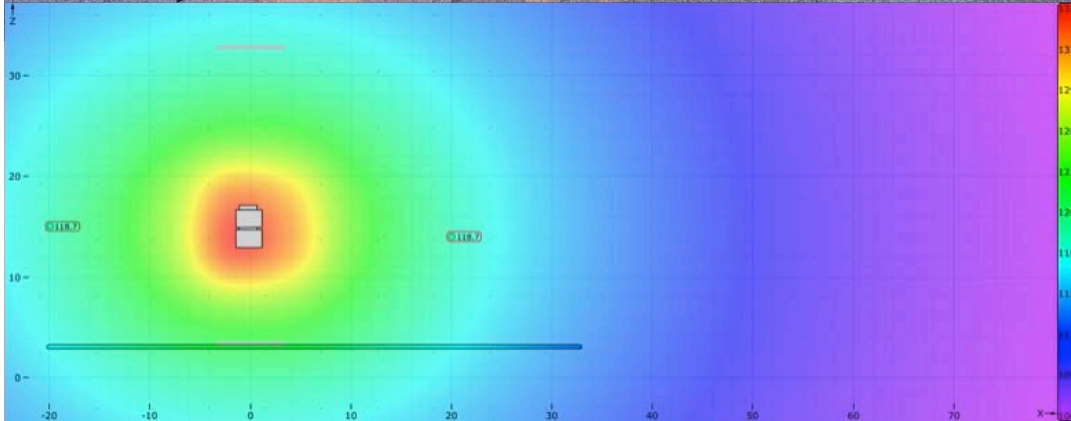


# *Directional Subwoofer Arrays: A Practical Approach*



## **Introduction: Why Are Subwoofer Arrays Receiving So Much Attention?**

Many have written about subwoofer arrays, and especially the 'cardioid phenomenon' currently occurring in the industry. In reality, the acoustical principles that govern low-frequency transducers differ from those of higher frequencies only by physical scale and proportions. The industry has focused on low frequencies, however, because the physical scale of these wavelengths is large relative to the human world. That is to say, interference zones that occupy inches or less at high frequencies occur over feet or tens of feet at low frequencies, making them much easier to spot, observe and manipulate. With the availability of low-cost digital signal processing, it is no surprise that audio professionals have spent quite a bit of time and effort on subwoofers, and methods of combining them in clever ways.

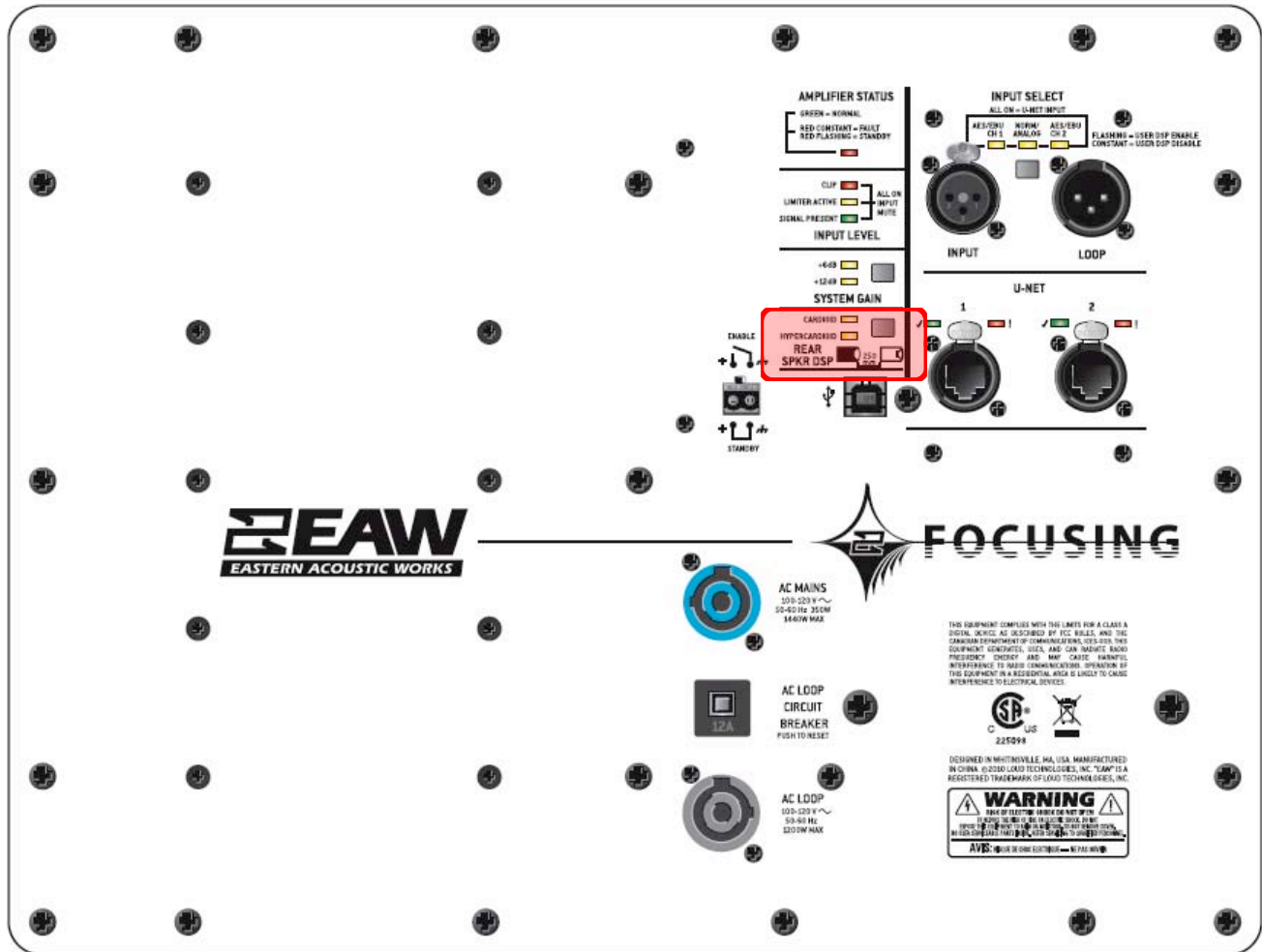
The purpose of this paper is two-fold:

1. **Practical Application:** A step-by-step guide to implementing directional subwoofer arrays with EAW products. This requires only a minimal understanding of the science behind these techniques, but yields valuable real-world results.
2. **Theoretical Discussion:** A more thorough examination of the different types of directional subwoofer arrays, and the benefits and drawbacks of each.

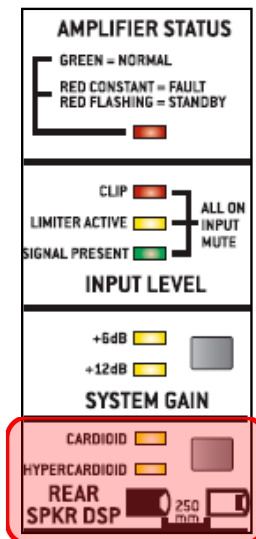
**Part I: Step-By-Step Instructions for Implementing Cardioid Arrays with the NTS250**

Though the theory of directional subwoofer arrays can grow quite complex, implementing them with EAW products is not. EAW engineers have made the process relatively painless, allowing highly effective and versatile arrays to be created with nearly any currently-offered subwoofer in the product line.

Users can easily create directional arrays using NTS250 subwoofers. No computers or additional equipment are needed. With multiples of two NTS250's, the user need only space the subwoofers by a specified distance and engage the 'cardioid' or 'hypercardioid' modes via the rear panel of the rear-most subwoofer (that which is closest to the region of desired cancellation).

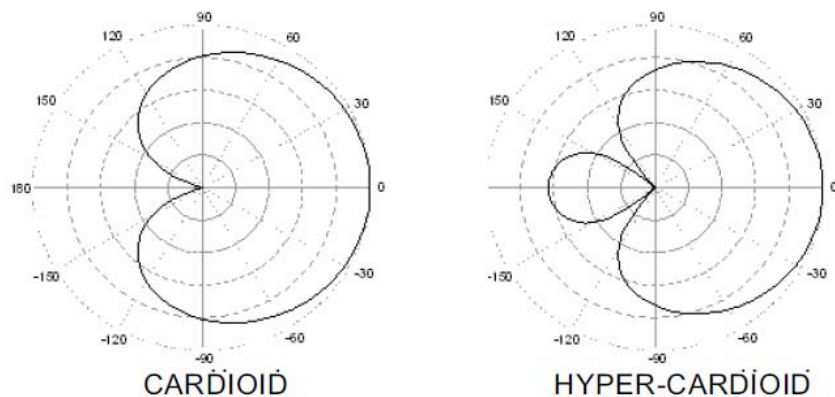


**Figure 1:** Rear panel of NTS250 subwoofer, illustrating push-button cardioid and hyper-cardioid functions and physical subwoofer arrangement necessary to implement them.



**Figure 2:** Close-up of NTS250 section, from which user can activate cardioid and hypercardioid functions.

The user has the choice of a cardioid pattern (with greatest attenuation directly behind the array), or a hypercardioid pattern (with greatest attenuation diagonally off-axis in either horizontal direction).



**Figure 3:** Horizontal polar plots of cardioid and hyper-cardioid patterns available with two or more NTS250 subwoofers.

This setup can be scaled to achieve greater SPL output, but it is important that the front and rear 'stacks' remain matched in size. That is, the number of front and rear NTS250's should always be the same (1 in front of 1, a stack of 2 in front of a stack of 2, etc.). Though it is possible to use differing quantities of NTS250's and adjust output levels to match (for example, 2x forward NTS250's and 1x rear NTS250 with +6 dB of gain), it is not recommended; because the rear subwoofer's gain has been increased, it will clip at a lower level than the forward subwoofers, reducing rear cancellation at high drive levels (when it is arguably most important!).



## Step-By-Step Instructions for Implementing Cardioid Arrays In EAW Pilot

Though cardioid and hypercardioid arrays are most easily created with the NTS250, nearly any current EAW subwoofers can be used to create advanced directional arrays through the use of the UX8800 and UX3600 processors.

To begin the process, connect to the UX processor and go to an unused output leg (Channels 1 through 6 or 8, depending on which processor you have). Click on “Select/Configure Greybox”.

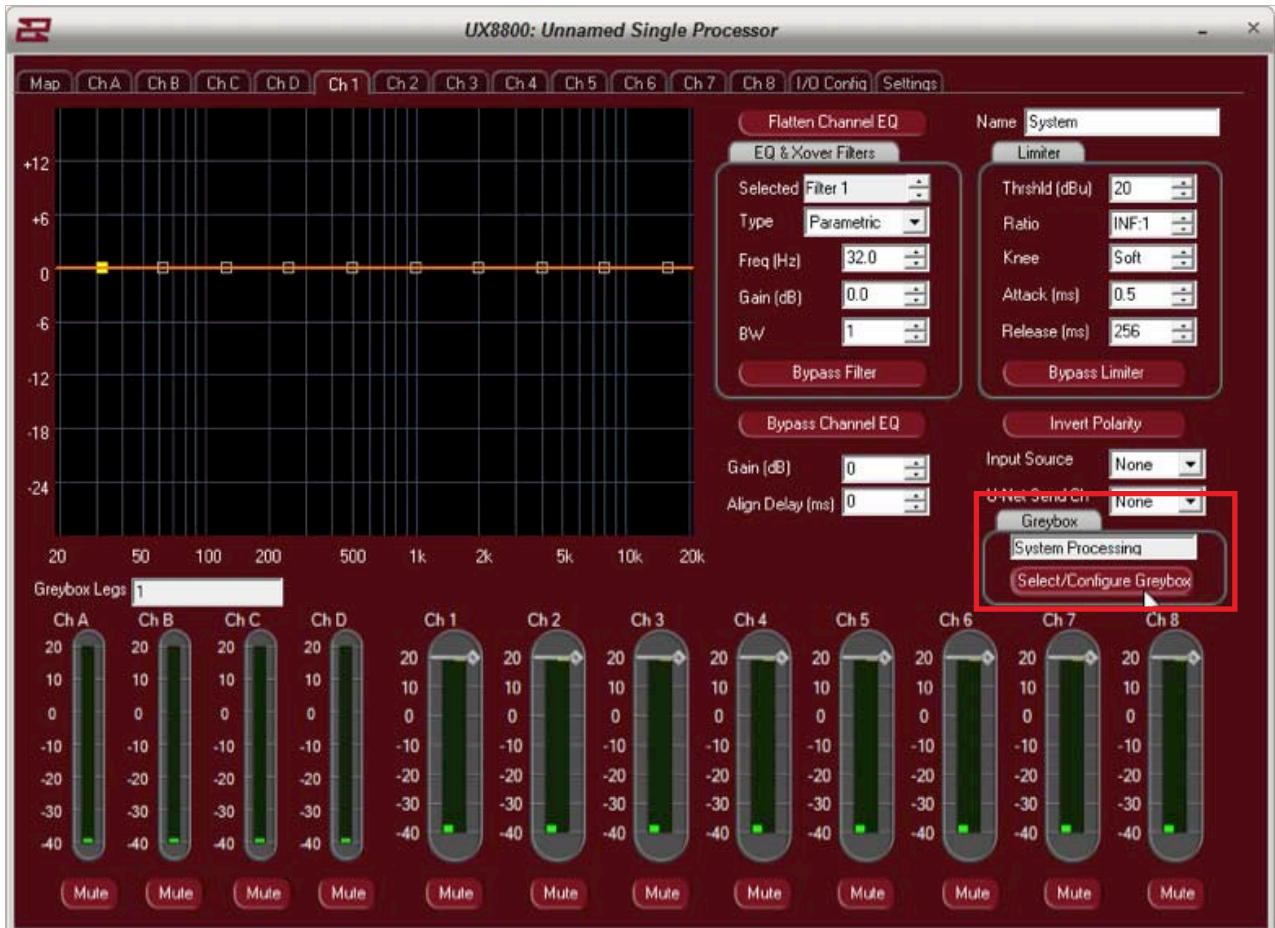
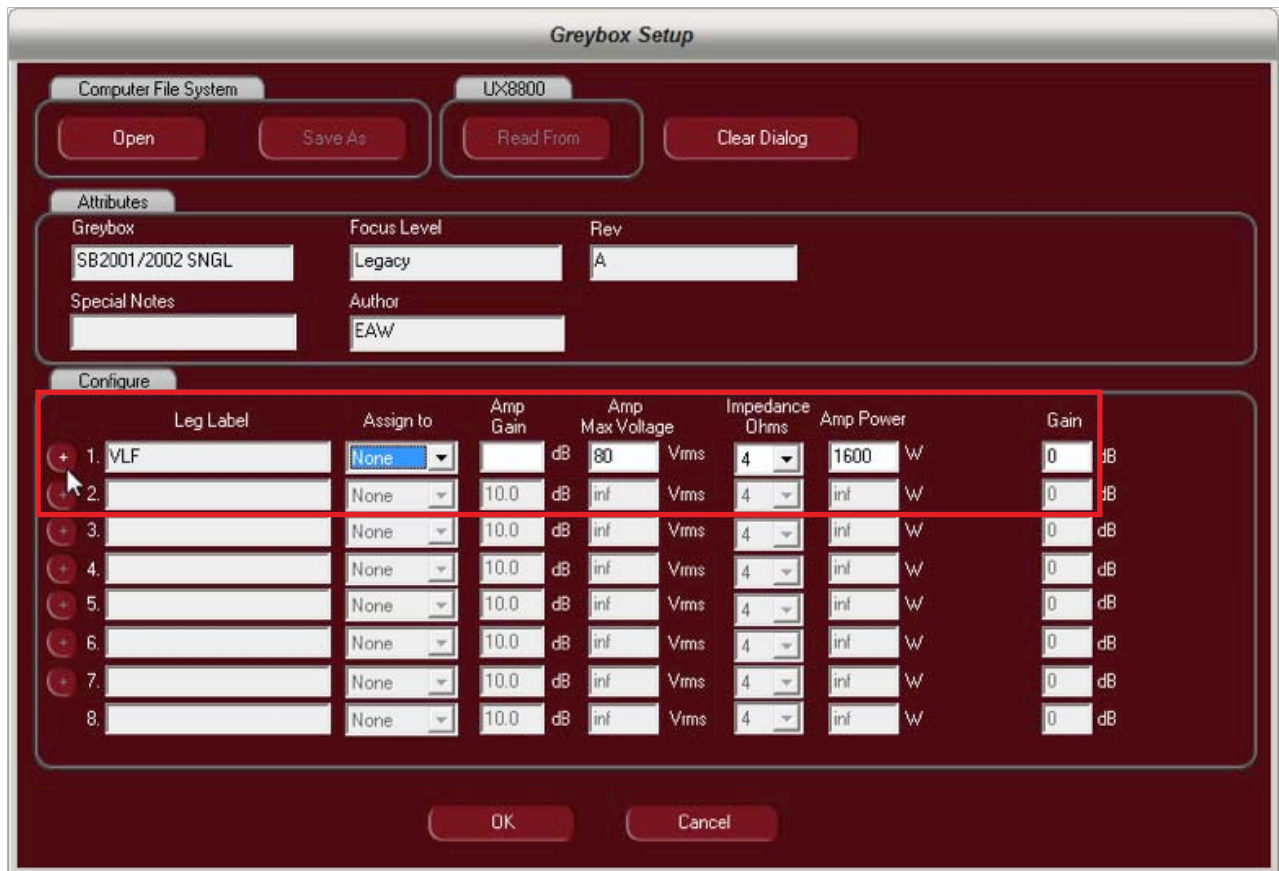


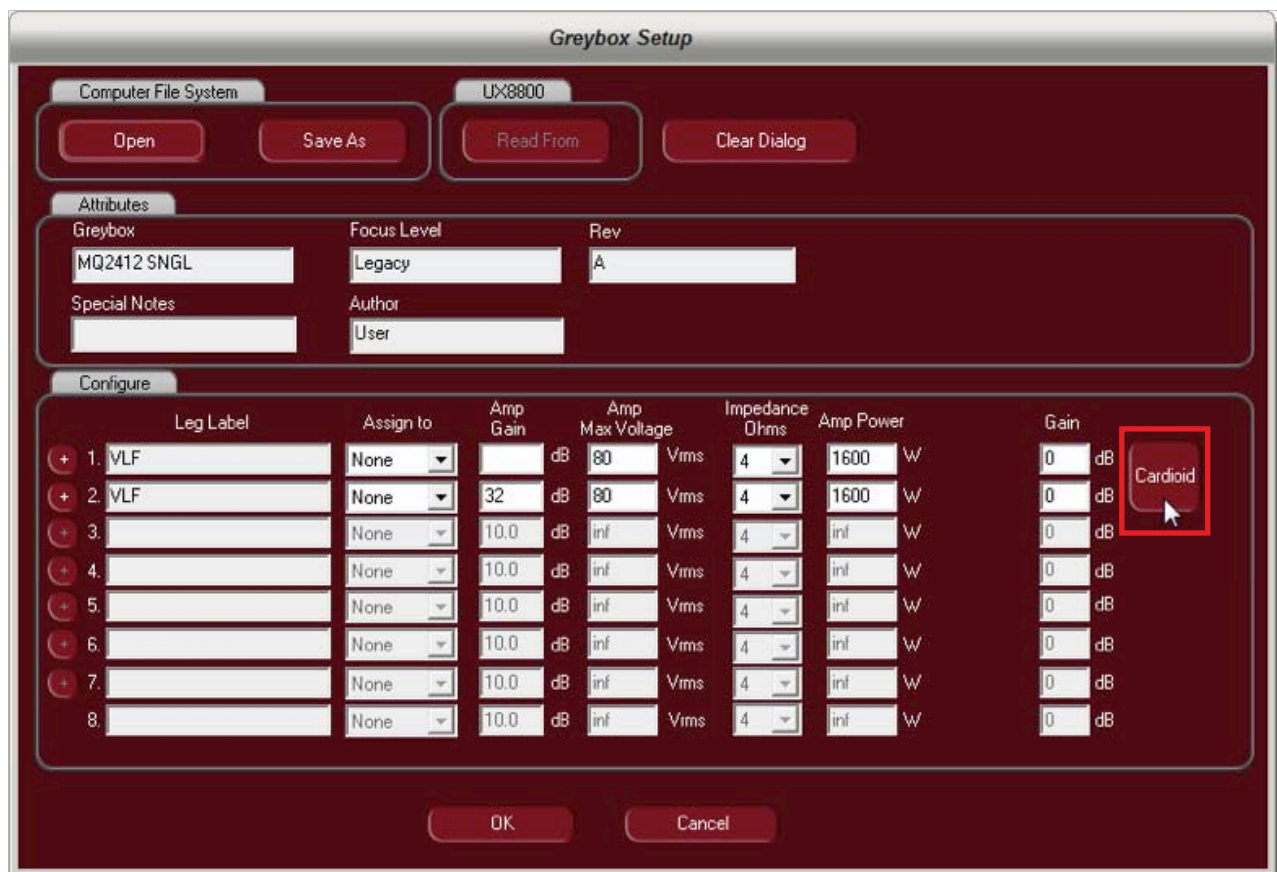
Figure 4: One of the output tabs within a UX8800 processor.

Within the “Configure Greybox” window, select “Open” and choose an EAW subwoofer Greybox (that is, any Greybox with a leg labeled “VLF”). In most cases, a single leg will appear.



**Figure 5:** The Greybox Setup window immediately after loading a subwoofer Greybox. Notice that a single leg appears.

Within the Greybox Setup window, select the “+” button to the left of the VLF leg. A second leg will appear on the next line. Assign each VLF leg to a processor output. You will also notice that a button labeled “Cardioid” has also appeared on the right side of the screen. Click on the Cardioid button to configure the directional array.



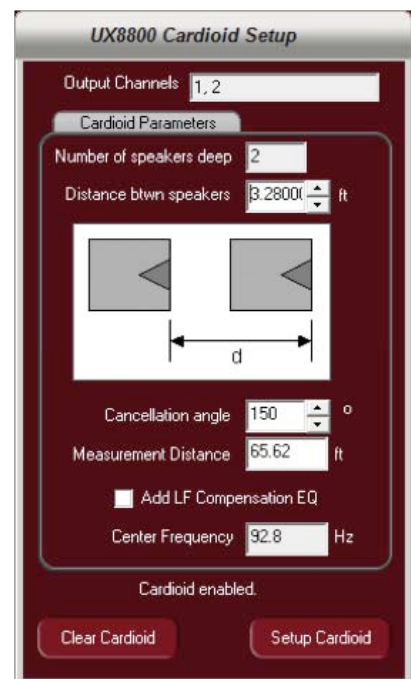
**Figure 6:** The Greybox Setup window with a second VLF leg added. Notice that the “Cardioid” button appears to the right of the VLF legs.

Click on the “Cardioid” button to begin the subwoofer array setup process.

Within the Cardioid Setup window, the user needs only to enter the following data:

1. The distance between the fronts of the loudspeakers.
2. The desired cancellation angle (see Appendix note 1), between 110 degrees (for hypercardioid) and 180 degrees (for cardioid).
3. The measurement distance, or distance at which max summation and cancellation should occur. The default value of 65.62 feet or 20 meters is generally fine for this unless the array is extremely large or it is necessary to achieve cancellation at an extremely small distance from the array.
4. As an option, the user may also choose to apply a low-frequency boost to compensate for the 6 dB/octave roll-off (see Appendix note 2). This does not affect directivity, since it is applied to both the forward and rear subwoofers.

After this information has been entered, click the “Setup Cardioid” button. The appropriate processing has now been applied to the “VLF” outputs of the Greybox.



**Figure 7:** Cardioid setup wizard in UX8800 and UX3600 Pilot software.

## ***Part II: Theory Of Directional Subwoofer Arrays***

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To begin our discussion of the theory behind various directional subwoofer arrays, we list a number of common misconceptions that exist in the marketplace (and about which we are frequently asked):

### *Common Misconceptions/Myths*

1. All cardioid arrays trade rear cancellation for reduced forward output.
2. Some subwoofers in a cardioid array must always face backwards for proper 'phase cancellation'.
3. Only certain types of subwoofers can be used for cardioid arrays.

We are often asked, for example, "Which EAW subwoofers can be used in cardioid arrays?" Though products such as the NTS250 make this implementation easier because of on-board processing presets, the truth is that nearly any wide-beamwidth (omnidirectional) subwoofer can be used – this includes almost all subwoofers, except for those with very large horns. After all – to manipulate low frequencies, all that is needed is for the sources to interact!

We are also often asked, "What type of cardioid setup is best?" In the coming pages, we hope to provide some insight into this topic.

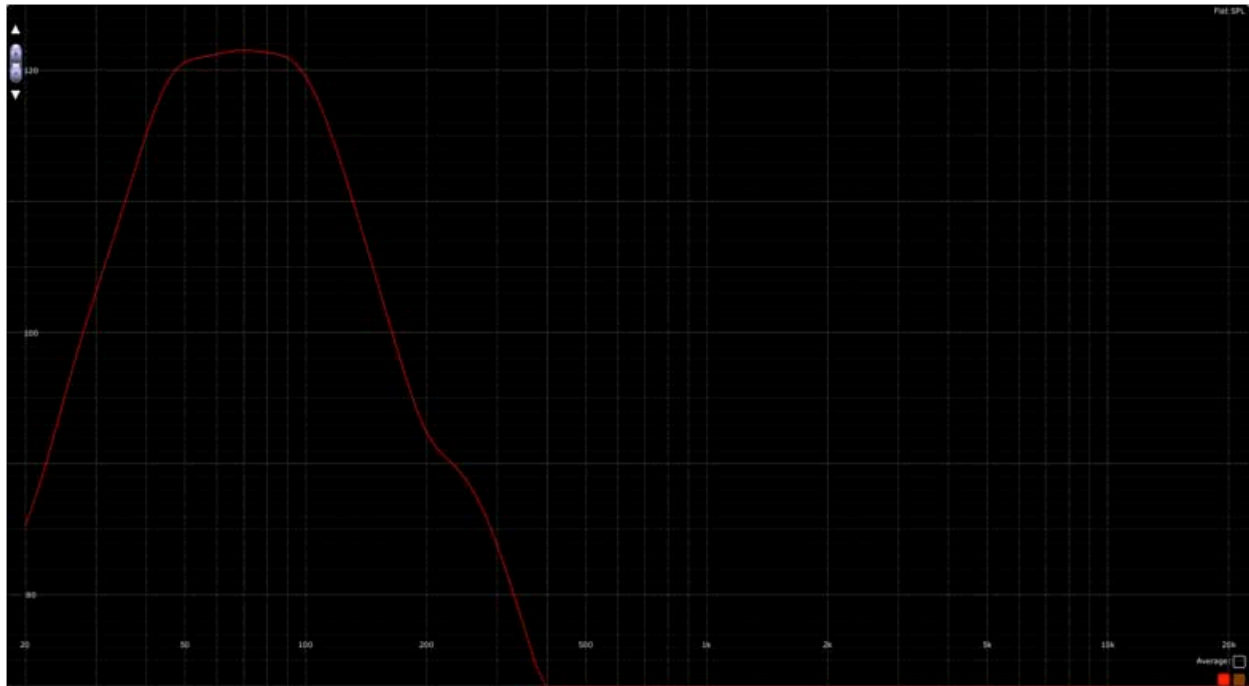
NOTE: The prediction data used in this paper was generated with EAW Resolution, a free tool available to anyone for download via the EAW website. Users are encouraged to use Resolution to re-create and verify the illustrated configurations (available for download with the paper).



## Types of Subwoofer Arrays

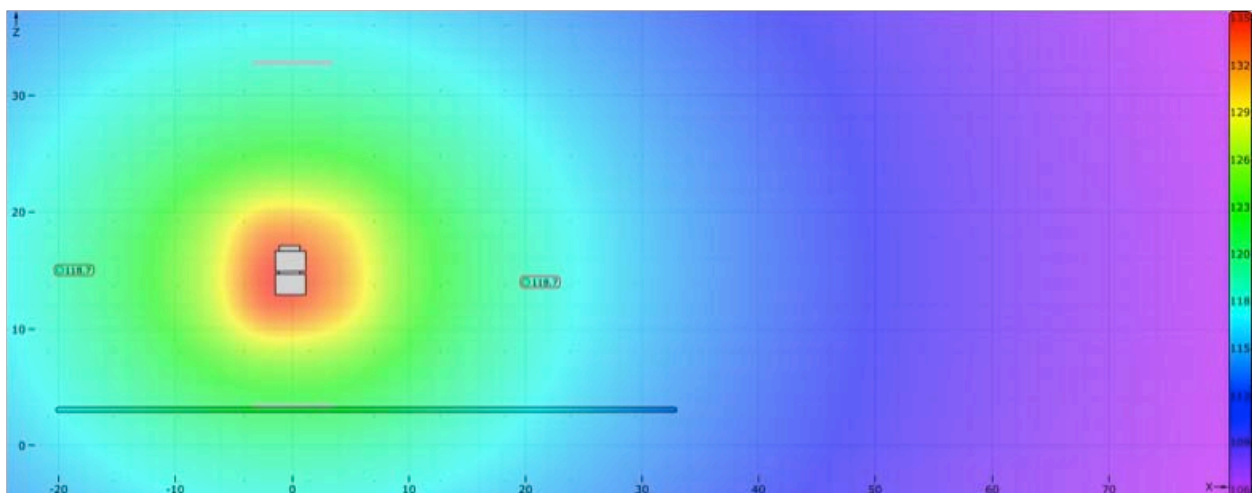
### Omni-directional (AKA 'Pile O' Bass)

To begin experimenting, we first need a control group. We have modeled a simple 1-over-1 stack of subwoofers, both elements facing forward, with identical processing. The results are as we would expect – they sum all around, and the array has very little directivity (it is nearly omni-directional).



**Figure 8:** Frequency response at equal distances in front and behind 'normal' array.

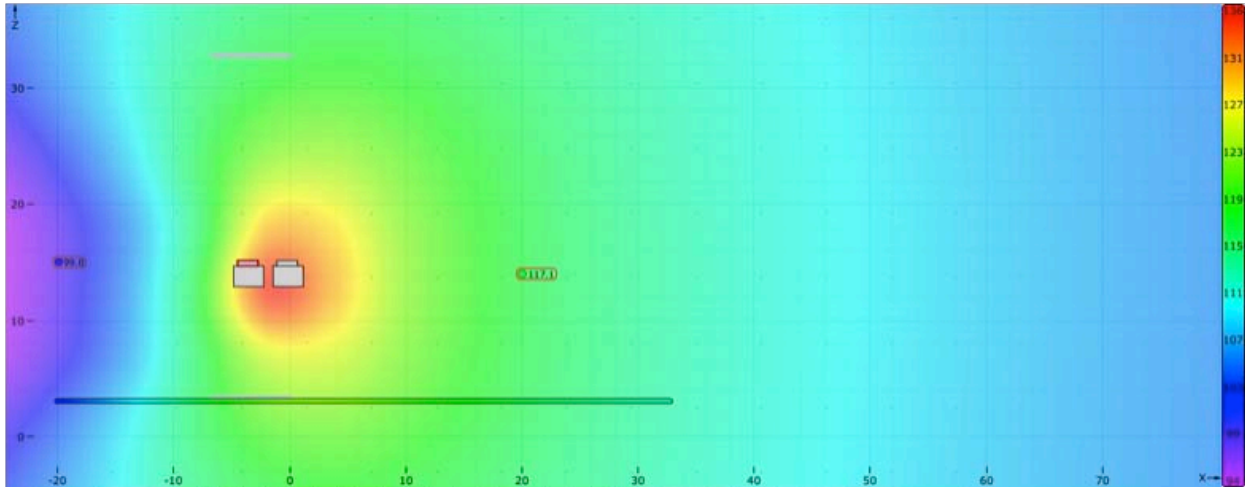
In the above chart, the red trace is a measurement microphone placed 20 feet in front of the array, and the amber is its mirror image, behind the array (at the same distance). In this case, the two traces overlap completely because the array is radiating nearly omni-directionally.



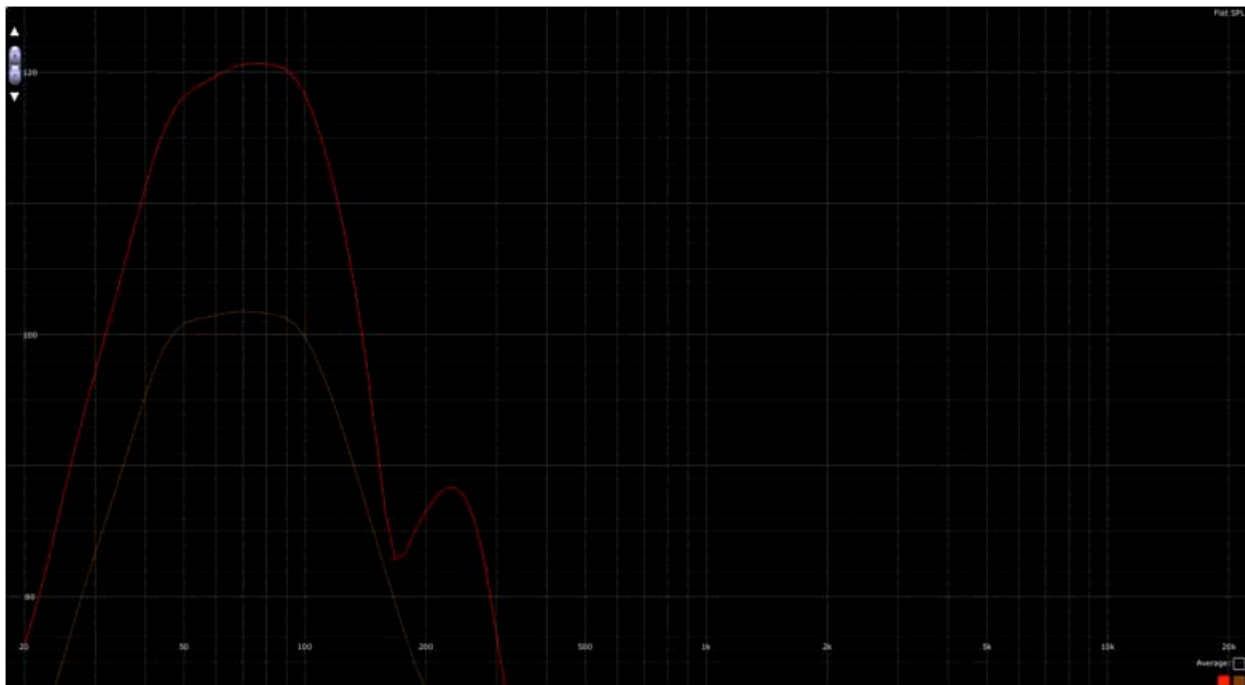
**Figure 9:** 100 Hz section-view prediction showing radiation pattern and measurement microphone location with 'normal' configuration.

### End-Fire or 'Shotgun' Array

The first type of cardioid array we will explore is commonly referred to as an "end-fire", or "shotgun" array. In this case, one subwoofer is placed behind another, with a polarity inversion and delay applied to the rear loudspeaker. The configuration and results of an example setup are shown below.



**Figure 10:** 100 Hz section-view prediction showing radiation pattern and measurement microphone location of 'end-fire' array.

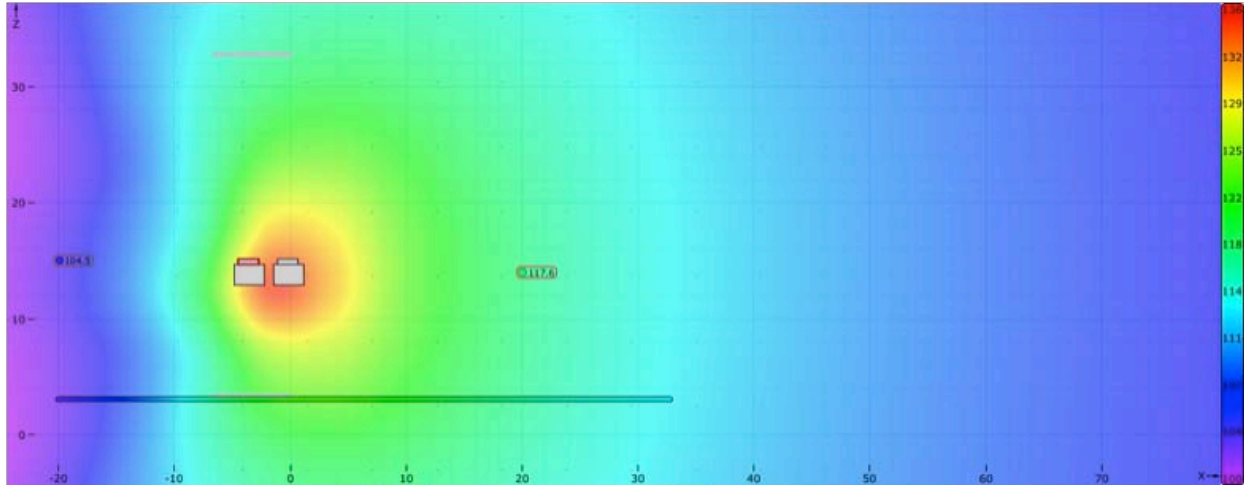


**Figure 11:** Frequency response at equal distances in and front (red) and behind (brown) 'end-fire' array.

This configuration yields nearly identical forward output as compared to standard two-subwoofer stack, yet provides approximately 20 dB of broadband cancellation behind the array. In observing a section-view prediction, we can also see that cancellation and summation regions are spatially consistent and relatively wide.

### Quasi-End-Fire or 'Quasi-Shotgun' Array

Another often-seen cardioid configuration is also commonly referred to as 'end-fire' or 'shotgun' array, but provides drastically different performance. To distinguish it from the previous configuration, we will instead dub it 'quasi-end-fire' or 'quasi-shotgun'. Using the same physical configuration, straight delay (without a polarity inversion) is applied to the front subwoofer to align it with the energy from the rear subwoofer.



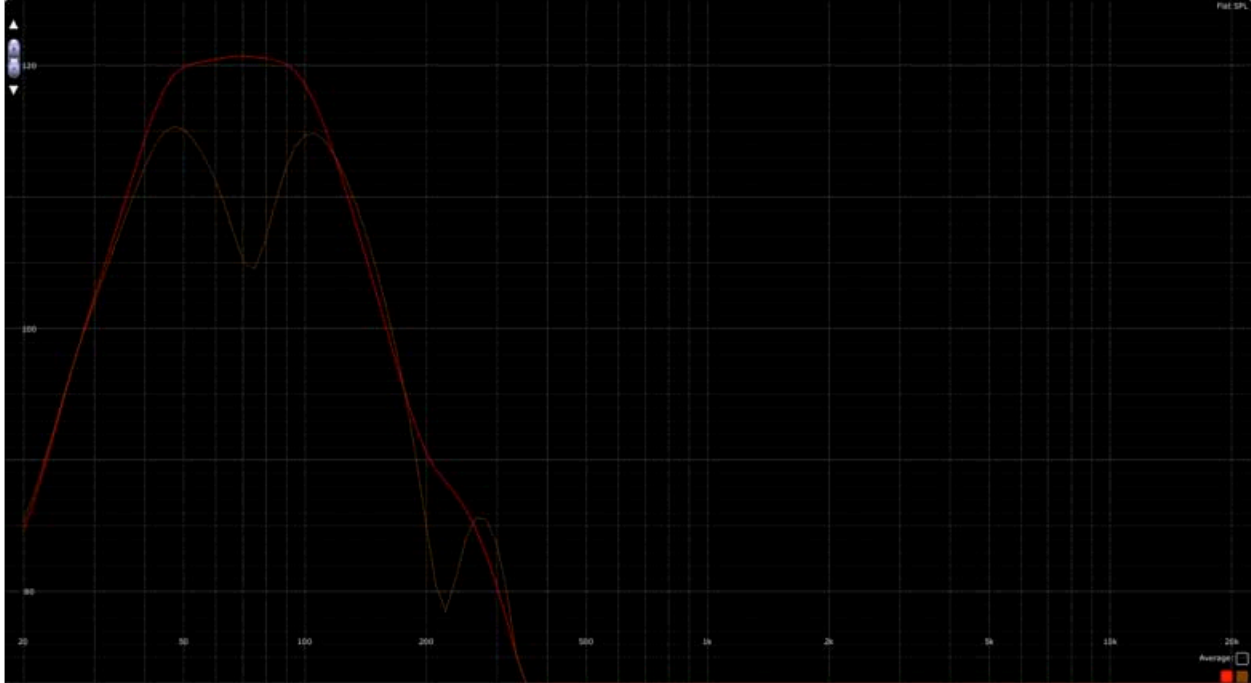
**Figure 12:** 100 Hz section-view prediction showing radiation pattern and measurement microphone placement of quasi-shotgun array.

Within a narrow frequency band (say, the  $\frac{1}{2}$ -octave around 100 Hz), this might look effective and we are inclined to ask, "What's the difference between this and our previous end-fire array?" The problem with this configuration becomes clearer when we look at its performance across the entire low-frequency band:



**Figure 13:** Frequency response at equal distances in and front (red) and behind (brown) 'quasi-end-fire' array.

Though the delay does produce appreciable cancellation, the effect is very narrow in bandwidth (in this case, we have 'tuned' the system to achieve maximum cancellation at about 100 Hz). In fact, we can modify the cancellation center frequency by varying only the delay time:



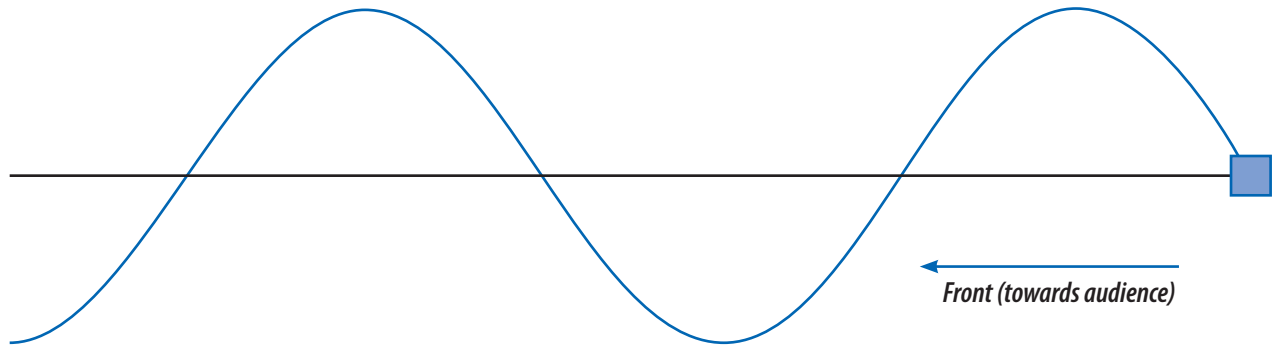
**Figure 14:** Frequency response at equal distances in and front (red) and behind (brown) 'quasi-end-fire' array, with delay adjusted.

In practice however, the frequency-dependence of this system is not a trivial issue! A ragged frequency response on-stage can not only significantly reduce gain-before-feedback, but can create an uncomfortable listening experience for the artists; certain bass notes are emphasized and 'boomy' while others are nearly inaudible. Thus, more is demanded of the monitors to compensate, but these are already handicapped because of gain-before-feedback issues. Thus, the vicious cycle continues and nobody (artists, engineers, or audience) are satisfied with the result.

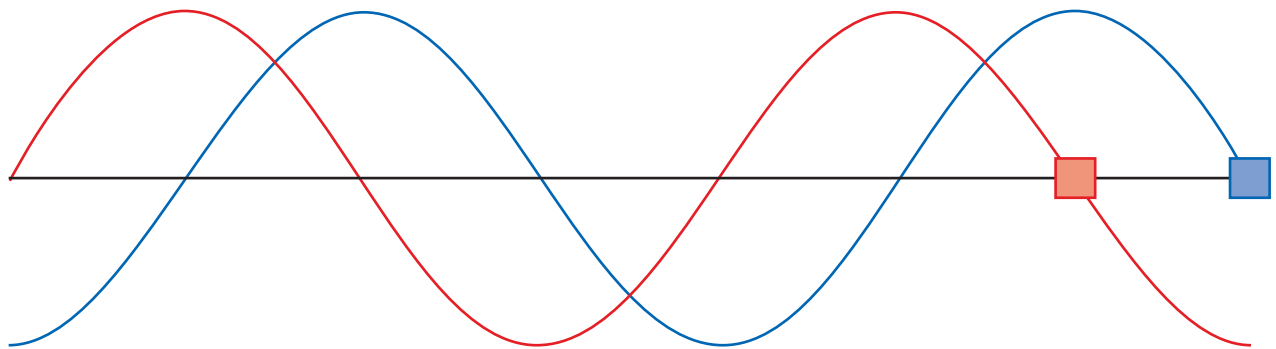
## Stacked Cardioid

Often, we are asked why EAW recommends an end-fire or 'shotgun' arrangement instead of the 'stacked cardioid' configuration often used in live sound reinforcement. In truth, they are almost exactly the same thing! To see why, let's consider what is actually happening when we put one subwoofer in front of another and apply delay (see Appendix note 1) and polarity inversion. For the purposes of discussion, we will assume that these sources are infinitely small and omnidirectional.

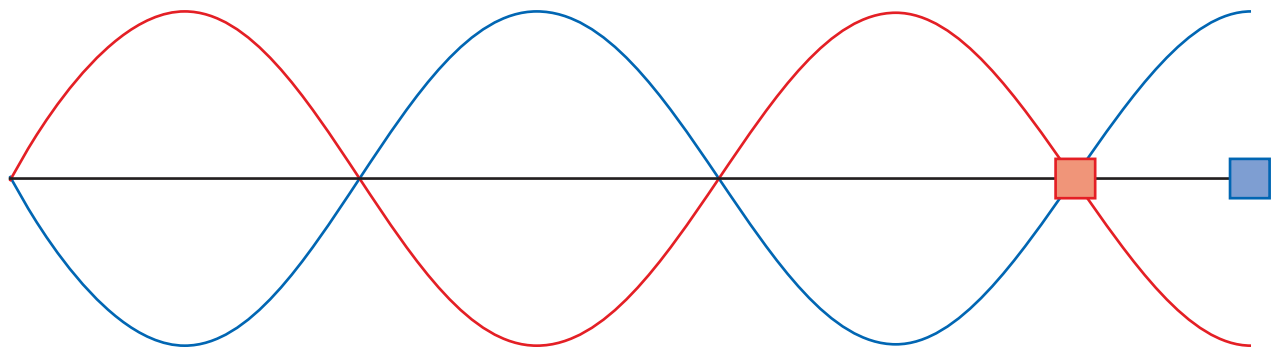
Starting with one source:



Next, we add another source, but spaced  $\frac{1}{4}$ -wavelength in front of the first:

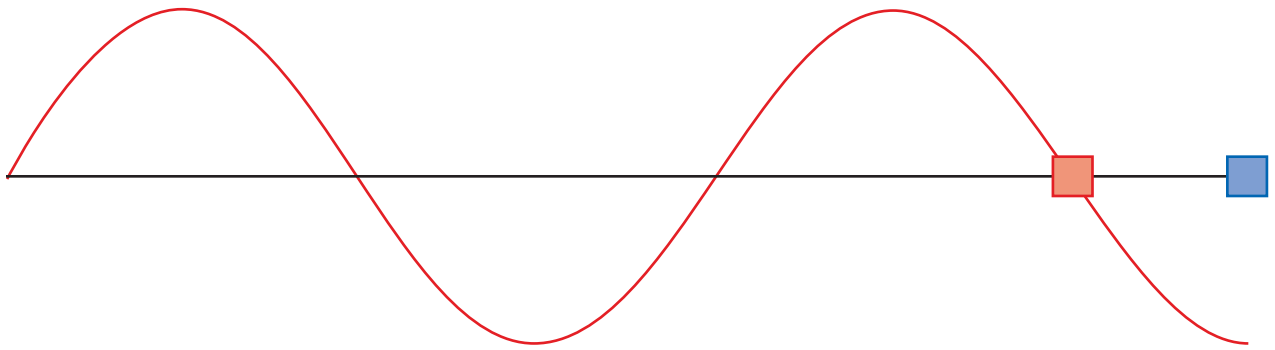


We then add delay to the rear source, corresponding to the  $\frac{1}{4}$ -wavelength physical spacing:

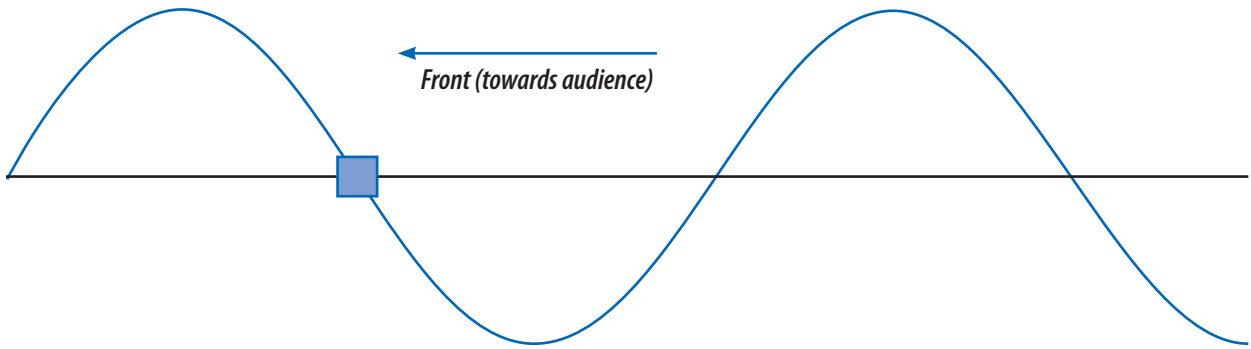


Notice that we now have total cancellation in the forward direction. By inverting the polarity of the rear source, this becomes summation (blue and red sine waves are overlaid):

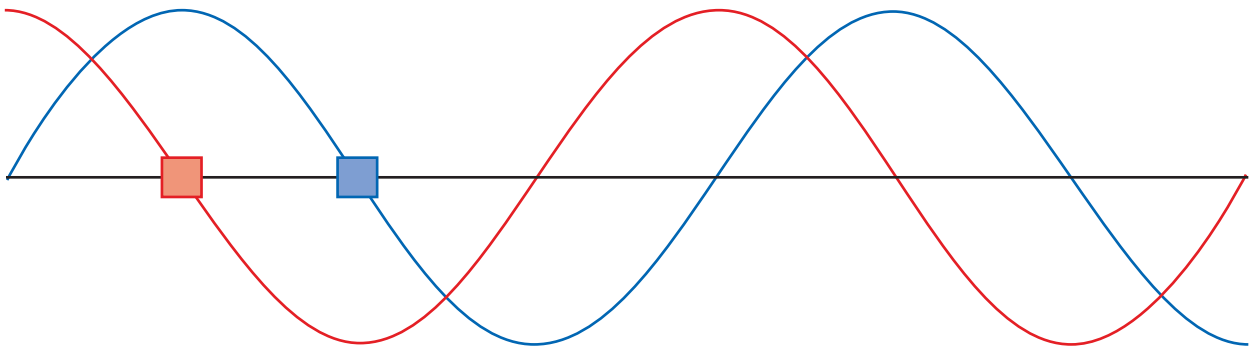




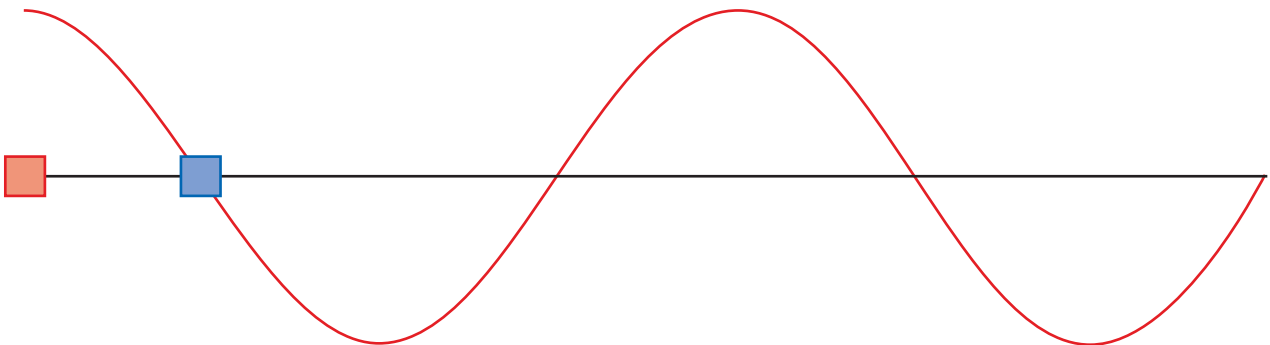
We can now examine the same process (spacing, delay and polarity inversion), but from behind the system. Starting again with one source:



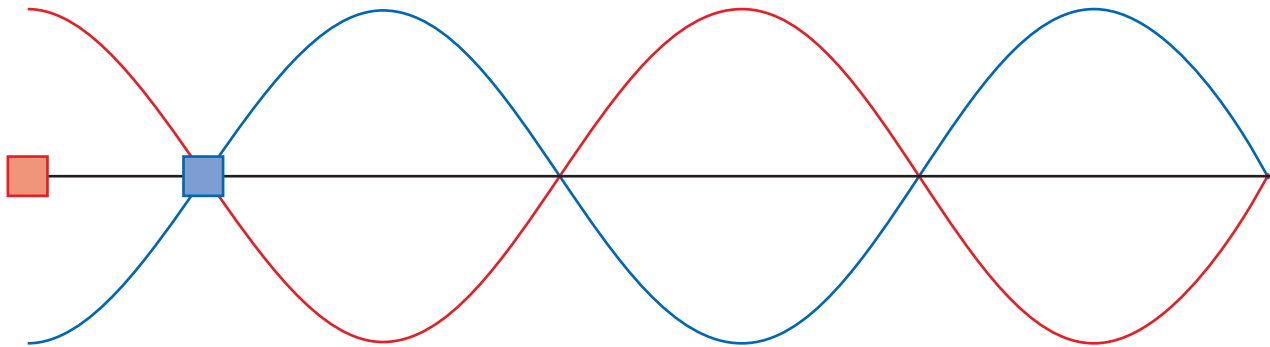
Add a second source in front of the first, again spaced at a quarter of a wavelength:



Now, add alignment delay to the rear source (as before):



Notice that the two sine waves are now overlaid, summing completely. To change summation to cancellation, invert the polarity:



Having gone through all this, we can see that with pure point sources, the direction the subwoofer is pointing is not significant. Thus, 'stacked cardioid' and 'end-fire' arrays function in exactly the same way; it is only an issue of the source spacing that can be achieved.

But in the real world, what changes when the rear subwoofer is physically inverted as opposed to being placed behind? There are a few critical differences:

1. The 'front' of the inverted subwoofer is now actually the rear of the enclosure. The rear of the enclosure doesn't radiate sound! Even at such low frequencies, baffle effects will cause these sources to exhibit some directivity. This means that the rear-facing subwoofer will contribute less to the forward-going energy than a forward-facing subwoofer.
2. Because the subwoofers are now vertically *and* horizontally offset, there will be mechanical 'steering' of the sound. The 'acoustic axis' of the system will no longer be horizontal, but instead tilted. This means that the area directly behind the array is no longer the primary zone of cancellation, and the area in front is no longer the primary zone of summation.
3. In most cases, the physical depth of the enclosure is *not* the appropriate spacing for a cardioid array. In other words, just spinning a subwoofer around and lining up the front and back with the non-rotated subwoofer probably will not provide the desired  $\frac{1}{4}$ -wavelength gap. In fact, it will probably be a lot less.

This doesn't mean that the system won't generate a cardioid pattern, but it does mean that there will be a loss in energy because the frequency of best summation will be shifted up in frequency (because of the reduced spacing). And because all systems including a polarity inversion suffer from attenuation (at a rate of 6 dB/octave) between their peak amplitude and 0 Hz (see Appendix note 2), shifting this peak frequency higher will increase the energy lost at low-frequency.

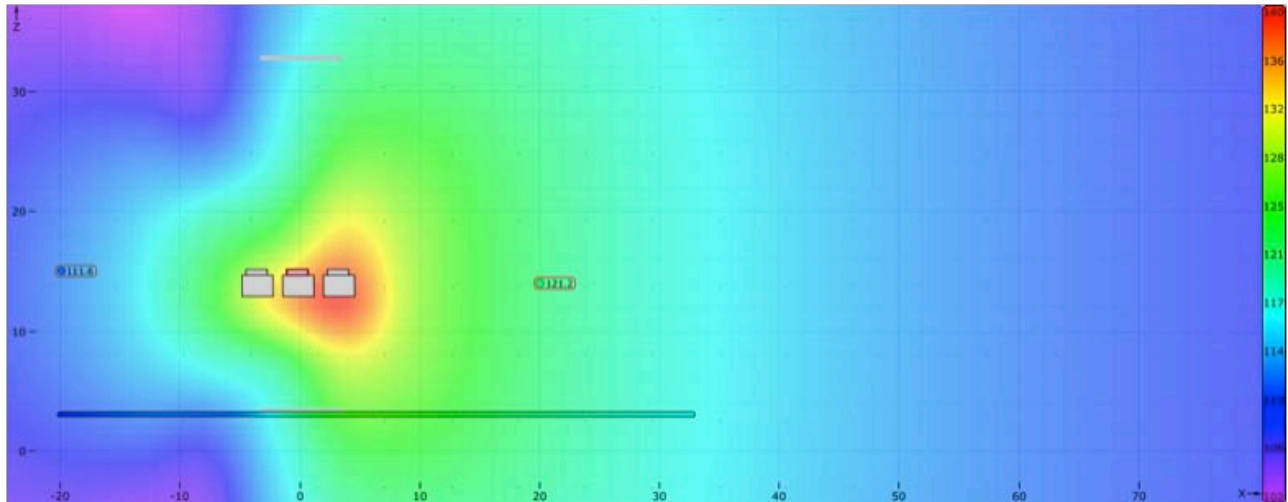
4. In arrays of odd quantities (stacks of 3 subwoofers are quite common), it is necessary to apply a gain offset to the rear- and forward-facing enclosures. This translates into a *headroom offset*. If two subwoofers face forward and one faces to the rear, the rear subwoofer will need to be boosted by between 3 and 6 dB. This means that it will also reach peak output at 3-6 dB lower level than the forward-facing subwoofers. Once it does, any further increase in input to the system will cause the directivity of the system to change. In other words, the system will sum and cancel less effectively approaching maximum output, *which is exactly when you need the most cancellation and summation!*

To summarize: the stacked cardioid configuration does work, and at the fundamental level, it functions on the same basis as our end-fire or 'shotgun' array. In some cases, it may be the only viable option – for example, if available depth is limited. But if the physical space is available, an end-fire or 'shotgun' array is likely the best choice.

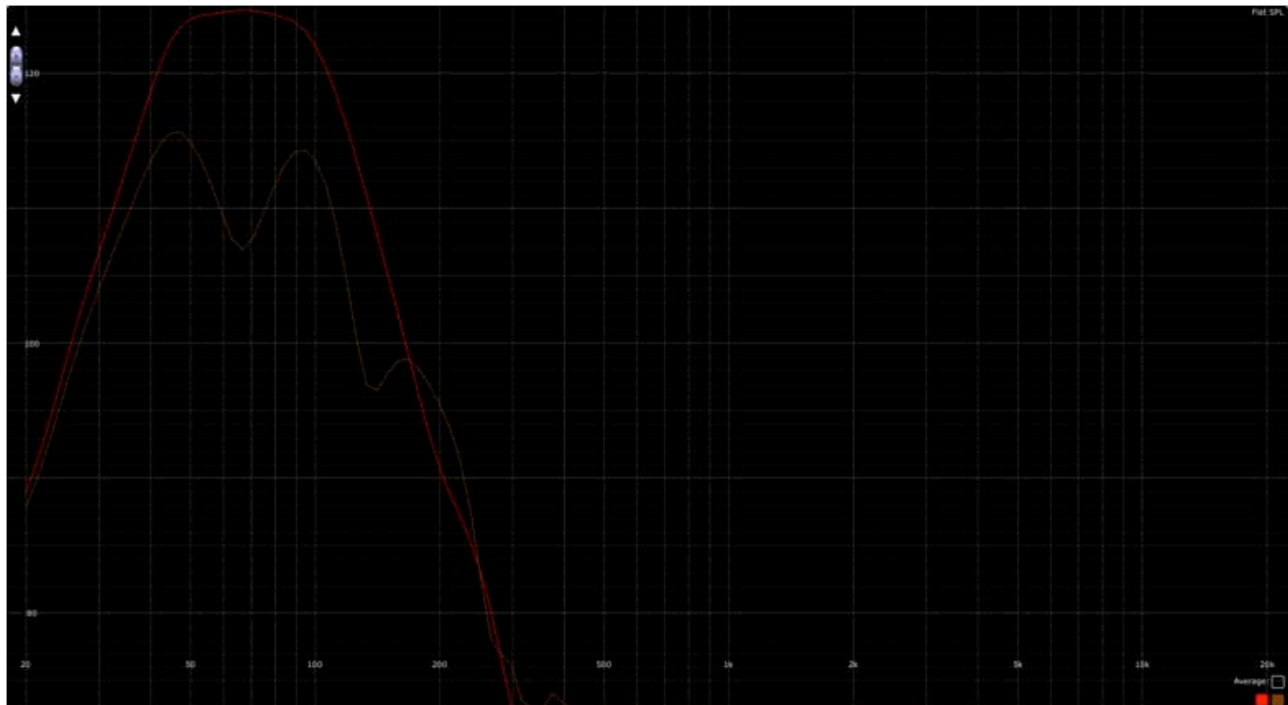
## Scaling Arrays

While we have examined each type of directional array on the smallest scale, it is important to mention the degree to which each configuration can be scaled to achieve greater output and/or directivity. That is to say, you can continue to add subwoofers in line (with progressively more delay) to create an increasingly narrow beamwidth.

Let's try this with three subwoofers (adding delay to the 3rd subwoofer as appropriate):



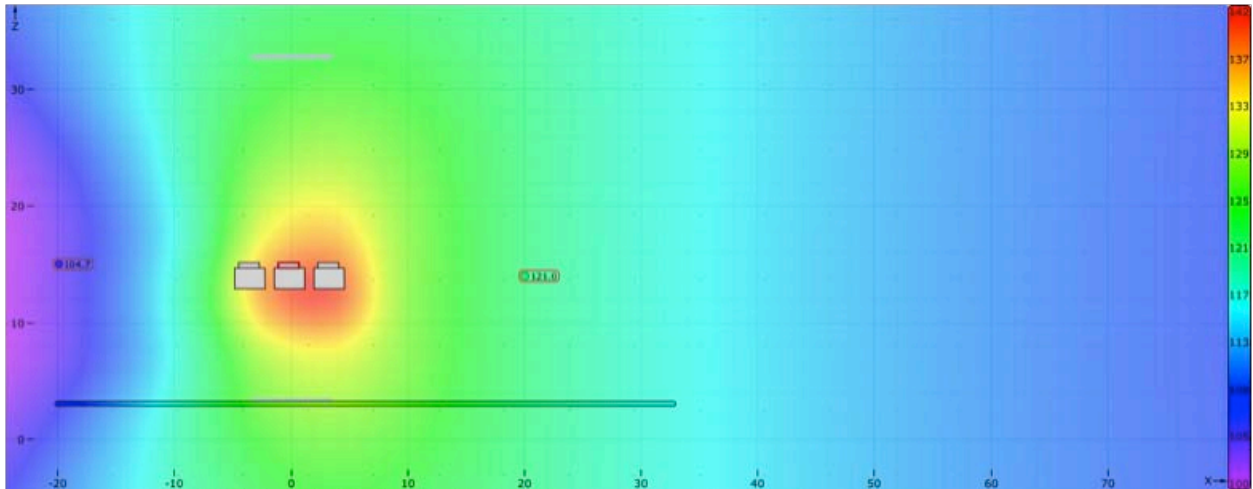
**Figure 15:** 100 Hz section-view prediction showing radiation pattern and measurement microphone placement of 'quasi-shotgun' array.



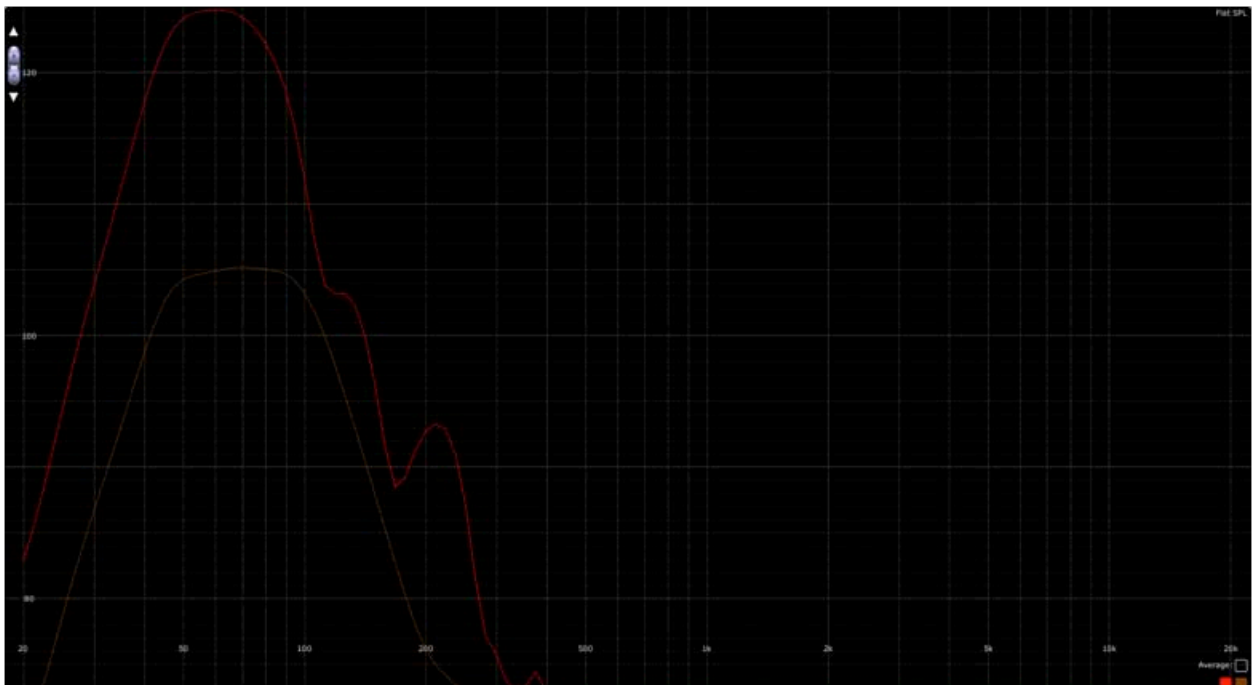
**Figure 16:** Frequency response at equal distances in and front (red) and behind (brown) 'quasi-shotgun' array, with third subwoofer added.

While it is true that we can achieve additional cancellation with more subwoofers, we cannot beat the extreme frequency-dependence of the system. No matter what, the result of this approach will always be an inconsistent, peaky response in the cancellation region.

Fortunately, we can also scale true end-fire or 'shotgun' arrays – it just takes a little more than straight delay and polarity inversion. Observe the following setup, physically identical to that of the quasi-shotgun system we just measured:



**Figure 17:** 100 Hz section-view prediction showing radiation pattern and measurement microphone placement of true shotgun array with third subwoofer added.



**Figure 18:** Frequency response at equal distances in front (red) and behind (brown) shotgun array, with third subwoofer added.

As can be seen, in this scenario we are able to maintain total summation from all three subwoofers in the forward direction, while still achieving broad-bandwidth cancellation behind. But what was done differently, if no physical changes were made?

To achieve this, we have utilized the same technique as with the two-sub end-fire (delay and phase shift). This is easy with two subwoofers, since nearly all processors can apply 180 degrees of phase shift (i.e. polarity inversion).

In this case, we have applied our typical alignment delay to the rear subs as before, but with 120 degrees of phase shift. The mathematics behind this is beyond the scope of this paper (and the DSP techniques to implement it even more so), but suffice it to say that we have determined this phase shift by dividing 360 degrees by the number of subwoofers (or rows of subwoofers). In the case of two loudspeakers,  $360 \text{ degrees} / 2 \text{ subwoofers} = 180 \text{ degrees}$  (a polarity inversion). Now,  $360 \text{ degrees} / 3 \text{ subwoofers} = 120 \text{ degrees}$ . And if we were to add another subwoofer, we would need  $360 \text{ degrees} / 4 \text{ subwoofers} = 90 \text{ degrees}$ . Remember, this is also in addition to the physical alignment delay that is applied progressively from front (no delay) to back (most delay). Though the detail of how and why this works may not be clear, the fact that it does work is clearly shown.

## **Conclusions**

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So, what can be learned from these experiments and discussion? Let's review our list of common misconceptions and see if we've managed to clear any of them up:

### *Misconception/Myths:*

1. *MYTH:* All cardioid arrays trade rear cancellation for reduced forward output.

*FACT:* As has been clearly shown, most cardioid arrays do not result in decreased forward summation.

2. *MYTH:* Some subwoofers in a cardioid array must always face backwards for proper 'phase cancellation'.

*FACT:* We have shown that both 'stacked cardioid' and 'end-fire cardioid' arrays work, but have different qualities and tradeoffs.

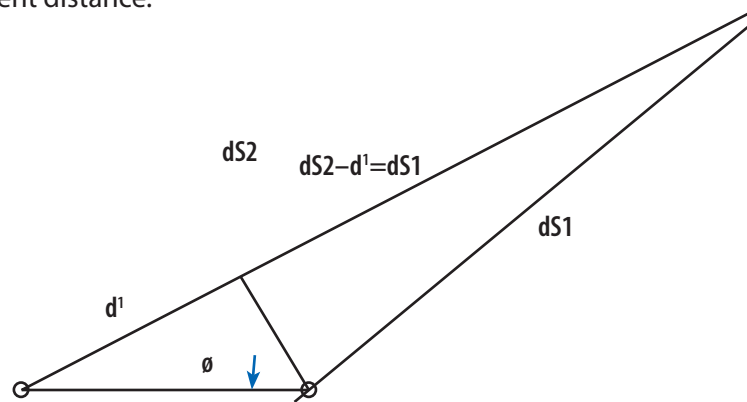
3. *MYTH:* Only certain types of subwoofers can be used for cardioid arrays.

*FACT:* As shown, nearly any subwoofer that radiates omni-directionally can be used to create a cardioid array. Issues come into play as related to physical enclosure depth and subwoofer spacing.



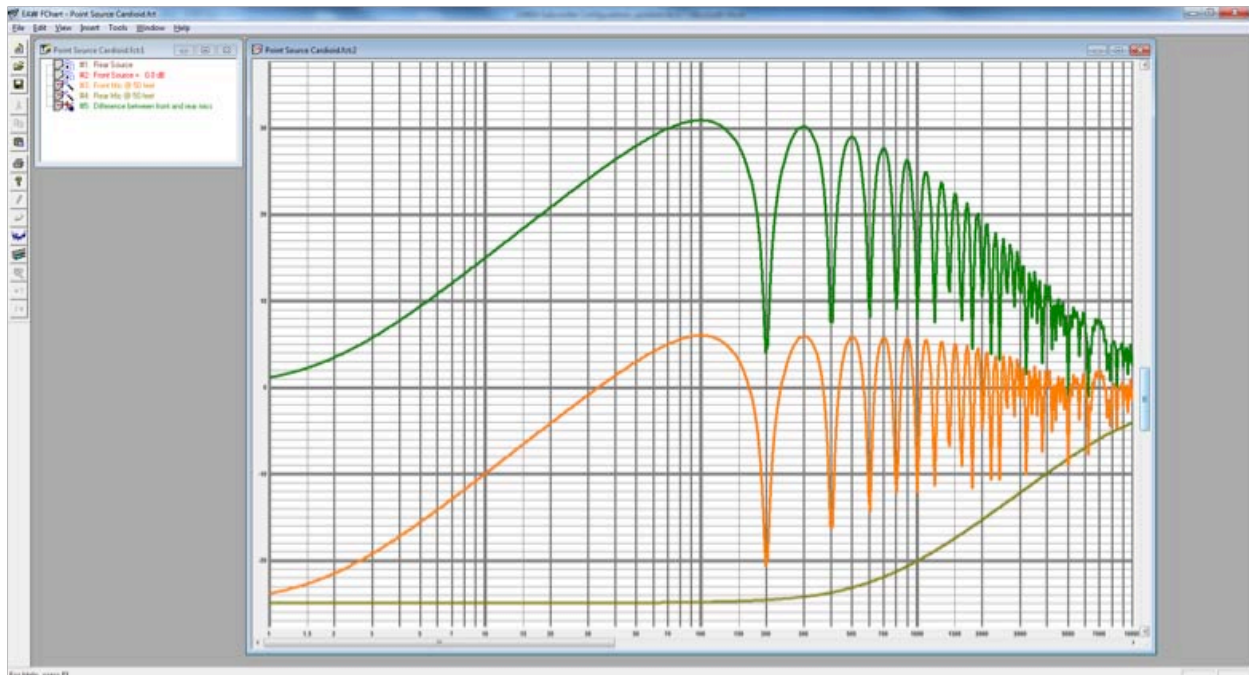
## Appendix

**Note 1:** When discussing alignment delay, it is important to understand that everything is relative to the listener position. That is, the relative delay between two subwoofers will depend on the angle and distance of the listener from the array. By varying the delay, the cancellation 'null' can be shifted from -180 degrees (directly behind the array; cardioid) to approximately 110 degrees (almost directly to the side of the array; hypercardioid). This is why the Cardioid Wizard asks for a cancellation angle and measurement distance.



**Figure 19:** A plan view illustrating two subwoofers with a spacing  $d$  and a listener position "mic". The difference between  $dS1$  and  $dS2$  (and therefore the amount of delay required to align them at that microphone) will depend on angle  $\theta$ . Or put another way, the location where the alignment occurs can be shifted by varying the relative delays of the two subwoofers.

**Note 2:** This is because at 0 Hz ("DC"), wavelength and period are theoretically infinite. Thus, time delay is irrelevant, and any system with matched normal- and inverted-polarity sources will exhibit cancellation. Above 0 Hz, this phenomenon continues to exhibit itself as a 6 dB/octave roll-off between the peak amplitude and 0 Hz.



**Figure 20:** An illustration of the 6 dB/octave roll-off inherent in cardioid systems. With sources spaced 2.8 feet or 0.85m (corresponding to  $\frac{1}{4}$ -wavelength at 100 Hz) and appropriate polarity inversion and delay applied, we see a peak in forward amplitude at 100 Hz, decreasing to 0 at 0 Hz. The middle trace (orange) is a measurement taken 50 feet in front of the array, while the bottom (yellow) trace is the same distance behind. The top trace (green) is the difference between the front and rear measurements.

