# Learning Modern Acoustical Design from Traditional Choir Venues

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## Abstract

Since the birth of modern acoustical science at the beginning of the 20th century, acousticians have avoided concave focusing geometries. This despite the fact that the buildings choirs have sung in for centuries have concave barrel vaulted ceilings or domes or both. New mathematics and, just as importantly, the software that makes the mathematics accessible, is revolutionising modern acoustical thought. Non-uniform Rational B-splines (NURBS) now allow acousticians to calculate reflections off of curved surfaces whereas previously, they could only be calculated off of flat surfaces. This paper uses NURBS to study the acoustics of a church that the author has sung in for 20 years, including its barrel vaulted ceiling. Both objective and subjective reviews are presented. Other conceptual rooms have also been studied, with an aim to learn from traditional building geometries that have been abandoned for more than a century.

The image opposite is where I've spent every Thursday night and Sunday morning for 20 years. A fundamental component of this room's design is so obvious, we can't even see it. I didn't – for ages.

It has what every acoustician, including myself, tells you to avoid. A great big focusing element. Its barrel vaulted ceiling. But it's one of the finest acoustic spaces in Toronto. I know it like the back of my hand. Glenn Gould recorded there shortly before he died.

… and if any of you know of Gould's infamous hatred of concert halls, my church's 4 second Reverberation Time may have had a hand in his early demise!

If you're ever in Toronto, I'd advise you to check it out. Like any other Anglican institution it is reeking with tradition. One of which – at least in our family – is a trip to the pub after church. Just let us know when you're in town and the first pint's on us …
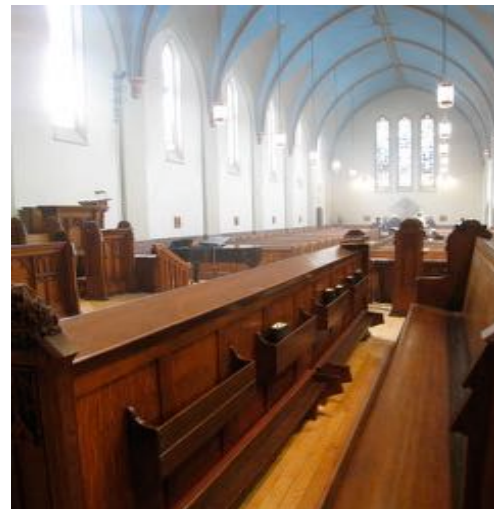


Figure 1 St. Martin in the Fields Church, Toronto Canada.

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… second one is on you!

It took me a long time to figure it out, sitting there in that seat, but it eventually dawned on me. Why are focussing elements a bad thing? Why can't they be a good thing? Why can't we use them to our advantage? Learn the lessons of the past, even if they don't fit into the current received wisdom. A perfect example is shown in Figure 2. And one that this paper has taken inspiration from.

Raf Orlowski and Yann Jurkiewicz's very sensitive renovation of Wigmore Hall in London. Their subsequent paper on the subject initiated, I would suggest, a new understanding of – or perhaps a new respect for – forms that don't fit received wisdom. Forms that have focussing elements. This is all about what modern acousticians will tell you not to do.



Figure 2 Wigmore Hall, London

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But this building, along with the building shown in Figure 3, work pretty well.  Now you people here in London would know better than I, but I haven't heard too many complaints about focussing in St. Paul's Cathedral.

Many of us here today know of the importance of what we call spatial sound because of the work of one of us in the room – Mike Barron.  Among a few others, it must be said.  One of whom is a Kiwi (Harold Marshall) and two others who – I don't mind telling you – are Canadians!  (John Bradley and Gilbert Soulodre)

Later reflections – sound that has reflected around 3, 4 or 5 times –  needs to arrive at the listener from the sides.  This creates something we now call Envelopment.  The focus of the dome in St. Paul's Cathedral is shown at the intersection of the top of the two blue X's in Figure 3.

But what happens after that?

After the focus, the dome changes into a scattering device.  That's typically a good thing. Reflections are directed to the side walls below the dome.  And eventually make their way to listeners in the transept and, when you think of it in three dimensions, probably to a lot of the rest of the congregation as well.  Arriving at the listeners from the sides; creating, one would expect, Envelopment.
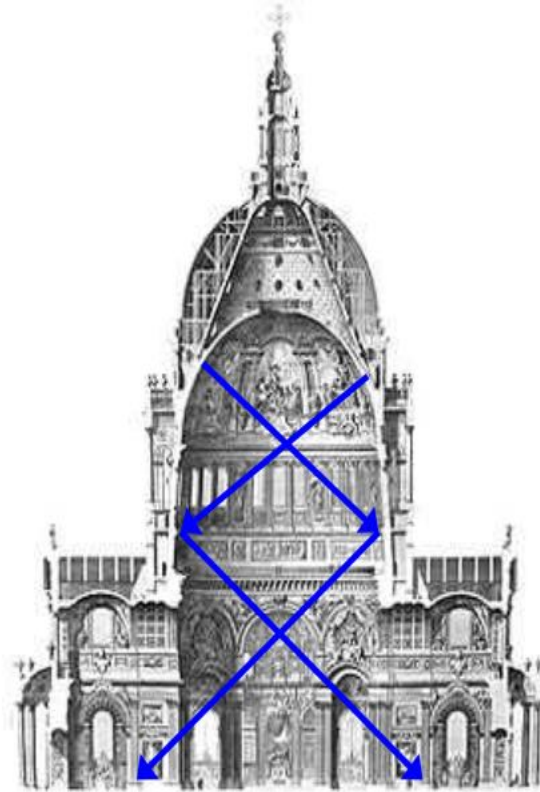


Figure 3 St. Paul's Cathedral, London

But let's return to the room I know so well, St Martin's in Toronto, shown again in Figure 4. There are no focussing problems in this room but on Thursday nights, when it's just a choir of 20 people in the room, with the unoccupied 4 second Reverberation Time, the late decay ends up about where the arrow in the image indicates. Which I always thought must be the focal point.

Interestingly, when the room is occupied on Sunday mornings, that late decay "focus", in inverted commas, isn't there. One might think that it should be the other way around. On Sundays the Reverberation Time is shorter, probably just above 2 seconds to my ear. One would think that a focus would stand out more with fewer reflections to cover it up.

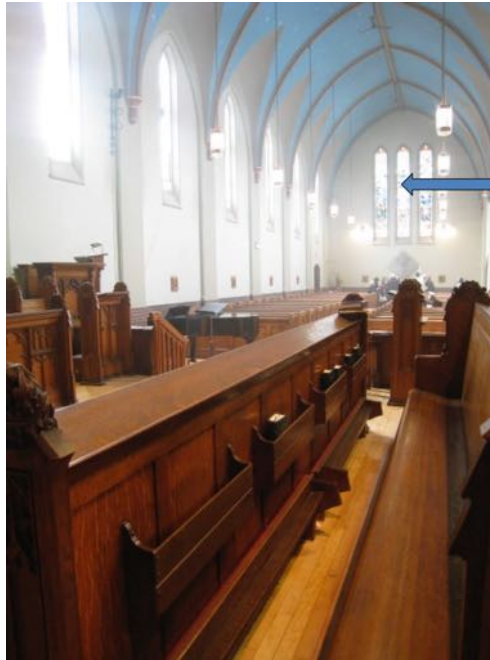But that is not the case. So where is the focus?



Figure 4 St. Martin in the Fields showing late the decay location.

And this is where it gets interesting.



Figure 5 First order focus in St. Martins

Well, if we look at just first order reflections, we find a pretty obvious focus, shown in Figure 5.

Figure 6  1st, 2nd and 3rd order foci in St. Martins.  (Only the 1st and 3rd order foci are evident in this image.)

But when we look at 2nd and 3rd order reflections as well, as shown in Figure 6, it's not quite so obvious. We have three foci, only two of which are evident in this image.  And when we look in three dimensions, the story becomes even murkier because my ear hears the late decay finishing around where the arrow is pointing to in Figure 7.  But this 3rd order calculation suggests that there are no reflections off the barrel vaulted ceiling in that vicinity.
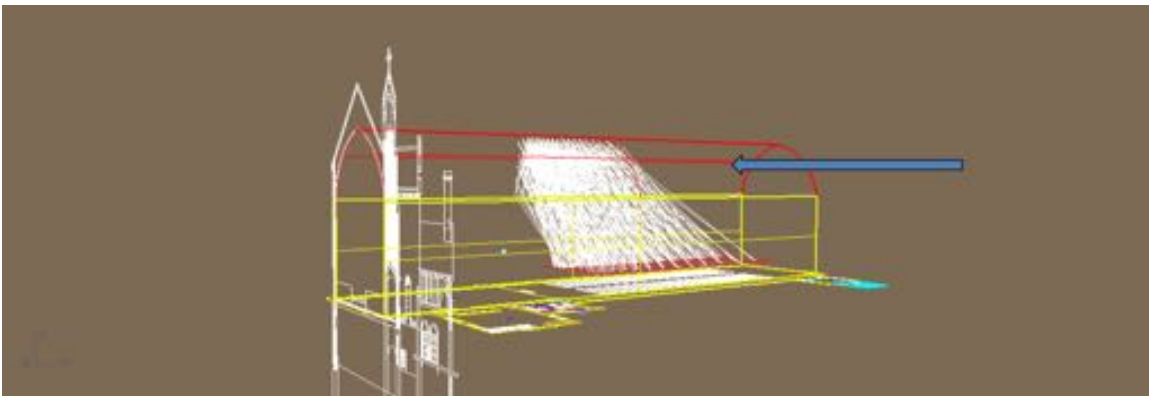


Figure 7. 3-D representation of Figure 6.

Which brings us to the topic of why I'm so interested in focusing and learning from the plethora of ecclesiastical places of the past.  These days, so many musical groups employ so-called "found spaces".  Often churches that look just like this one.  Well, why can't we, as designers, incorporate these geometrical forms into new buildings?

I think we can now.  But let's return to a bit more of the recent past.

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I've always thought that if you look at the history of science or technologies such as our own, the important ideas of the day tend to focus on what can be measured or predicted at that time. For a good part of the 20th century, the concept of Reverberation Time ruled. That was because until the 70s or 80s, before the age of accessible computer power, that's all that one could measure or predict with any kind of confidence.



Figure 8. Two dimensional B-spline

Since the dawn of modern acoustics if you wanted to calculate a reflection off a surface, either by hand or computer, it had to be a flat surface. If it was a curved surface it had to be broken down into a series of contiguous flat surfaces; a procedure prone to inaccuracy. An obvious reason why acousticians might have been afraid to learn from traditional forms of the past, i.e. curved forms.
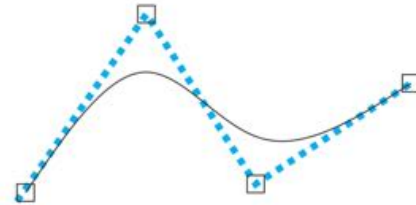
This is no longer the case, thanks to NURBs. Non-uniform Rational B-splines. NURBs are to three dimensions what B-splines are to two dimensions. Please see Figure 8. Originally developed in the 1960s for the automotive industry, their impact on architecture and acoustics is only now being realized with easy access to cheap powerful computers. Anything from rubber duckies to opera houses are now being designed with NURBs. Through easily accessible software like Rhino and others, NURBS are changing the form of our built environment. They are, I suggest, one of the most exciting things happening in our little world of acoustics. And just three weeks ago my friend Eckhard Kahle and I chaired the very first session ever on NURB based acoustic design.

With NURBs, one no longer needs to fracture a curve into a series of flat surfaces and then still pretend that it's a curve.
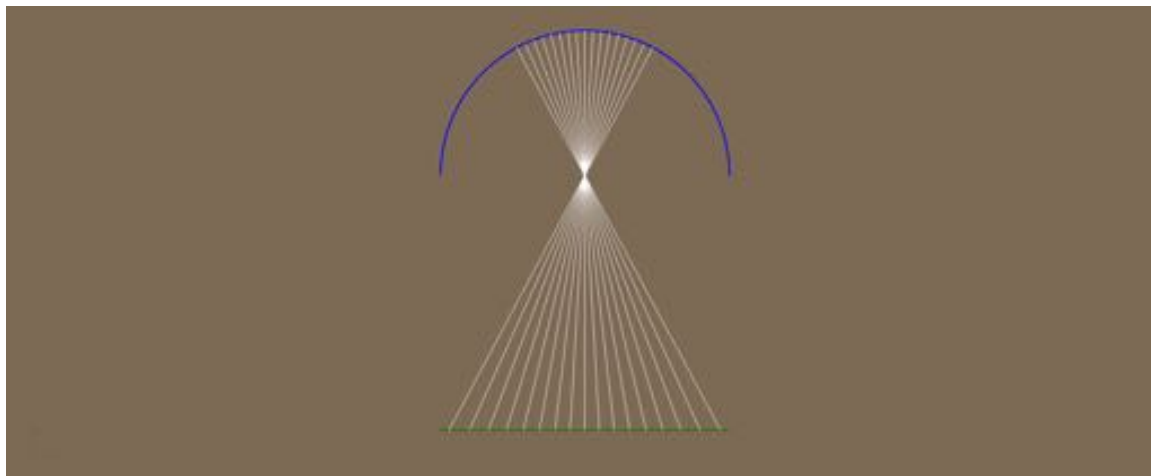


Figure 9  2-D representation of circular focusing.

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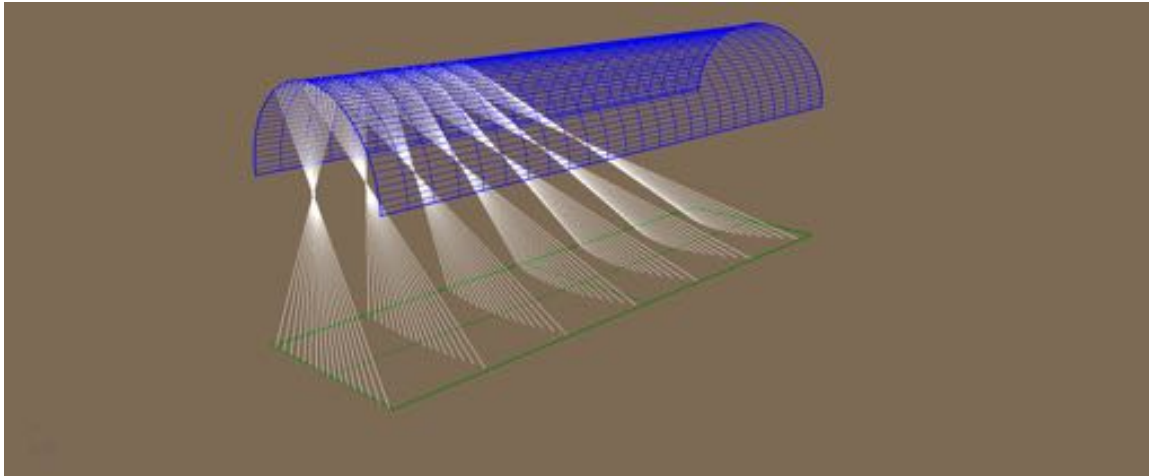Learning Modern Acoustical Design from Traditional Choir Venues



Figure 10  3-D circular reflections.

So, let's go over the basics of concave surfaces and focusing.  There are three zones to consider; Circular, Parabolic and Elliptical.  In a circular focus, the source/receiver distance equals the radius of the curve.  Figure 9 shows you what it looks like in two dimensions.  But things get a little more interesting in three dimensions, as shown in Figure 10.

Parabolic reflections occur when the source/receiver distance is half the radius.  Parabolic reflections propagate in parallel lines away from the reflector. But as you can see from the 2 dimensional representation shown in Figure 11, things aren't quite that simple.  The source/receiver distances near the centre are half the radius, resulting in parallel lines but at the extremities the distances are no longer half the radius.  Resulting in the two foci, shown in the image.
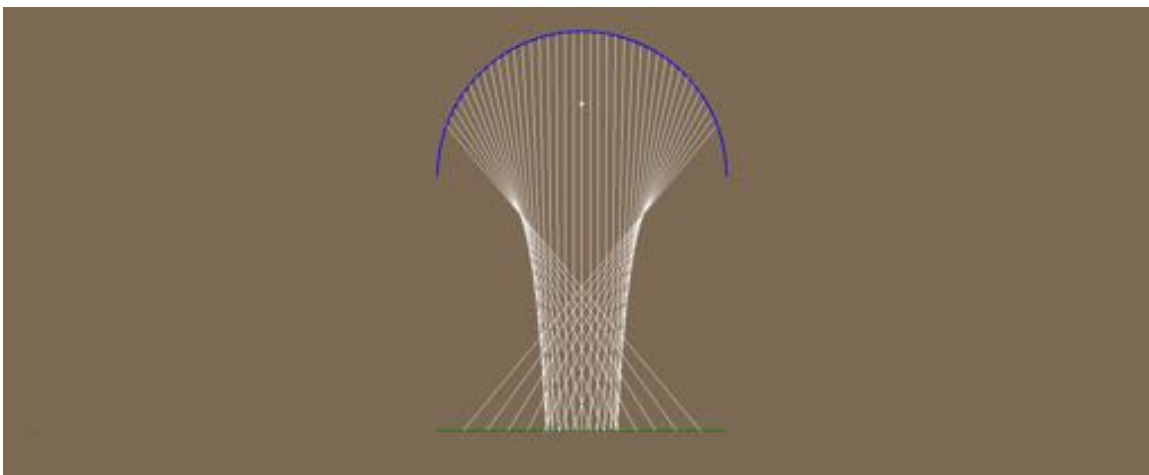


Figure 11 2-D Parabolic reflections.

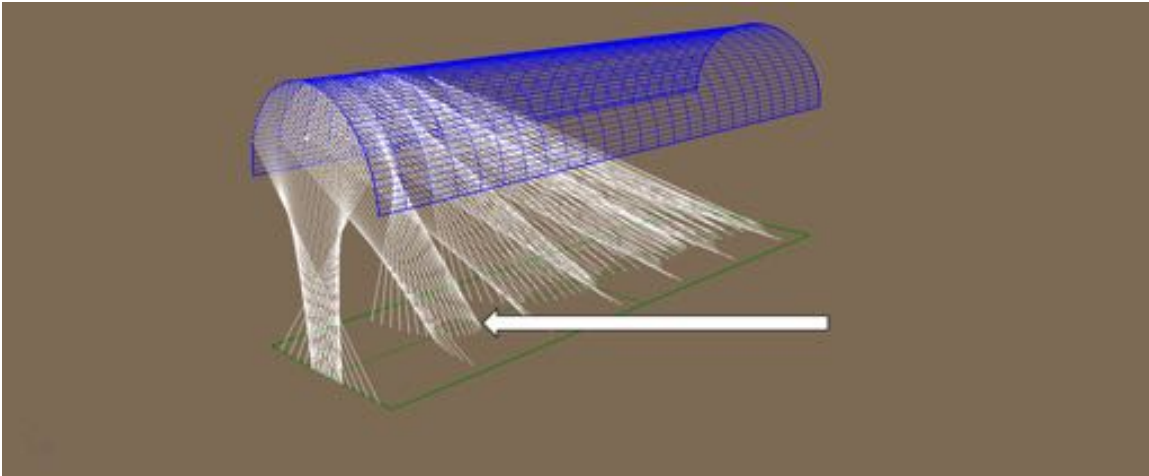Learning Modern Acoustical Design from Traditional Choir Venues



Figure 12  3-D Parabolic reflections.

Things get even more interesting in 3 dimensions.  Note the circular pattern starting at the arrow shown in Figure 12.  It expands as the sound propagates towards the back of the room.

The most interesting reflection zone for us however is the elliptical zone.  For elliptical reflections, the source/receiver distance is greater than half the radius, where the source is at one focus of the ellipse and the sound converges at the other.

Here's an experiment we're working on. We're trying to optimise side wall soffit reflections. Soffit reflections have three salient advantages.  Being lateral reflections, as we all know, they will improve spatial impression.  Recent work by Tapio Lokki and his team indicates that lateral reflections are
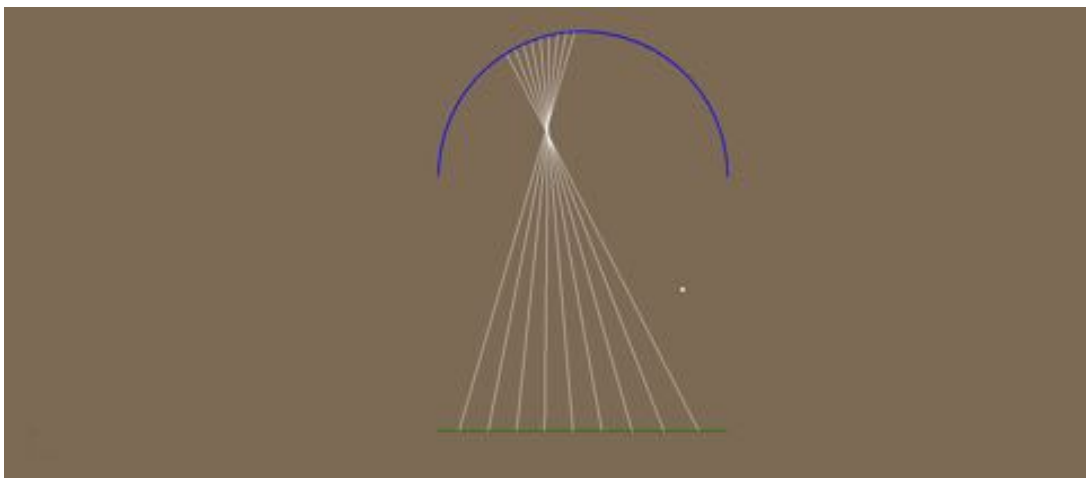


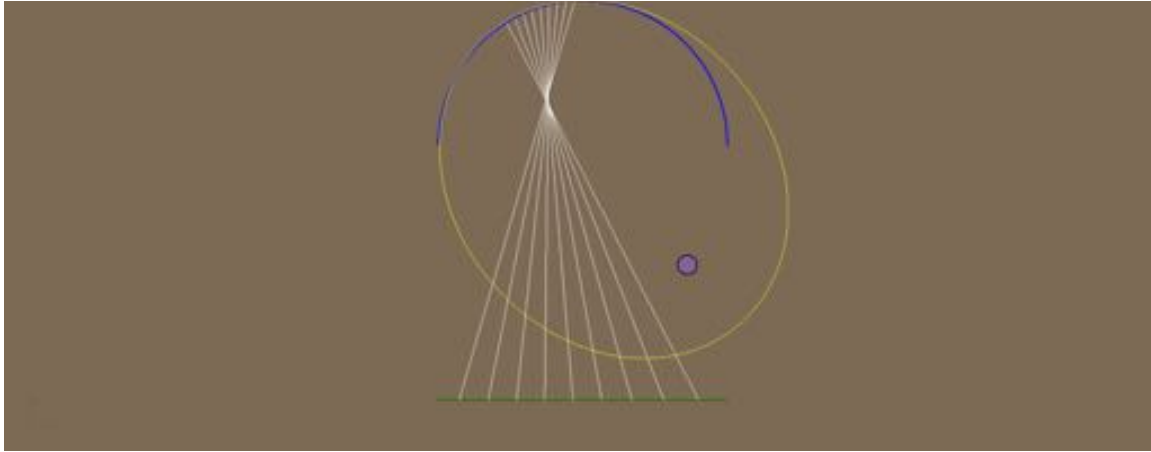Figure 13  2-D Elliptical reflections.

Figure 14  Elliptical focus showing the two foci.

perceived as louder.  And if you might doubt that, as Tapio points out, think about it the next time you have trouble understanding someone and you turn your head to the side.  What are you doing?  You're listening for lateral sound.  And finally, soffit reflections do not arrive at the listener from grazing incidence and are not therefore subject to low frequency destructive interference attenuation.

The trick with elliptical reflections is, where does one locate the elliptical focal point?  Too close to the audience is a bad thing, as we all know.  But too far away is also a bad thing because it creates too much diffusion.  The sound is, as it were, sprayed around too much and is not always directed to the critical listening plane.

We know where the sound source is and that becomes one of the two foci of the ellipse.  Which can be seen in Figure 15.
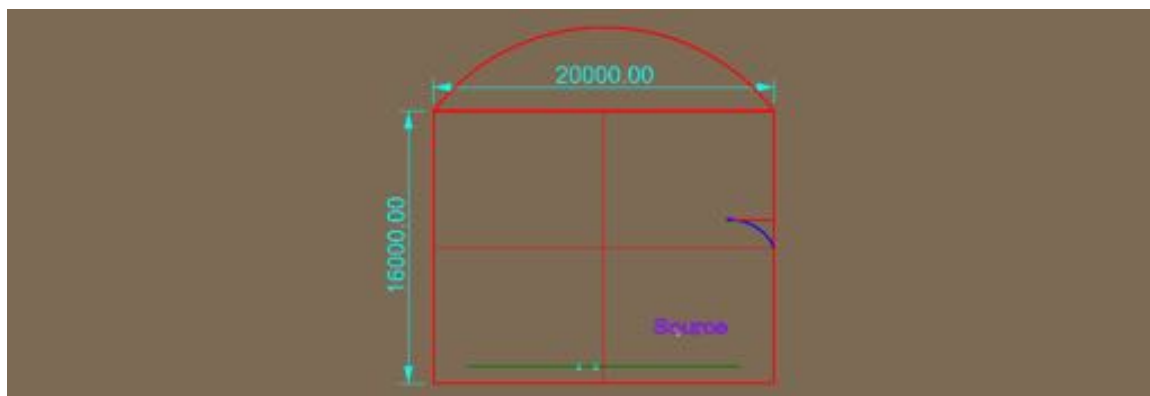


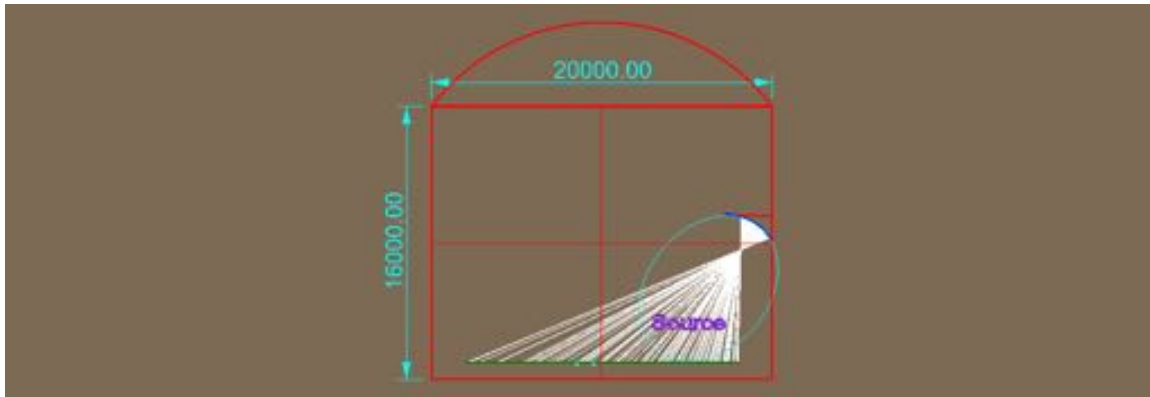Figure 15  Soffit reflector optimisation.

Figure 16  Same as Figure 15, showing the reflection distribution.

We then create a partial ellipsoid to generate the soffit reflections.  The focus of which has been strategically located to be high enough to avoid image shift but not so high as to diffuse sound away from the receiving plane.

Lately, we've taken things even a step further, using computer optimisation algorithms originally intended for aircraft wings.  We no longer have to optimise reflector design with perhaps a dozen or so iterations by hand.  Computer based optimisation allows us thousands or perhaps tens of thousands of iterations.

I'll finish with the interesting image shown in Figure 17.  It brings up one of those topics that is best described as: "food for thought".  I apologise for the image.  It's not very good.  It was taken with my iPhone at a recent concert that my wife's choir performed. And I'll draw your attention to the single bass player in the orchestra, shown with the big arrow.

Being a bit of a Jazz fan, where these days, even in the tiniest of rooms, the string bass is amplified, my first thought when I heard his sound was: "Okay, so where's the amplifier?"  Of course, there was no amplifier.  At least no electronic amplifier. But there was, as you can see, a beautiful barrel vaulted ceiling.

Parenthetically, it's worth noting that the choir's next concert included a string bass *with* an amplifier. I suppose he thought he needed to fill a bigger room than he was used to.  He didn't.  And his sound was seriously compromised.

Back to the concert.  I was sitting with our daughter in the balcony and, as you can see from the schematic representation in Figure 18, I was not all that close to the focus of the barrel vault ceiling. But that single bass was coming in good and loud. It filled the whole room with a wonderful spatial sound.

But, hold on, perhaps I was close to the focus!  Not the geometric focus but the focus of a wave front. In geometric acoustics, we assume that sound waves perform as light does, like a line.  In effect with

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Figure 17  Cantores Celestes at Runnymede United Church, Toronto.

an infinitesimally small wavelength.  And, insofar as focusing is concerned, we're used to a conversation based around a point in space.  But that's not the real world.

Despite the temptations of modern computer based acoustical software, sound is – and will always be – a wave!  So, what's the wavelength of that bass player's instrument?

The low E string is 41 Hz and the high G string is 98 Hz.  That corresponds to wavelengths of 8.37 m and 3.5 m respectively.  Shown in Figure 19.

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And I'm still trying to get my tiny brain around that one.
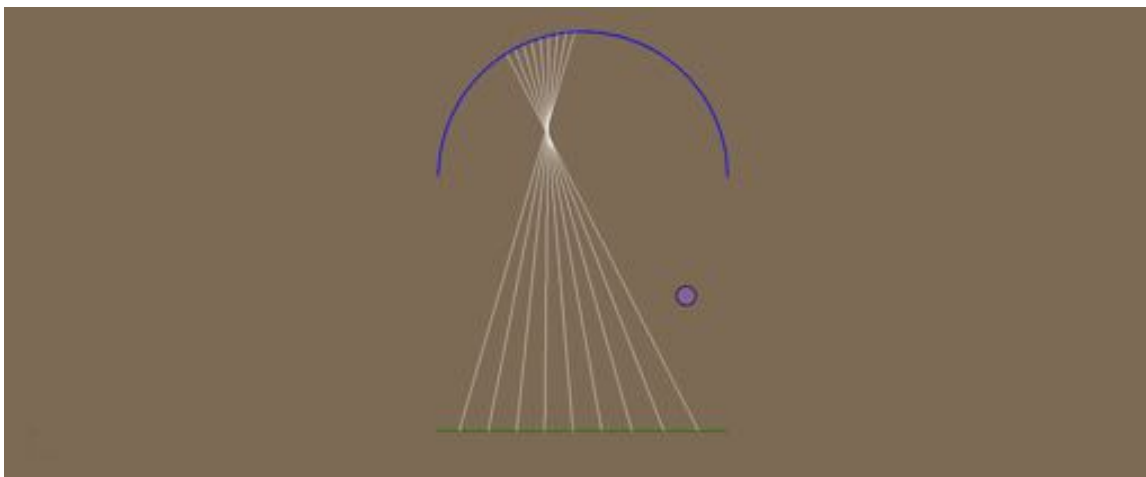
Thank you very much for your time.



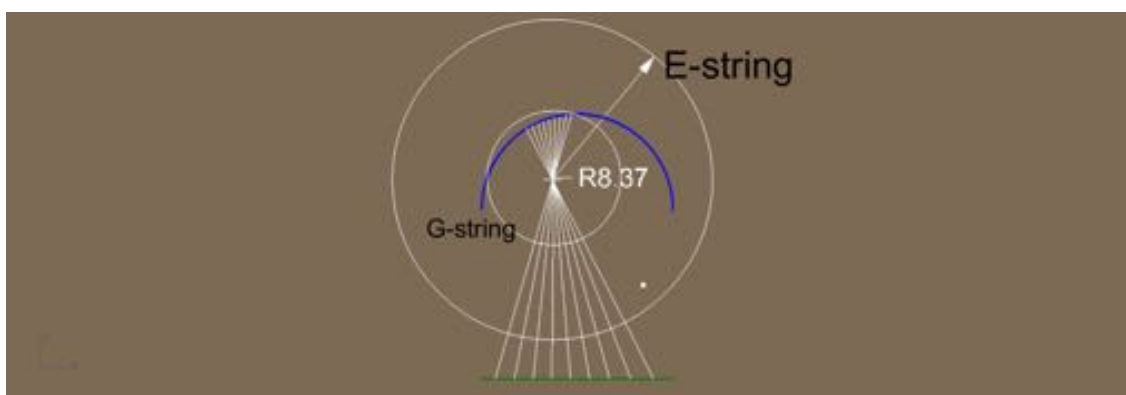Figure 18 Schematic of the focus at Runnymede United Church



Figure 19  Same as Figure 18 showing the wavelengths of the E and G strings on a double bass.