

# Kairos

## High-End Monitor Loudspeaker

(Kairos: Ancient Greek word that means – “to have perfect timing”)

By Jeff Bagby



## Introduction

In the ancient Greek language there are two words for “time”, chronos and Kairos. Chronos refers to the passage of time; hence we call some watches chronographs. Kairos refers to a specific time. Kairos means the right opportune moment, the defining moment of something, or something that takes place at the perfect time. Those moments in our lives that define us take place in Kairos. Kairos is right, correct, or perfect timing. Kairos then became the perfect name for the direction this speaker project took.

I have designed several speakers using drivers from SB Acoustics. Their drivers offer a cost to performance ratio that is near the top of the speaker driver industry. The level of speaker development and construction that you are able to obtain at such a low price is remarkable. In my opinion there are very few drivers which compete well against the SB drivers for the money. This was an important consideration in their selection for some kits, as it allowed people to get into higher- end designs at a much lower price.

So when Mark asked me to consider a design with the new SB Acoustics Satori drivers I was a bit concerned. They did not appear to offer the kind of value I usually looked for in selecting drivers for a design, and I was concerned a kit with these drivers might not attract many builders. However, after working with the drivers a little I began to think that I might be wrong about this. Although these are not inexpensive drivers, they offer a level of performance that is found in very few speakers available today. And in a short time I realized that their unique characteristics gave me the opportunity to create a very special kind of speaker, one that should attract people seeking the highest degree of accuracy in a two-way monitor. If someone wants the very best, I feel these drivers offer us the opportunity.

## The Midwoofer

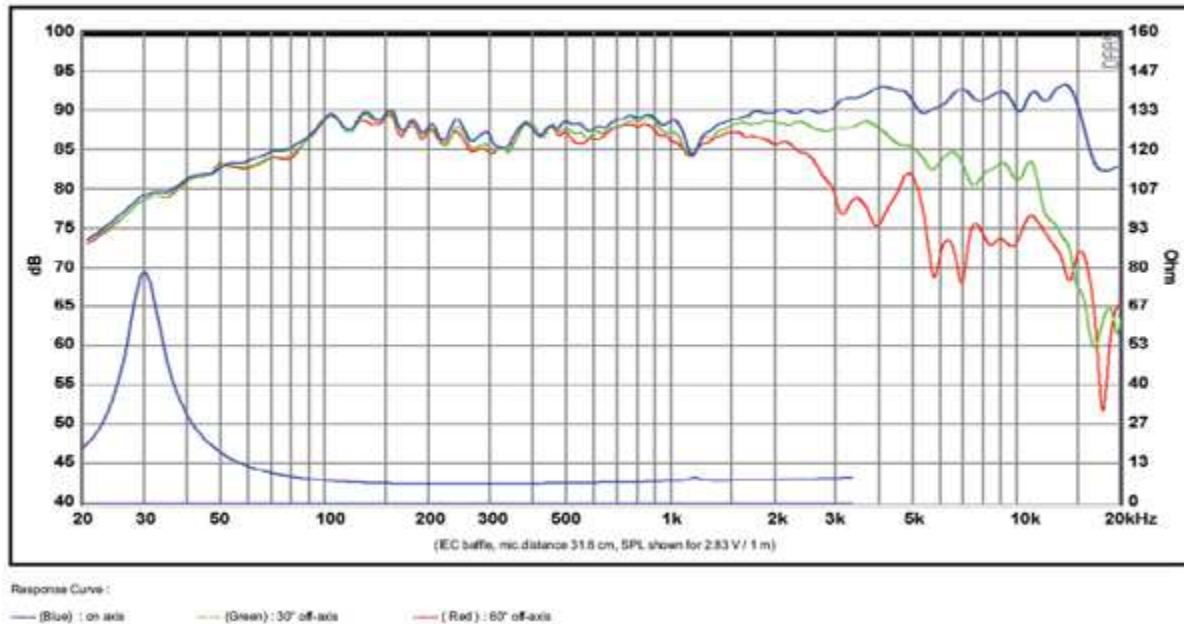
**The woofer is the new SB Acoustics MW16P Satori midbass driver.** This is a 6.5” cast frame driver with a cone made of a paper formulation reinforced with Egyptian Papyrus reed fibers to increase stiffness. The motor on the woofer is state of the art consisting of a neodymium magnet, aerodynamic chassis, fiberglass former with a CCAW voice coil and silver leads. It has an extended copper sleeve on the pole piece to reduce inductance and its associated distortion. This reduction in inductance combined with the light stiff cone produces a very extended frequency response from the driver; a response that begins to approach that of some full-range drivers.

Here are a couple pics of the woofer



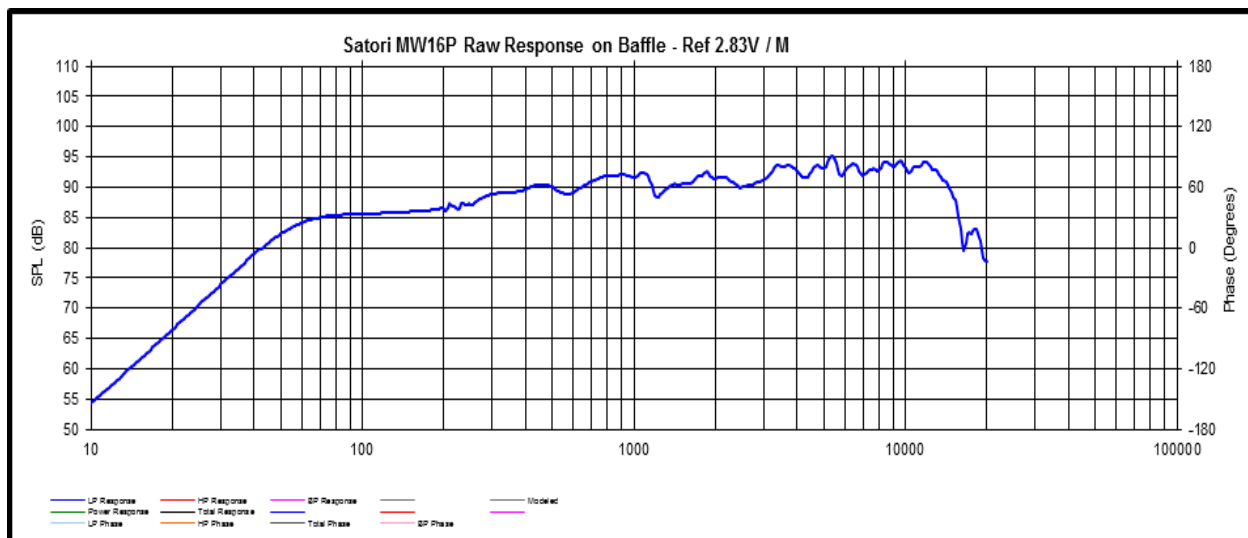
The woofer possesses some excellent measured T/S parameters, as my samples measured right on spec for  $F_s$  at 29Hz right out of the box, and  $L_e$  was a mere 0.19mH.

The manufacturer's published frequency response is here:



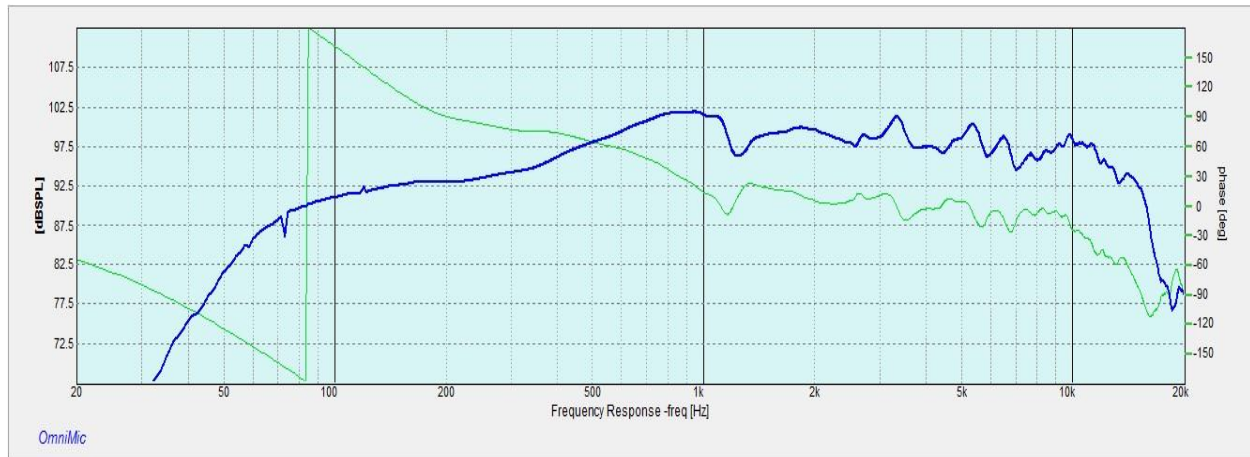
You will note the extremely wide and extended bandwidth of the driver. The notch at 1200 Hz I will comment on in a moment.

Here is the quasi-anechoic free-field response I measured for one of my samples on the baffle at one meter normalized to a 2.83V input level:



I measure the exceptional bandwidth of the driver too; the only other real difference between my measurement and the SBA graph is that my measurement shows the baffle step and hump associated with the driver being measured on my 9" x 16" baffle. This chart shows 1/48<sup>th</sup> octave smoothing.

Here is the same measurement in the nearfield at 1/24<sup>th</sup> octave smoothing showing the baffle step and hump more clearly.



The notch in the woofer's response at 1200 Hz is real. It is most likely due to the cone's edge resonance where it terminates to the soft rubber surround. In my opinion though it is not an issue to be concerned with, as narrow band notches are generally inaudible, and I have never noticed anything in my listening sessions that I would attribute as an issue in this frequency range.

## The Tweeter

**The tweeter is the new SB Satori TW29R.** It will be immediately recognized by many as a close relative to the SB29RDC. In fact, the two tweeters have a very similar frequency response and impedance as well. However, there are some differences too. Both tweeters are a type of "ring tweeter", but the SBA approach to this type of driver is a bit unique, as it creates an obvious dimple in the center of the dome. In a dome tweeter it is not unusual for the apex (tip) of the dome to move independently and oscillate out of phase with the base of the dome near the voice coil. This can create frequency response irregularities. SBA counters this issue by attaching the tip of the dome to an internal post which eliminates this issue and smoothes the frequency response of the tweeter. This is why you see this dimple – there is nothing wrong with your tweeter, it was made this way.

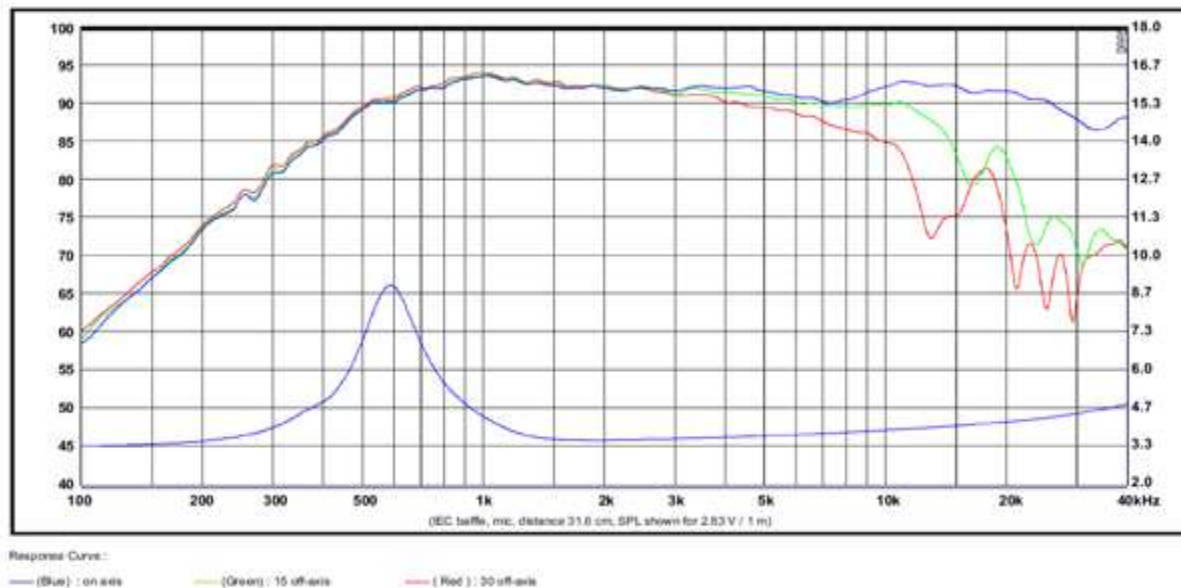
The TW29R has a two-piece face plate designed to decouple the tweeter from the baffle and reduce the effects of baffle resonances being translated to the tweeter. Like the woofer, it has a CCAW copper voice coil with silver wire leads and has dual copper caps on the pole-piece to reduce inductance and its distortion. I measured the  $L_e$  of my samples at .02mH. The cast aluminum chamber behind the dome is aerodynamically shaped to absorb the back-wave of the tweeter with as little reflection back into the dome as possible. My two samples had a measured  $F_s$  of 578 and 581 Hz, so it is a very low resonance dome tweeter.

Here are some pics of the TW29R Satori Tweeter:

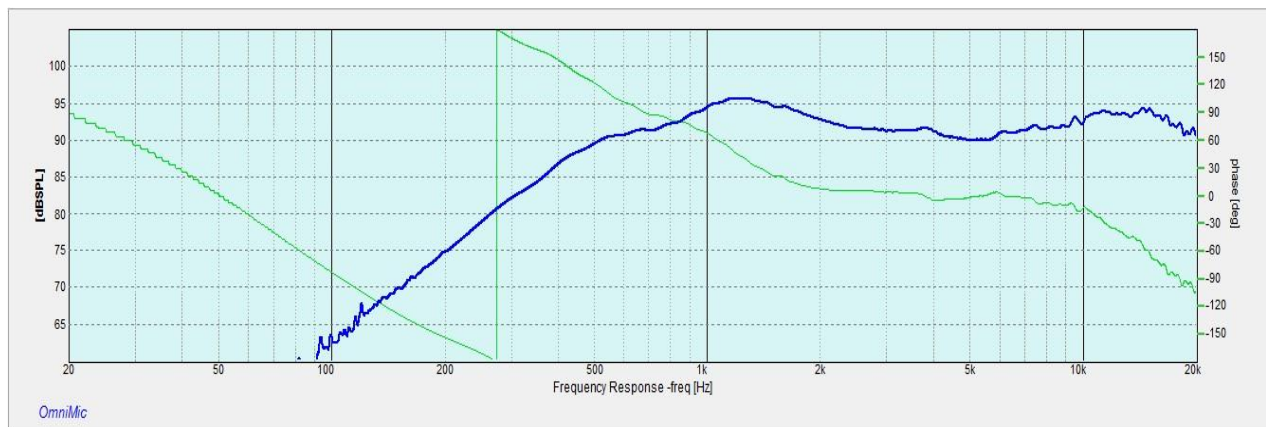




Here is the manufacturer's published frequency response for the TW29R out to 40 kHz:

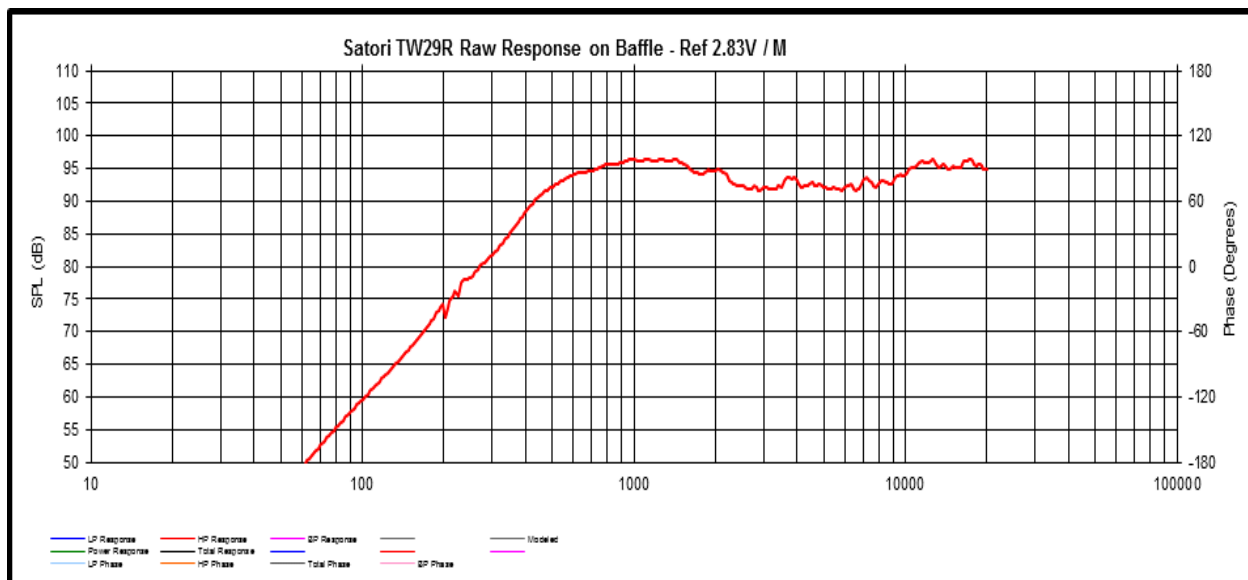


Here is my measured quasi-anechoic minimum phase response of the tweeter on my “infinite” baffle:



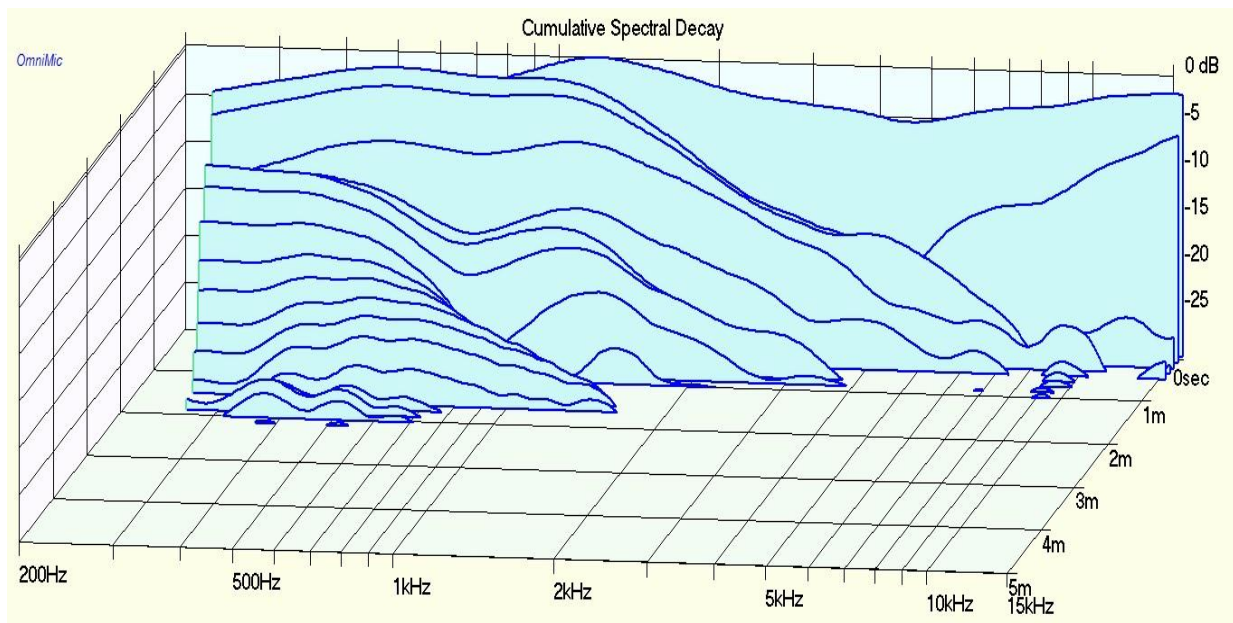
Part of the hump at 1200Hz is due to baffle diffraction in my set-up, so you need to ignore some of that, and even though my scale is compressed a bit from SB's, the two curves match up very well .

**Here is the quasi-anechoic minimum phase free-field response I measured for one of my samples on the speaker baffle (16" x 9") at one meter normalized to a 2.83V input level, the same conditions as the woofer measurement above:**



The broad hump centered at 1 kHz is due to baffle diffraction, but this is very easy to accommodate in the crossover design. As you can see, this tweeter has strong output down to 500 Hz, and relatively high sensitivity.

**The cumulative Spectral Decay is quite clean for the tweeter:**





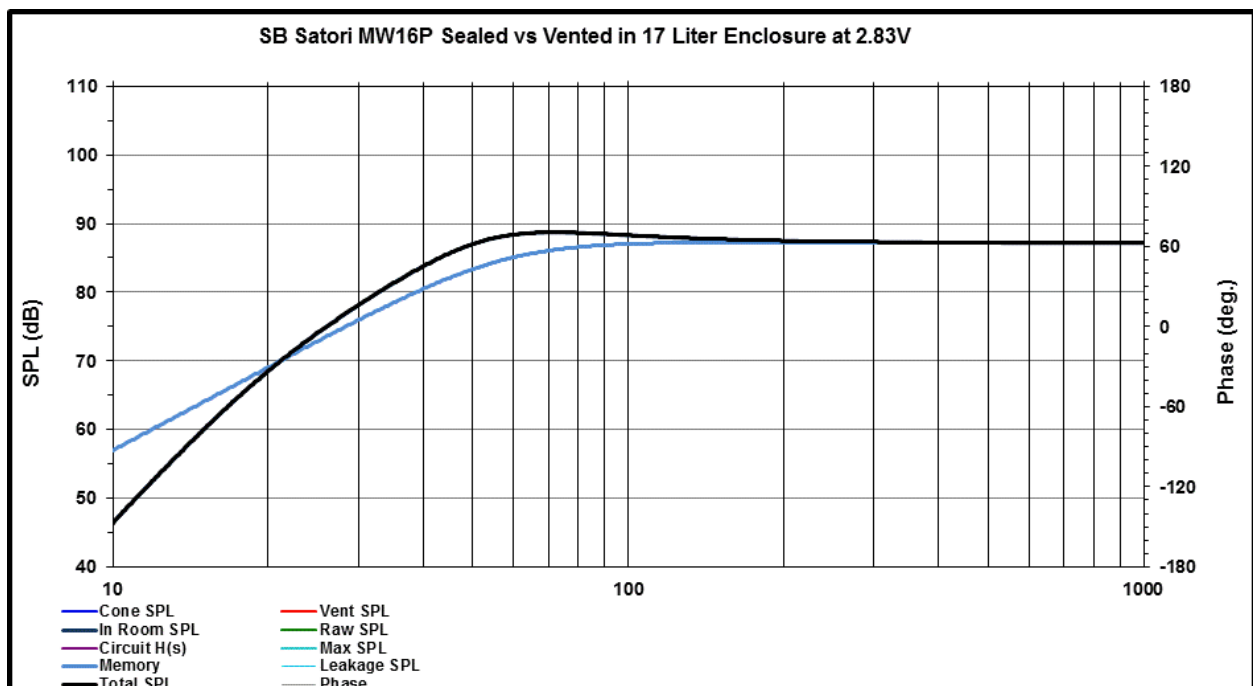
## Box Model Design

I did not design this speaker as an optimum vented alignment. That would require an enclosure much larger than I wanted to go for this speaker. Instead I selected a volume that was about as large I was comfortable for this type of speaker, but it is also a volume that is nearly optimum for a sealed alignment. The vented version has a small lift in the midbass, but does extend deeper into the bass.

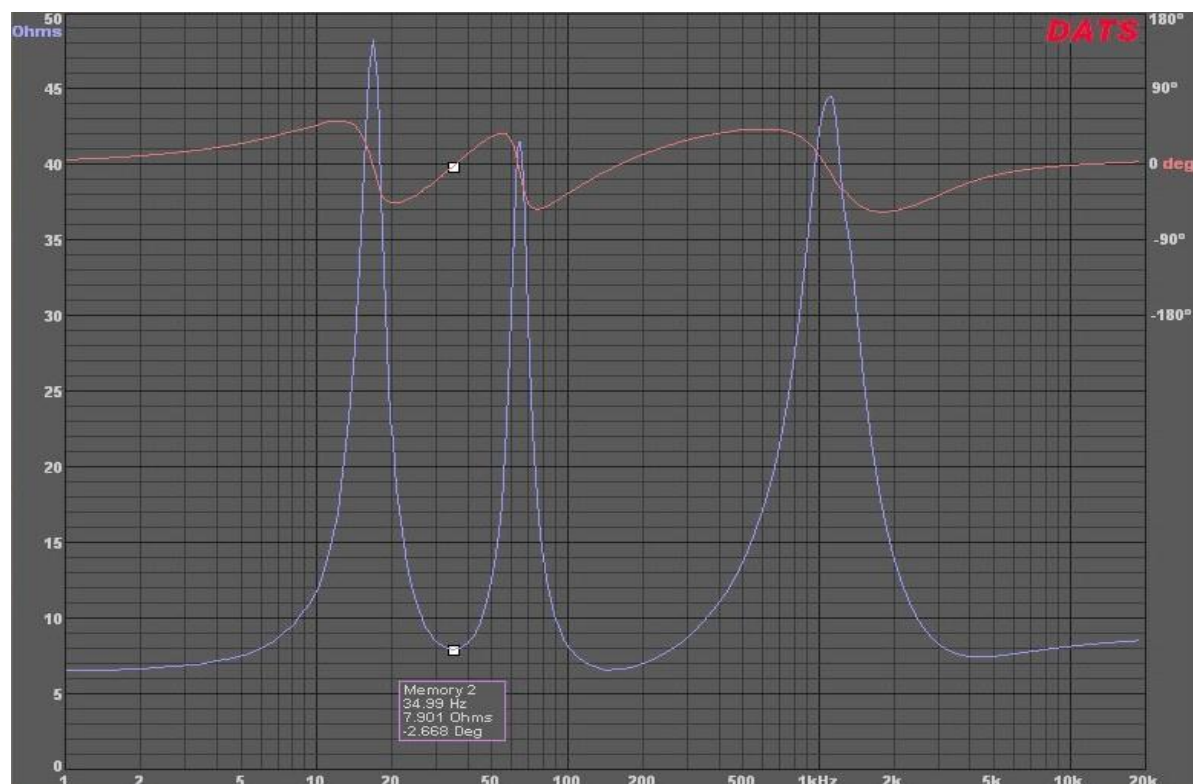
The enclosure is about 17 liters. The Qts of my samples comes in at .39 with the series resistance of the crossover included. As a sealed box the Qtc works out to be .71, which is a very flat sealed alignment. The -3dB point for the sealed box is 53Hz and the -6dB point is 41 Hz.

The kit comes with a 2" diameter port that tunes the enclosure to 35 Hz. In vented form the loudspeaker has a -3dB point of 44Hz and a -6dB point of 37 Hz, but it also has a small lift of 1.3 dB centered at around 70 Hz. When playing by itself in a typical room I find this alignment to give the perception of a much more extend bass response than you would expect. I do not notice any midbass emphasis that detracts from the speaker. However, when I run the speaker with my subwoofers I plug the ports (using a plug of rolled acoustic foam) and make use of the sealed alignment which blends very well with my subwoofer crossover and also helps to control cone excursions at lower frequencies.

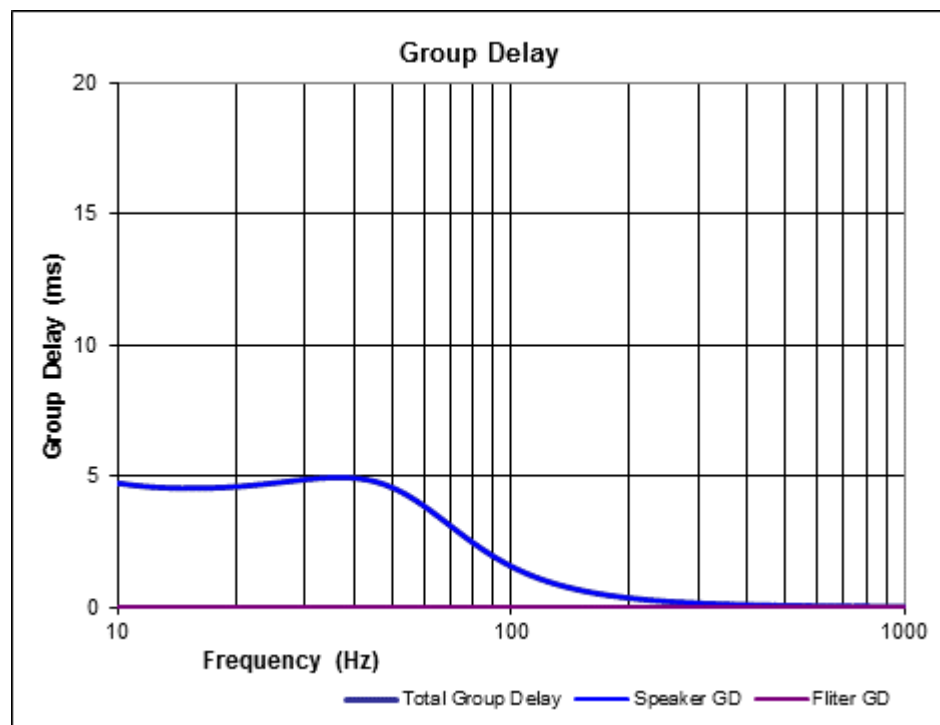
Here is a graph showing the difference in the response between the vented and sealed modes of the speaker.



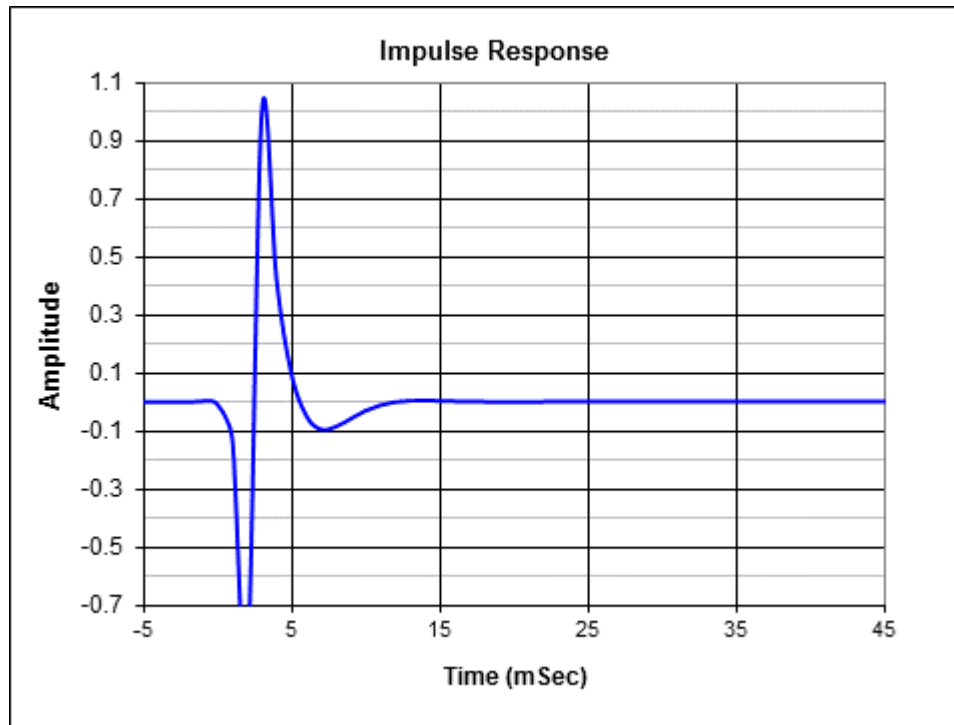
Below is the measured impedance of the final system using DATS that shows the tuning frequency of 35 Hz at the valley between the two box impedance peaks:



For the purist - the group delay of the sealed system is very low



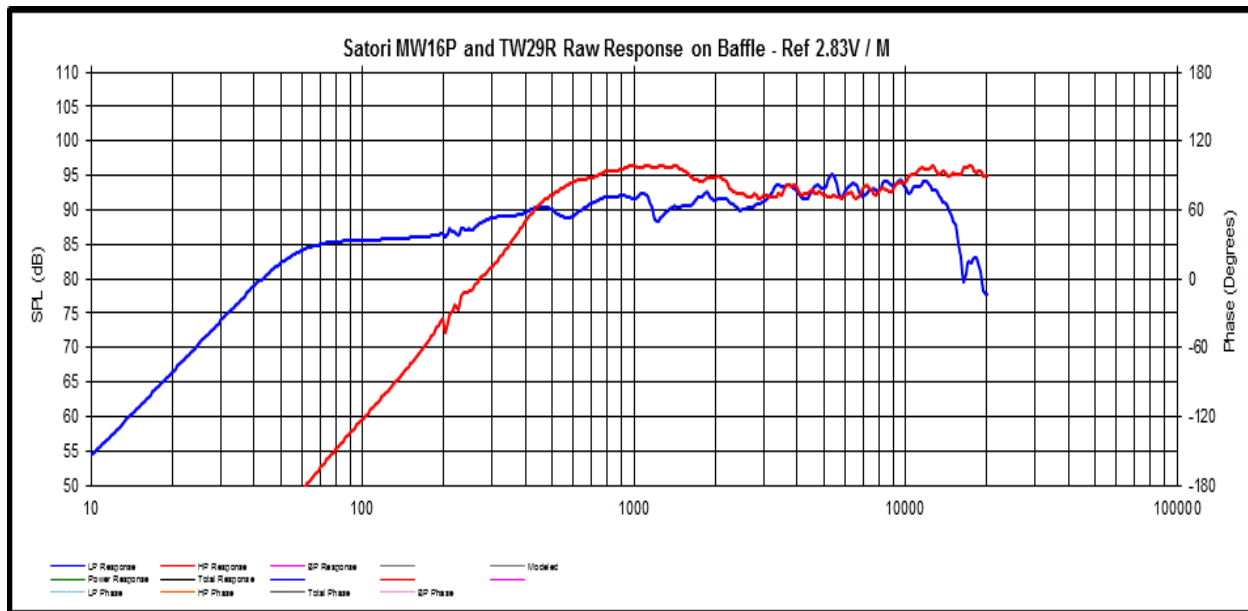
And the Impulse response is very clean with very little ringing



## System Crossover Design

The most common type of speaker design these days is a two-way loudspeaker incorporating an LR4 (4<sup>th</sup> order Linkwitz-Riley) Crossover. This is usually very easy to accomplish with most drivers especially with tweeters that have an inherent second order roll-off in the 2 kHz region. All that is required is a properly tuned second order filter and you have it. I have designed many speakers using this tried and tested approach. However, as certain as I am that these drivers would sound wonderful in just such a design, it still seemed to me to be waste of their wonderful potential. It is rare to find drivers with such exceptional bandwidth and low distortion, and they seemed to be crying out to be taken advantage of in some way. I mean why else would they create a woofer that extends to 15 kHz?

Systems that are transient perfect are usually close to impossible to pull-off with most drivers. What a lot of people don't realize is that when a driver begins to roll-off naturally, even when it is an octave beyond the crossover point, there is a significant shift in the driver's phase response, even at the crossover. So, the idea of using first order filters and achieving linear phase response is mostly a myth due to the roll-offs of the drivers themselves. However, when drivers have very wide bandwidth and overlap each other over much of it, and when a tweeter has the capability of handling low crossover points and shallow slopes, then we have an opportunity to target systems with very special phase characteristics that we can't achieve with most other drivers.



The graph above shows the raw frequency response of both the woofer and tweeter measured under identical conditions on a 9" x 16" baffle. This demonstrates the broad overlap in their frequency response. Based on this overlap and the linear, low distortion behavior of the drivers I opted to design a speaker that is time and phase accurate as well as one that has flat extended frequency response.

## The First Attempt

The first step in designing a system that is perfectly time and phase accurate requires determining the proper time arrival relationship between the two driver's acoustic centers so that they can properly aligned. Once this is determined, there are a couple of ways to align the drivers passively – you can use stepped baffles or you can use a sloping baffle. In an active system you can use digital delay to compensate for time arrival differences, but since this is a passive design we will focus on passive solutions.

Both the sloping baffle and stepped baffle have advantages and disadvantages. With the sloping baffle you are typically a few degrees off-axis from the tweeter, so depending on the tweeter's response this can sometimes significantly impact the top octave. The stepped baffle on the other hand will allow you to remain on the tweeter axis, but the step itself can introduce some diffraction issues into the frequency response. Some designers have used felt along the step to absorb the sound from the tweeter at this edge to reduce the diffraction effects with good success.

I experimented with both methods and in the end chose to go with the sloping baffle for a number of reasons. First, I found this type of cabinet more attractive, and once the angles are derived it is not really much more difficult to build. Second, I preferred the smoother frequency response with sloped baffle over the stepped baffle and its inherent diffraction issues. And third, the SW29R tweeter has a rising response in the top octave, so listening a few degrees off-axis on the tweeter did not result in any serious top octave issues on the design axis.

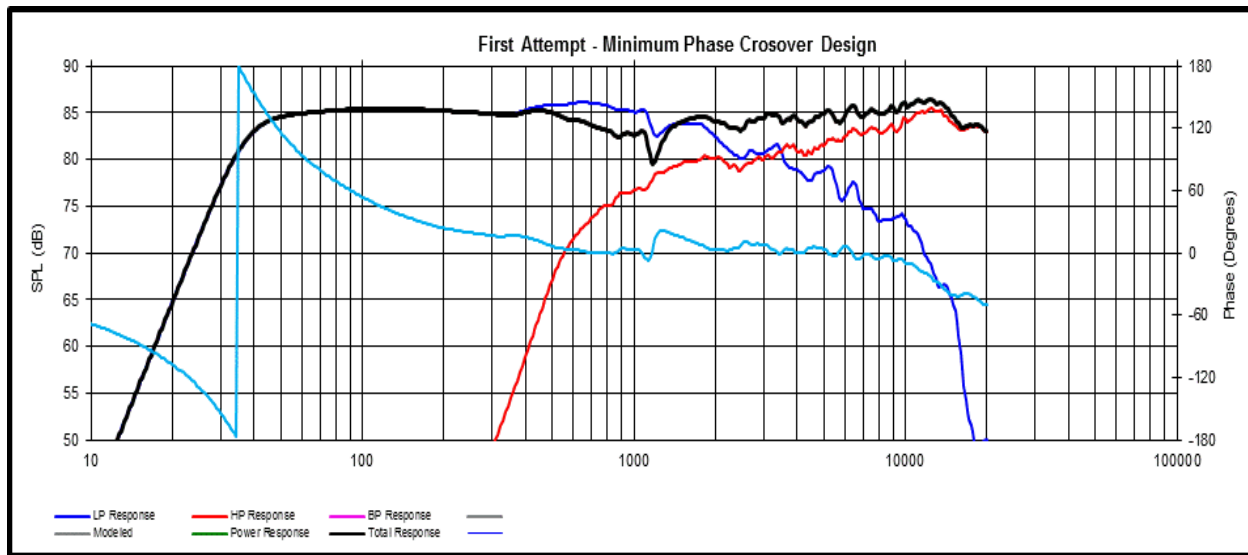
**Here's a side view showing the angle of the baffle.** The baffle is tilted back at a 14 degree angle to add the appropriate delay to the tweeter and align the time arrival of both drivers:



My first design with these drivers was an attempt at a true transient perfect loudspeaker; one where the drivers sum to flat response with zero phase error; with flat minimum phase response through the entire operating spectrum of the speaker. With computer modeling and quite a few measurements I was able to arrive at a successful outcome. This crossover was built and tested and measured exactly as modeled, showing no error in the phase response. However, the design was not without other problems.

In order to achieve the proper summation I had to cross over high enough that the tweeter's response was not rolling off steeper than first order for at least two octaves below the crossover point, otherwise its roll-off brought excess phase into the design. Here is a graph showing the response of the drivers, system, and phase for this design. The light blue line is the phase response of the summed system.





The crossover point occurs at about 3 kHz with a broad overlap in the response. This created two problems. First, with such a broad overlap lobing became problematic, and a few degree above and below the design axis the response became quite ragged as nulls developed. The second problem was that in order to accomplish this summation the tweeter's response is extended to a very low frequency before rolling it off and this meant that there would be much greater power demands on the tweeter than I would normally want to impose.

**Despite the fact that my on-axis measurements were exceptionally nice, this speaker failed my sitting-standing test** where I check for audible changes in the response between sitting and standing at my listening distance. In this case the change was very noticeable. So, even though this was a nice experiment I decided to look for a compromise – one that would have better lobing behavior and offer much better tweeter power handling.

## The Compromise – A Hybrid Crossover Type

It was back to the computer to see if a reasonable compromise could be achieved. After several simulations I arrived at a hybrid crossover type that appeared to meet all of my criteria. It was actually a crossover type that I had developed some time ago but just in computer simulations. I have experimented with computer models of this type of system for several years, but the Satori drivers gave me the necessary wide flat bandwidth to pull it off in a real loudspeaker. I used a self-derived asymmetrical quasi-transient perfect crossover - where the tweeter is rolling off ultimately at a much higher order, the woofer much shallower with a first order acoustic roll-off, and the delay in the cabinet helps achieve a summation that is still flat and nearly minimum phase. The tweeter's transfer function is actually derived in a subtractive way to mirror that of the woofer's roll-off, which is what allows for a flat summation.

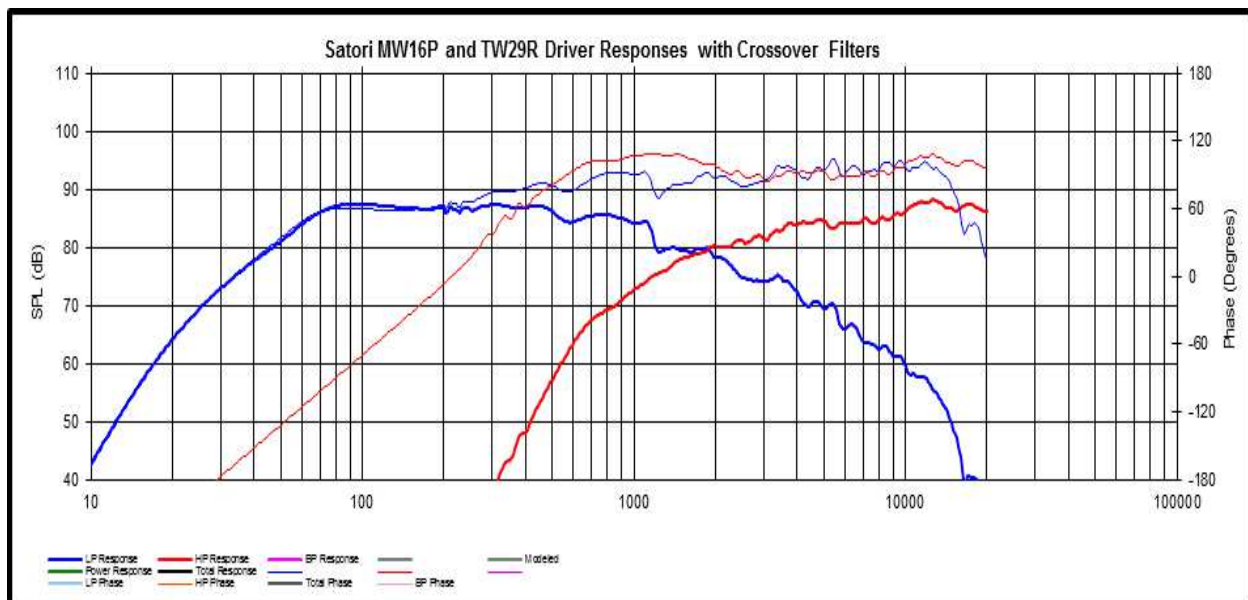
Of course, when you design these crossovers the phase is determined by the final acoustic response of the driver and crossover combined, and not just by the circuit itself. So when I talk about the tweeter's acoustic roll-off it has to include the tweeter's natural roll-off too. In reality, below about 600Hz the

tweeter is rolling off 4th order, but this is far enough out to not impact the crossover behavior too much. The tweeter's crossover actually rolls-off like a first order network in the beginning at higher frequencies. It does this, as you will see, as a mirror image of the woofer's acoustic roll-off. Then it transitions into what is closer to a second order L-R response shape at the crossover point, and finally at very low frequencies below the tweeter's resonance, it is rolling off with the much higher slope.

Even though this higher slope may be two octaves below the crossover point, the phase shift associated with it impacts the driver's phase in the crossover region a small amount. The solution is one that was computer derived. It includes the combination of using asymmetrical slopes between the two drivers, a very precisely derived time-alignment that delays the tweeter's first arrival the correct amount to help compensate for the phase shift, and the act of inverting the polarity of the tweeter relative to the woofer for its electrical connection. This may sound odd, but it is a matter of the second order behavior in the crossover region and the offset of the sloped baffle that when the tweeter is connected with inverted polarity it brings it back into phase with the woofer and results in a flat summation and very little phase error in the crossover region.

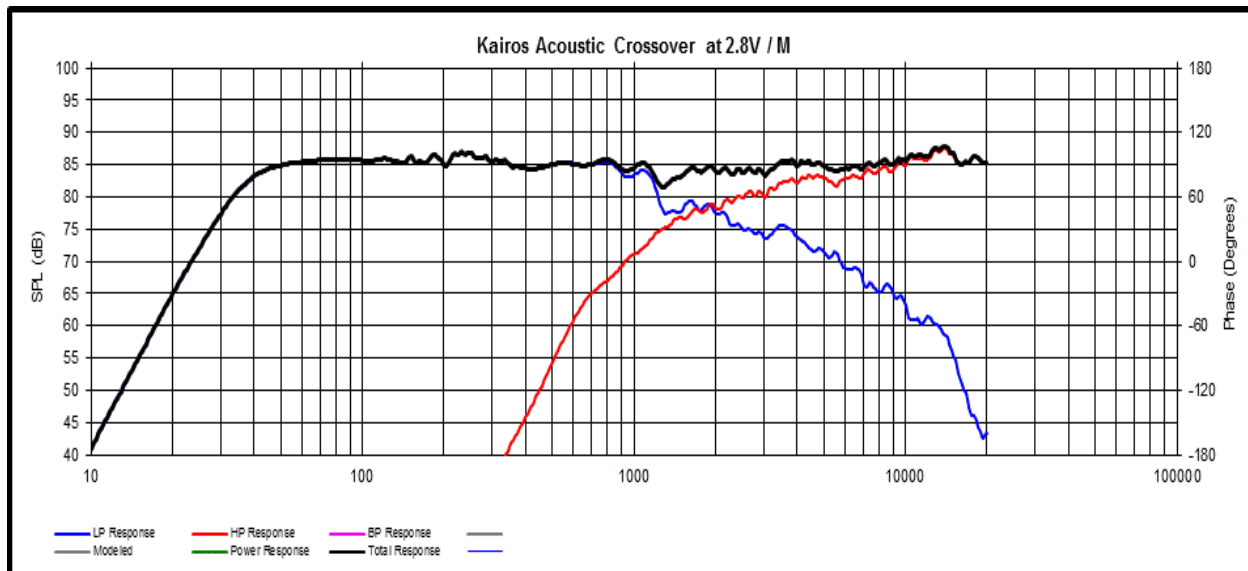
## System Measurements

Here's a graph showing the response of the drivers through their crossover filters:



As you can see the crossover point is at 1.8 kHz, and the behavior at the crossover point is essentially the same as a second order LR crossover.

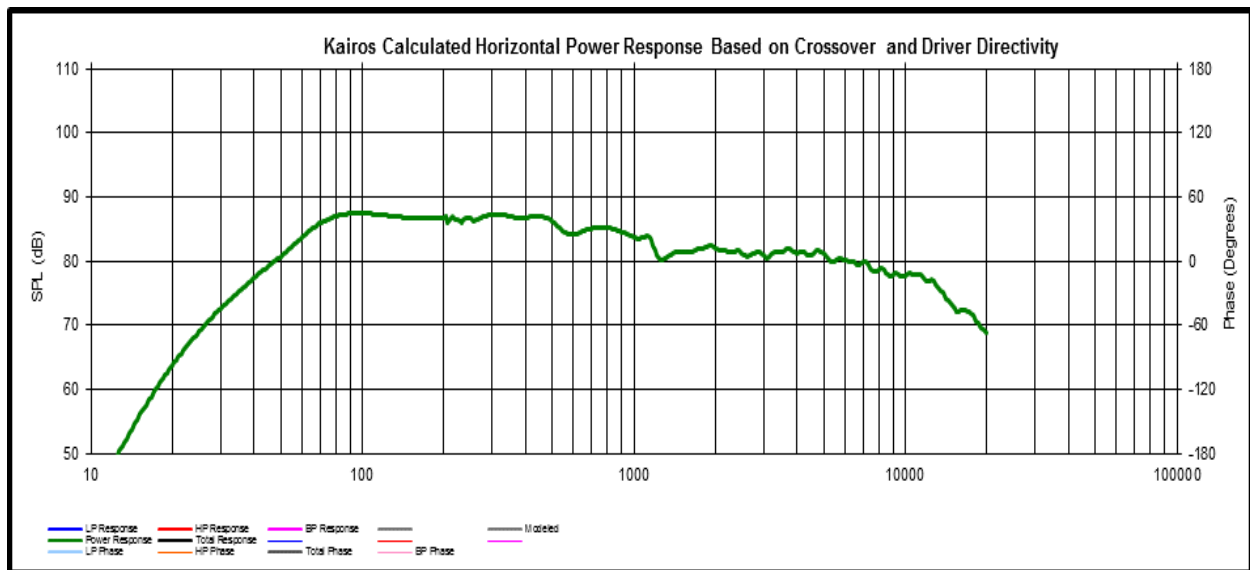
The graph below shows the summed response through the crossover region and clearly shows the asymmetrical nature of the acoustic crossover between the woofer and the tweeter.



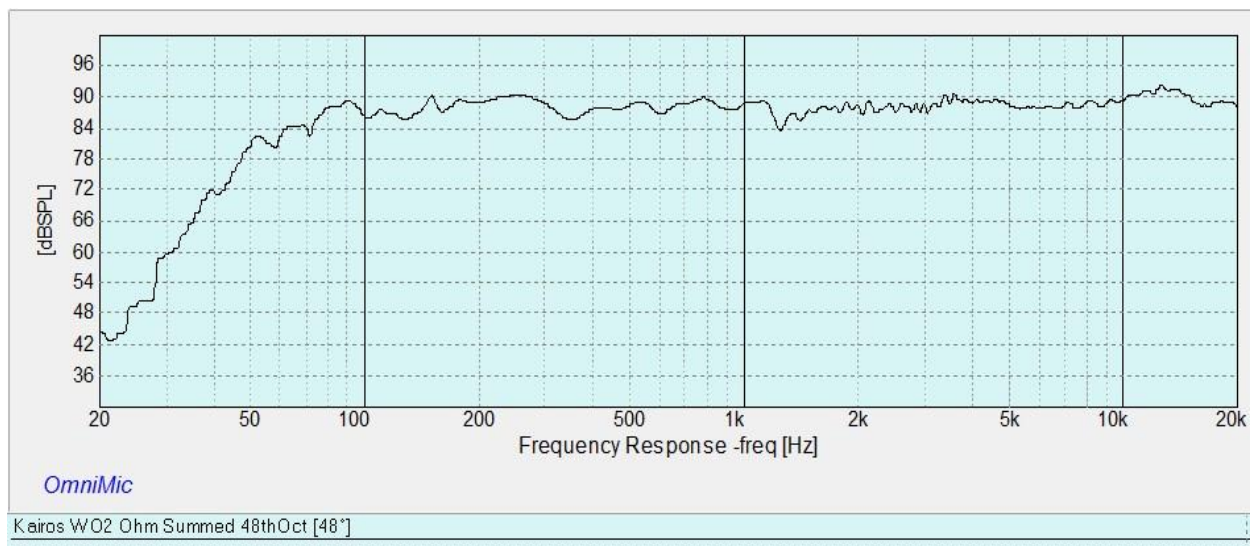
I do not have measurements along the vertical axis captured, but due to the time aligned nature of the speaker the primary lobe is straight forward on the speaker's main axis. The main design axis, by the way, was with the mic positioned between the woofer and tweeter. The nulls of the lobing are properly aimed at angles that point to the ceiling and floor. The sitting to standing test results in very little audible change in the speaker's response, which was one of my primary goals.

I would also like to add a comment regarding the horizontal response family and the power response. A single axial frequency response doesn't really tell the whole story. Although it is true that our primary impression of a speaker's "character" is shaped by the first arrival on-axis response, it is also true that this character is "seasoned" by the off-axis response and how this acoustic information reflects in the rooms and reaches our ear. When a speaker has a high crossover point so that the woofer's directivity is entering into the off-axis response before it hands off to the tweeter, then you will find an increasing dip in the response with increasing off-axis angle. So, although the on-axis response may be flat, what we perceive with our ears may not be if this off-axis dip colors the sound reaching our ear. By using a lower crossover point, in this case under 2 kHz, we can dramatically smooth the off-axis response in the crossover region. The result will be an off-axis response free of this dip and less coloration of the first arrival sound. The power response of a speaker is a mathematical construct that integrates the response on every axis into one averaged response curve. The general consensus is that the correct or ideal power response is one that is smooth and tilted downward with increasing frequency, but without peaks and dips in the midband response. The Kairos low slope / low frequency crossover point results in just such a power response, so not only is the on-axis response flat, but the off-axis response is nearly ideal as well.

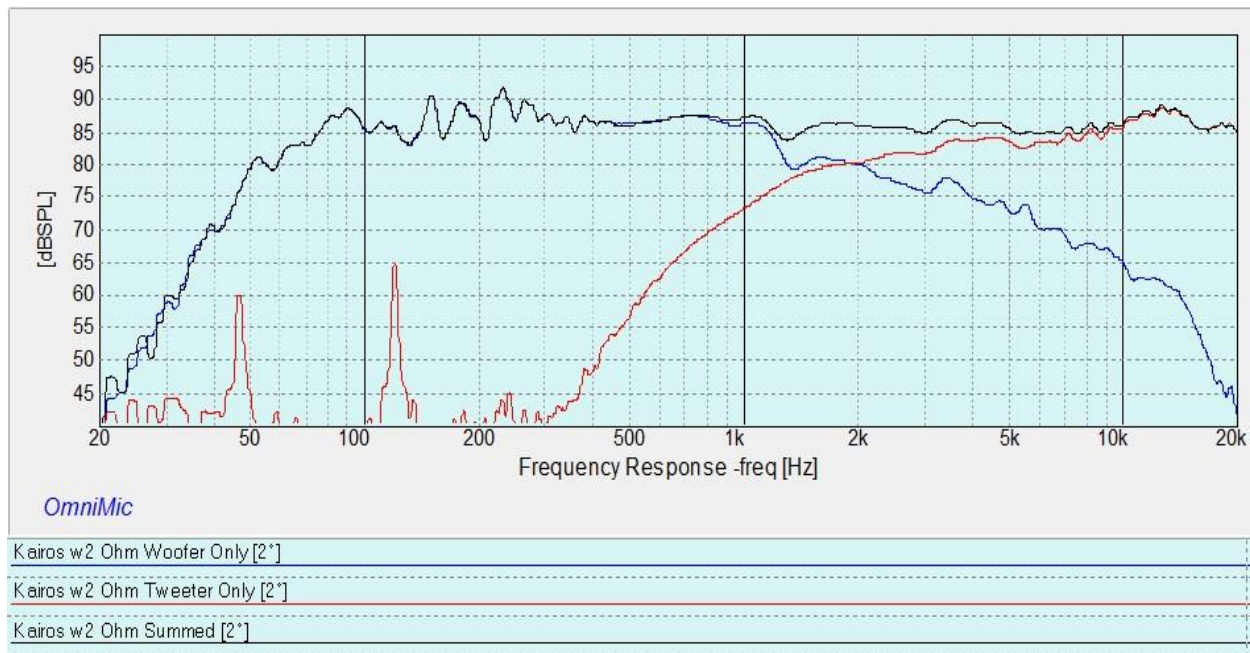
Here is the calculated power response graph:



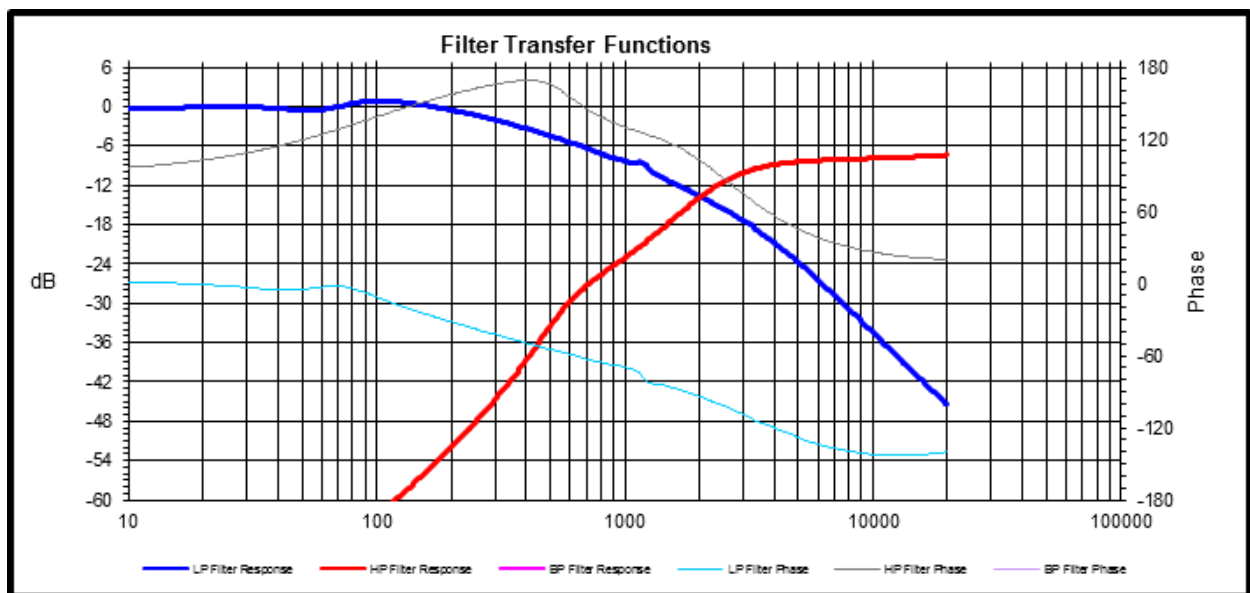
Here is a plot of the actual measured on-axis response in my family room, at one meter, using 1/48<sup>th</sup> octave smoothing. This is a capture from the measurement software to show that there is no doctoring of the measurement in any way:



Here's a plot of the actual measured acoustic crossover. As you can see, it matches the plot above perfectly. The data in this graph is good to about 300-400Hz, below that the room begins to take over. This can be seen in the graph, but its purpose is intended to show the actual measured acoustic crossover response and summation of the drivers:



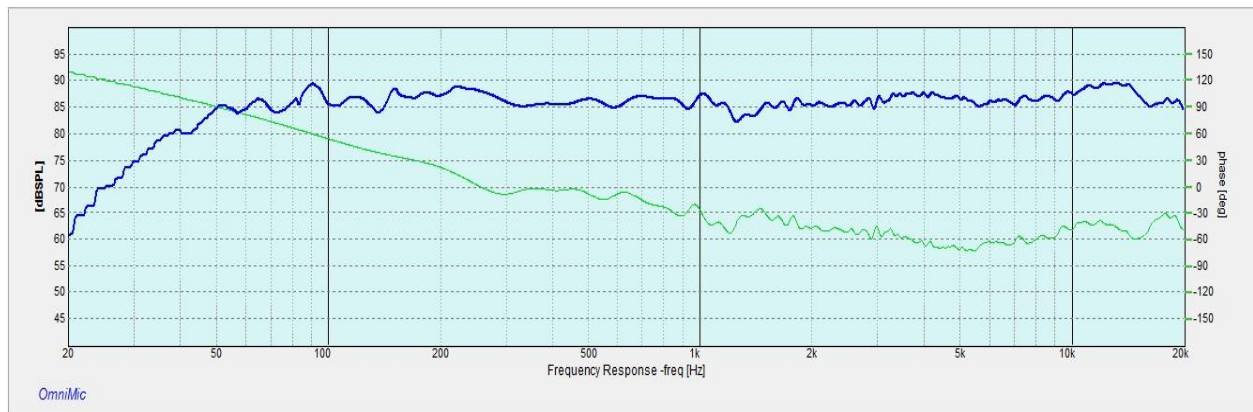
**For those that are interested, here are the actual filter transfer functions.** The early initial roll-off of the woofer's filter is for the purpose of compensating for the baffle diffraction step. The measured response shows how well this simple curve flattens the response:



So how did the system phase response turn out? Remember this is a system with asymmetrical crossover slopes and ultimately a fourth order slope on the tweeter with it using a low Q second order electrical filter to achieve this.

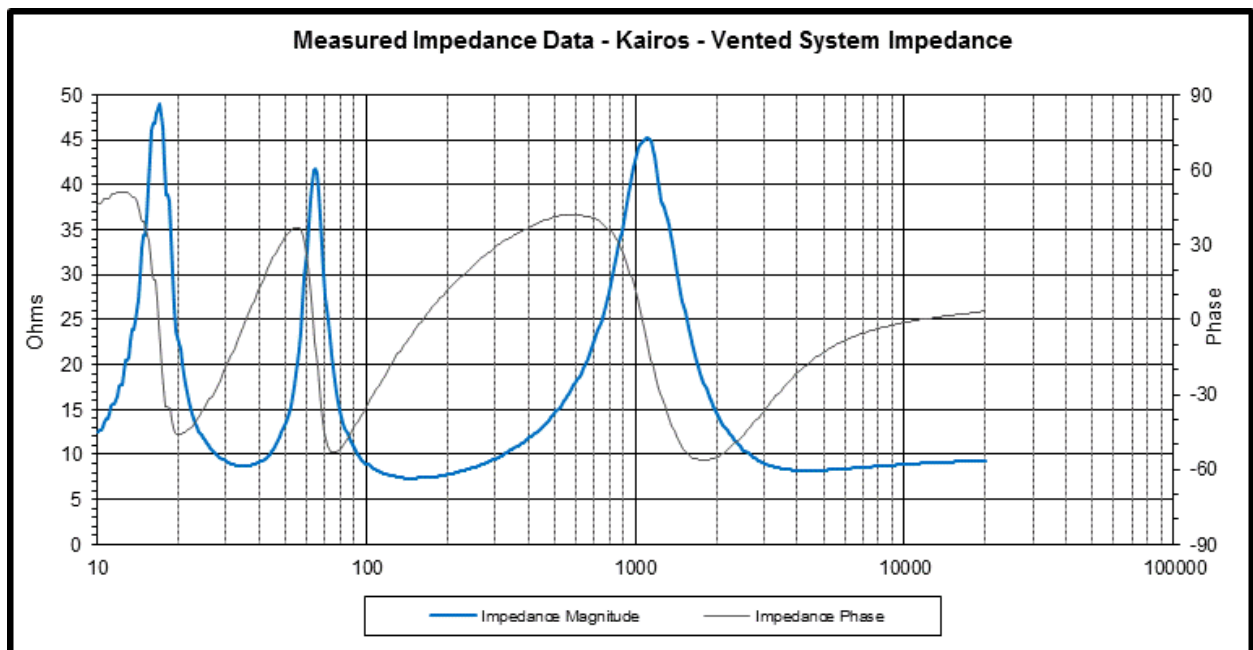


Here's the actual measured frequency response and phase of the speaker in my room at one meter on the design axis with the port plugged (the irregularities in the response below 300Hz are due to room reflections):

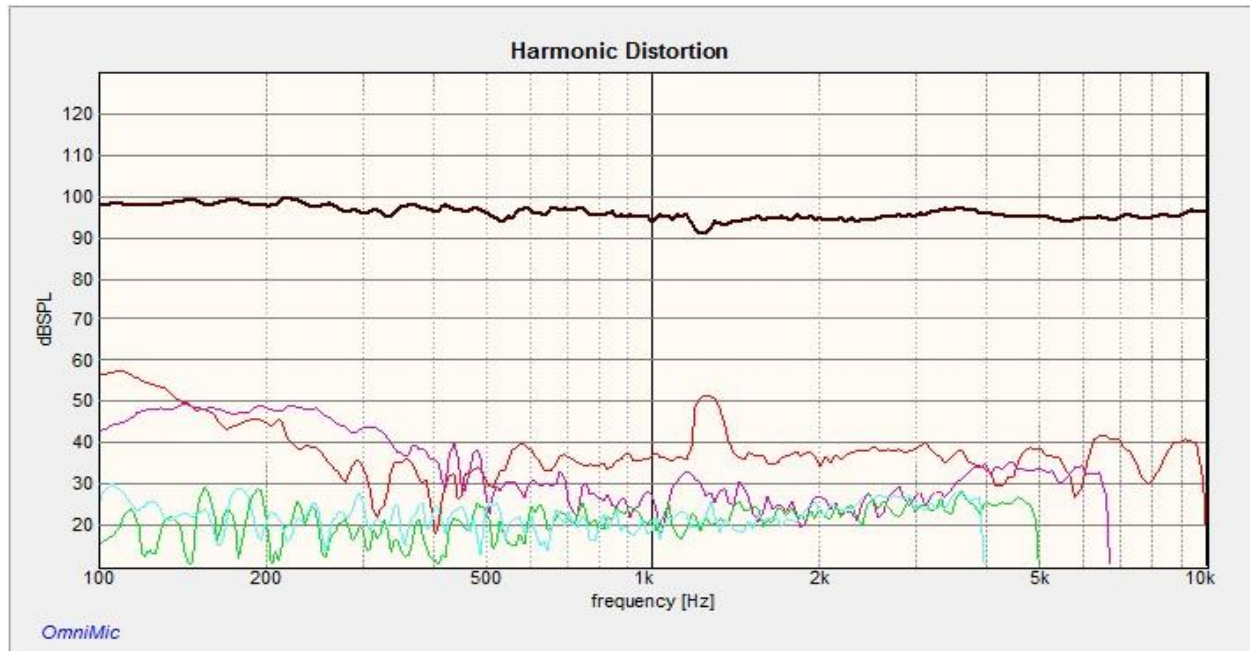


The blue line is the on-axis frequency response in my room and the green line is the actual measured phase response. It is not perfect, but at the same time the error is small and it is very close to being a minimum phase / transient perfect system and will preserve transients and time domain information better than all but a couple of speakers available on the market today. The speaker is exceptionally linear in both the frequency domain and the time domain and offers a level of performance not often found at any price.

A couple of other measurements that should be included are the **system input impedance**, which is also shown above, but here it is again in a different format:

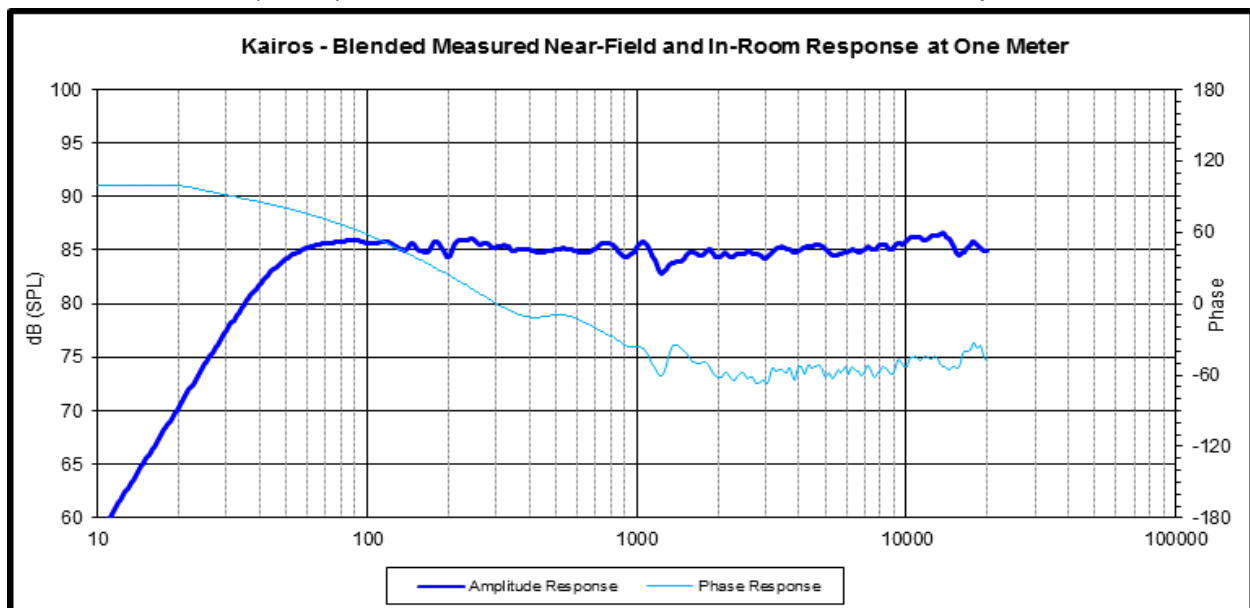


And here we have the **system nonlinear distortion** at 95db (which was pretty loud):



As you can see, nonlinear distortion remains quite low. The woofer's edge resonance creates, not just the dip in the response at 1200 Hz, but also a narrow peak in second order harmonic distortion. However, this peak is still low in level and fairly benign and second order distortion is fairly unobjectionable to begin with. The distortion that causes most audible issues are third order harmonics, and those remain low, at 0.1% or less THD over most of the spectrum from 300 Hz up.

Here is one more response plot. **This is the blended near-field and one meter response.**



I have found this to be an extremely well-balance speaker in my room.

## System Specifications

Two-way stand mounted monitor loudspeaker

Woofer: Satori MW16P , Tweeter: Satori TW29R

Dimensions: 16" tall x 9" wide x 13.5" deep at bottom, 9.5" deep at top.

Sensitivity: 85.5dB / 2.83V

Impedance: Nominal 8 Ohm input impedance, Impedance minimum: 6.7 Ohms at 140Hz

Bass extension:

Sealed: Qtc of .7, -3dB at 53Hz, -6dB at 41Hz

Vented: Fb of 35Hz, -3dB at 44Hz, -6dB at 37Hz

Group Delay: Sealed – Max GD 5ms at bass -3dB point

Crossover: 1.8 kHz Asymmetrical 1<sup>st</sup> Order / 2<sup>nd</sup> Order slopes at crossover point

Time Domain: Time aligned first arrival impulse

Phase Response: Minimum Phase within 30 degrees error through crossover region

## Personal Comments

I have designed a lot of speakers and listened to even more. To date the Kairos is the most musically satisfying and natural sounding two-way speaker that I have ever had the pleasure of listening to for an extended period of time. The crossover is so coherent that everything appears to come from one homogeneous source. Voices, pianos, guitars, have the most natural balance I have ever heard from a loudspeaker. Midrange reproduction does not get much better.

By themselves these are obviously not the best speakers for loud rock music, but with smaller scale music such as acoustic jazz and vocal ensembles these rival state of the art systems. The bass extension is surprisingly clean and deep, and as long as the SPL's are not pushed too high for the small cone to handle they sound amazingly full-range.

The high frequency reproduction of the TW29R is pristine. Cymbals are resolved with almost life-like clarity that leaves most other speakers sounding lifeless and plastic. You do not hear the muddled splashiness associated with so many other tweeters due to their distortion. Triangles and hats both sound extremely clean and sharp, the sonic edges are very crisp, and when listening to jazz being carried by a ride cymbal I feel I am almost transported to the room the musicians are in.

Imaging is excellent, as you would expect for a small monitor that is time and phase coherent. Of course, this really depends on how the recording is mixed, but when I listen to minimally mic'ed jazz, like "Jazz at the Pawnshop", and I place myself in the sweet-spot between the speakers it takes on a three-dimensional soundstage. With the tinkling of the glasses, if I close my eyes I feel like I am in the middle of the room with the audience.

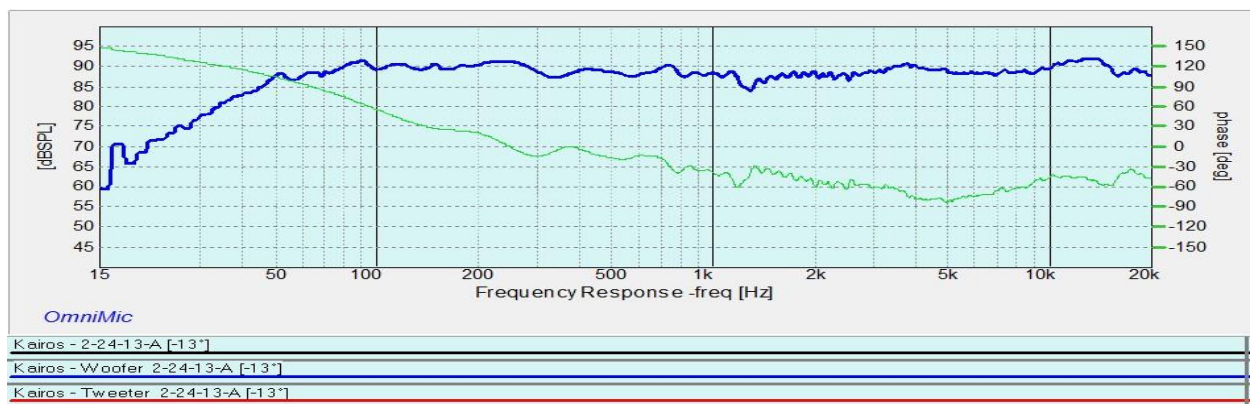
I also have an active system that I listen to these in. It consists of a pair of sealed subwoofers with TC Sounds 12" drivers and separate 500 Watt amps for each, and a 4<sup>th</sup> order highpass active filter for the 200 Watt Carver amp driving the monitors. I use a 50 Hz high pass for the Kairos with their ports plugged and adjust each of the subwoofer crossovers for frequency, gain, and phase until I get a flat summation

between them and the Kairos. (I use a similar method with other small monitors as well). With the deep bass filtered and the subs dialed-in the Kairos and the dual subwoofers present my room with a powerful and honest musical presentation from 18 Hz to above 20 kHz, that seems to be nearly state of the art for the electronics and room they are being played in.

I can't keep everything I design. I get that "look" from my wife as it is. So, I have sold off many of the speakers I have designed over the years. However, the Kairos are sitting on stands in my living room and I can't imagine ever letting these go. I plan to enjoy these speakers on a personal level for many years to come. I believe those of you who give them a try will find yourselves in the same position.



Here's one more recent measurement in my room at a different mic position. Note the tonal balance of the frequency response and the linearity of the phase response for a real-life in-room response measurement. Most designers would not show you an in-room response plot, but since that's where we listen to our music, I feel I owe it to you. I have nothing to hide, the speaker speaks for itself.



## **Final Note**

You have probably noticed that the details for the cabinet plans and the crossover schematic are not presented in this write-up. Those are part of the kit available through Meniscus Audio. This is to protect Meniscus and the kit design that I have provided for them.

However, Mark at Meniscus will sell the crossover and plan separately for anyone who already possesses the drivers but would like to build the Kairos. Mark will also provide alternative pricing on crossovers using exotic parts or even more economical parts, whatever the user may prefer.

Submitted for your enlightenment and enjoyment, may you savor the music.

Jeff Bagby  
March 8, 2013