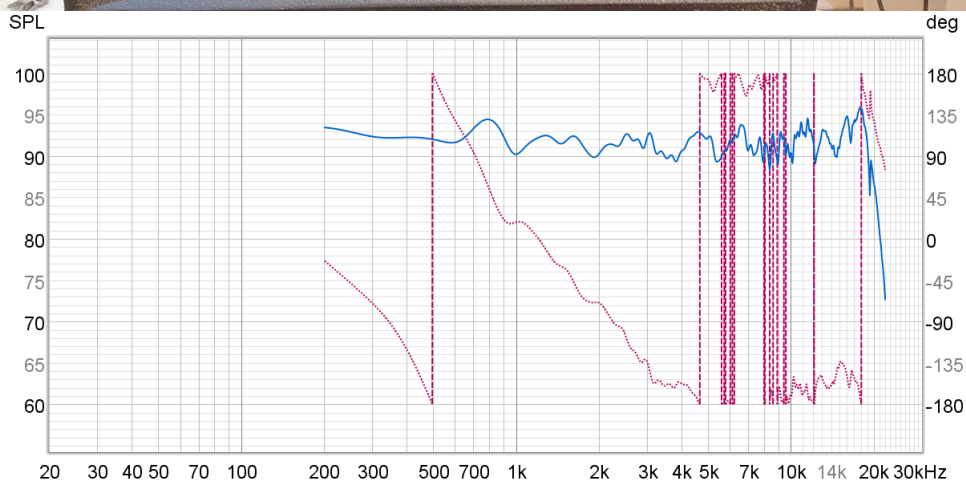
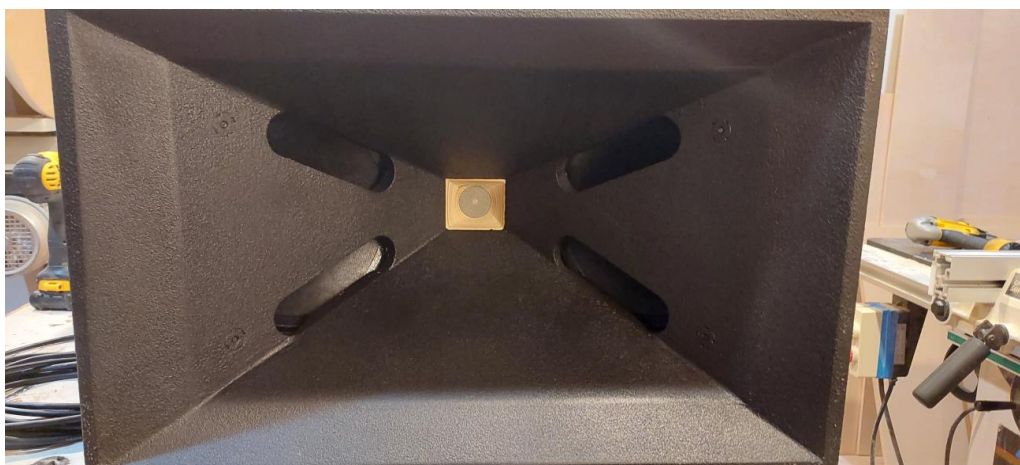


# Multiple Entry Horns Or “The Ultimate Loudspeaker...and I call it MEH”

By

Scott Hinson



## Introduction

It is a truth universally acknowledged, that a single person in possession of a good fortune, must be in want of amazing loudspeakers.

So, I decided to rectify that situation and do a very complete writeup of a style of loudspeaker called a Multiple Entry Horn (MEH). I've been enamored with these designs for quite some time, dating back to my very early days of DIY loudspeakers when I moderated a Listserv out of The University of Texas called The Basslist. Lots of luminaries of loudspeaker design chatted in that forum...and at the time I understood almost none of it. I understand it significantly better now, well enough to have designed multiple MEH systems...so here goes.

## History

A discussion of MEH loudspeakers wouldn't be complete with a brief discussion of how we got here. This isn't meant to be exhaustive in any way, but it is helpful to understand the problems current MEH designs solve before delving into this design example. MEH have multiple types and sub-families within them. The design style started with examples of compression driver manifolds used as far back as the 1930's, and possibly earlier. Early RCA, Western Electric, Klangfilm speakers would use these multiple entry manifold structures to couple any number of compression drivers onto a high frequency horn. Inevitably the maximum SPL and sensitivity of these systems was somewhat less than a pure summation calculation would indicate you should achieve. You'd also tend to see evidence of comb filtering if you had enough frequency resolution in your measurement. The reason for this was typically that the manifolds had different path lengths for the wavefront traveling through the manifold resulting in cancellation and poor summation.

This is also the primary reason a compression driver has a phase plug, if the pathlengths from radiating diaphragm to exit are different then the same cancellations will set up. The problem is, at high frequencies, the path length differences are small enough that it doesn't take much of a difference. The wavelength of 20kHz is  $\sim .68''/17\text{mm}$ , meaning that you can have  $.34''/8.5\text{mm}$  of a difference in path length and you'd have complete cancellation...since that's half a wavelength or 180 degrees. If you're 90 degrees out of phase, you lose 3dB in your summation, that's only 4.25mm at 20kHz. You can see where this means precision is important...

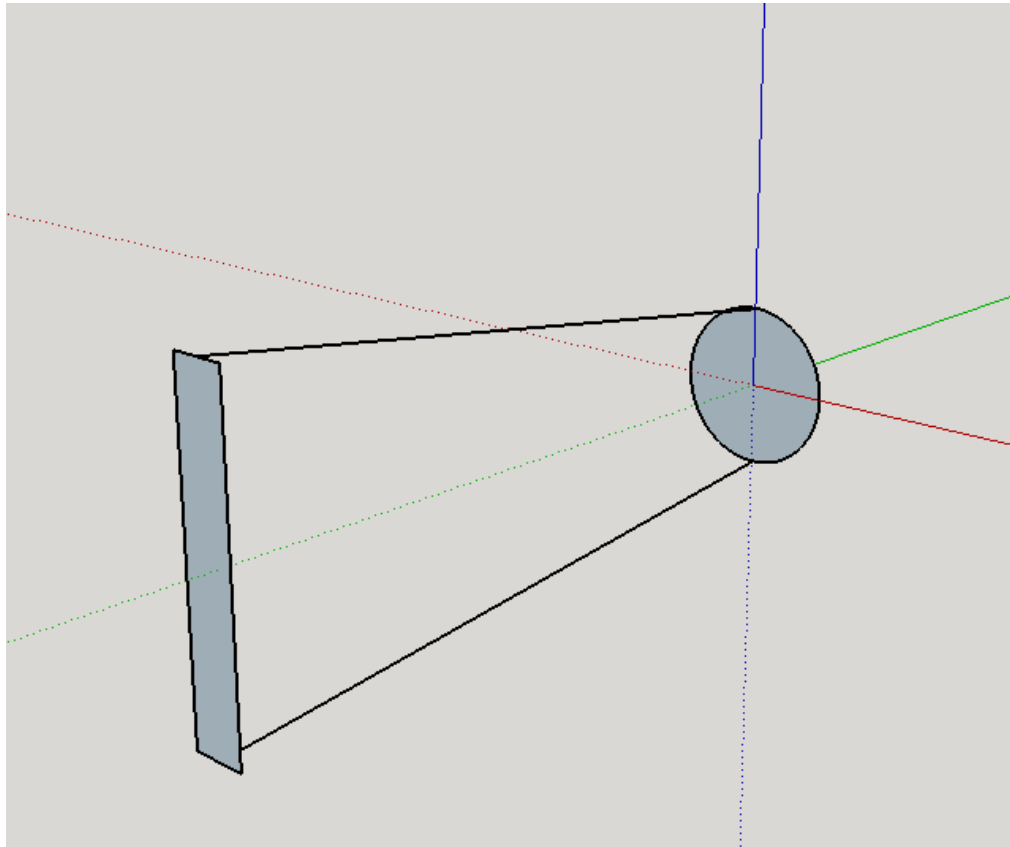
Over the years designers tried multiple solutions for this...but it all started to really heat up in the 1990's. Meyer Sound, Renkus-Heinz, JBL, Bose, L-Acoustics and Sound Physics Labs all started coming up with solutions to this path length problem that were relatively easy to manufacture and worked really well. Many of these inventions were centered around turning the output of a compression tweeter, which they roughly considered a circular flat, single phase



wavefront (it's not, but that's beyond the scope of this document) into a line source. Or as stated in the L-Acoustics patent for the V-DOSC:

"This wave guide aims to transform a planar circular isophase (membrane of a loudspeaker or output of a compression chamber) wave surface into an isophase planar rectangular wave surface."<sup>1</sup>

To translate that as a picture...



*Figure 1 Circle to Rectangle...but with sound.*

It's a really fancy way of saying "I make the circle go rectangle". Then...in theory you can stack up all the rectangles creating a true line source and comb filtering is eliminated. In practice the rectangle isn't perfect...and the comb filtering isn't eliminated, but it is reduced a heck of a lot and the system works a lot better than anything that had come previously before it.<sup>2</sup> Note that the exact geometry of the system is important and the wavefront launch into the waveguide is

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<sup>1</sup> <https://patents.google.com/patent/US5163167A/en>

<sup>2</sup> Note, this is why you can't just stack small horns and call it a line array, we've all seen those pictures where someone has taken some pole mount PA speakers and flown them....and it's just not the same thing.



pretty critical too. I've seen some misguided attempts using soft dome tweeters....that's not a good idea and the results will be sub-optimal at best.

The point of these advancements, in a broad overgeneralization is that it allows you to get enough high frequency drivers close enough together, without cancellation to cover long distances in a live sound setting. It also allows you to get midrange/woofer drivers close enough to the tweeters where, at long distances they are close(ish) enough to avoid comb filtering. The effectiveness of that is...well...hotly contested, and all sorts of things have been tried over the years to make the physical result closer to the ideal.

When you look at one of these first gen V-DOSC (or other) type line source systems you might have wonder how well such a design controls horizontal directivity. The answer being...good enough...maybe...ish?



Figure 2 Sideways L-Acoustics V-DOSC System (<https://www.solarisnetwork.com/used/v-dosc/30904>) FYI, those mids are likely made by Focal...not kidding...there's a connection between concert sound and your home audiophile speakers you weren't expecting....

The loudspeaker drivers themselves are setting the horizontal coverage for the tweeters in the example above, but they aren't a nice smooth waveguide like we normally want to see/use...so



as a result, physics being...well...undefeated...the horizontal pattern wasn't as even as one might like.

Lots of iterations on a theme have been tried over the years by JBL/Meyer/L-Acoustics and others. These typically can be summarized as providing a smoother surface with enough opening to let the lower frequency sound out. The horn loading of the mid is minimal to moderate at best, and typically non-existent...we'll come back to that in a bit.



*Figure 3 Minimizing Driver Profile and Center to Center Distance Impact, JBL Example <https://jblpro.com/en-US/products/vtx-v20>*

One challenge with these types of line array systems is that used as a single box they typically make a pretty poor performer in singles. Sure you can EQ the daylight out of them and make them sound alright (lord knows I've given enough presentations/speeches at renewable energy events with JBL small format line array elements used as reinforcement in singles. Sure...speech is intelligible (ish) and feedback is reduced (ish) but I wouldn't ever want to listen to music on them that way). To come up with a useful point source Renkus-Heinz patented a multiple entry horn design in 1995.





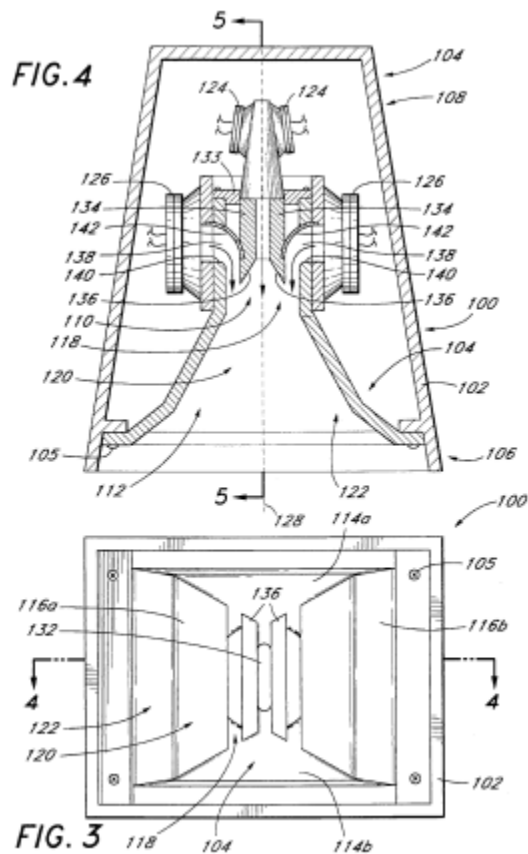


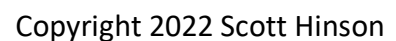
Figure 4 Renkus-Heinz Multiple Entry/Co-Entrant Loudspeaker (from <https://patents.google.com/patent/US5526456A/en>)

Reading through the patent a lot of attention was paid to getting multiple drivers coupled into the same horn where the entry points (sometimes called “taps” in the various forums) don’t interfere negatively with the high frequency drivers. A lot of attention is also paid to the idea that the lower frequency path length and the upper frequency path length is roughly the same,

MEH

FIG. 1 (PRIOR ART) shows two views of a prior art speaker assembly. The top view is a cross-section of a speaker mounted within a rectangular frame 52. The speaker consists of a central cone 60 with a top cap 58 and a bottom cap 64. The cone is supported by a central baffle 62. The frame 52 is shown in cross-section with hatching. The bottom view is a perspective view of the same speaker assembly, showing the frame 52, the central cone 60, and the baffle 62. The frame 52 is shown in perspective with hatching. The bottom view also shows the speaker's mounting points 54 and 56. The bottom view is labeled with a dashed line and the number 2, indicating it is a perspective view of the assembly shown in the cross-section.

Figure 5 shows the typical coaxial horn arraignment (again from the Renkus Heinz patent) used prior to about 1996-2000, and still used occasionally today. There are multiple significant issues with this design....the higher frequency horn can take up substantial volume of the lower frequency horn. If you take this into account in the expansion of the low frequency horn you can mitigate this somewhat, but then you have a poor wavefront exiting the horn no matter what you do. If you push the lower frequency horn up to meet the upper frequency horn, the



response will be ragged because of this and reflections from the smaller horn. The smaller horn will always be relatively far in front of the lower frequency device in time, making accurate summation without digital delays difficult or impossible. (Typically the distances are such that passive all-pass delay networks aren't a realistic choice, the values get to be large quickly.)

If you just use a standard layout of horns adjacent to each other that means that the phase relative to each other changes with listening angle. Direct radiator speakers have this issue too, which is one of the reasons that people advise a mid be placed as close as possible to a dome tweeter. But in a direct radiator system that distance might be 5-7" for a 1800Hz crossover, for a horn system that distance might be 20" or more. The Renkus-Heinz solution largely these issues. There is a single wide bandwidth source for sound (the horn mouth) the path length differences are largely eliminated and reflections/ripple caused by nesting large horns is reduced to whatever issues are caused by the discontinuities of the horn expansion by the taps of the lower frequency sources. The patent drawings show a two way version of this...but there's no reason it couldn't be extended to a 3 way (or more) but the already difficult mechanical construction would become even more complex. Note...this is in no way a comprehensive review of all the various solutions to these issues. Sound-Craft patented a long waveguide version of a coaxial horn system in 1989<sup>3</sup>, Bose Corporation, Cerwin-Vega, JBL, and many many many others went on a patent spree at the time. *The question then becomes....is there a simpler way to get multiple drivers to couple into a single horn. And the answer is...yes...absolutely.*

## Unity Summation Aperture

In 1999 Tom Danley and Sound Physics Labs applied for a patent entitled "Sound reproduction employing unity summation aperture loudspeakers."<sup>4</sup> The patent was applied for on 4-28-1999, granted on 6-25-2002 and expired on 4-28-2019 having lived out its 20 year lifespan. (Note, if the Patent Office takes too long to review, patent lifetime could be extended past the 20 years from application, in this case we are now past 20 years since being granted.)

Okay...first thing's first. The Unity concept takes advantage of the fact that you don't have to drive the horn from the end. You can tap into the sides of the horn with your midrange and woofers...and there are correct ways to do this. There are also less correct ways to do this. The correct way to do this is to take advantage, over at least a portion of the drivers bandwidth that the horn is performing an impedance match to the driver...and you are getting a very large increase in sensitivity as WELL as the benefit that out of band distortion elements are reduced because those distortion elements won't get the impedance match.

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<sup>3</sup> <https://patentimages.storage.googleapis.com/37/d9/7d/65e3eda2d57608/US5046581.pdf>

<sup>4</sup> <https://patents.google.com/patent/US6411718B1/en>





I've seen this in well designed bass horns where the driver is being pushed way too hard but the distortion is filtered out and the system operator has no idea the woofers are crying for help internally. The subwoofer sounds great...and then it doesn't sound like anything at all.

To take advantage of the impedance match over the length of the horn...as Tom Danley puts it in the patent:

*"While there are many types of expansion rates such as hyperbolic tractrix, exponential and parabolic, there is only one general type that will function in an embodiment, that is the conic or quadratic flare generally provided with horns having more or less straight walls. "*

There is an elegance to the conical/quadratic flare in that the flare rate changes fast enough to allow you to get drivers tapped into the horn at ideal or nearly ideal spots. Other horn profiles such as exponential, tractrix etc...don't. As a result you can tap into the sides of those horns but you aren't getting all the benefit...and in some cases like exponential the flare rate/cutoff frequency isn't changing at all. You're fighting physics instead of working with it.

The next critical thing to glean from the patent is this:

*"A multi-way speaker system is provided herein to include a three-way system with a mid-range, a tweeter, and a base speaker for a transformation over the entire range where all of the drivers are acoustically highly coupled to each other."*

Translation....a properly done multiple entry horn has high levels of impedance transformation over a large amount of bandwidth for the driver. Obviously this is lost at low frequencies...the mouth of the horns just aren't large enough. But that last 6 words are super duper critical...."acoustically highly coupled to each other"

This is something that most folks don't understand about the Unity style design. They see those driver entry taps and think it's a set of multiple acoustical sources. They are not.

For lack of a better description you have to think of them as pressure injectors. And since the wavelengths of the sound they are injecting into the horn is so long it combines to form a single acoustical source in the horn, *\*---never to separate again-----\**. In a dynamic system, say a column source of tweeters you can almost always find evidence of comb filtering. There is destructive cancellation at some frequency/angle off axis.

So...once that sound enters the horn...it is a single acoustical source even though there might be 6 midrange taps. And...if done correctly through the crossover region it forms a single coherent wavefront with the woofers, even though that might be 4 entry taps. The subjective result of this is that the listener experiences an softball sized acoustical source floating in the middle of the horn emitting the sound.

Next up from the patent.



*"When one compares a conical/quadratic flare to an exponential or other more common type, one sees that with the conic horn (like a hollow pyramid with the driver at the apex) that the expansion rate is initially very rapid (the reason for poor low frequency loading). With this type of horn, in effect, the flare rate gradually slows or becomes suitable for a lower frequency the further you put the throat towards the mouth.."*

Here Tom is reinforcing the idea that a conical/quadratic flare are the correct ones to use. In an exponential horn the cutoff frequency/flare rate is constant over the length of the horn. So even if you tapped in closer to the mouth of the horn (biggun end) it's not going to benefit you.

Again from the patent:

*"Because the mid and lower frequencies are produced by drivers, and because the larger area provided at the introduction of the signals, a lower throat pressure results in much lower than typically observed distortions due to the air nonlinearity effects discussed above"*

If you try to get too wide a bandwidth out of a horn you run into a couple of problems. The first is that the mass of the driver and air in the horn will present such a high impedance that a high frequency (for the driver) rolloff will be introduced. The patent describes the fact that distortion will be introduced by the pressure of sound in the throat. There is a JBL tech note that describes this happening in the phase plug of a compression driver<sup>5</sup>.

In the Unity horn since you're not forced into tapping into the smallest dimension of the horn, you can avoid an artificially high distortion limit.

Now one of the things that happen when you tap into these horns is that the sound pressure injected into the horn travels in both directions. Some towards the throat some towards the mouth. The sound that travels towards the throat will reflect off of the throat of the horn and start traveling back towards the other direction. At 1/4 wavelength it will create a deep cancellation notch. This will set your high frequency limit for the midrange. You could have the worlds best midrange driver, with the highest motor force, an infinitely light and stiff cone and, you'd still have this notch. You'll just need to work with it....not against it.

Here's an example.

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<sup>5</sup> [https://jblpro.com/en/site\\_elements/tech-note-new-optimized-aperture-horns-and-low-distortion-drivers](https://jblpro.com/en/site_elements/tech-note-new-optimized-aperture-horns-and-low-distortion-drivers)

See Appendix 4. The whole document is a great read though.



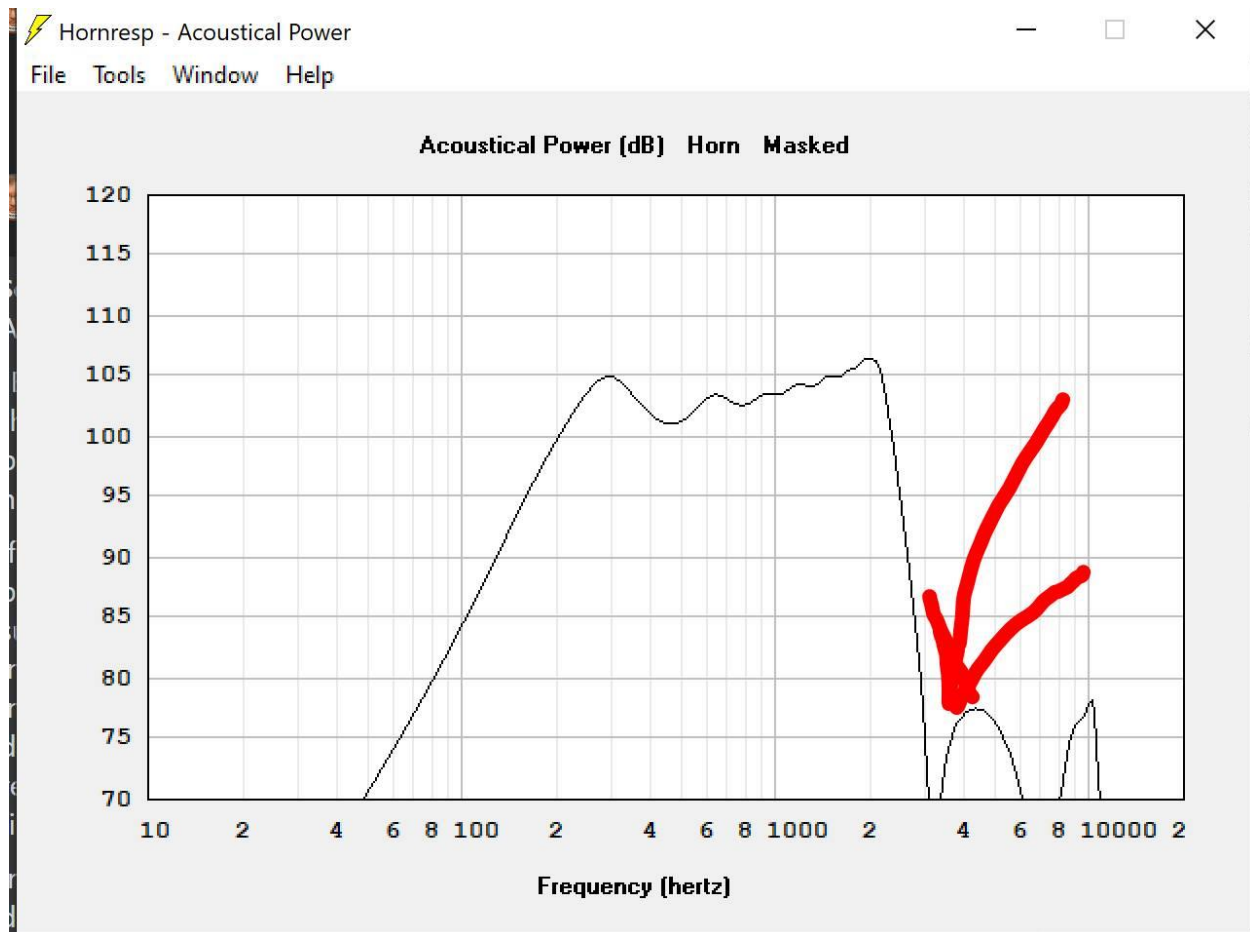


Figure 6 Throat Reflection Notch

Now let's talk about the tap itself....when you bolt the driver to the back of the horn wall it traps a volume of air under the driver.... You also have a volume of air in the hole drilled in the wood (typically 12 -18mm thick) for the tap itself. This sets up an acoustical reactance that serves as a low pass filter.

This is a benefit in that you can use very inexpensive drivers without shorting rings and all sorts of other distortion reducing features. In fact I've done designs using \$.75 full range buyout drivers as the mids that will hit 105-110 dB in their passband at < .1-.3% THD<sup>6</sup>. The easiest way to see this is to play with the chamber tab in Hornresp.

The chamber schematic using the Ctrl-E loudspeaker wizard input is shown below. 1 = Rear volume, 2 = volume captured under the cone, 3 = the tap hole into the horn. The red line is the driver diaphragm.

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<sup>6</sup> <evil grin>



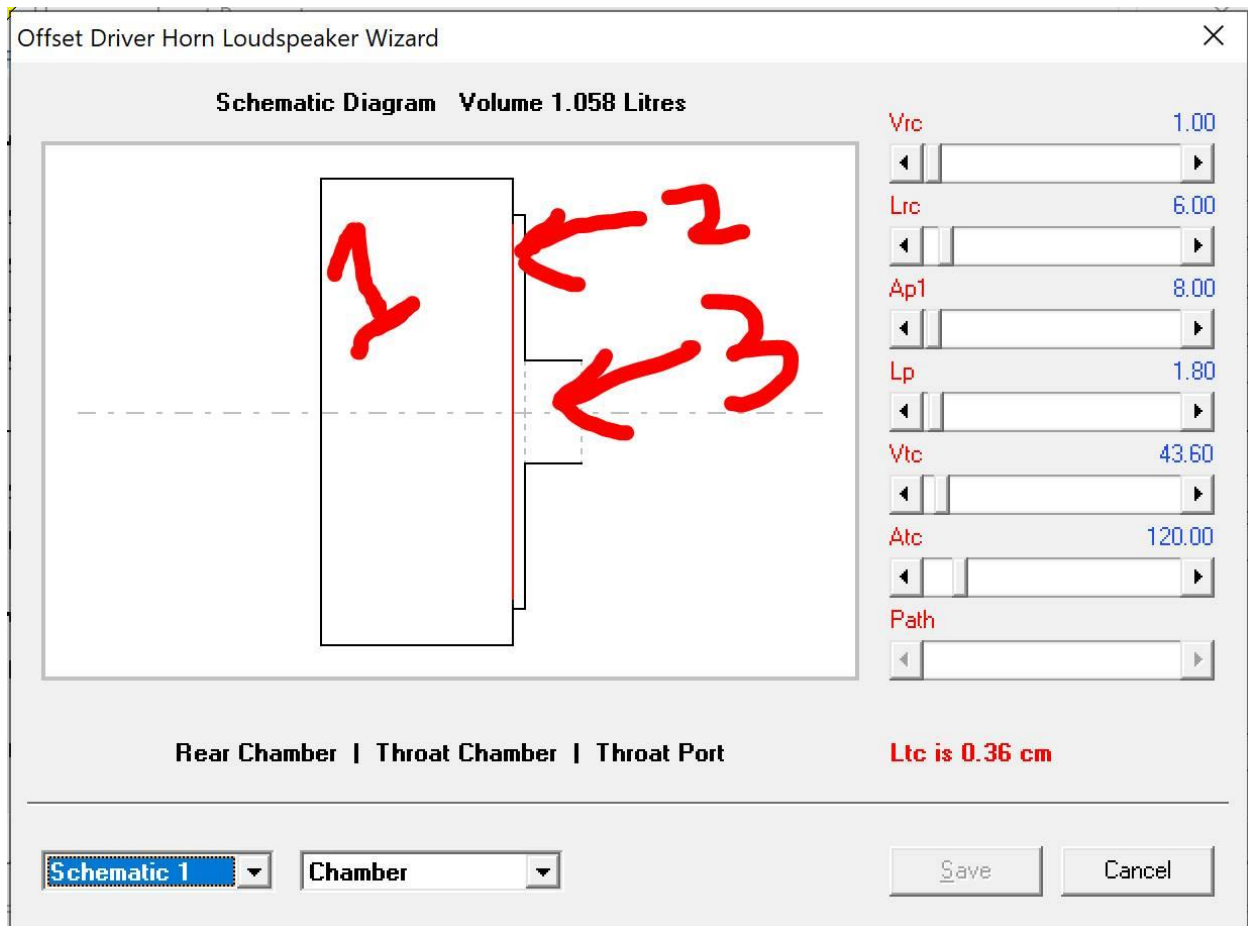


Figure 7 Throat Chamber for MEH In Hornresp

I doubled volume 2 from the original value...notice that the midrange is now rolling off much sooner than before...but that throat reflection notch hasn't changed. I didn't change the L12 distance along the length of the horn so it's going to be in the exact same spot.

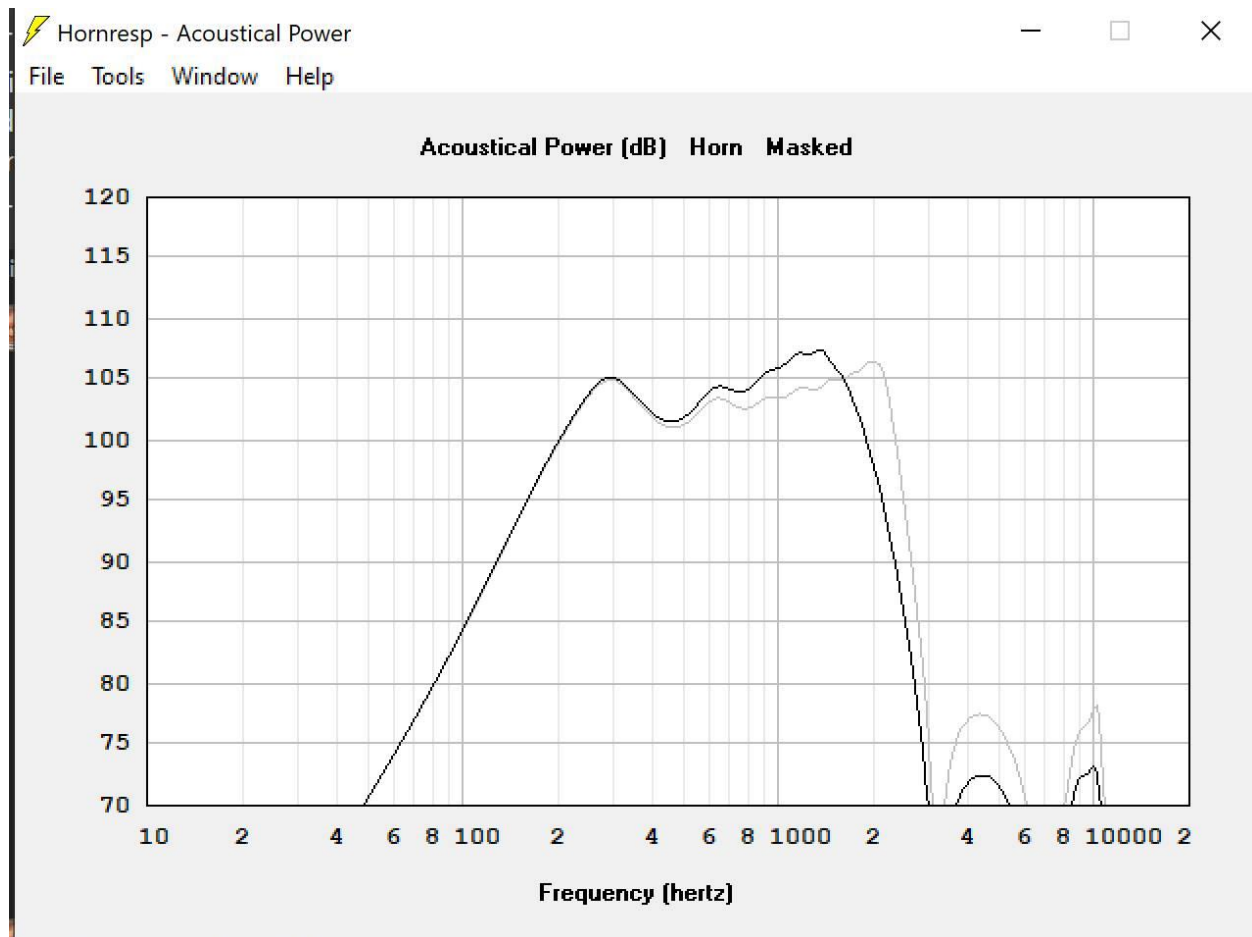


Figure 8 More trapped air

You'll find that it takes some practice...but you need to adjust those three volumes as you're working with a given midrange. Volume 1 is typically pretty tiny....and can be used to drastically shape the low frequency response of the midrange. Volumes 2 and 3 impact the high frequency response. And L12 distance will impact both...so be prepared to juggle the values for quite some time. After you've simulated like 400-500...you'll get to the point where you can determine which make good driver choices and which ones don't.

Now let's talk about issues with midrange taps being too small. You'll find that you can push the HF corner up very close to the reflection by minimizing the volume under the driver cone and making the tap hole smaller and smaller. There's a catch to this...at low frequencies the pressure can be quite high. I've have never done it myself, but I know it's entirely possible to tear cones in an offset driver horn entry like this. The things that typically make for a good midrange response out of a driver also make it inherently more likely for this high pressure situation to develop.



One way to get around this is by using more midranges....I suspect but don't know for sure that hitting maximum output numbers without tearing the midrange cones is why the commercial products will sometimes include 6 midranges.

For a home audio situation, it is entirely possible to get to hearing damaging levels with 2-4 3" midranges in a good Unity style MEH horn design, so don't go chasing output for output's sake unless you need actual PA levels and longevity.

Another issue is midrange tap placement...you see them in the corners so they don't add to the ripple associated with the tweeter response.....this is another reason some woofer taps aren't holes but long racetrack style shapes....it gives you more area for air velocity without intruding into the horn. I've measured horns with/without the midrange taps taped over and it makes almost no difference to the tweeter response.

## But is there a way to cheat?

One of the things that has always frustrated me is the difficulty in finding a great midrange driver, and the complicated assembly for a horn like the one Danley describes in the 2002 Unity summation patent. There's a number of drivers that work okay, but what you really want for that driver is something with a very stiff cone, relatively small diameter (helps you fit it close to the tweeter in the horn) very high BL and high Fs. You can drive the Fs higher by making a super tiny back chamber, but that can only get you so far for practical implementations and construction methods available to the DIYer. Celestion, Eminence and a few others make pretty usable drivers but I really wish I had a magic wand to get something specific made without having to commit to thousands of drivers.

Even when you have a good mid driver the construction difficulties for a 3 way co-entrant system is complex...added to the compound miter joint construction is a set of midrange driver taps into the horn, back cups/enclosures etc. And since the taps into the horn need to be within  $\frac{1}{4}$  wavelength of each other you typically use 2 or more midranges. That means extra precision and lots of extra parts. There has to be an easier way!

Enter the DCX-464 It's a dual diaphragm 1.4" exit compression driver. The mid frequency unit, on the right horn is specified to be useable down to 300Hz.

Whoa....

Knowing what I know about that variable flare rate....it's possible to get up to 400-600 Hz with 10" or 12" woofers depending on the coverage angle of the horn. That means...whoa....I can go directly to the compression driver from the woofer, and still have a three way system.

Whoa....again. That's a game changer.







*Figure 9 This Tweeter. Look at it. Keep looking at it. It's amazing. Also...the airport security folks do \*not\* know what to make of it. Photo (Source: B&C Media Release)*

The specs for the tweeter are impressive...you can cross over the “mid” frequency diaphragm as low as 300Hz and the AES power handling for that voice coil is 110W. Sensitivity is a whopping 111dB/2.83V/1m. The HF coil handles nominally from 3.5kHz on up, handles 80W and also has a ~111dB/2.83V/1m sensitivity.

For folks used to home audio drivers, especially tweeters, the power handling specifications may not sound that impressive, but they are. Home audio tweeters rated to the IEC specifications can't handle remotely the power that pro audio drivers rated to AES specifications. The IEC specification is more accurately described as a system specification.....the voice coil for a dome tweeter is likely to melt if it is dissipating in the 5-10W range.

Considering my use for these speakers is in a residential setting ....that means that this tweeter will literally be coasting, with drive levels for LOUD listening sessions clocking in at probably



.283V-4V peaks. It also means that there is literally zero dynamic compression in the midrange/tweeter range for a speaker like this when used at home. (You can absolutely get them to compress...I have...but it was a PA situation and well..that was loud yo.)

## Getting prodded to make something...

Tom Voight contacted me to give a talk on loudspeaker design at Burning Amp in October. He wanted me to come and talk about loudspeaker design, and cool technology. I couldn't think of a better way to show off multiple entry horns than to design and build a set in roughly 60 days, and take them to a show in a city 1500 miles away. I mean speaker designs are complicated enough....let's make one of the most complicated under a time crunch and then go display it in public! Sounds fun!

So....what did I make.

I made this:



*Figure 10 Behold. I made a thing.*

## Expectations and Level Setting/FAQ

Q. Is this the best sounding speaker ever?

A. I don't know, I haven't listened to them all.

Q. Is this the best sounding speaker you've ever made?

A. Yes. By far, it's not even close.



Q. Will everyone like this speaker?

A. I'm not everyone, I don't know.

Q. How many people have gone wide-eyed listening to them for the first time?

A. Not all of them...just the overwhelming majority. And those that didn't go wide-eyed...did nod in approval and refuse to give up their listening seat for quite some time.

Q. It's expensive to make!

A. Yes, but that's not a question.

Q. You know what I mean.

A. Also not a question.

Q. Stop it.

A. No.

Seriously the speaker is staggeringly good. For DIY'ers that are used to home audio woofers and the bass/capabilities presented by even quality 10" units you're in for a bit of a shock. The low distortion, ultra high power handling 10NW76 woofers are an absolute treat to work with. The 76mm voice coil and extensive cooling features mean that in a residential setting if you're thermally endangering these drivers, much like the DCX464....you're going deaf.



*Figure 11 Behold. The woofer of your dreams. Not that anyone dreams about woofers.*

Now, this is not to say that the speaker is without compromises. Loudspeaker design is a series of compromises where you have to make certain choices, otherwise the design isn't buildable. This speaker makes one major compromise that I couldn't figure out how to work around, and you just have to live with it. In use it's a minor issue, and again, if you're hearing a problem you're probably playing the speakers at such high volume you're damaging your hearing. Or, you're playing test tones at tuning frequency...which gives a hint at what the issue is.

### Super Woofers and the Port Problem™

Hmm....that sounds like a bad 80's cartoon. As long as the theme isn't as catchy as the Smurfs, I hate that thing<sup>7</sup>.

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<sup>7</sup> You know you're humming it. If you haven't heard it...go look it up on Youtube. I dare you. Also don't hate me.



I've written about this off and on around multiple forums...and possibly even some of these DIYRM writeups (maybe the single 18" vented PA sub?) but it deserves a more detailed explanation.

For any vented speaker woofer motion is at a minimum at the tuning frequency. You can see this in any modelling software that allows you to plot woofer SPL separate from total system SPL or even driver excursion by frequency. You can also see this in the actual woofers watching closely with a frequency sweep done at a drive level that gets the woofer moving.

As the port air mass velocity increases things start to go a bit haywire...turbulent air starts to form at the exit and along the side walls, this disrupts the flow. Eventually the port will start to make audible noise...and if driven hard enough (depending on the geometry) the port will effectively close over. It's not as good as an actual sealed box...it's quite lossy...but at high drive levels with a poor enough port design you can see the impedance of the enclosure shift from the classic double hump vented box shape to a weird looking single hump design. When this happens obviously the frequency response of the system changes, as does the excursion. No longer do you have that excursion minimum, and the port itself is probably making all sorts of ugly noises.

Now...what about modern super-woofers and the port problem? As driver technology has advanced over the years the drivers have gained the ability to over-drive almost any port you can design. In some cases, I would argue that there is no physically realizable port that would handle the absolute best of the best drivers. Why? Is it the excursion? Nope. It's the power handling. Remember that relationship of driver motion minimum at resonance frequency....excursion is taken out of the picture.

In this design I used two 10NW76 in roughly 45L with 2 3"/75mm diameter ports 7.25" long. If you limit the port airspeed to 17 m/s (onset of audible chuffing) and the input power to the AES limits of the woofer you can determine the approximate maximum output for each enclosure. BASTA! can model it quite easily.

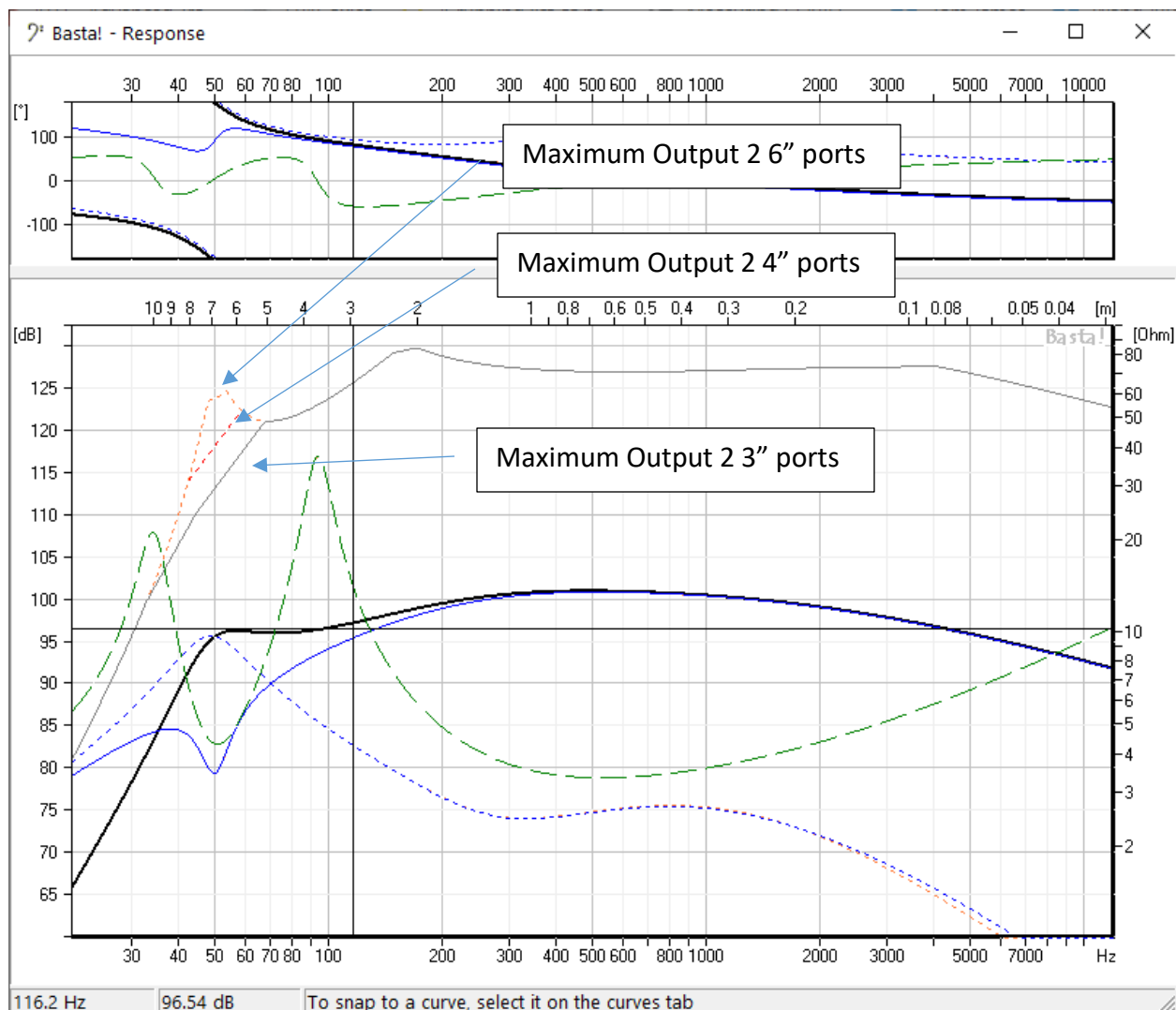


Figure 12 Maximum output, three port sizes.

Figure 12 shows the predictions from BASTA!. I modelled the design as I built it...with 2 3" ports, and also with 2 4" ports and 2 6" ports. You can see that the two 3" ports are clearly overpowered by the woofers. Maximum output level is limited by the port from 70Hz on down. The catch is....nothing bigger would fit. A 4" port would have to be ~13" long and a 6" port would have to be 31" long. Based on where the drivers and horns are I suspect that there's no good way to get those in there...even if you use a pipe elbow. If you make a sharp right angle you can induce 3-6dB of losses, so going with a bigger cross sectional area but making a sharp right turn often reduces your overall output.

Normally when you can't fit the port in a box, passive radiators are an option...even here there's not enough room...so....while it's not ideal I had to make the compromise of a port that fit. So...two 3" ports it is. It's not a huge compromise since the output of the system is such





that you'll be able to damage your hearing in reasonably sized rooms before the port distortion is objectionable...but yeah...just know, I know, this design could use some bigger ports. (Even flaring the ports is not an option...where they physically sit they barely miss the driver frames as it is...trust me I looked at a lot of options.)

### The Knuckle Test.

How many of us have gone into a speaker store and given a speaker a good old knuckle test. Boom = bad, sore knuckles and little sound = good right? The review magazines and audiophile companies will have you believe that:

1. This is a valid test (it really isn't)
2. That this will improve midrange performance.

Right?

So in a traditional dynamic driver two way system...sure...overall enclosure deadening is important. There's obviously overkill scenarios where you've gone too far, but for the most part, especially for DIY'ers throwing in a little extra bracing is effectively free and easy to do so why not. Go for it.

In three way systems the story gets a bit more complicated....the midrange driver is often in a sub chamber. As long as the resonances are pushed up enough in frequency for the woofer, and damped well enough, and the woofer is rolled off enough before those panel resonances kick in....really....how audible is it going to be? The answer is, not really that audible.

In order to keep multiple entry horn design as logistically friendly as possible I built it out of a combination of 12mm and 18mm Baltic birch ply. The sides/top/bottom/back panel are 12mm and horn elements are 18mm. I also have Penn-Elcom handles inset into the sides. This means if you give it an unscientific knuckle test, especially on the two side panels...it won't sound that impressive. Does that impact midrange performance? Heck no. The horn is stiff enough and the compression driver doesn't activate those resonances in the side panels. The woofers could, but it's really not that noticeable given the low pass filter for the woofers. I did put a bit of constrained layer damping material on the sides....so that helps some too.

If your audiophile friends come over and thwack the sides, they're probably going to declare this cabinet a poor design. Just smile...nod and play the speakers. They'll change their mind on midrange clarity reeeeeeal quick. In theory you could try to add some bracing there...but it's a really tight fit getting the mounting bolts installed as it is...adding anything else might make it impossible. I had to go to extreme lengths to get the two interior most bolts tightened on each

woofer as it is<sup>8</sup>....so...beware if modifying the cabinet design. An external access point might be best...but I'll leave that as an exercise for the reader.

## Hornresp Modeling

I used the Multiple Entry Horn Wizard tool in Hornresp to model the input taps for the woofers. A full tutorial on how to use these would make this increasingly long document even longer, and will have to wait for another writeup. The agreement between model and results is more than reasonable:

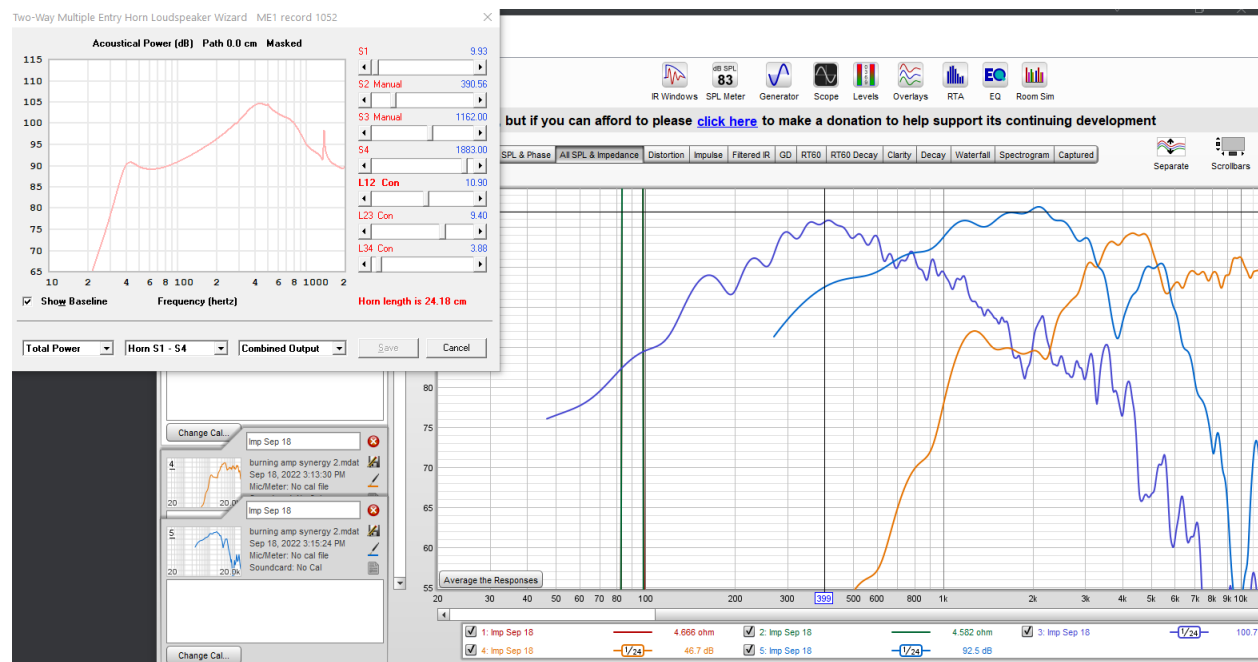



Figure 13 Hornresp vs Measured speaker

<sup>8</sup> More on that later.

 **Hornresp - Input Parameters** — □ ×

File Tools Window Help

<b>Ang</b>	<input type="text" value="4.0 x Pi"/>	<b>Eg</b>	<input type="text" value="2.83"/>	<b>Rg</b>	<input type="text" value="0.00"/>	<b>Fta</b>	<input type="text" value="53.53"/>
<b>S1</b>	<input type="text" value="9.93"/>	<b>S2</b>	<input type="text" value="390.56"/>	<b>Con</b>	<input type="text" value="10.90"/>	<b>F12</b>	<input type="text" value="0.00"/>
<b>S2</b>	<input type="text" value="390.56"/>	<b>S3</b>	<input type="text" value="1162.00"/>	<b>Con</b>	<input type="text" value="9.40"/>	<b>F23</b>	<input type="text" value="0.00"/>
<b>S3</b>	<input type="text" value="1162.00"/>	<b>S4</b>	<input type="text" value="1883.00"/>	<b>Con</b>	<input type="text" value="3.88"/>	<b>F34</b>	<input type="text" value="0.00"/>
<b>S4</b>	<input type="text" value="0.00"/>	<b>S5</b>	<input type="text" value="0.00"/>	<b>L45</b>	<input type="text" value="0.00"/>	<b>F45</b>	<input type="text" value="0.00"/>


---

<b>Sd</b>	<input type="text" value="20.00"/>	<b>Cms</b>	<input type="text" value="1.60E-04"/>	<b>Mmd</b>	<input type="text" value="2.00"/>	<b>Re</b>	<input type="text" value="6.00"/>
<b>Bl</b>	<input type="text" value="8.00"/>	<b>Rms</b>	<input type="text" value="3.00"/>	<b>Le</b>	<input type="text" value="0.05"/>	<b>Nd</b>	<input type="text" value="1"/>
<b>Vrc</b>	<input type="text" value="1.00"/>	<b>Ap1</b>	<input type="text" value="0.00"/>	<b>Vtc</b>	<input type="text" value="1.90"/>	<b>CAUTION:</b> <b>Atc &lt; Sd</b>	
<b>Lrc</b>	<input type="text" value="8.00"/>	<b>Lp</b>	<input type="text" value="0.01"/>	<b>Atc</b>	<input type="text" value="10.00"/>		

**Comment**

Figure 14 Horn Inputs



 **Hornresp - Input Parameters** [Minimize] [Maximize] [Close]

File Tools Window Help

<b>Ang</b>	0.0 x Pi	<b>Eg</b>	2.83	<b>Rg</b>	0.00	<b>Cir</b>	0.00
<b>Ap1</b>	170.00	<b>Ap2</b>	170.00	<b>Lp</b>	1.80	<b>F12</b>	0.00
<b>S2</b>	0.00	<b>S3</b>	0.00	<b>L23</b>	0.00	<b>F23</b>	0.00
<b>S3</b>	0.00	<b>S4</b>	0.00	<b>L34</b>	0.00	<b>F34</b>	0.00
<b>S4</b>	0.00	<b>S5</b>	0.00	<b>L45</b>	0.00	<b>F45</b>	0.00

---

<b>Sd</b>	320.00	<b>Cms</b>	1.21E-04	<b>Mmd</b>	43.34	<b>Re</b>	5.50
<b>Bl</b>	20.00	<b>Rms</b>	2.52	<b>Le</b>	0.38	<b>ME1</b>	2P
<b>Vrc</b>	45.00	<b>Ap</b>	92.30	<b>Vtc</b>	1400.00	<b>NOTE:</b>	
<b>Lrc</b>	34.00	<b>Lpt</b>	28.00	<b>Atc</b>	855.00	<b>Record activated</b>	

**Comment** B&C 10NW76 Compound Driver

Figure 15 Woofer/Rear Chamber/Tap/Port Inputs

## Crossover Design

I have a passive crossover design for these speakers...but I'm still refining it. It's going to be quite expensive since it requires a 15mH to 18mH inductor for the woofer section, with low DCR. Because of availability issues and a lack of choices I decided to go active. I used the Hypex Fusion FA253 amplifiers. These are three way amplifiers with more than enough DSP horsepower to get a response that I wanted. Looking at the measured curves to get a response flat to the mid 40's you can see that some equalization is necessary. If you're worried about the total number of parametric EQ points I used then this isn't necessarily the design for you. Invariably when I talk with DIYers who prescribe to the less is more camp on filtering/equalization I find that they really haven't performed good measurements, or measurements at all and are cherry-picking source material that doesn't run afoul of the issues resulting from the low order filters. You also have to be careful not to iron the speaker flat



within some fraction of a dB, since those variations may be different from speaker driver to speaker driver....especially with HF units. You can easily be adding to the frequency domain errors of the speaker. So a bit of restraint is a good idea. If you don't like the exact way I stacked up system level EQ vs driver EQ, feel free to modify it....I'm (more than) happy with the final performance...so I'm sticking with it.

So....here goes. Ready??? Is a lot. Is...a lot a lot.

Woofers:

Type	Frequency	Order/dB	Q
LP	63	2 <sup>nd</sup>	.707
Boost/Cut	110	-2.3	3
Boost/Cut	370	-4.8	3
HP	30	2 <sup>nd</sup>	.707
HP <sup>9</sup>	30	2 <sup>nd</sup>	.707
Stage Gain -3dB			

Midrange

Type	Frequency	Order/dB	Q
HP	310	2 <sup>nd</sup>	.707
HP	310	2 <sup>nd</sup>	.707
LP	2200	2 <sup>nd</sup>	.707
Boost/Cut	1070	-8.9	3
Boost/Cut	2000	-8	3
Boost/Cut	5650	-4.72	3
Boost/Cut	2600	-1.7	1
Stage Gain: -4.0dB			

---

<sup>9</sup> Note the two HP filters are optional and can help with woofer port chuffing being audible. They also help with power handling. You can leave them out but it is more likely that you can over-drive the woofers at extreme LF. All speaker measurements in this paper include those filters.



## Tweeter

Type	Frequency	Order/dB	Q
HP	4400	2 <sup>nd</sup>	.707
Boost/Cut	14250	-6.5	6
Boost/Cut	4620	-6.3	4.5
Boost/Cut	7140	-3.8	6
Boost/Cut	3640	-7.3	6
Boost/Cut	10000	-5.4	6
Stage Gain: +.5dB			

## System

Type	Frequency	Order/dB	Q
Shelf High	500	-.5	.707
Shelf High	7000	-2.5	.707
Boost/Cut	4500	1.5	2
Boost/Cut	2000	-2	.707
Boost/Cut	2800	-2.5	3

WHEEWW....right???

BUT WAIT THERE'S MOREEEEE!!!

There's a series parallel L-Pad on each of the compression drivers consisting of a 6 ohm series resistor and a 1 ohm parallel resistor. You'll need two of these per speaker, one for each coil. And yes...I'm serious it's 6/1. With 1 ohm in parallel with the coil...for a nominal sensitivity cut of ~18dB. More on that in a bit.

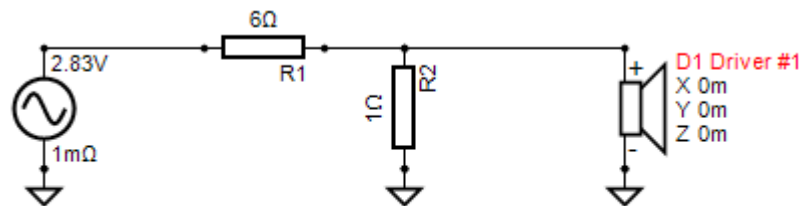


Figure 16 L-Pad Schematic (BOTH MID AND HF COILS!!!!)

So...what does all that EQ buy you?





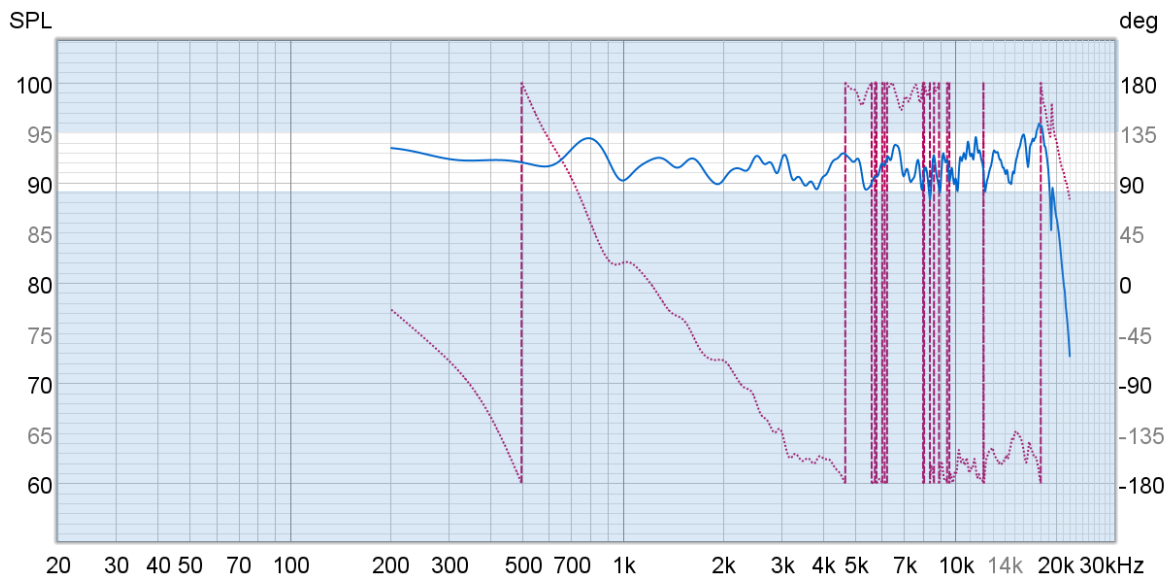


Figure 17 Final Frequency Response/Phase 5mS Gate, no smoothing, unshaded region +/-3dB

Figure 17 shows the final frequency response and phase of the completed system. It's effectively +/- 2dB for a wide swath above 200Hz. In my listening room, without any room correction or equalization for room response the unsmoothed response is:

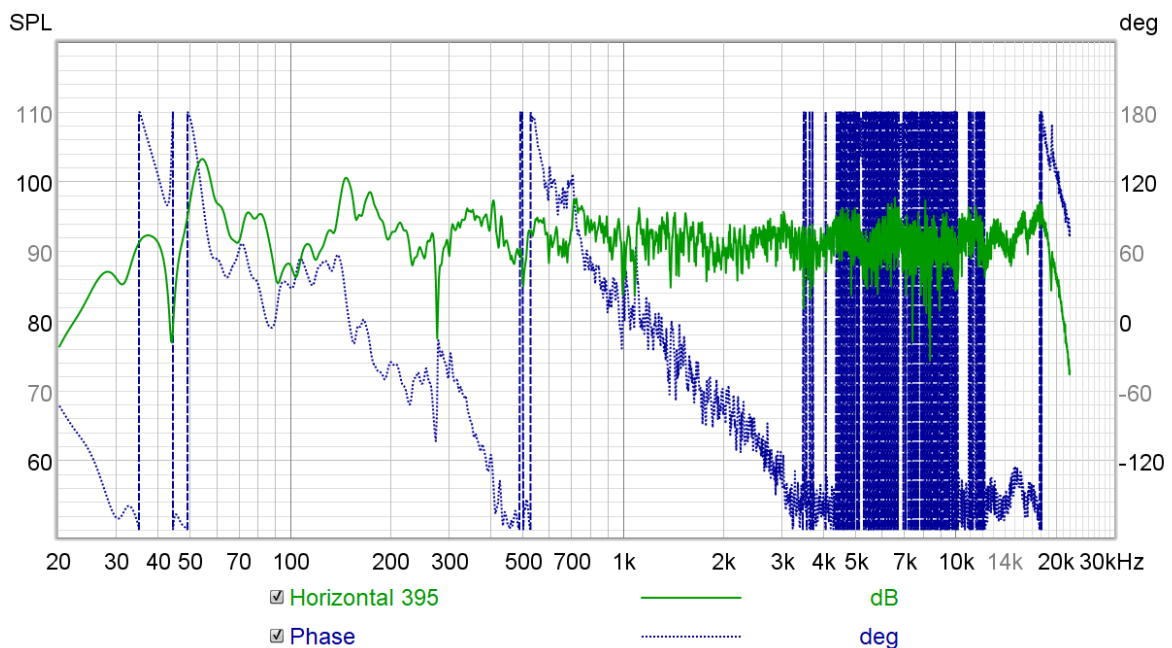


Figure 18 In room Response



Comparing the room response with the gated response, with a mere 1/48'th octave smoothing added to the room response shows how effective the design is at keeping side wall/floor ceiling reflections out of the listening response.

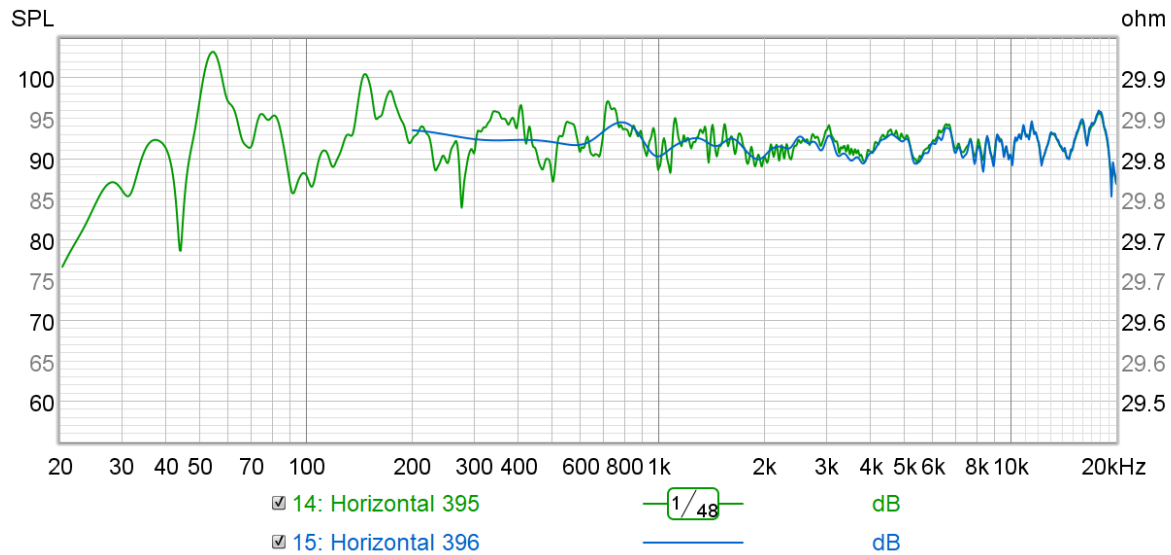


Figure 19 In Room Compared to Gated

I'm not particularly concerned about getting the speaker even flatter. First, the unsmoothed plots are a very revealing, unvarnished look at the speakers performance, and they are pretty smooth. I've written about the impact of smoothing, frequency range, scale many times before. If you plot the speaker using ERB smoothing it looks like Figure 20. If you feel so inclined to make it "better" go for it..there are a ton of biquads left in the filtering<sup>10</sup>.

<sup>10</sup> For me, the speaker is well into better is the enemy of good enough. In this case it should be better is the enemy of it's already great....just stop.



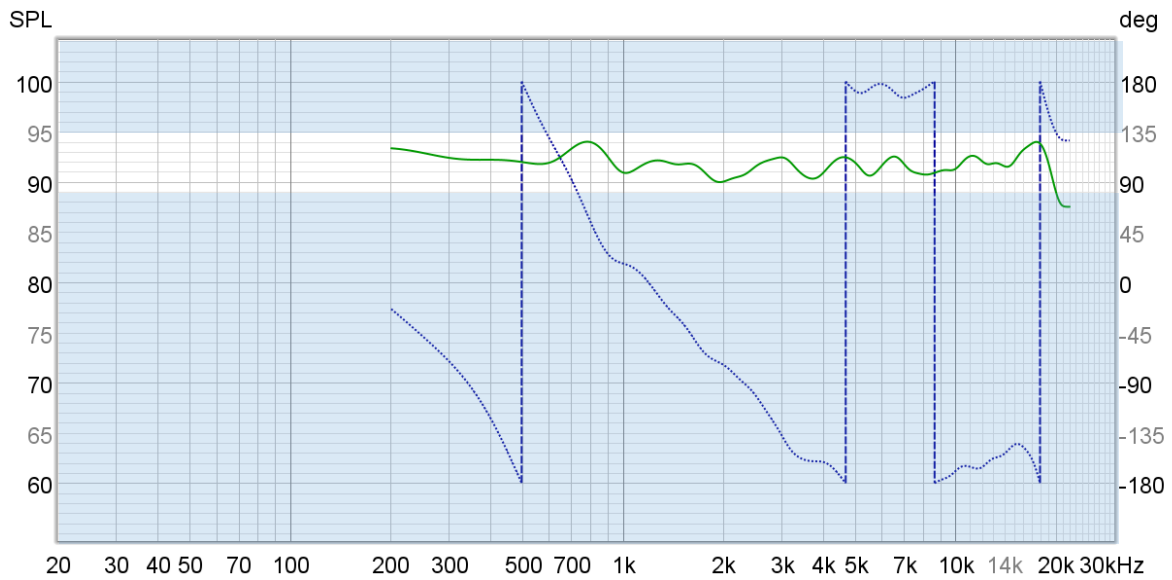


Figure 20 Smoov.

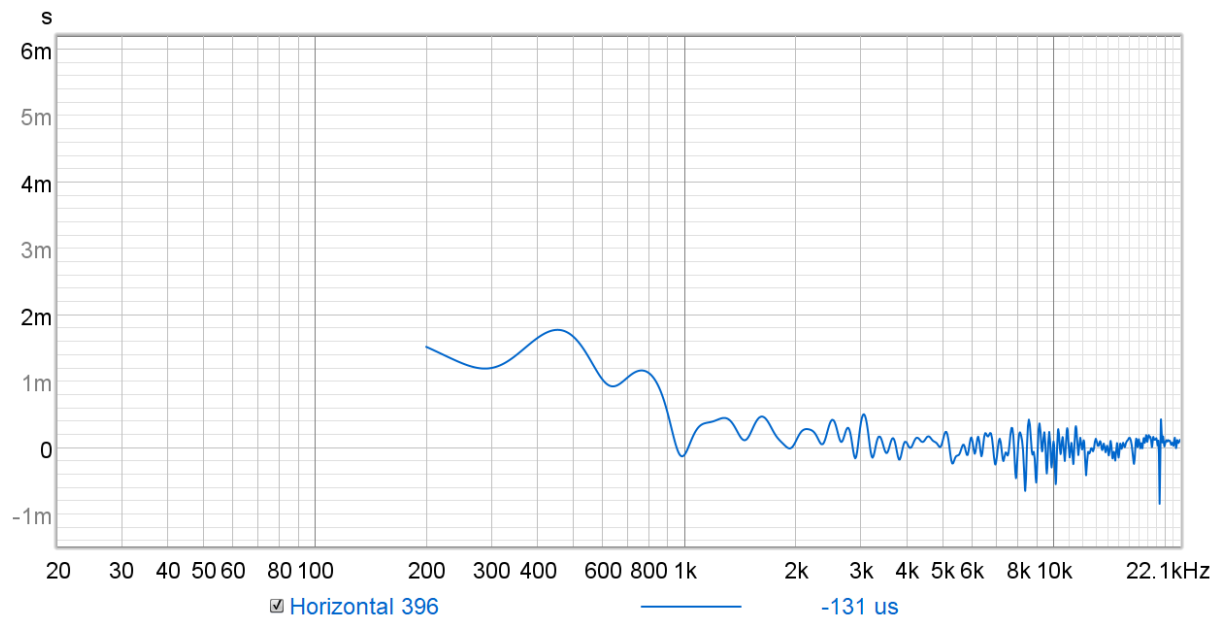


Figure 21 Group Delay

Group delay is well under audible limits for variation. The design is not time domain accurate, you cannot put in a square wave and expect it to follow it. I could have fixed that with FIR capable processing, but I have found no reputable reason to do so. The step performance shows that the tweeter/mid/woofer are all so close to one another that they fall well within the limits of audibility.



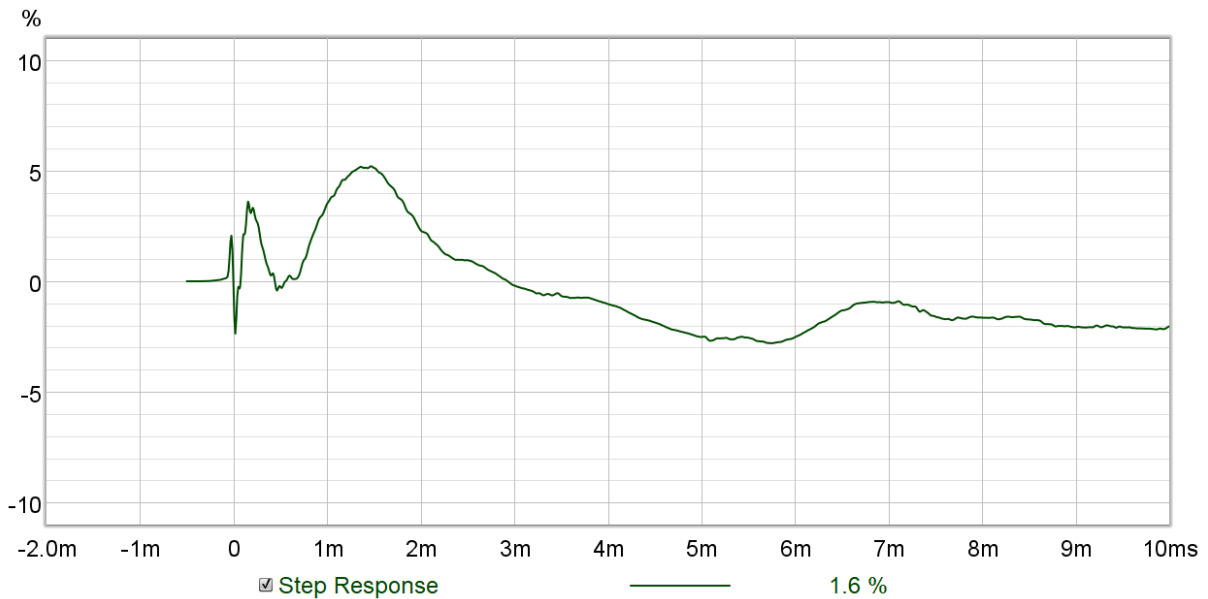
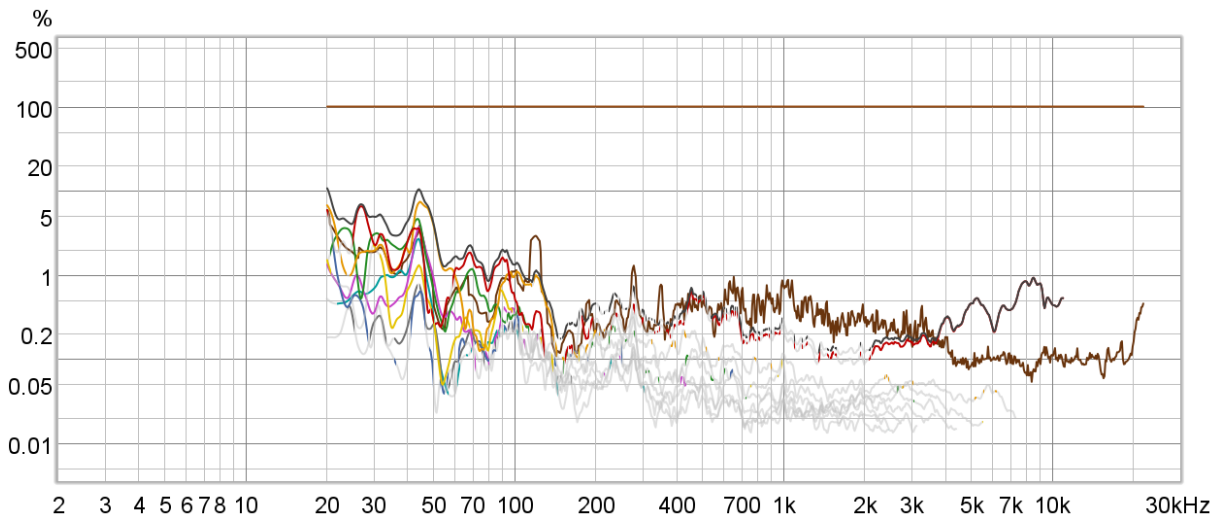


Figure 22 Step Response

Lastly distortion at 93dB 1m is astonishingly low. I need to get to a quieter location....I was running into noise floor problems for this measurement every time. Everyone who heard them at Burning Amp will attest...they are not shy in terms of bass or total output capabilities. My main listening room is about half the square footage and 4 foot shorter ceilings than burning amp. In ~16x20' with 9' ceilings these things will crush you. And sound reaaaly good doing it.



## Those Passive Padding Networks, or the Story of Lots and Lots of Measurements

Now back to those passive pads, the 6/1 ohm network for each compression driver voice coil. They are there for two reasons. The first...is buying a bit of hiss/noise rejection from the amplifier. The Hypex amps have a more than respectable -109dB signal to noise ratio. That means background noise for the amplifier stages is between 70-110uV, depending on which amplifier channel you're talking about. In practice, with reasonable length unbalanced analog cables (10 feet) or longish (for measurements) balanced cables of about 50 feet the system SNR was higher than that. You could hear a tad bit of hiss with your ear next to the mouth of the horn. Throw in 18dB of passive padding and you don't have to use up that dynamic range on the digital end to match levels...and you eliminate audible hiss unless your ear is on the compression driver. Which I do not recommend. They are compression drivers. Not headphones.

But that's only a minor reason to do it.

The other reason is this, the two diaphragms are acoustically aware of each other. The midrange can cause the HF driver response to change if the MF driver is electrically unterminated. The same is true in the other direction. In a passive crossover, odds are there's low enough source resistance through the crossover range where this impact is minimized. In an active system since the amplifier is effectively a short circuit, it's not an issue. Except, in trying to make frequency response measurements for the system or when using L-pads...it would mean that the frequency response of the measurement would be different than the frequency response of the drivers individually depending on how the other diaphragm was terminated. This means you need to be aware of the impact when doing your system design. It also means that if you adjust the L-pad and the shunt element resistance gets too high the responses of both drivers could change.

So...how low does that shunt resistance need to be? Depends on how much shift you're willing to live with.

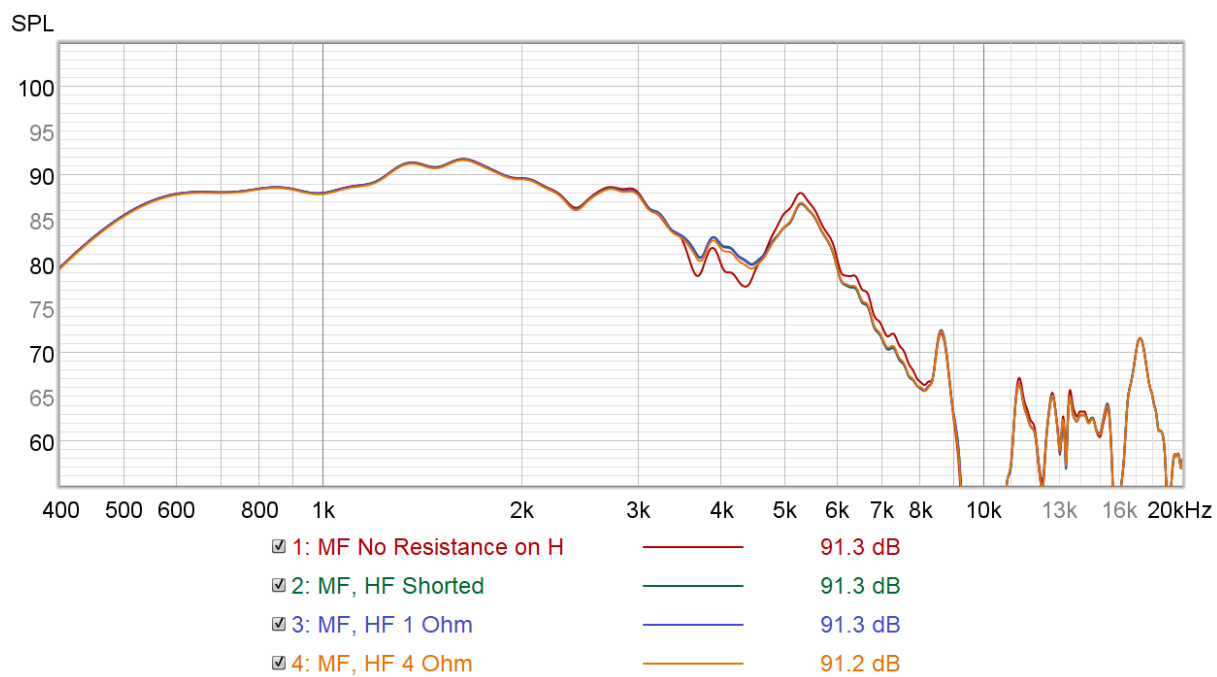


Figure 23 Mid Frequency Driver, HF Terminations Open Circuit, Shorted, 1 Ohm 4 Ohm

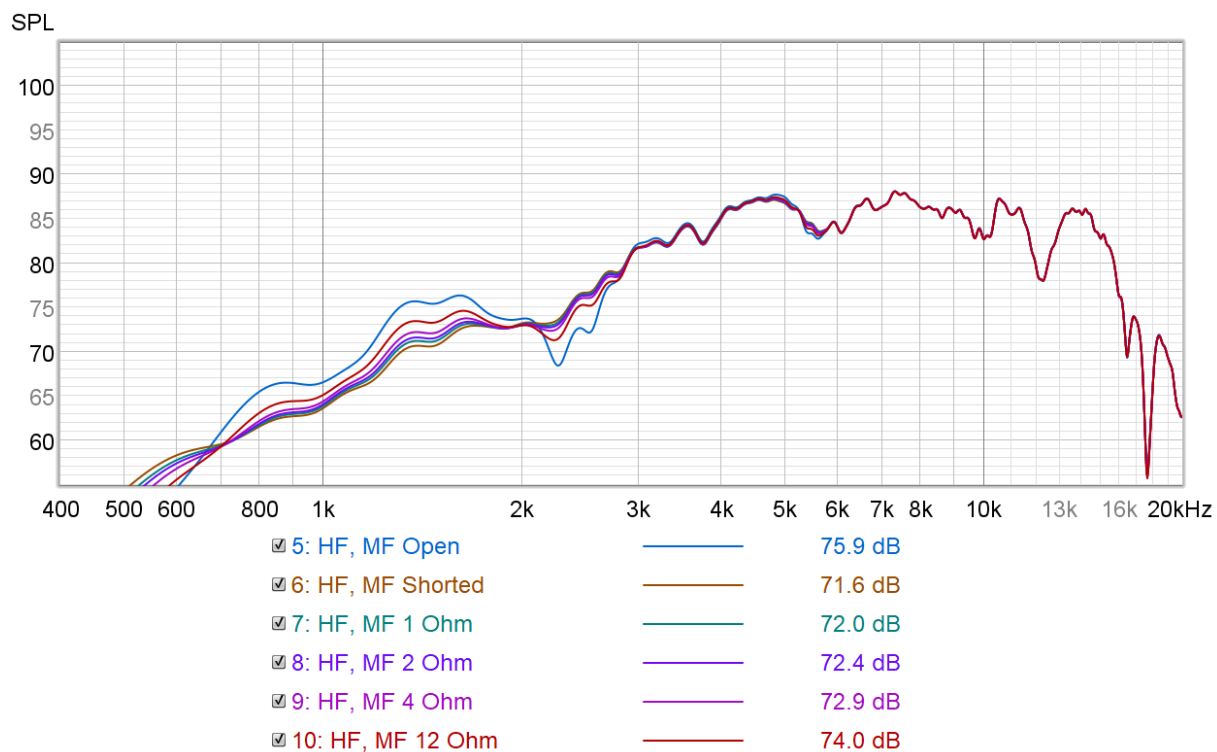


Figure 24 HF Driver, Various MF Terminations





As you can see from the measurements the differences aren't huge but could represent audible tonal shifts when trying to combine the two drivers in a crossover. If you're planning on rolling your own passive crossover, there might be a bit of hand tweaking where the response changes are a bit more than the impedance from the crossover might suggest.

When you shunt the coils with 1 or 2 ohms as part of the L-pad you guarantee that the output of the drivers is the same during measurements and in use, connected to an amplifier, or not.

## Cabinet Drawings

Buckle up. This is a rough ride. I pre-apologize for using a combination of metric/SAE units. I almost measured everything in hot-dogs and Ford 5.0L engines...but that would have been silly and reinforce the stereotype that Americans will use anything but the metric system. Over the years I'm so used to converting that it's automatic for me...I always have one of those construction calculators handy in the shop. I've included the Sketchup file for those wanting to re-dimension everything or figure out in better detail how this, admittedly complex design gets assembled.

First up is the long compound mitre secondary flares. The two long bevels are 45 degrees (not noted in drawing) and I highly recommend making a sled for this.

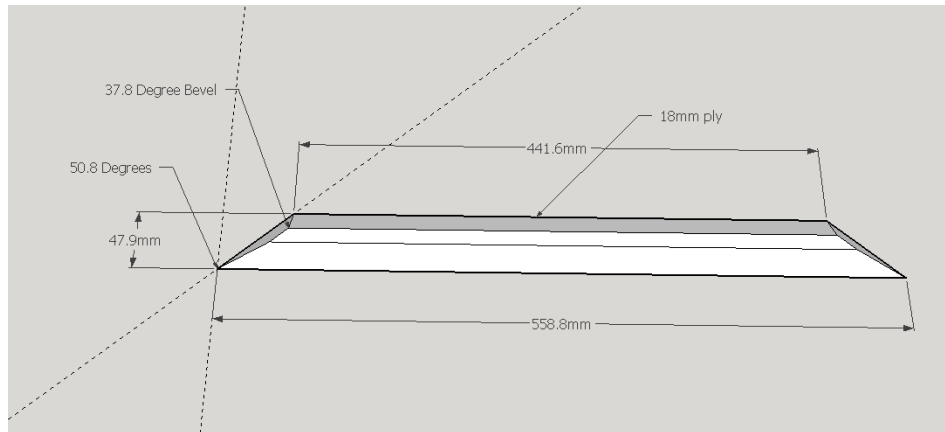


Figure 25 Make a sled for this.

I made this:

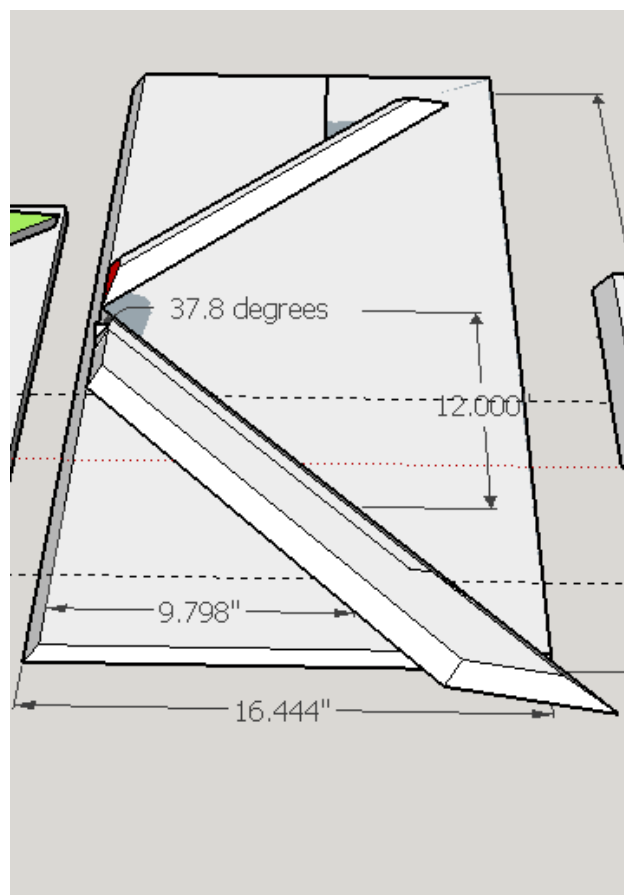


Figure 26 Mitre Sled



Next up is the top and bottom inner flares for the horn.

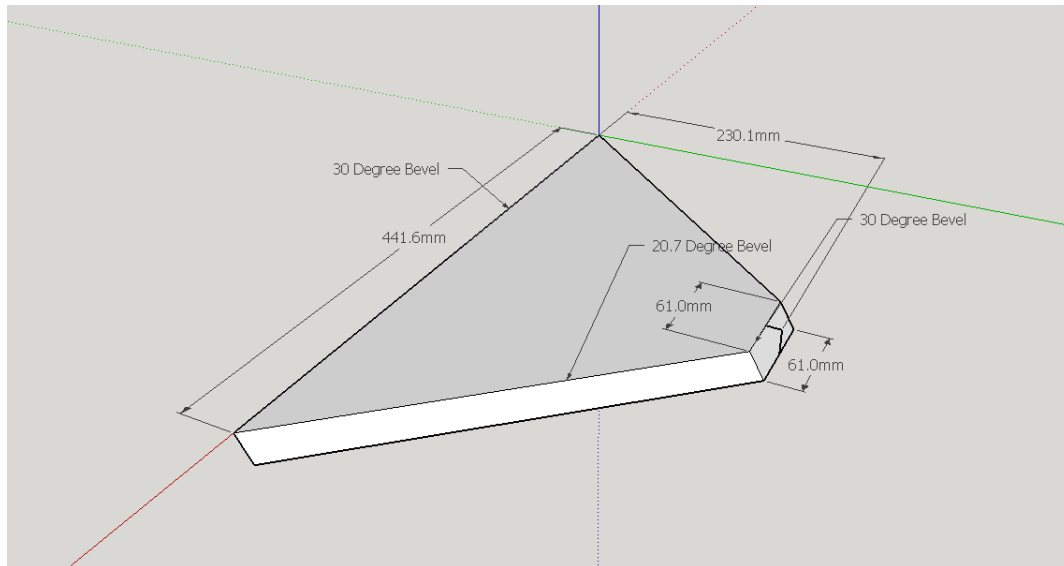


Figure 27 Top And Bottom Flares

Again I built a sled.

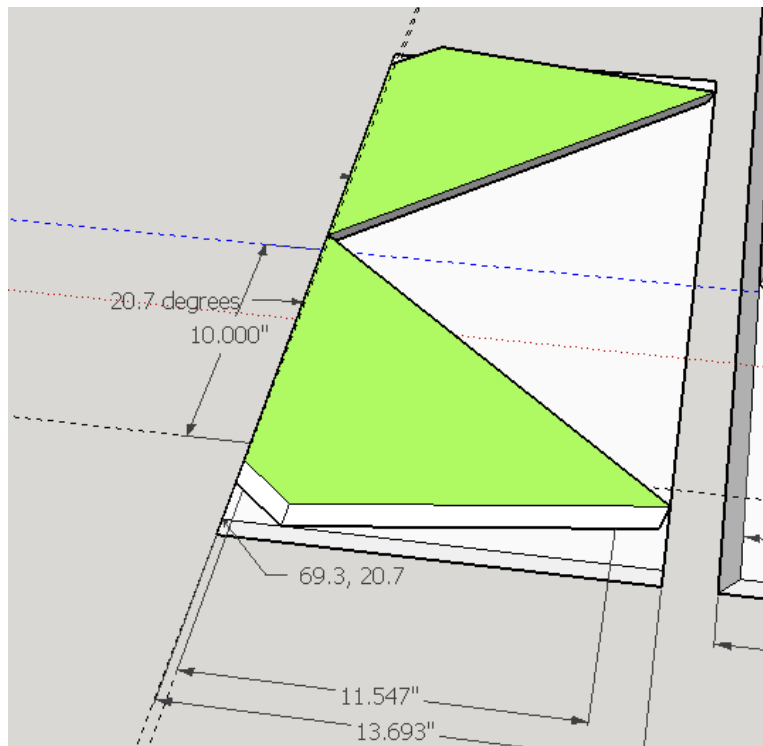
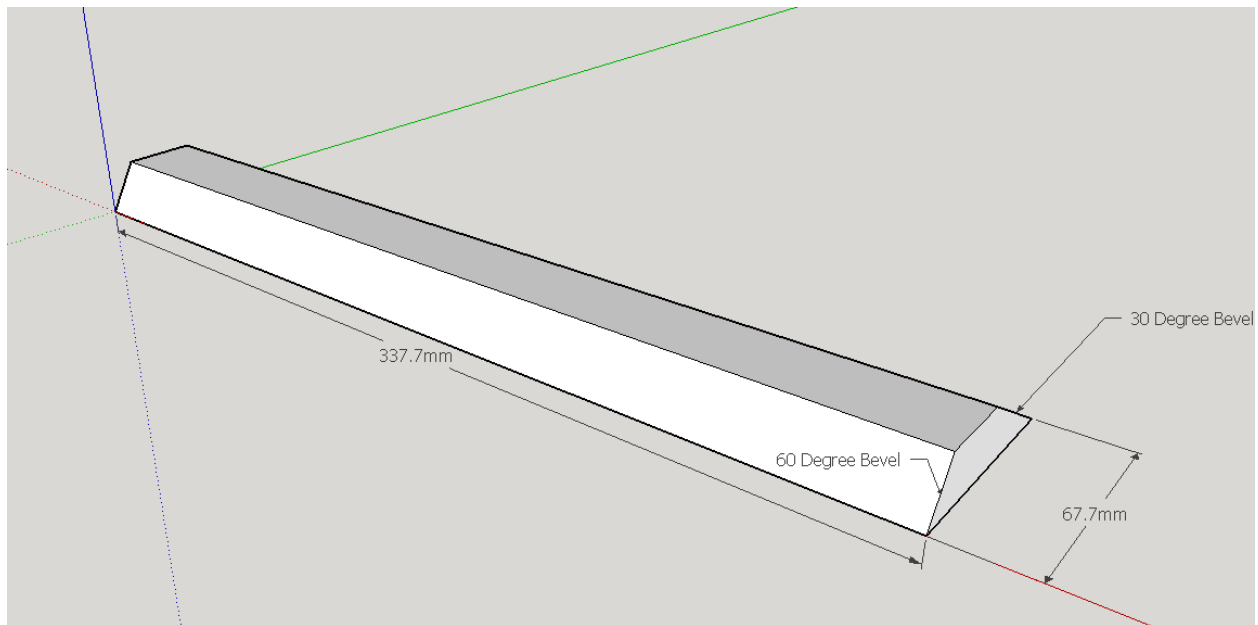


Figure 28 One more sled....



I made the sleds using a piece of  $\frac{1}{4}$ " mdf cut to slide in the mitre slots of my table saw. I glued them onto  $\frac{3}{4}$ " MDF that was oversized....then sent the blade to the angle desired and ripped them so they would become zero clearance sleds. I measured the angle of the pieces on the sled by calculating the run/rise for the angles. It's much more accurate than a protractor. For instance the primary flare pieces are 10" over and 11.547" up.



*Figure 29 Vertical Secondary Flare*

You'll want to make yourself a vertical sled to cut the 30 degree bevel, I made one that rides in the miter slot on the left side of the blade that I can clamp boards to. Be careful not to cut the clamps while you're running the boards through.

The flare that holds the woofers...is not simple.

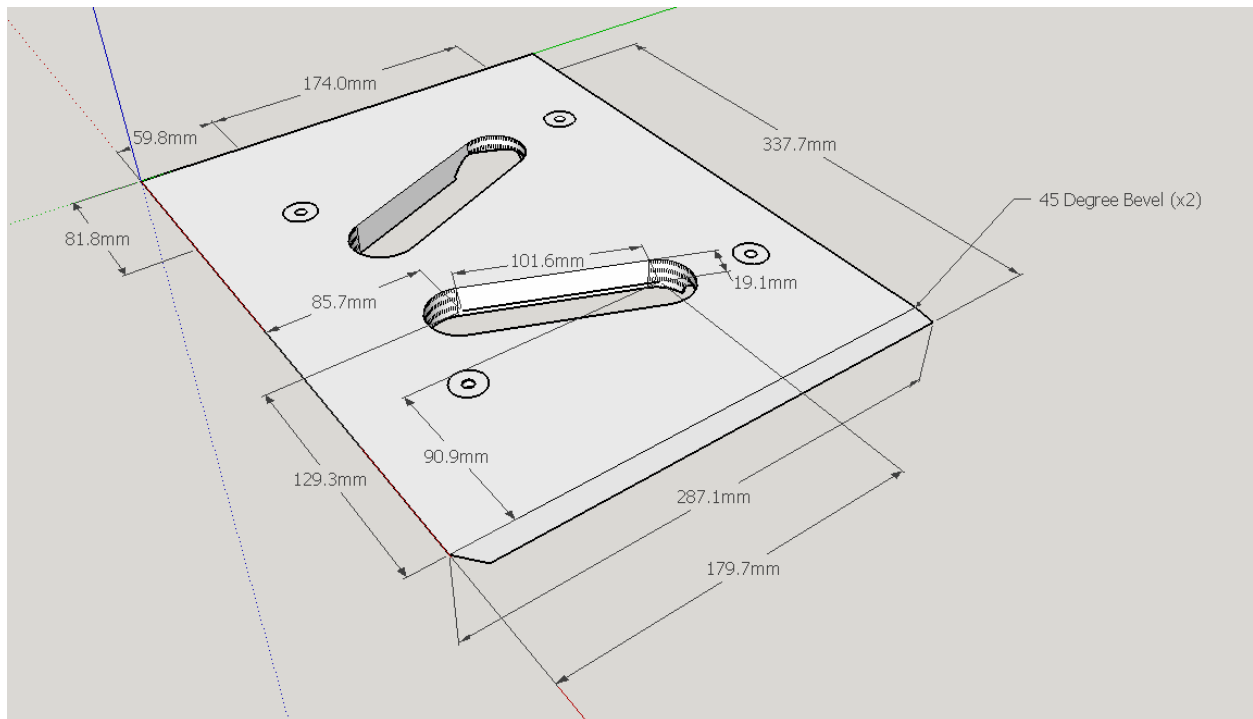


Figure 30 Be Careful on those bevels...cut them the wrong way and it doesn't work.

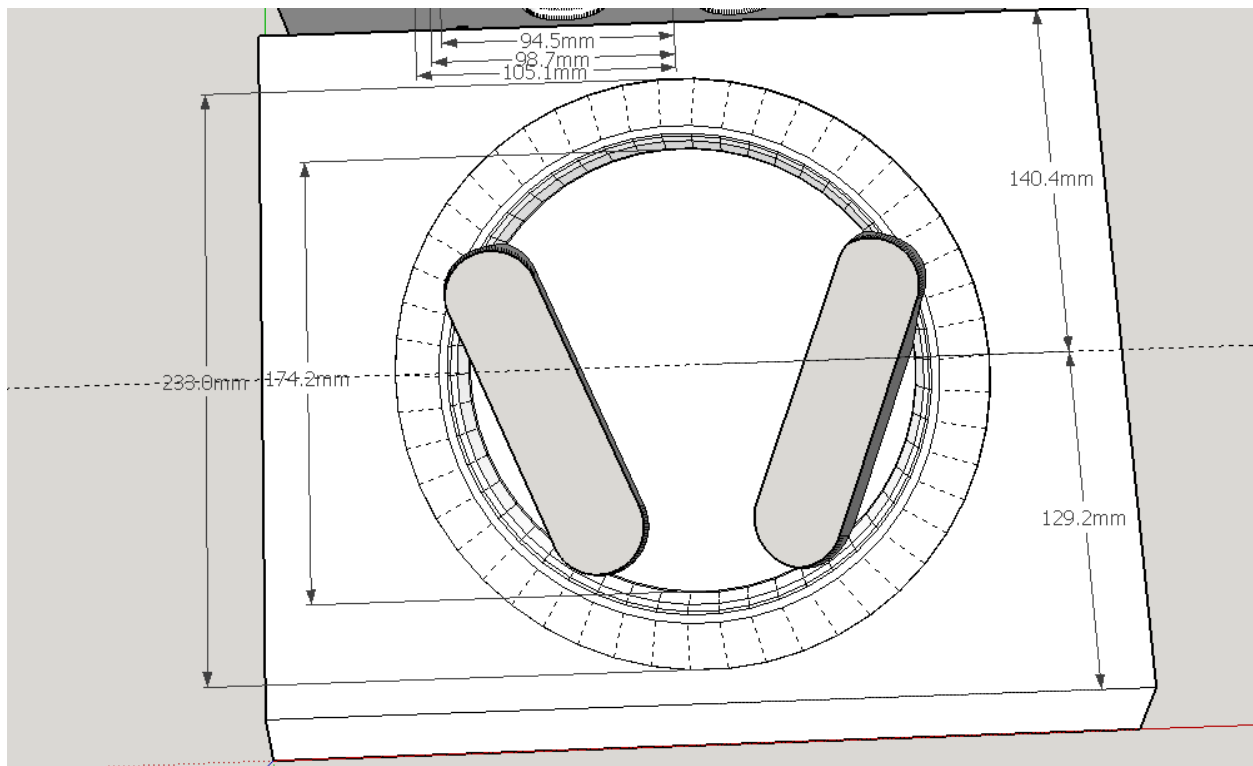
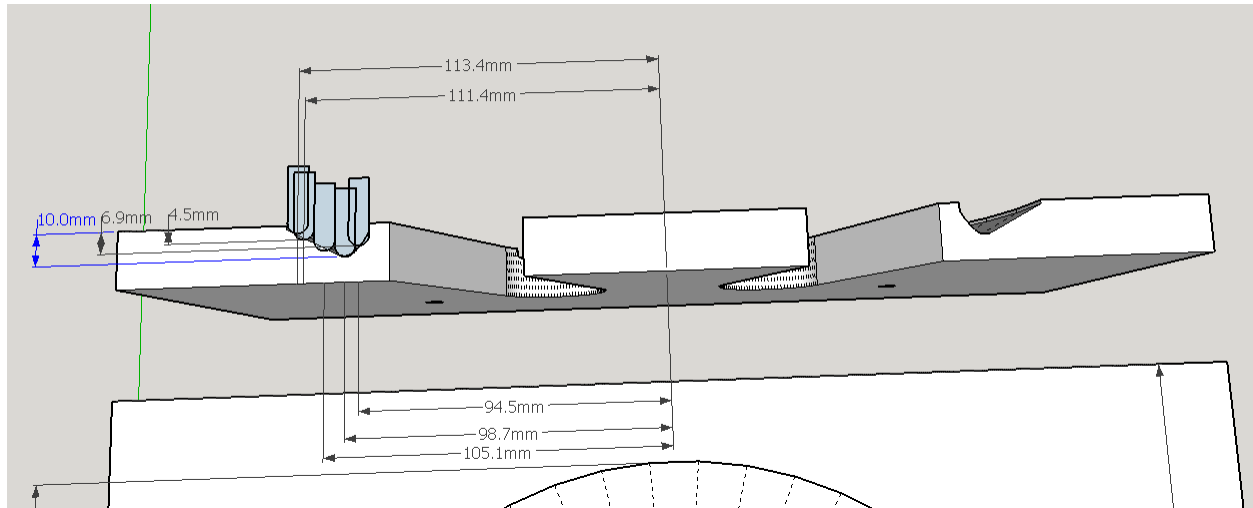


Figure 31 Gotta make room for the surround.

When you clamp a woofer to the back side of a board it's not uncommon for the surround to hit. I created a shape which roughly looked like what it needed to be for the surround/cone to not hit. I used a CNC, but you can do it with a router/circle cutting jig and some patience. You make multiple passes to approach the profile I did...then remove the rest with a Dremel/sandpaper/chisel.



*Figure 32 CNC for the win! Or circle jig and patience!*

To get the drivers in I contemplated two options. A frame system where the sides bolted on, or one where the back bolted on. I went with the back figuring that it would be easier to get one bolt on side to seal air tight....vs two.

The back also houses the Hypex amplifier and has the ports. This could be made by hand...but it would be much easier via CNC.

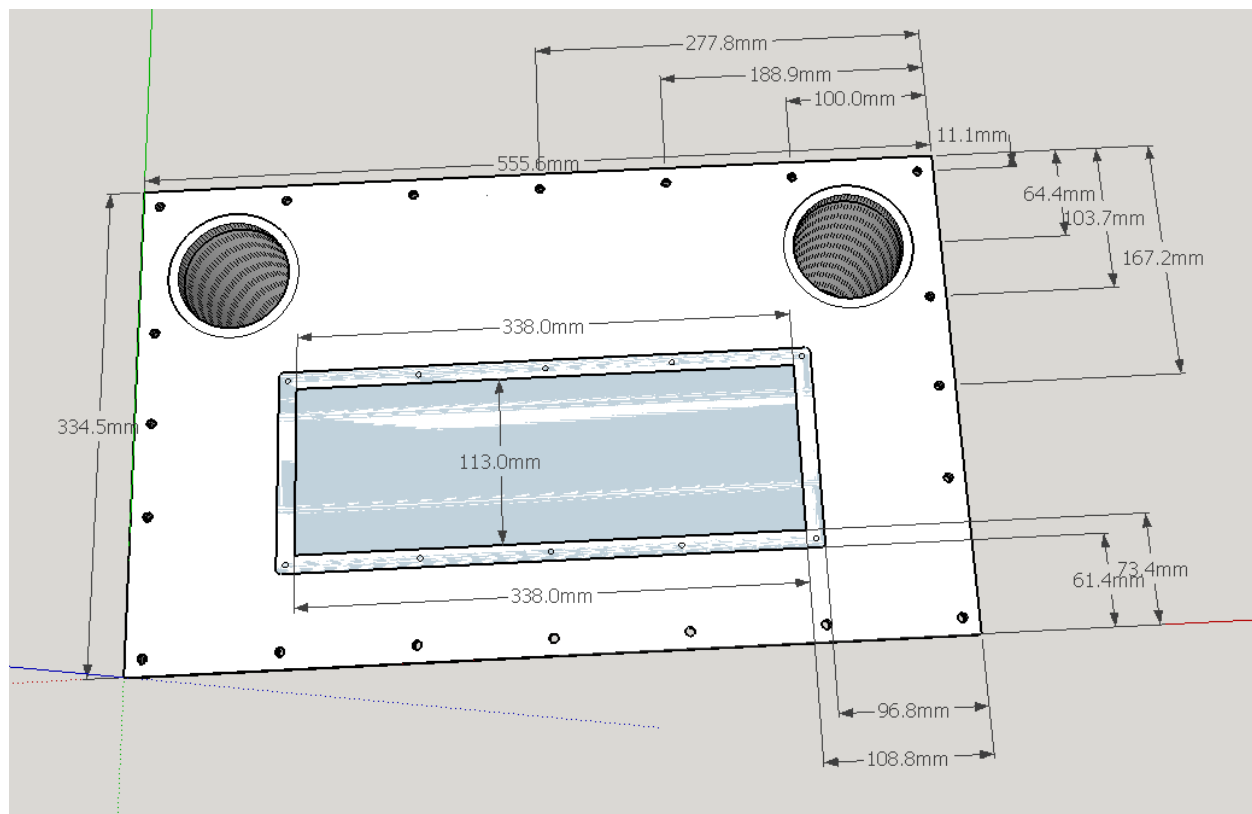
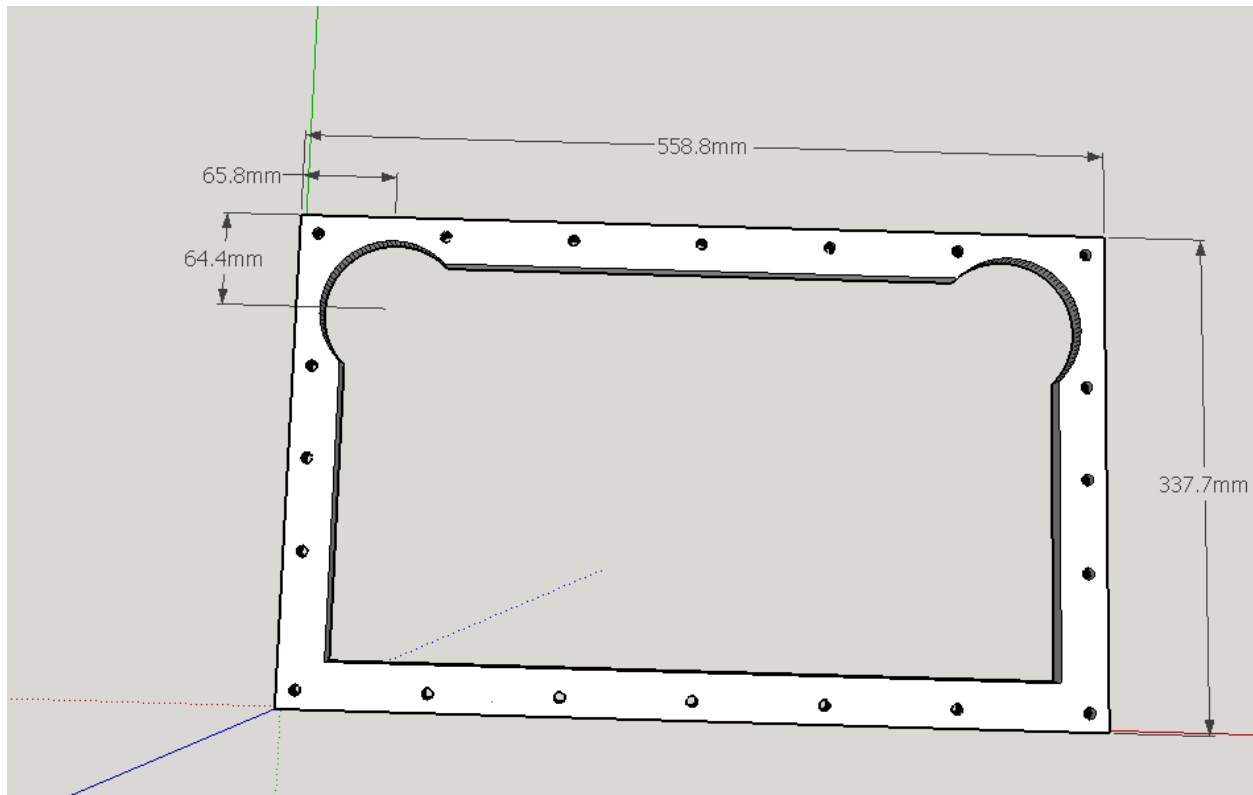


Figure 33 Yeah...I CNC'd this.

It's a tad smaller than the frame that it bolts to ...which I made out of 18mm material.





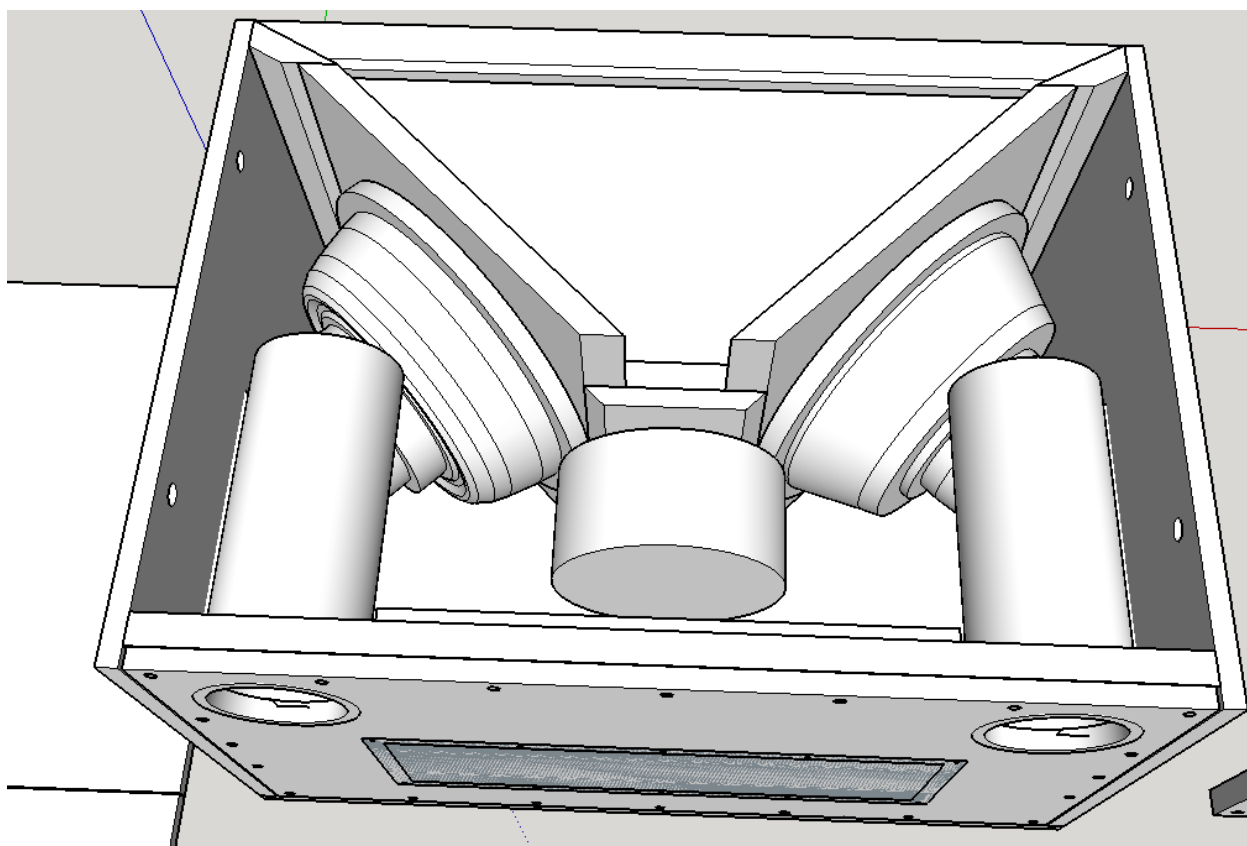
*Figure 34 Check Width/Height Carefully*

The mounting piece is slightly larger....were I doing this without a CNC I would have made one or the other first...and then used transfer punches to get the mounting holes transferred from one to the other. You can pull the pieces out of my sketchup drawing and create a dxf for CNC if you'd like.

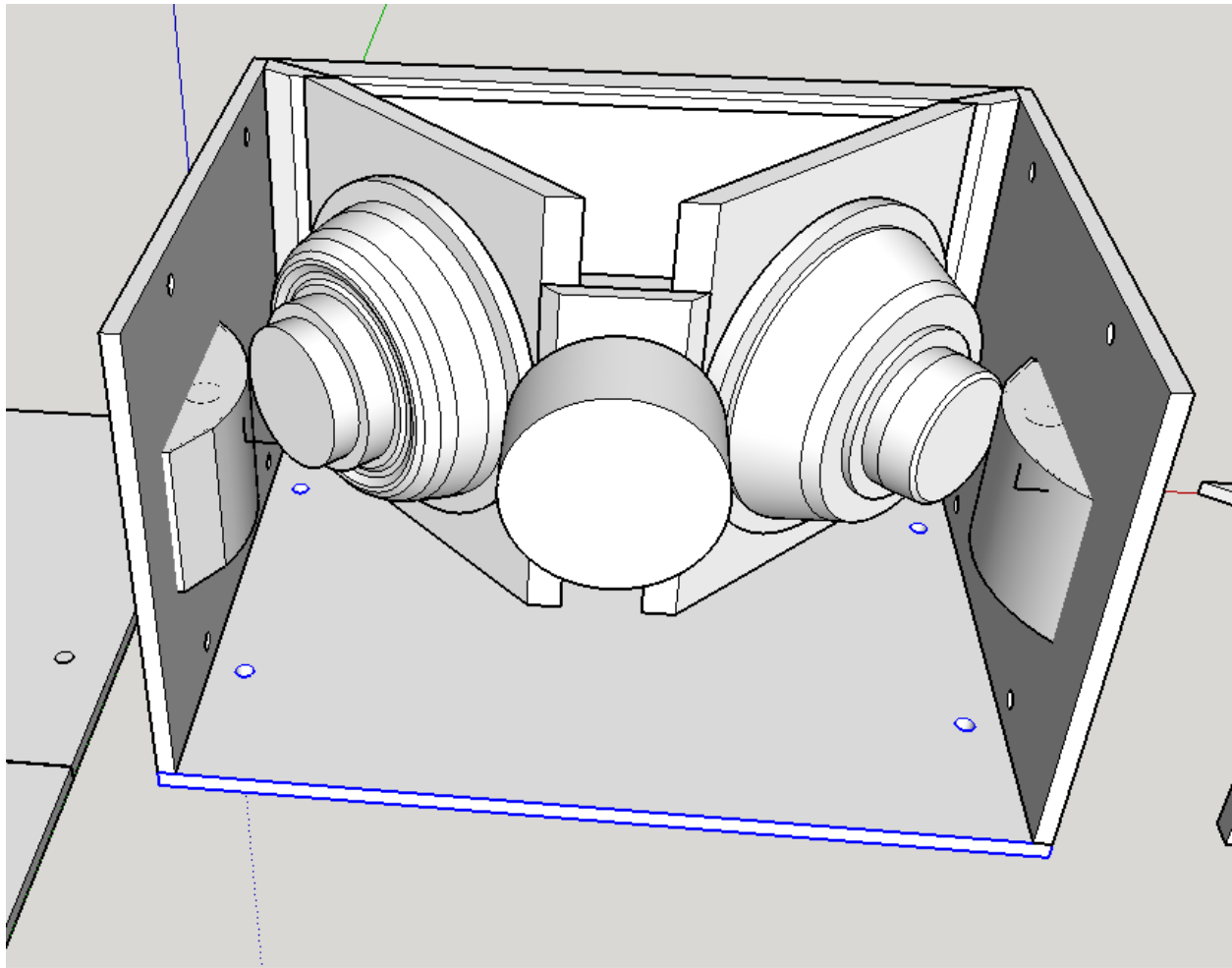
I used ¼-20 bolts with T-nuts, but I'll leave the attachment method up to you.

I will also provide an STL file for the throat adapter. I made it out of 18mm birch. A drawing...just won't describe it. If you're not planning on shipping your speakers all over the country a couple of times you could easily get away with a 3D printed version with pretty heavy fill.





*Figure 35 It's a tight fit.*



*Figure 36 Back Panel, Ports/ Top Removed*

If you include the Penn-Elcom side handles don't install them until **\*AFTER\*** you get the woofers mounted. The two bolts at the front end of the horn for each woofer are...well...kind of a pain to get in there. I had to create this:

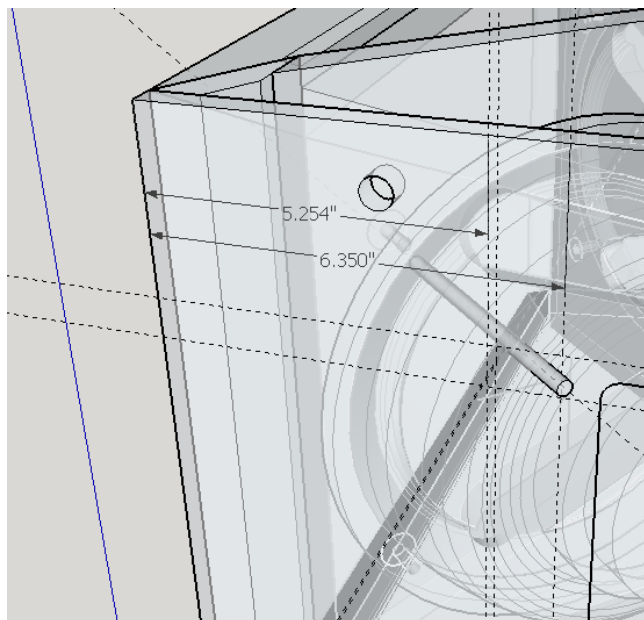


Industrial Design Engineer: Design for ease of assembly.  
EE doing DIY Speaker Design: I got you fam.



Figure 37 Difficult problems require creative solutions.

For those building one of these you may wish to consider adding access holes...I thought about it but when the Hinson-Wiha-Theorem was found to work, I stopped. Given the time pressures of getting the speaker ready for Burning Amp....I didn't want to figure out how to fill/cover seal those holes in a way that looked okay. It looks like an access hole of roughly 1" diameter would work...but I will leave the complete solution as an exercise for the reader<sup>11 12 13</sup>.



<sup>11</sup> I always hated that phrase in my college textbooks...now I use it with some amount of sinister glee.

<sup>12</sup> Sorry.

<sup>13</sup> Who am I kidding...no I'm not.



## Substitutions and Changes

A quick word are substitutions and changes. There are no driver substitutions that will work without redesigning the crossover. It would then be a different speaker. Other drivers will work in this box, but you'd be on your own for the crossover.

## Conclusion

As I said towards the beginning of this document...this is the absolute best sounding speaker I have ever designed. I don't do audio reviewer writing well....but the best way I can think of to describe the sound is this:

Take the best parts of multiple types of speakers, the midrange tonal perfection of a fine set of mini-monitors, the immediacy of electrostatic, the seemingly unlimited dynamic range of large horns and the elimination of room interaction by headphones and combine them all, without including any of the bad parts<sup>14</sup>. That's what you get with these, so I shall call them....MEH. 😊

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<sup>14</sup> Especially the "in-your-head" imaging problem of headphones...which I hate...