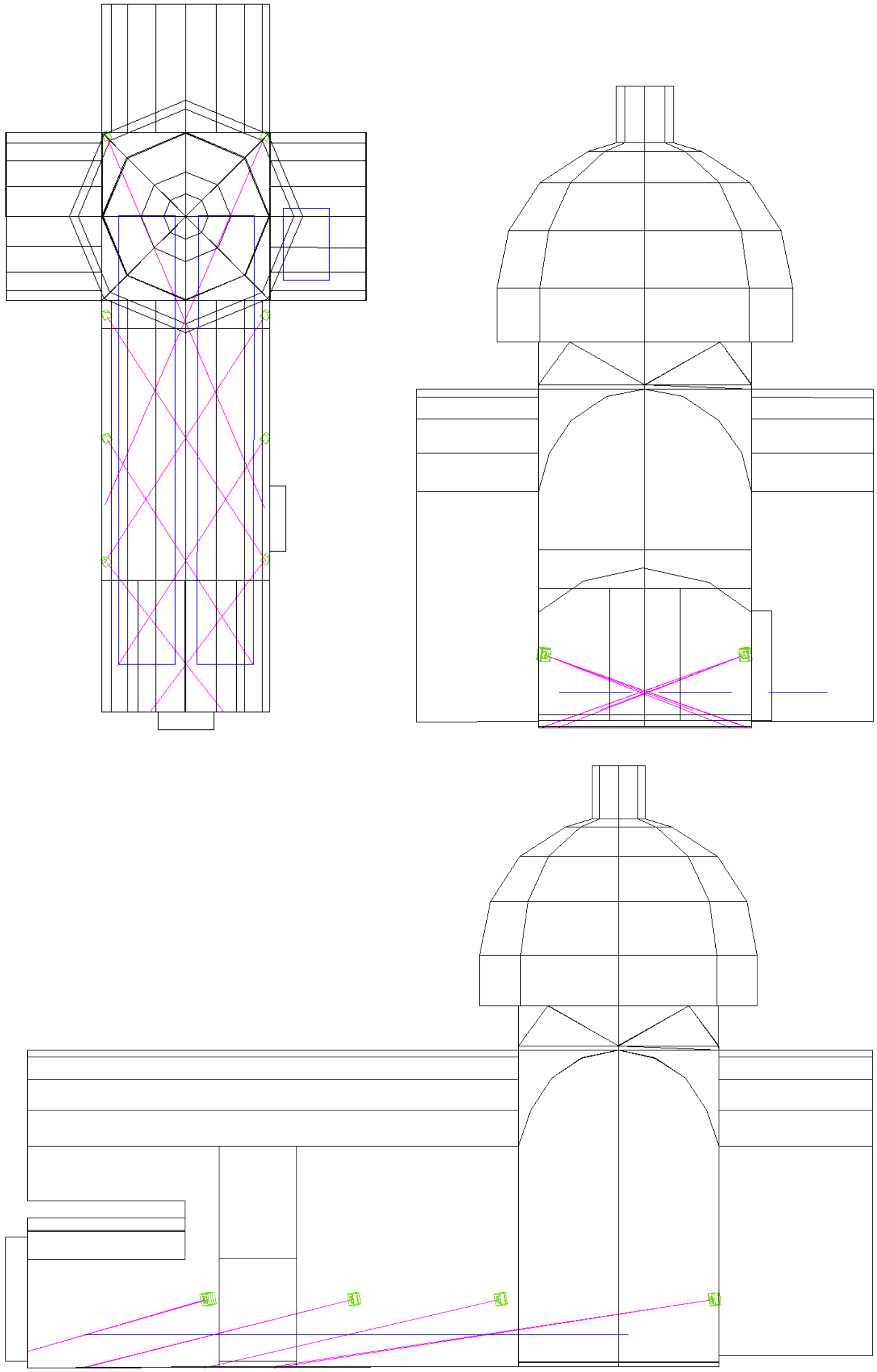

Figure 10 (2) HS1200 at front and (6) HS1200 along sides (SJD36)

The direct sound and direct to reflected sound levels are shown in Figure 11 below.

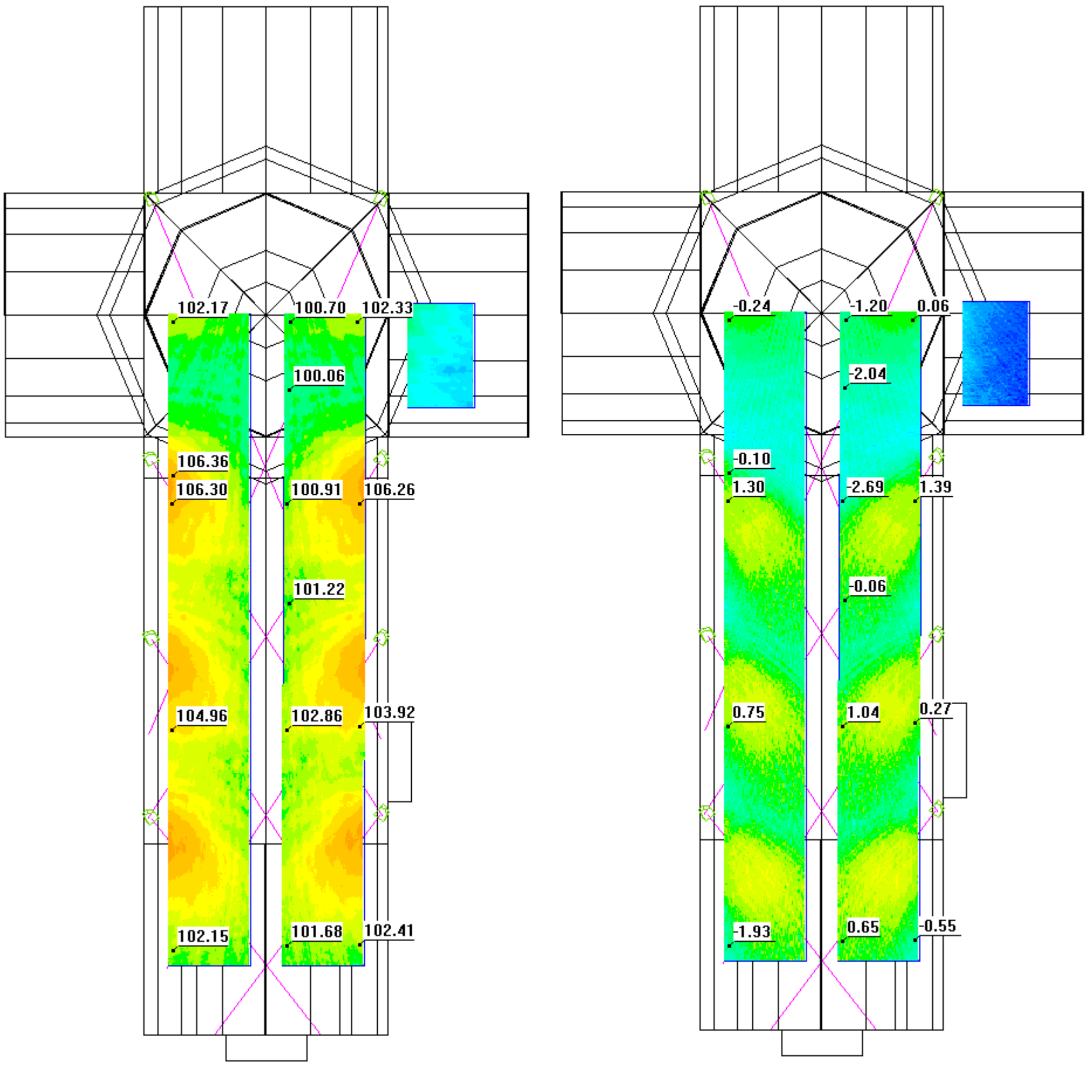

Figure 11 Ld (left) and Lr - Lr (right) for 2 front HS1200 and 6 side HS1200 speakers

The variation in direct sound (Ld) is 6.3 dB and the worst case direct to reflected sound (Ld-Lr) is -2.7 dB.

(8) HS1200 Side Speakers, Staggered

Here the same speaker complement is used but mounted along the sides of the crossing and nave in a staggered arrangement. The height is again 2.5 m (8-ft) but the speakers are aimed directly across the listening area left to right. The aim point is the far side of the listening area which works out to a tilt angle of 10 degrees. Note that the front most speaker will require a pole at the front of the right transept. See Figure 12.

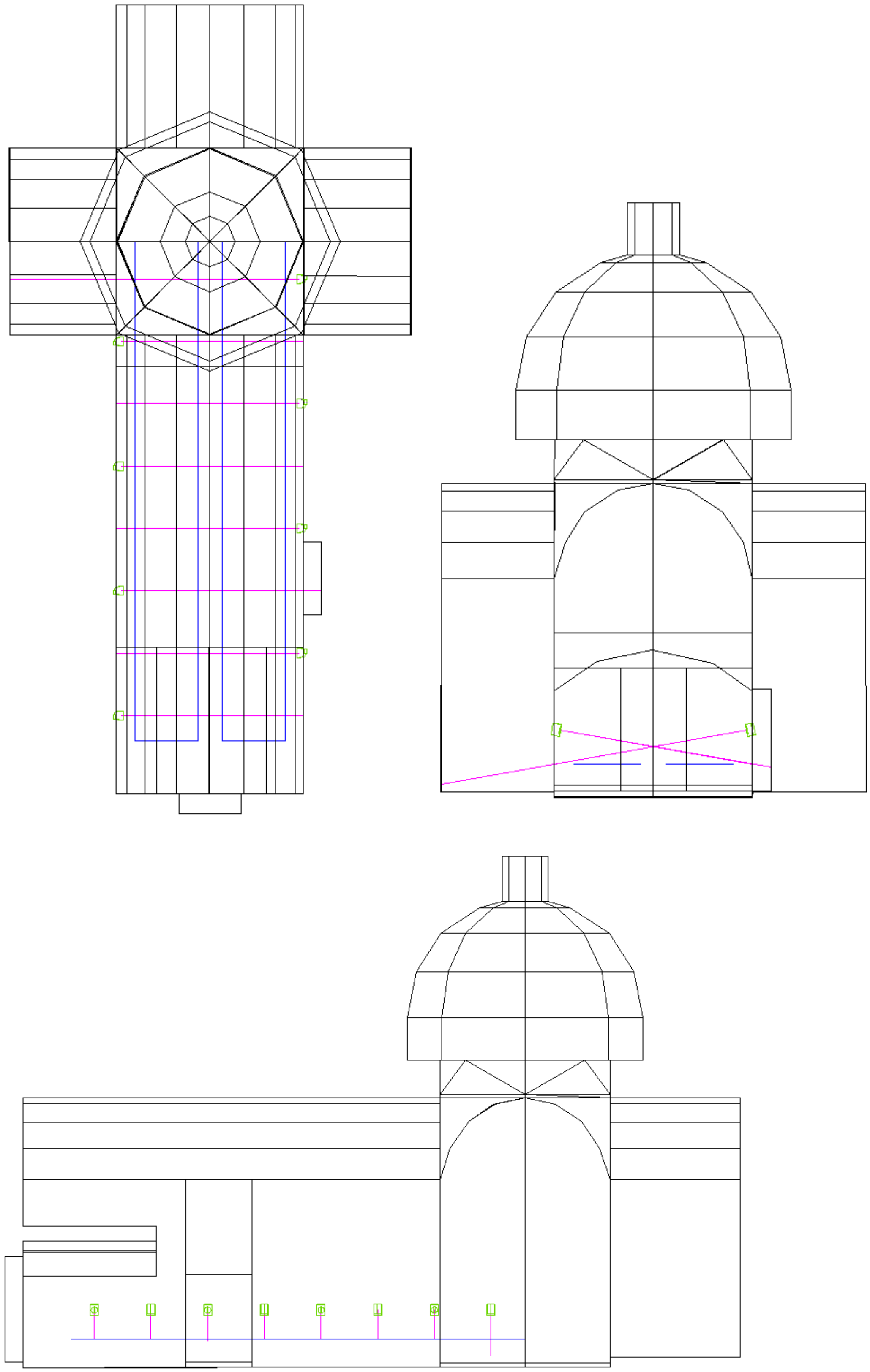

Figure 12(8) HS1200 speakers staggered along sides (SJD32)

The direct and direct to reflected sound level patterns are shown in Figure 13 below.

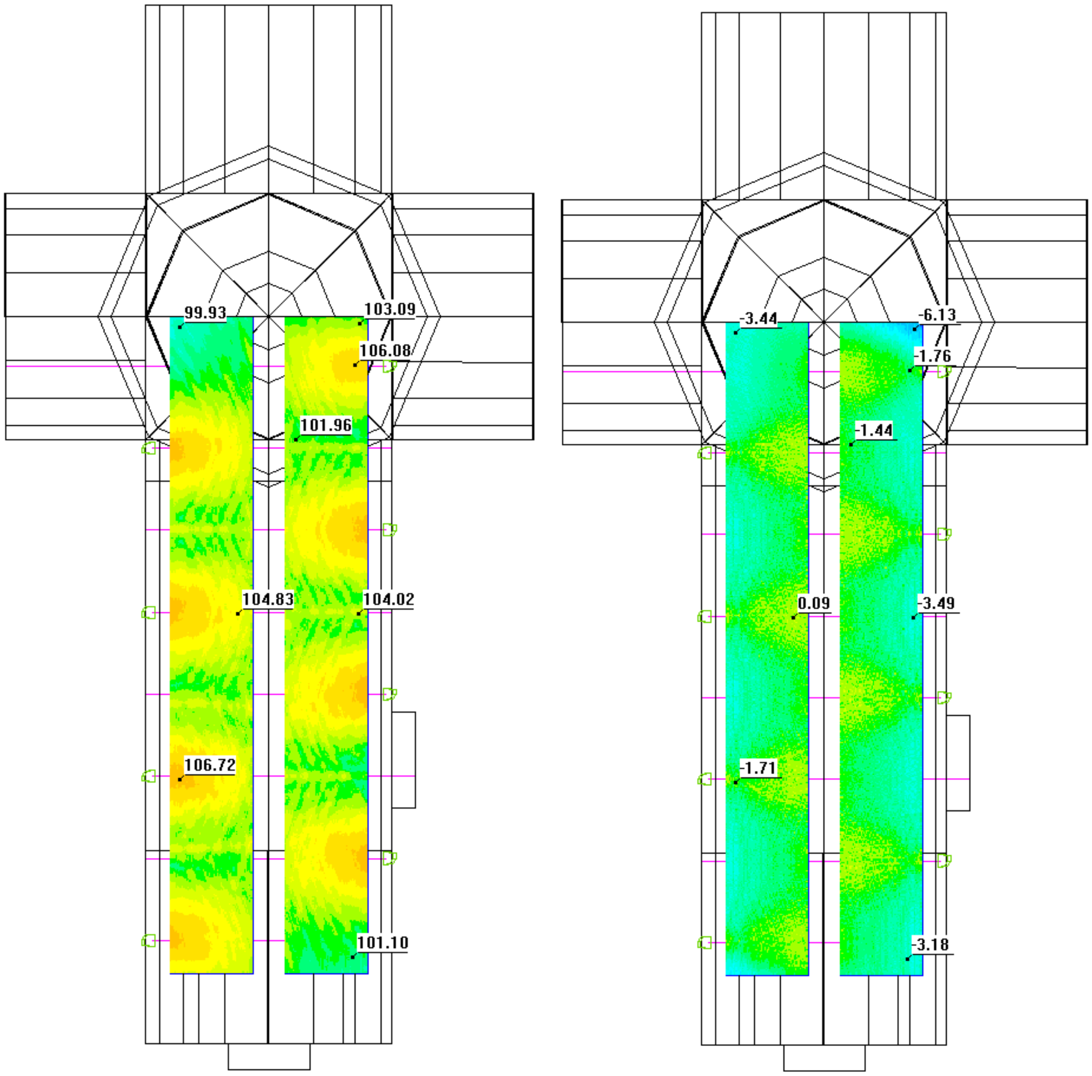

Figure 13 Ld (left) and Lr - Lr (right) for 8 staggered side HS1200 speakers

The variation in direct level (Ld) is 6.7 dB and the worst case direct to reflected level (Ld-Lr) is -3.5 dB excluding the one seat at the front right where it drops to -6.1 dB.

Right Transept Coverage

Table 7 summarizes the results so far in the crossing and nave seating areas.

Table 7 Performance in Crossing and Nave

Speaker Configuration	Direct Sound Variation	Direct to Reflected Sound (Worst Case)
(2) Front CS212 & (4) Side KR1 Speakers	8.9	-7.6
(1) Overhead HX5 Array	2.0	-9.6
(2) Front HS1200's & (6) Side HS1200's	6.3	-2.7
(8) Side Staggered HS1200's	6.7	-3.5

The overhead array provides the most uniform coverage but the worst direct to reflected sound. The two HS1200 systems provide nearly the same uniformity which while still rated poor is almost fair (<6 dB). Mounting them aimed toward the rear center as opposed to crosswise staggered provides the best direct to reflected sound. However, none of these systems were designed to cover the small listening area in the right transept.

If the front right column speaker in the third case above is re-aimed to include the right transept, we get Table 8.

Table 8 Performance of HS1200 System Including Transept

Pan angle of front right spkr	Ld variation incl right transept	Ld-Lr incl right transept
-113	10.4	-9.2
-100	8.8	-6.6
-90	7.5	-4.6

The first case in this table is the same one that provided the good Ld-Lr of -2.7 in the nave/crossing area alone. By re-aiming this speaker the right transept performance is improved but at a substantial loss to the crossing area. A better approach is to add an additional speaker to cover the transept listening area. A 9th HS1200 speaker is mounted at 2.5 m high along the outside wall of the transept and aimed as shown in Figure 14 below. The tilt angle of this speaker is 20 deg.

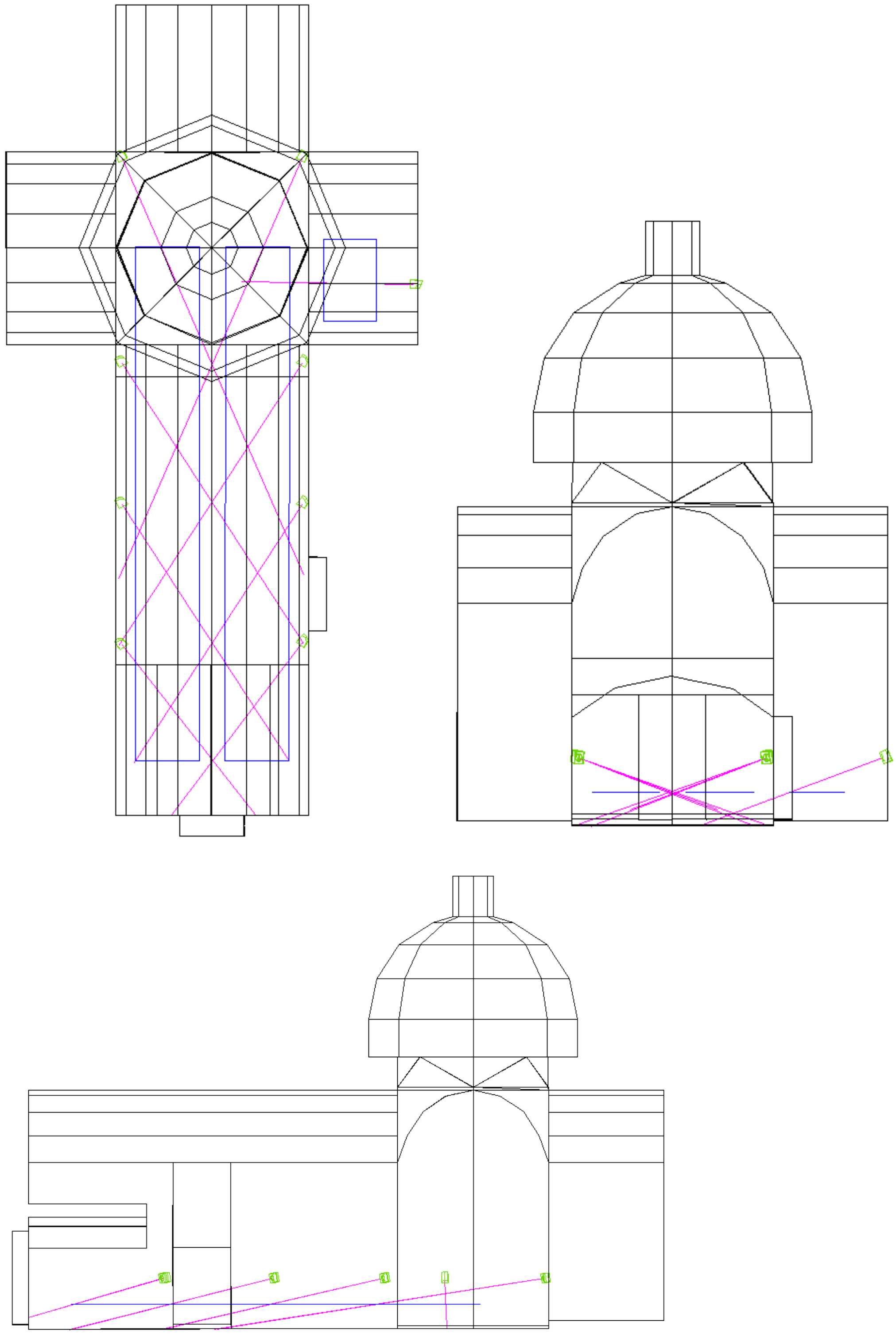

Figure 14(9) HS1200 speaker system (SJD37)

The sound coverage including the right transept is shown in Figure 15.

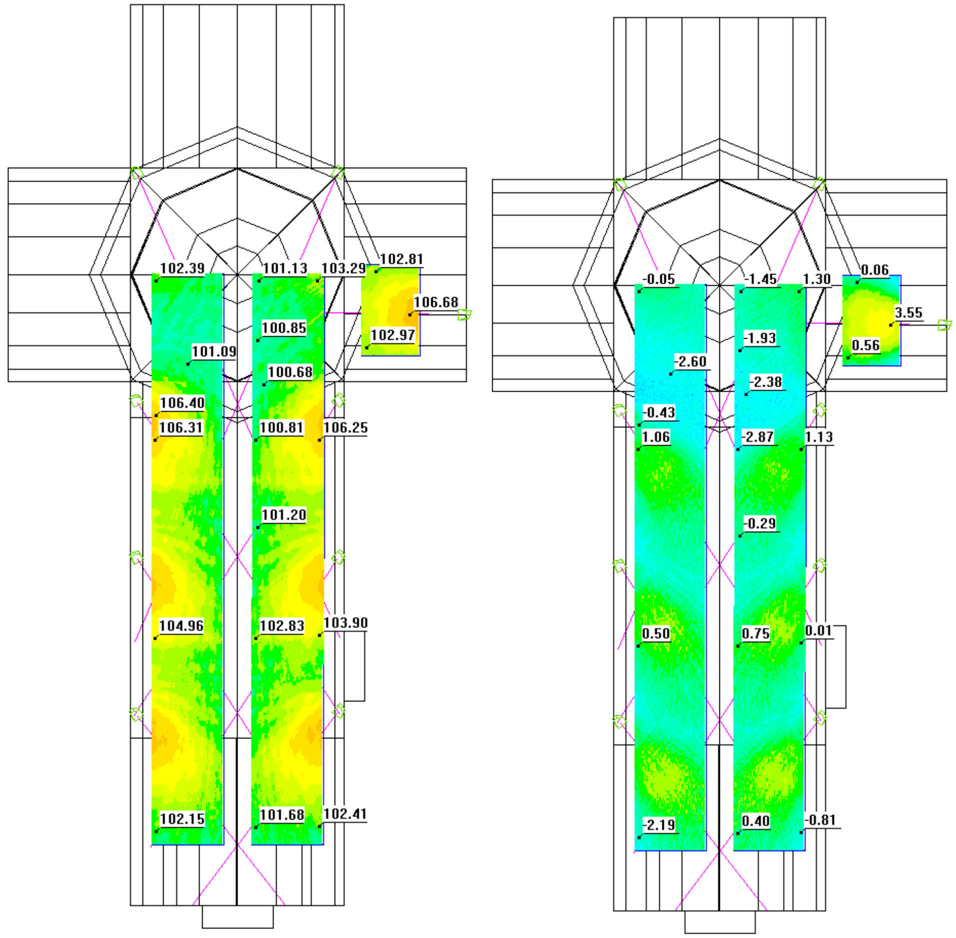

Figure 15 Ld (left) and Ld-Lr (right for 9 HS1200 System

The direct sound variation is 5.9 dB and the direct to reflected sound is -2.9 dB for the entire listening area including the right transept.

Performance with Audience Present

All the calculations so far have been with the pews empty. There are two different audience conditions.

The English Mass typically is attended by 30 or so people. Each pew can hold 5 people (per side) which means only 3 rows would be filled. But typically, people spread out such that the front 6 pews are half filled. In the simulation, the floor absorption in this area is changed from *hard seating empty* to *hard seating 2/3 occupancy*. For this case, it might be desirable to turn down or off the rear 4 speakers as well as that in the transept.

The Spanish Mass is attended by about 200 people. That means all 18 rows are packed as well as some of the aisles. (Portable seats are used for this). In this case, the floor absorption will be changed to *hard seating full*.

The results for each of these cases are shown in Table 9 below using the 9 HS1200 speaker system. The performance is only shown for the seating areas occupied. That is, for the English Mass, ∆Ld and Ld-Lr are only considered for the front third of the main seating area.

Table 9 Effect of Audience Seating on Performance

Seating	Speakers On	ΔLd (dB)	Ld-Lr (dB)
Empty	All	5.9	-2.9
Spanish Mass	All	6.2	-0.6
English Mass	All	5.8	-3.2
English Mass	Front 4 only	6.2	-1.7
English Mass	Front 4 + Transept	5.8	-1.9

The effect of seating on the direct sound variation is not significant, but the effect on the direct to reflected sound ratio is. Seating improves Ld-Lr more than 2 dB better in the Spanish Mass, and it is over 1 dB better In the English Mass as long as the rear speakers are turned off.

Amplifier and Wiring

The current amplifier has up to four inputs and a single 70 V output which drives all of the loudspeakers in parallel. (All speakers have built in transformers that are designed for connection to the 70 V line). The amplifier is rated at 100 watts output which is sufficient for the total load of the existing loudspeakers (about 75 watts). There is no way to change the zones with this system other than to manually switch off some of the loudspeakers, which is possible using the switches that were temporarily added at the center and rear speakers.

If the system is upgraded to (9) HS1200 speakers, the total load can be as much as 9x60 = 540 watts, not including the outdoor horn speaker. That is the maximum continuous power that these speakers are capable of delivering. But more likely, they would be connected using a 30 or 15 watt tap rather than 60 watt taps which would bring the power requirement down to 270 or even 135 watts. In any event, the current 100 watt amplifier is underpowered for this load. There are two other reasons to replace it.

(1) The measurements made with SMAART8 show a substantial amount of harmonic distortion at all locations indicating that the amplifier (and not a loudspeaker) is causing this.
(2) The system should be “zoned” with separate switches to enable the front speakers, the back speakers, the outdoor speaker, and the transept speaker. This will allow for better control with different audience sizes.

The PA amplifier that appears most capable of meeting these requirements is an OSD model PAM245 shown in Figure 16. It is rated for 240 watts continuous power output. It has 6 inputs and 5 zoned outputs. It costs $499.

Figure 16 OSD Model PAM245 Amplifier

The existing wiring is very messy and consists of conductors varying between AWG16 (zip cord) and AWG22 (bell wire). Some of these conductors run through electrical conduits and others are embedded in the plaster walls.

The new speakers should be wired using AWG18 conductors for each speaker pair with a common ground of AWG12. These should be run through a dedicated conduit embedded in the plaster walls. To minimize the dust and avoid damaging the Cantera columns, the conduit can be run on the plastered outside of the church at or above the 8 ft level. A small hole can be drilled through the wall at each speaker location and the speaker wiring connected to the appropriate conductors in a junction box mounted on the outside wall. If done properly, this should be nearly invisible. Alternatively, plastic conduit can be mounted on the inside walls.

Instead of placing the amplifier in the existing cabinet inside the sacristy, I suggest putting it in the transept where it may be controlled by someone seated nearby that can hear and adjust the volume.

Adding Surface Acoustic Absorption

The expected improvement over the current system is about 3 dB in direct sound uniformity and 6 dB in the ratio of direct to reflected sound, just by changing the sound system. That is significant and although the quality indicator puts it in the "fair" range, it may be adequate. Further improvement will require introducing acoustic absorption along the walls. This is very common in modern churches, but there is an understandable reluctance to do anything that would change the esthetics of a colonial era church like San Juan de Dios.

A typical commercial acoustic pattern is shown in Figure 17.

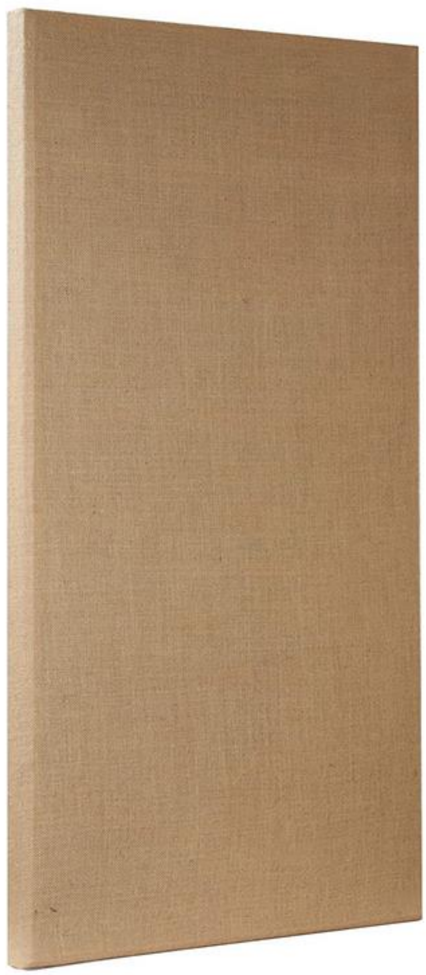

Figure 17 Typical Commercial Acoustic Panel

These panels cost about $50 for a 2 x 4 ft panel. However, they can be built for about half that cost using locally available fiberglass panels, wood furring strips and canvas type fabric. They can be built to any size or shape and hung using ordinary wall (picture frame type) hangers. For a church, the fabric color is usually chosen to be the same as the wall color so that they do not stand out.

To get an idea of the effectiveness of treating the various walls, the surfaces listed in Table 10 were treated one at a time in the Ulysses model. The current sound system was used with empty seating and all speakers on. The direct sound level is not affected, but the direct to reflected sound is improved.

Table 10 Effectiveness of Acoustic Panels

Wall treatments	Improvement in worst case Ld – Lr (dB)
South nave walls – 1” acoustic panels	1.0
South transept walls – 1” acoustic panels	0.7
Transept end walls – 1” acoustic panels	2.0
Nave side walls – 1” acoustic panels	3.0

The most effective surfaces are the nave side walls because these are the largest areas, but of course, they are also the ones most visible.

At this point, it seems best to wait until the new sound system is installed, then evaluate it using SMAART8 to see if further improvement is warranted.

Summary and Estimated Cost

The 2+6+1 HS1200 speaker system provides about 3 dB more uniform direct sound level. The direct to reverberant sound ratio is improved by about 6 dB.

A summary of the changes and their results is shown in Figure 18 and Figure 19.

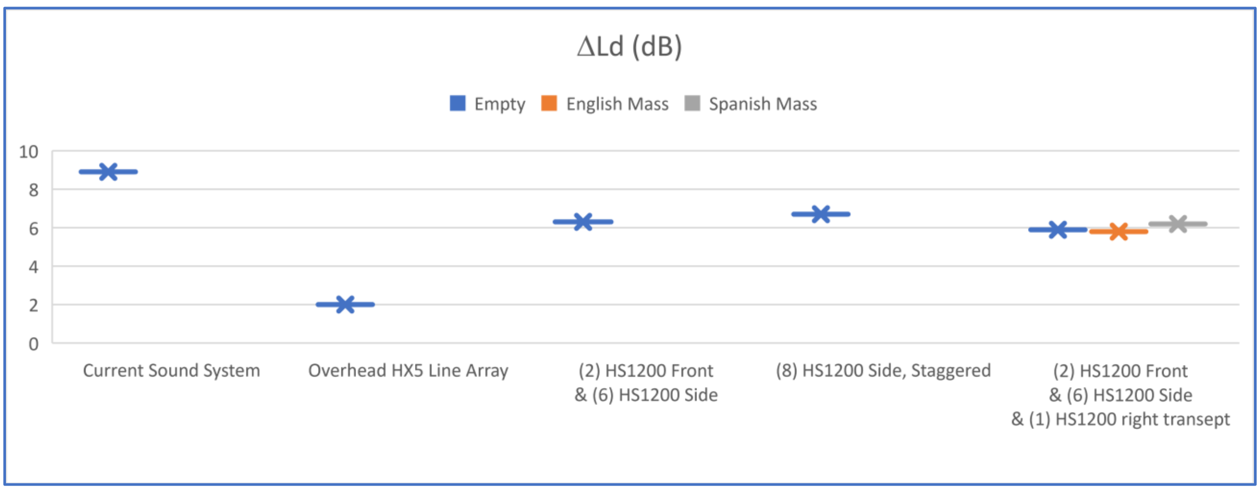

Figure 18 Summary of Direct Sound Variation (Lower is better)

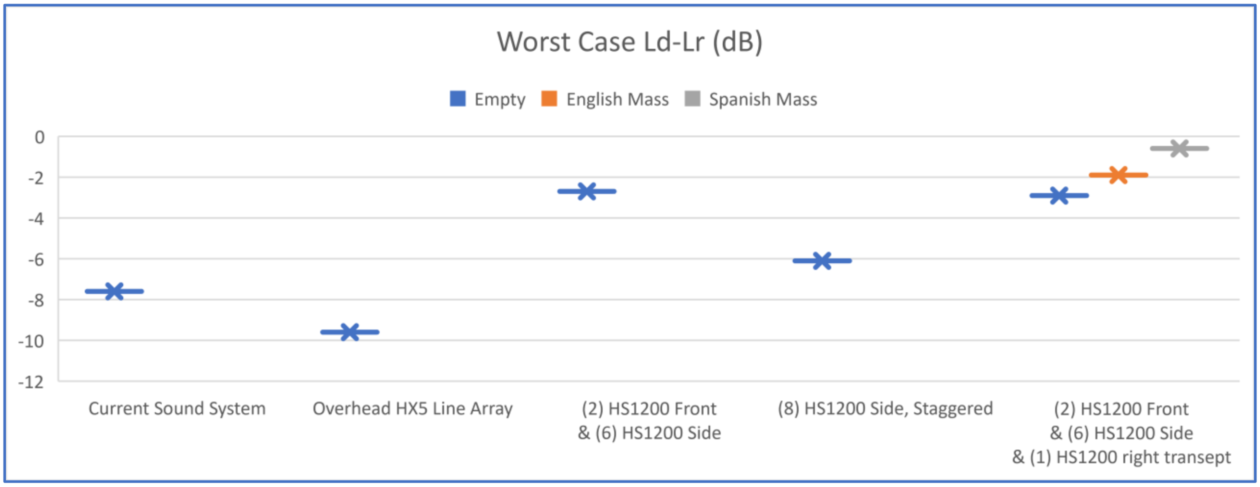

Figure 19 Summary of Direct to Reflected Sound (Higher is better)

Approximate cost of the new sound system is listed in Table 11.

Table 11 Cost Estimate

Qty and Description	Cost US$
(9) HS1200 Loudspeakers + shipping	9x346x1.2 = 3737
(1) PAM245 Amplifier + shipping	499x1.2 = 599
(9) Speaker Mounting Brackets (local fab)	9x25 = 225
Conduit, cable and junction boxes	200
Total	4761

Appendix A Ulysses Model of Church

The church interior is modeled using the program Ulysses made by ifbsoft.de.

The program allows prediction of acoustic characteristics at various locations throughout the building. Changes to the acoustic absorption of the walls and changes to the sound system (speaker location, type, etc.) can be made using this program.

Creating a model for the church interior is time consuming but relatively straight forward once the program commands have been figured out. Ulysses offers example models and a basic tutorial, but many of the details can be mastered only by trial and error. If an error is made, the model is fatally flawed because it results in a "missing wall". To avoid repeating a great deal of work, the best method is to frequently save the file under a different name each time a new step is taken during the construction of the model. Use the Ulysses command "Call Arnold" after each major step before saving the model to detect whether an error exists.

In the following, the model is developed in stages, and some notes are made to indicate what steps were taken. SJDxx are the file names for the Ulysses models.

The model includes the main dome, four rectangular floor areas, the balcony and two doors. The ceilings over the floor areas and below the balcony are barrel shaped.

The origin for the coordinate system is chosen as the floor directly below the main dome. The X axis points to the East, the Y axis North (towards the altar) and Z is oriented upwards.

Measurements

The room measurements were made using a tape measure and a laser measuring tool Bosch Model GLM30. The laser was especially useful in measuring heights. A plan view and two elevation views were then constructed using the “sketcher” in Free Cad.

The major surfaces were modeled to an accuracy of a few inches which is more than accurate enough for an acoustic model. However, minor features such as the statuary, upper windows, and internal architectural structures in the sanctuary were not included.

The plan view is shown in Figure 20. Elevation views facing East and North are shown in Figure 21 and below.

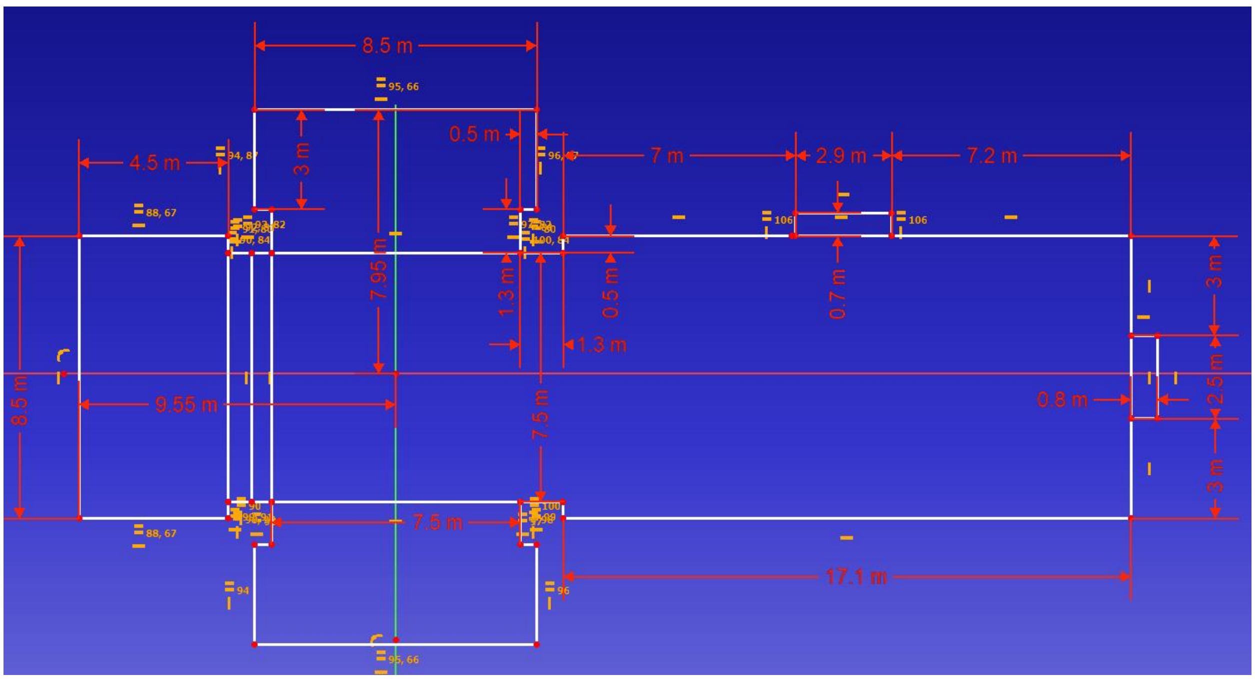

Figure 20 SJD Plan View Dimensions

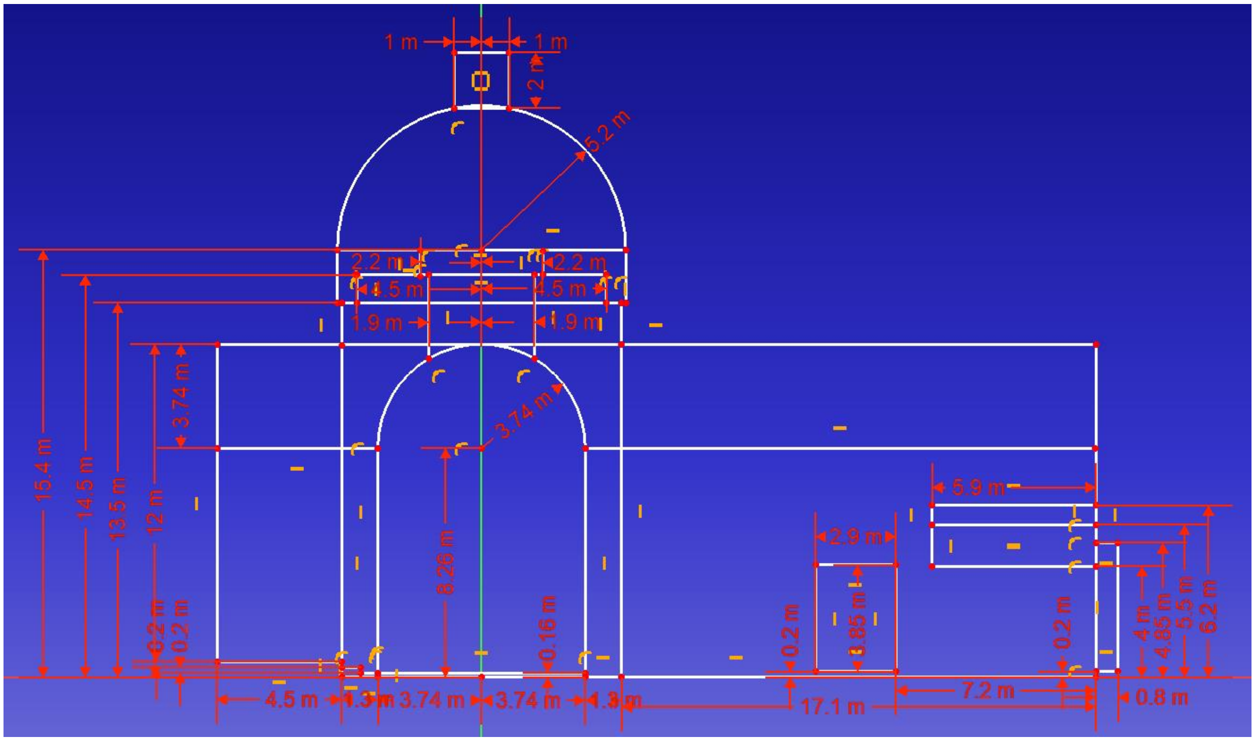

Figure 21 Elevation View Facing East

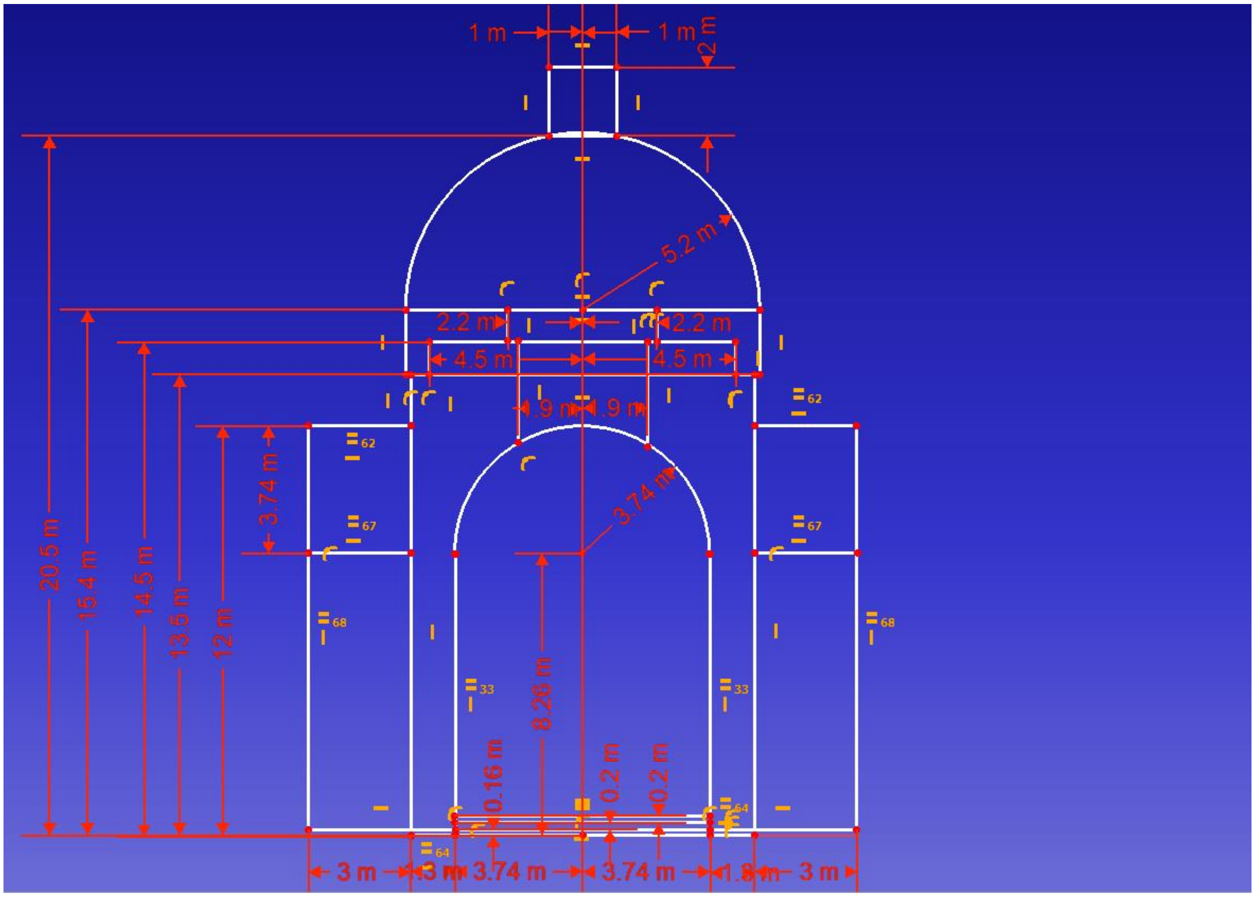

Figure 22 Elevation View Facing North

SJD01 - Draw boundary of dome

The dome is an octagonal shape when viewed from below. This can be created by first defining its outline in the XZ plane then rotating this outline in a “circle” that is approximated by 8 segments. The outline is first formed by creating a polyline with 12 points. The first point is the top center of the cupola above the dome and the 12th point is the origin below the dome. The coordinates for the dome itself (nodes 3, 4, 5, 6, and 7) were found by temporarily placing a 16 segmented circle of radius 5.2 meters at the point X=0, Z=15.4 meters. The points on the polyline are listed in Table 12 and were entered manually.

Table 12 Coordinates for the Polyline

Point (node number)	X (m)	Z (m)
1	0	22.5
2	-1.0	22.5
3	-1.0	20.5
4	-2.0	20.2
5	-3.7	19.1
6	-4.8	17.4
7	-5.2	15.4

8	-5.2	13.5
9	-3.74	13.5
10	-3.74	12.0
11	-3.74	0
12	0	0

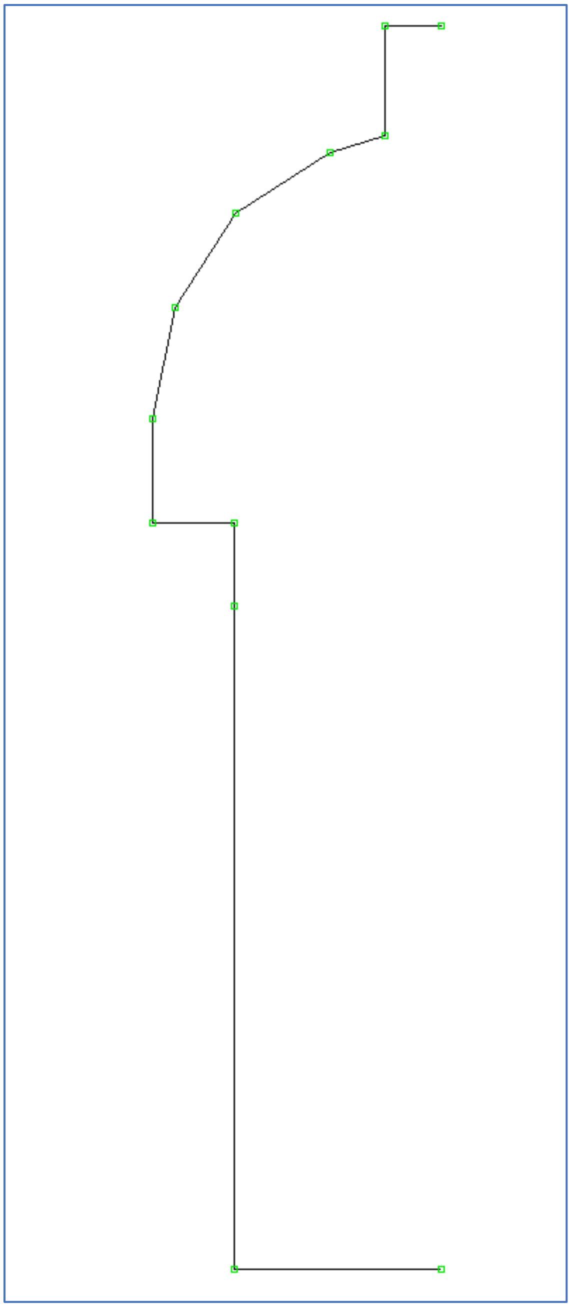

Figure 23 SJD01 Polyline

SJD02 - Rotate the polyline about the Z axis

The rotation is for 360 degrees in 8 segments. This must be done after switching to the XY view in Ulysses.

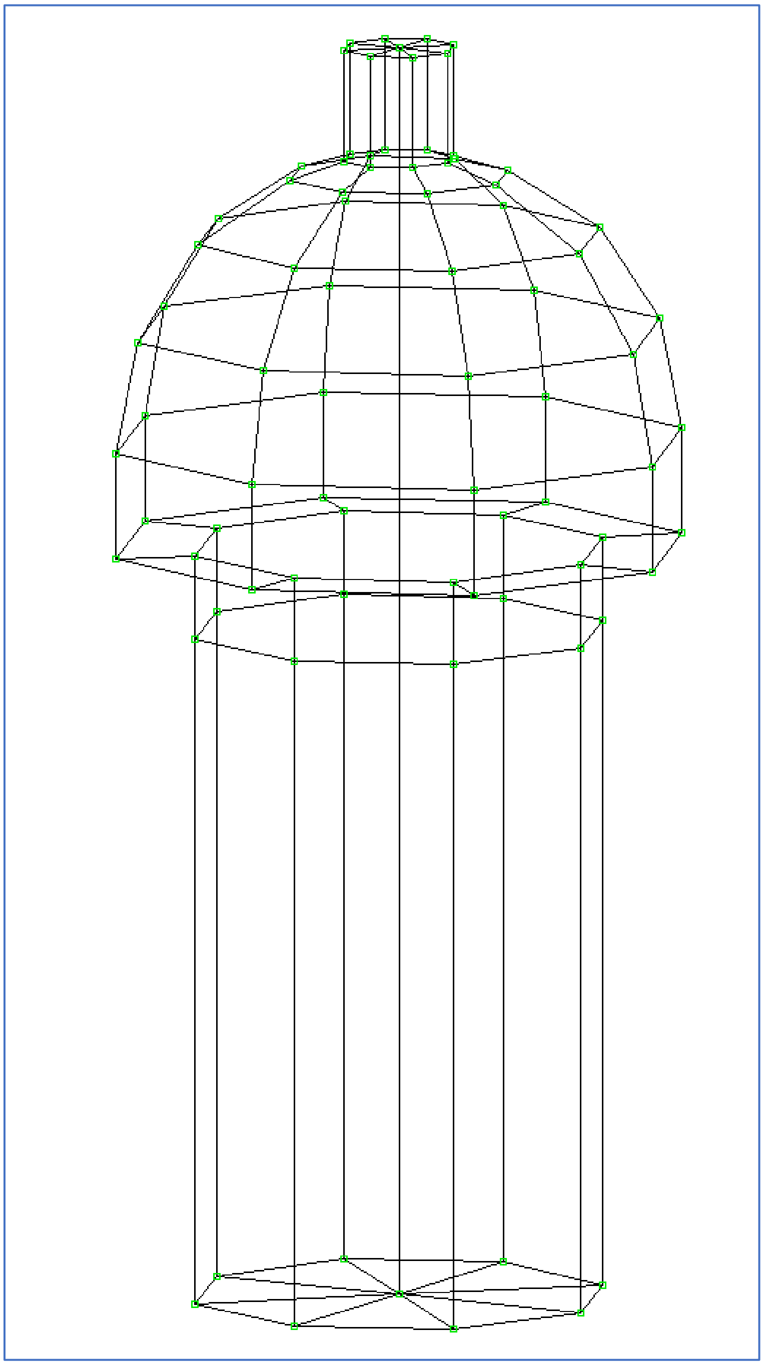

Figure 24 Polyline Rotation

SJD03 - Transition base of dome from octagonal to square

The 8 rectangular surfaces directly below the dome must be split diagonally into 16 triangles. Then the intermediate vertical nodes can be moved to the corner nodes to form a square base under the dome. At this point the base still has 8 surfaces but forms a square solid instead of an octagonal solid.

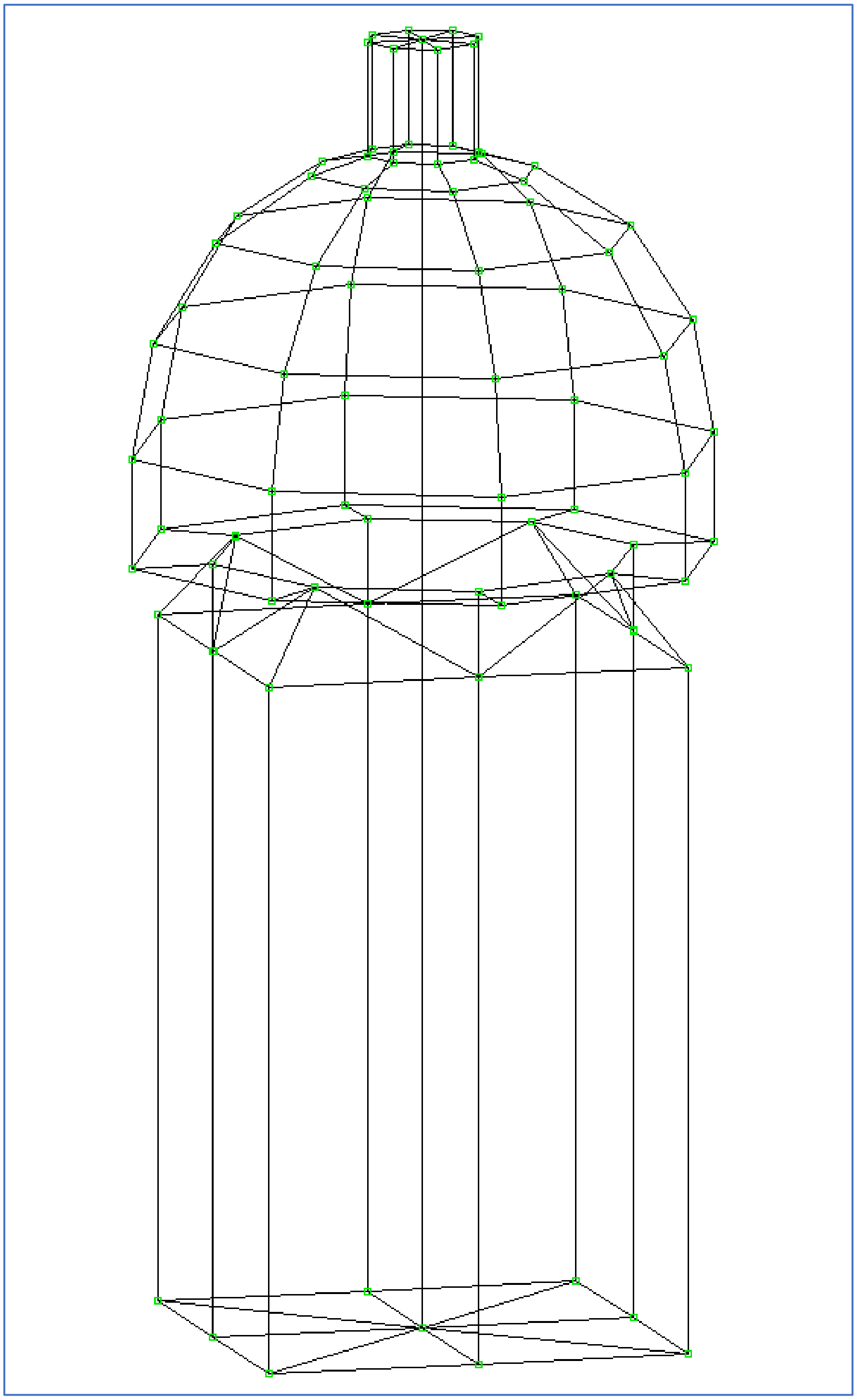

Figure 25 Dome Transition to Crossing

SJD04 - Combine the side surfaces below the dome

This is done by first adding 2 nodes to the center line of each of the sides. Then move these nodes to the corners. The result is 4 rectangular surfaces with twice the area and 4 surfaces with zero area.

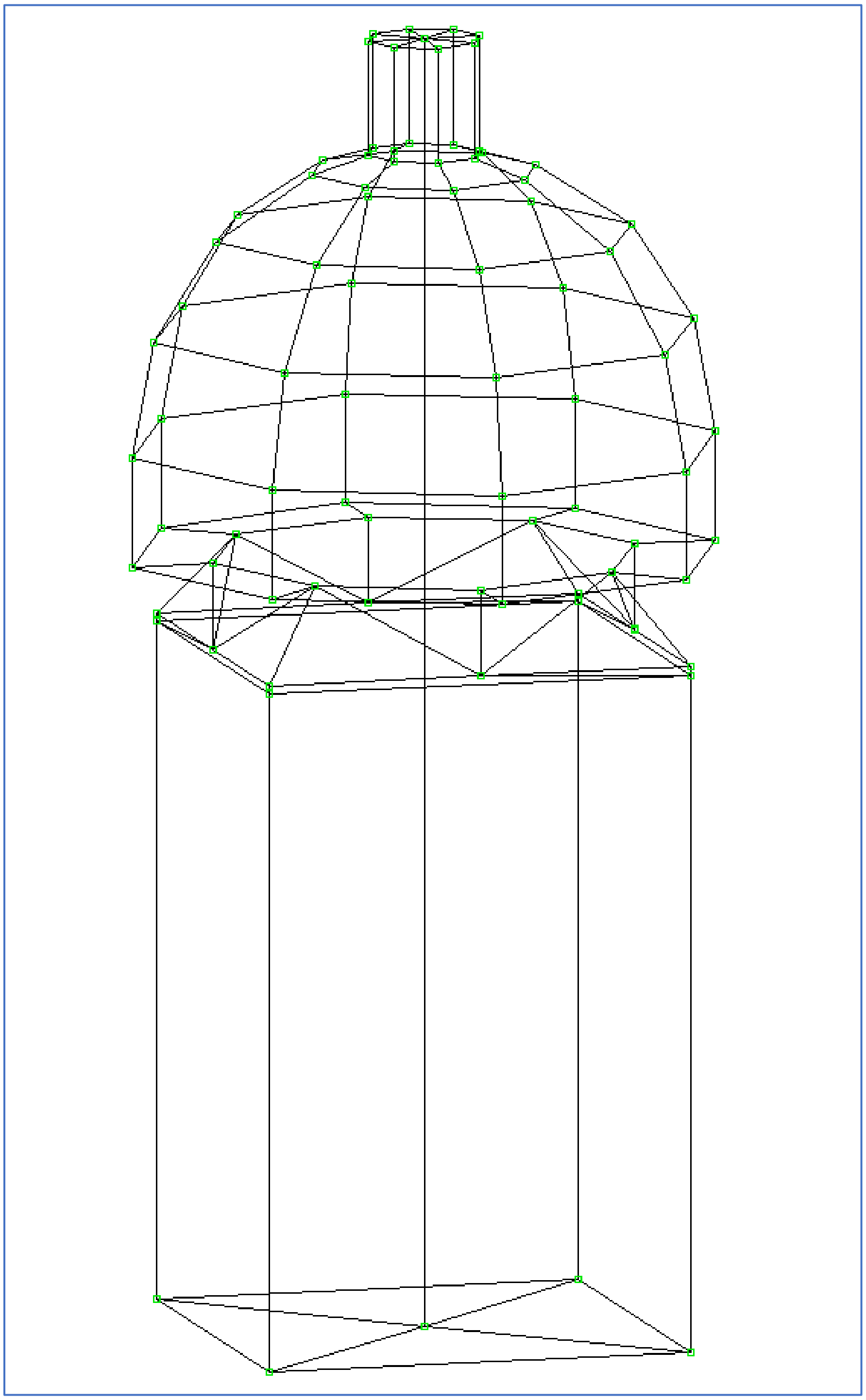

Figure 26 SJD04 Crossing Walls

SJD05 - Create the East Room

Split the East side horizontally into four surfaces then move four nodes along +X to create a room.

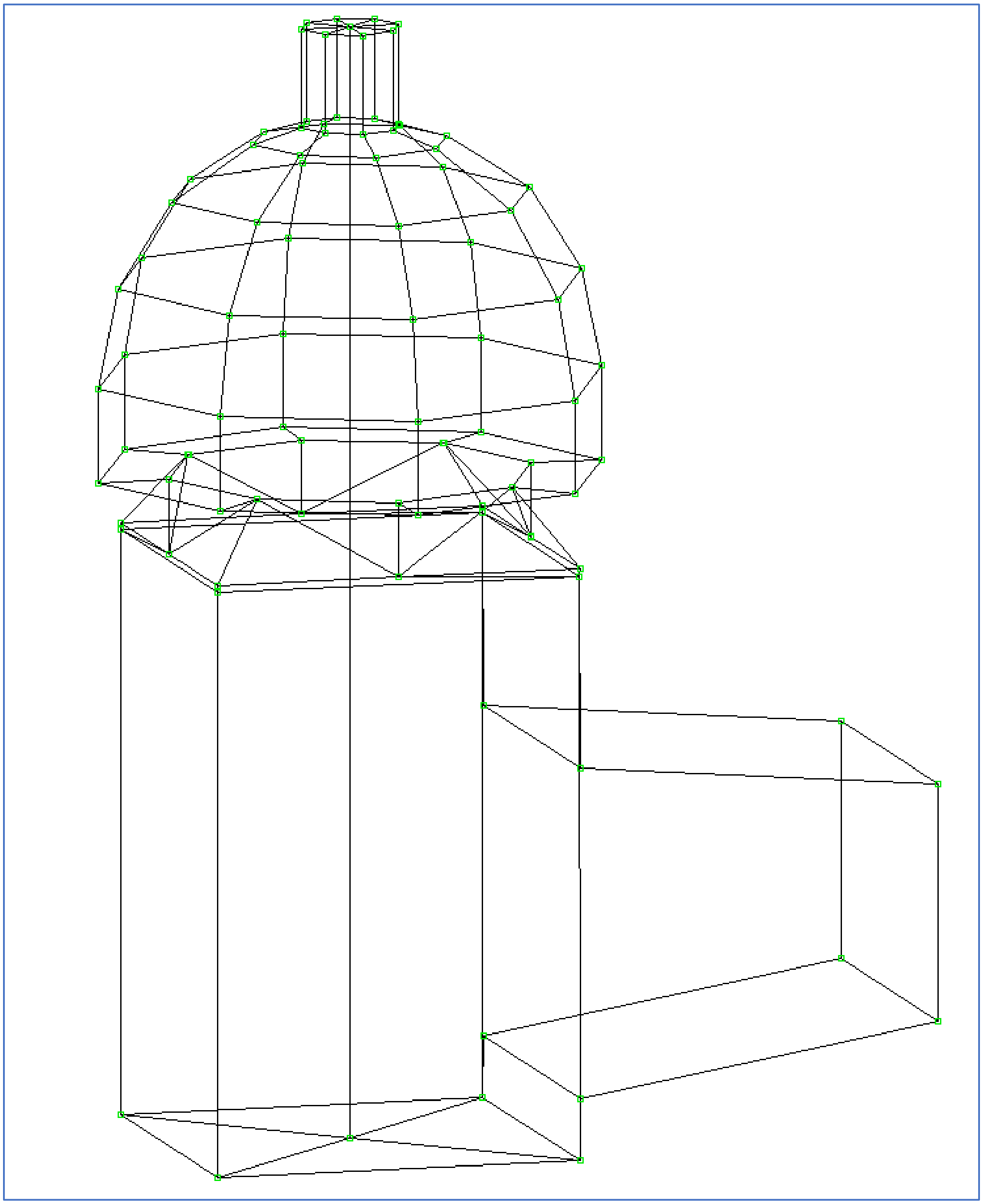

Figure 27 SJD05 East Room Creation

SJD06 - Adjust Dimensions of the East Room

Move the East room corner nodes to the correct coordinates. Note the East floor is raised .16 m above the main floor. Now split the West wall horizontally and repeat to form the West room.

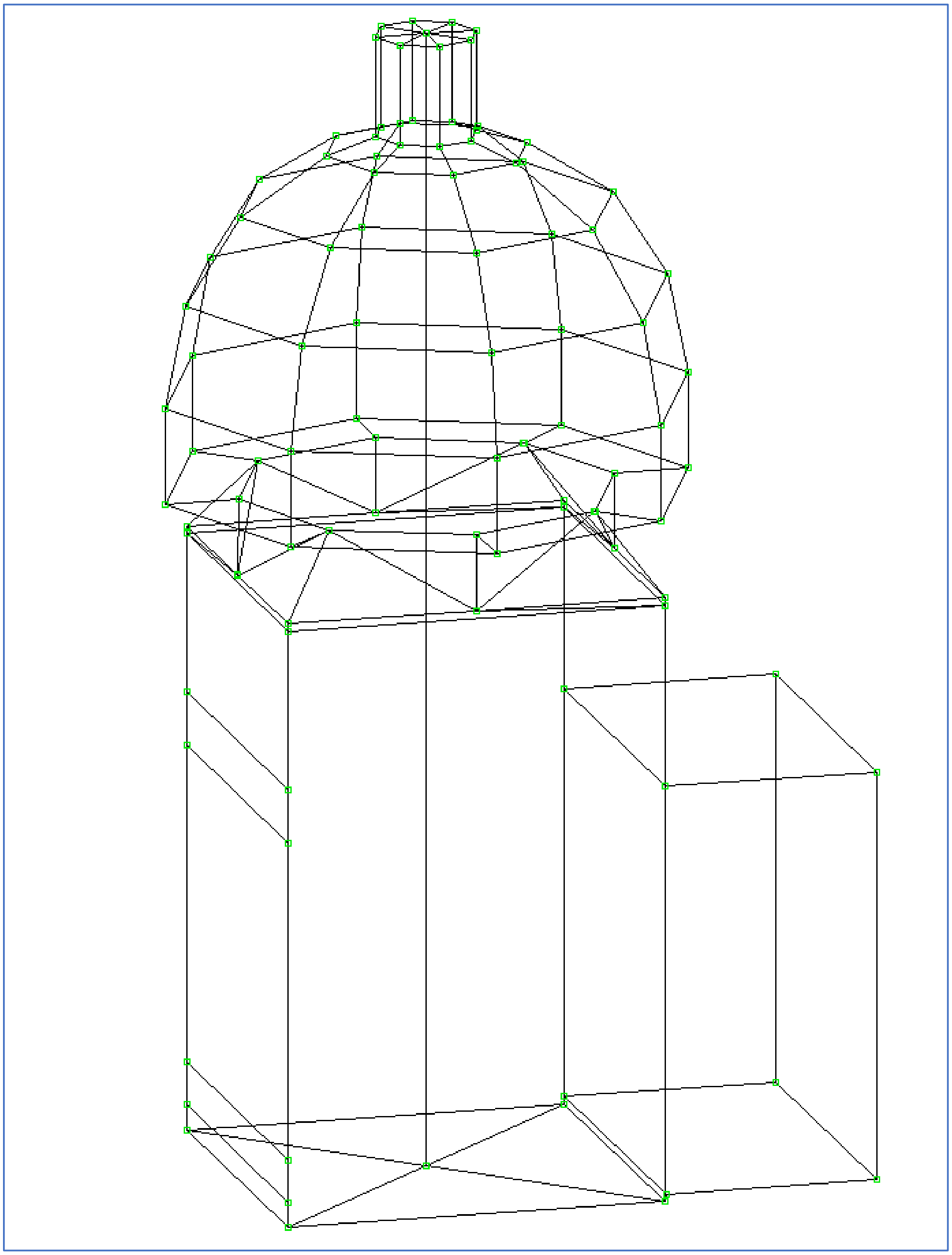

Figure 28 SJD06 East Room Dimensions

SJD07 - Repeat for North and South Rooms

Also add vertical corners between west and south room, etc. since otherwise a missing wall will be detected. The North room is raised 0.4 meters above the center and South floors.

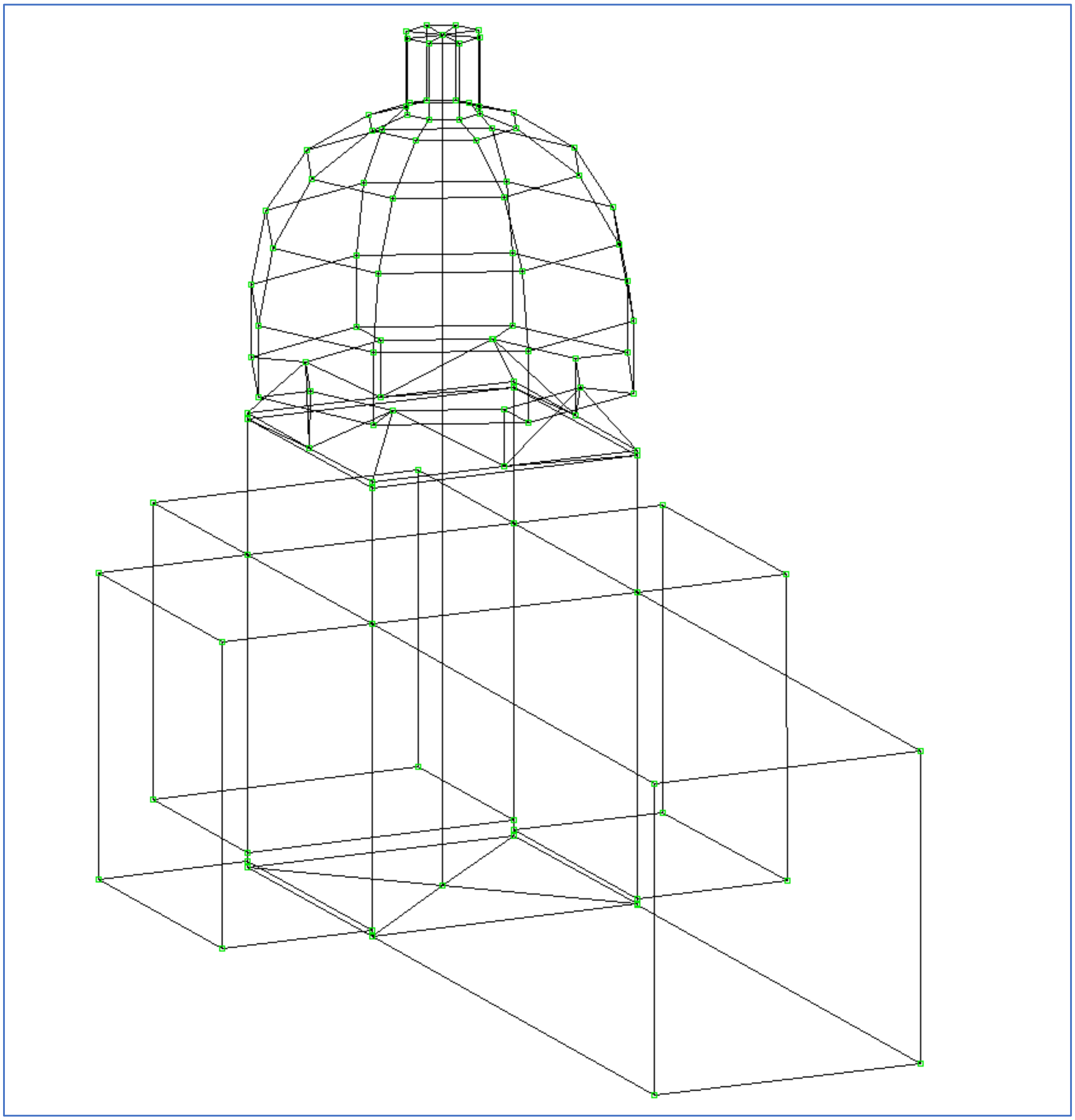

Figure 29 SJD07 North and South Rooms

SJD08 - Create Barrel Ceilings on East and West Rooms

First create a 16 segmented circle and extrude it. This is a temporary (auxiliary) drawing that will allow the ceiling segments on the East and West rooms to be lined up with the nodes along the Y and Z axis when they are viewed in the XY and YZ planes. Split the East and West room ceilings into 8 surfaces running East to West. Then move the nodes in Y and Z directions to match those on the auxiliary drawing. Finally, delete the auxiliary drawing.

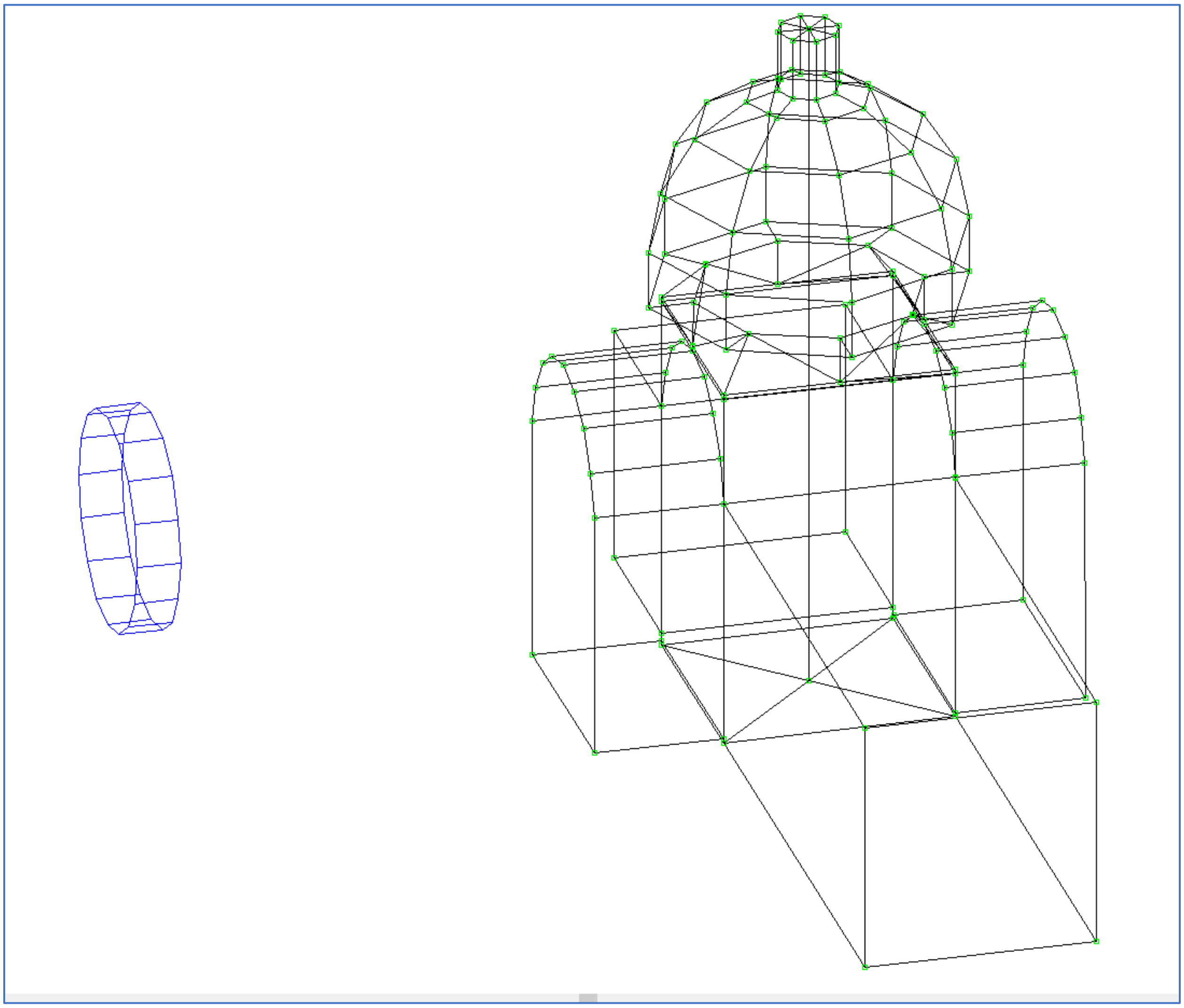

Figure 30 SJD08 Barrel Ceilings East and West Rooms

SJD09 - Repeat to Form Barrel Ceilings on North and South Rooms

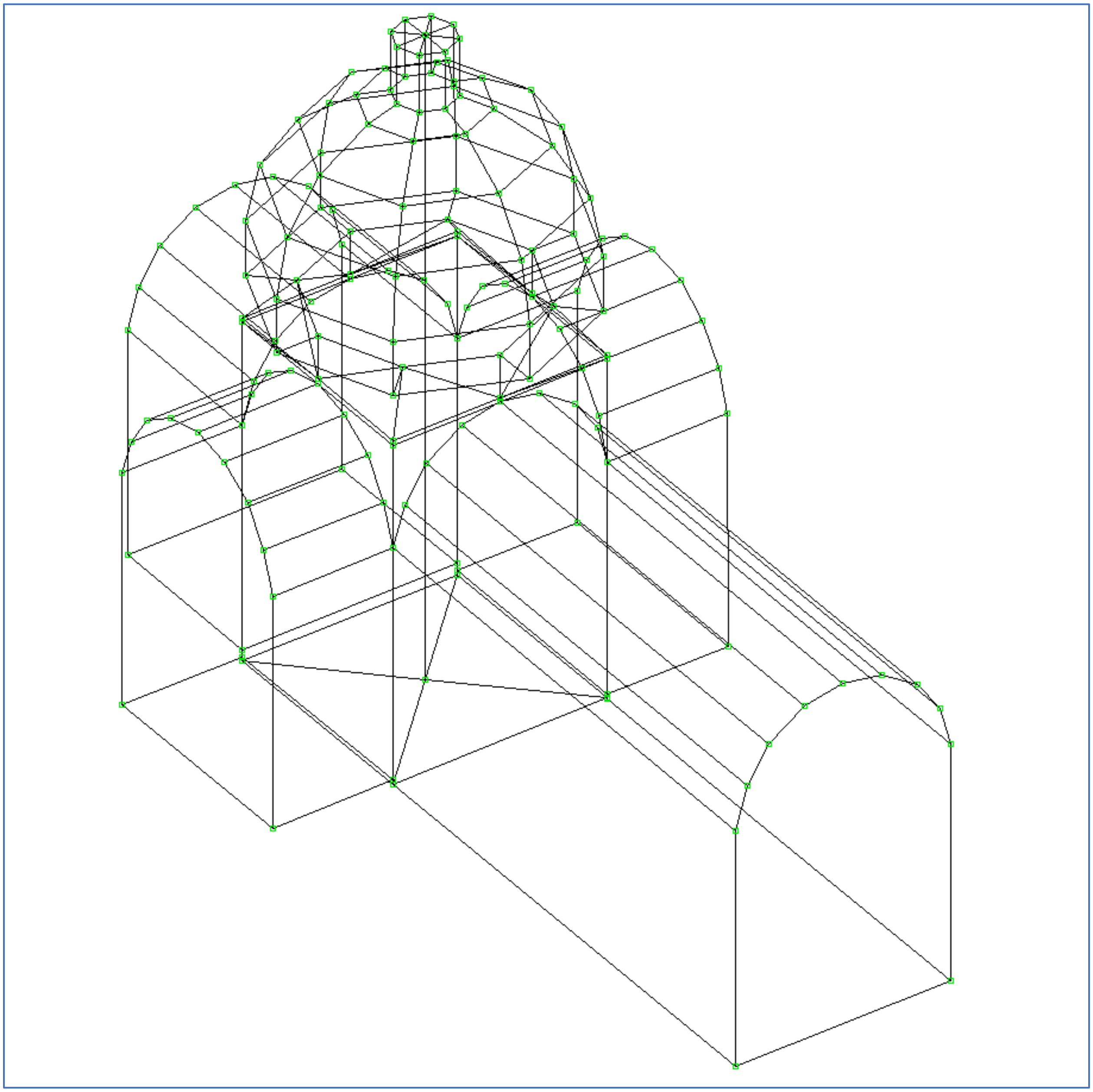

Figure 31 North and South Room Barrel Ceilings

SJD10 - Create the Balcony

Split the south wall horizontally in 4 places then move 4 of the nodes inside to form a rectangular intrusion. Now split the ceiling below the balcony along Y into 4 segments and form it into a barrel using another segmented circle to define the coordinates.

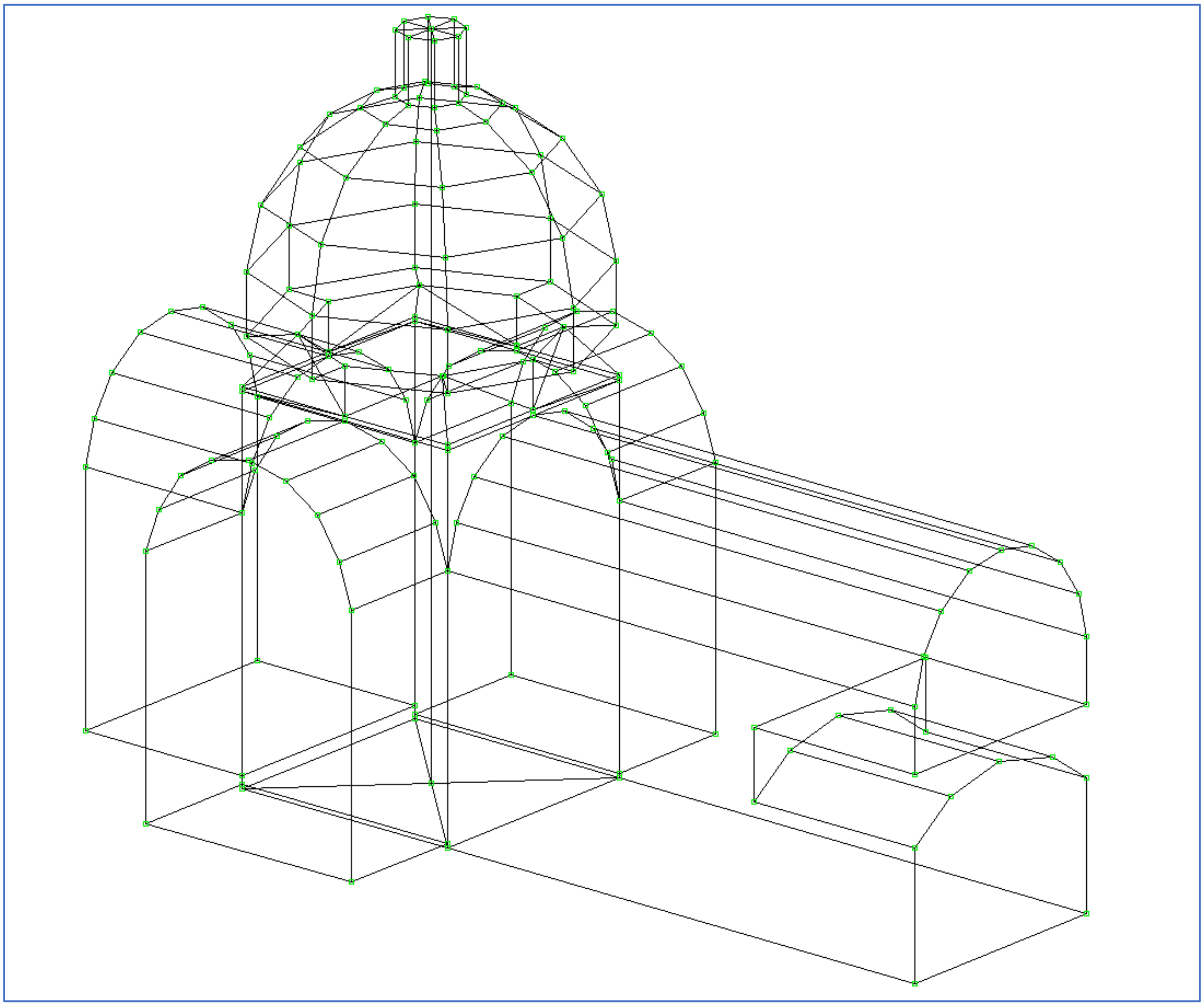

Figure 32 SJD10 Balcony

SJD11 - Create the Front Door

Split the South wall into four horizontal and four vertical segments.

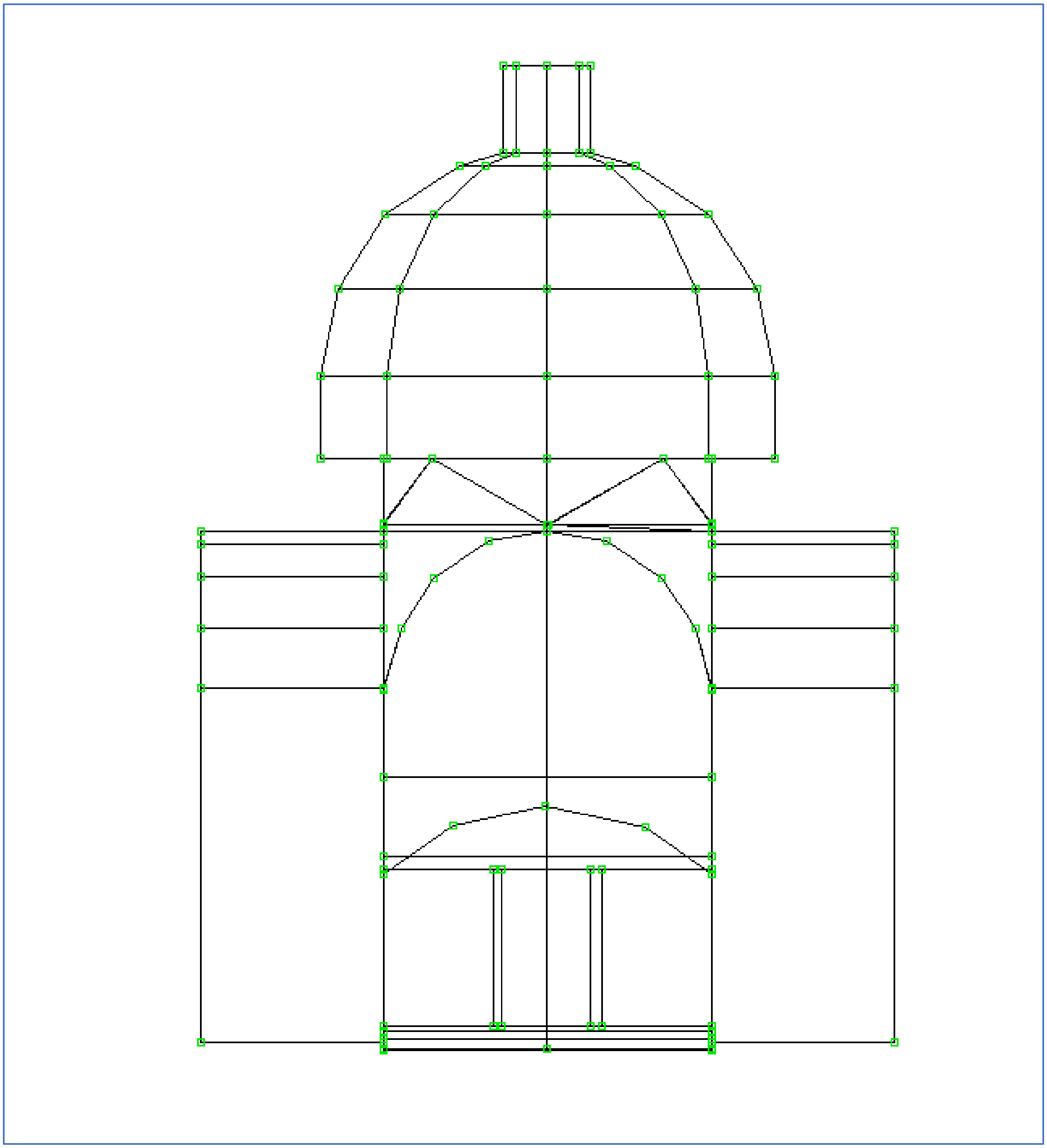

Figure 33 SJD11 Front Door

SJD12 - Complete the Front Door

Move the nodes to the correct coordinates then repeat this process to add the side door

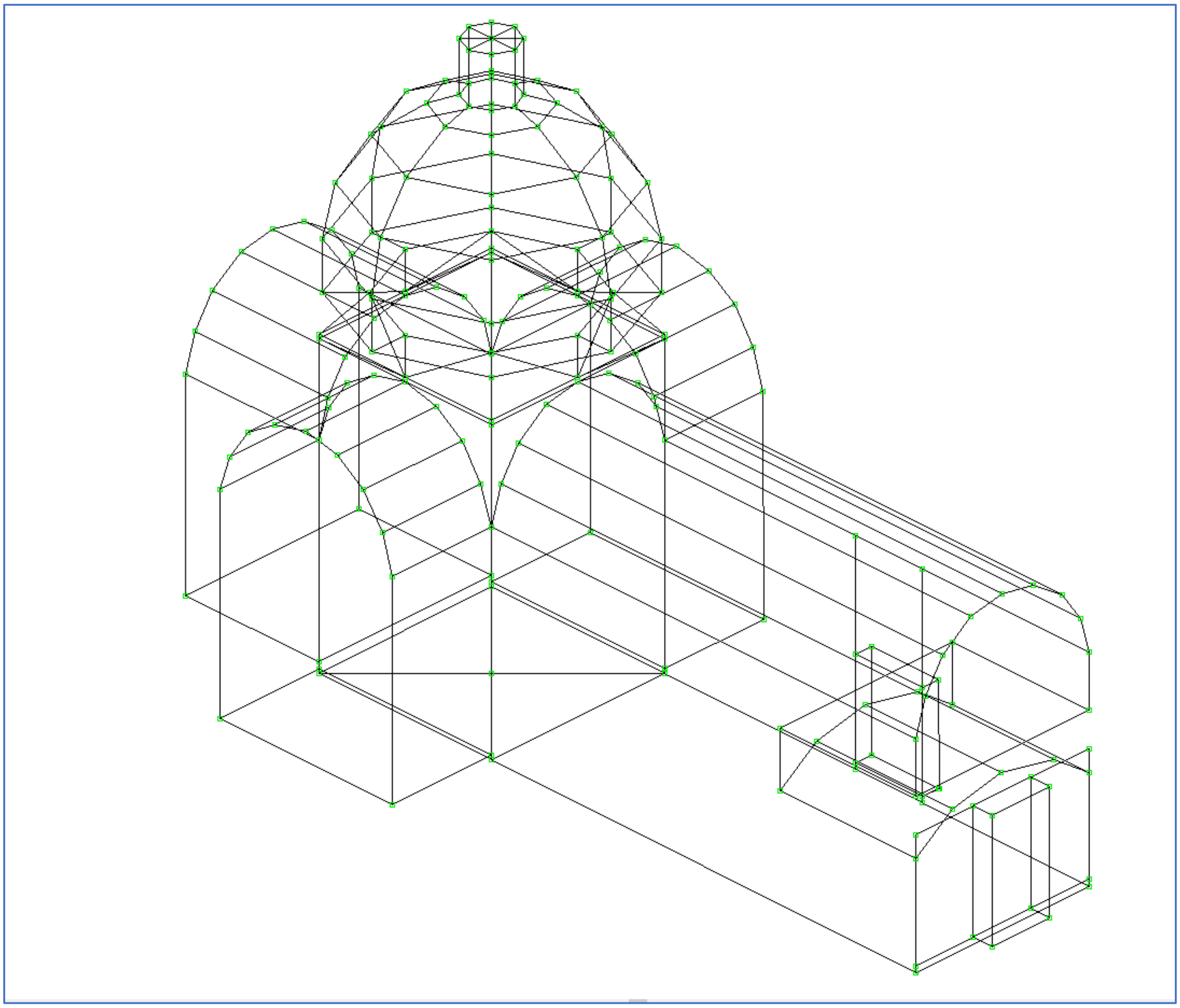

Figure 34 SJD12 Complete Front Door and Add Side Door

SJD13 - Add Listening Areas

Use the default height of 1.2 meters above the floor. Split the South room (Nave) floor to allow for two audience configurations.

These are shown in blue below. The floor split is at Y = -5.0 m.

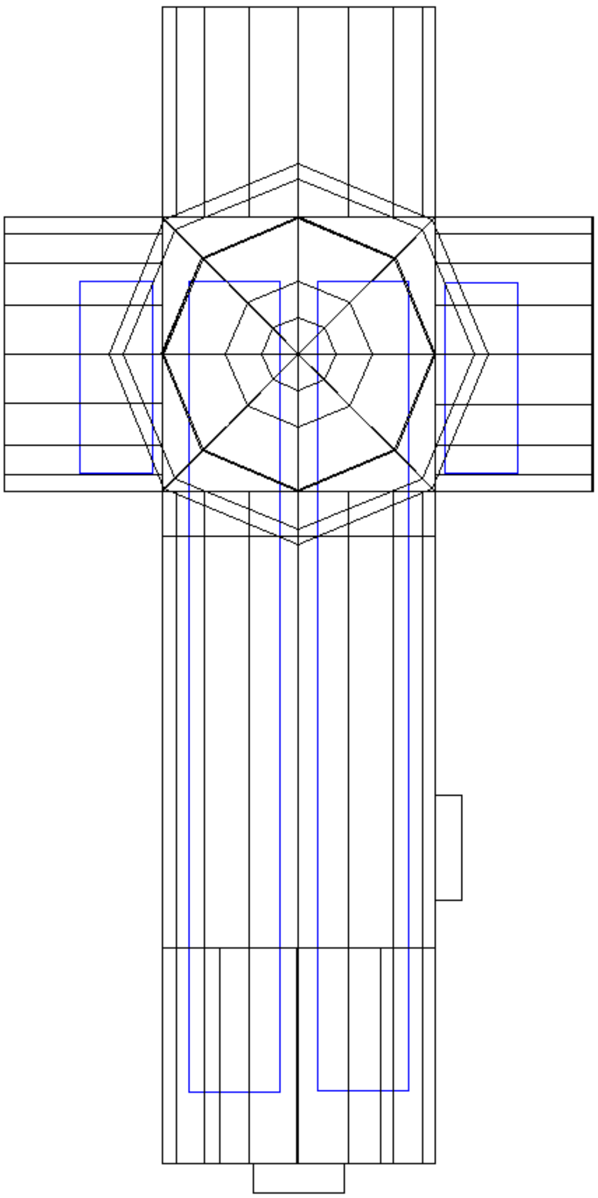

Figure 35 SJD13 Add Listening Areas

SJD14 - Install and Orient Speakers

The 6 original speakers are shown in green and the speaker axes are shown in magenta.

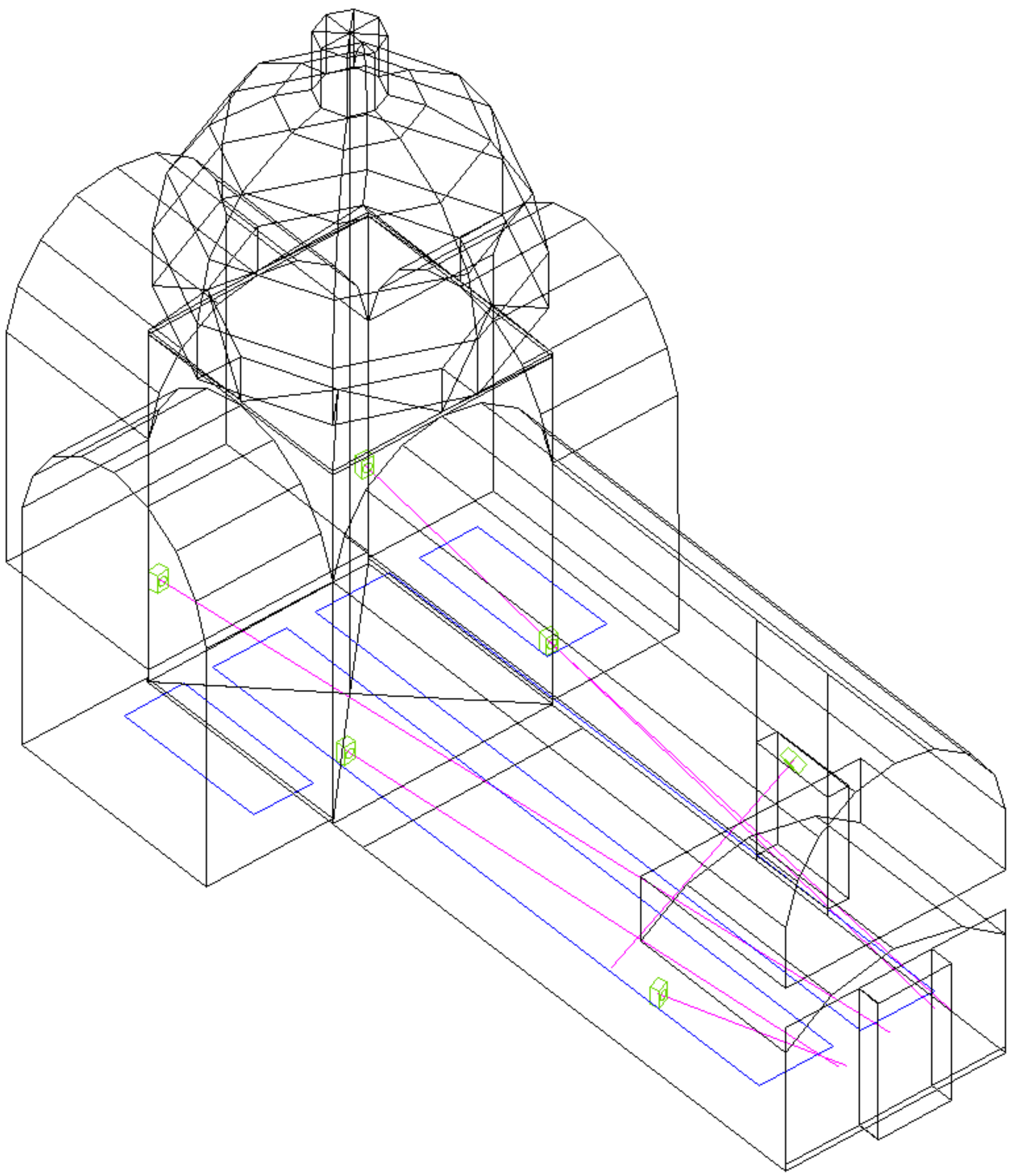

Figure 36 SJD14 Add Speakers

SJD15 - Add the Surface Properties

The actual North room (Sanctuary) contains a stepped cylindrical pedestal, multiple columns, statues, altars, steps, etc. that are far too detailed and complex to model accurately. The net effect however is to provide an acoustic dispersion to sound waves reaching the Sanctuary. A crude model is to change the surface reflection properties of the back wall to that of a plywood panel shaped into 90 cm chord semicircles. The other surface properties are Doors – Solid Wood Panels for the two doors, Carpet -1/4 inch ply glued down for the North (Sanctuary) floor, and Plaster-Gypsum over Masonry for the walls and ceilings. The other floors are Seating – Hard Empty. Note these surface properties were changed as discussed in Volume 2 to better match the measured reverberation time.

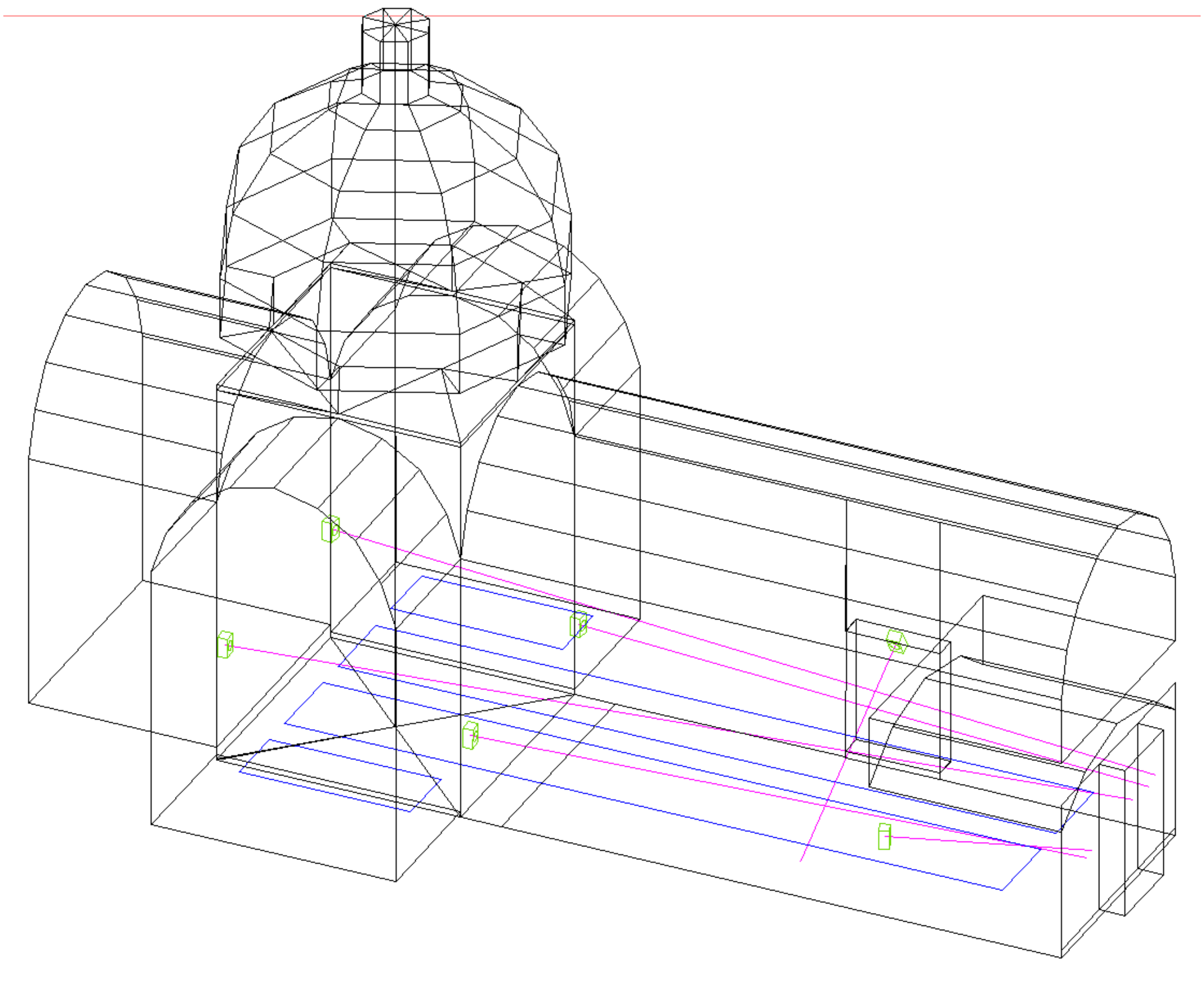

Figure 37 SJD15 Surface Properties