The Murphy Corner-Line-Array

An Open Loudspeaker Design Project

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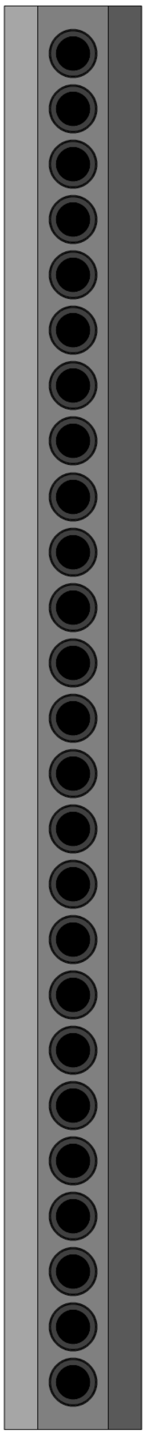
1. Project Overview



The MCLA

The Murphy Corner-Line-Array (MCLA) is a new type of line array loudspeaker system that is designed to integrate tightly with the room by precisely positioning the images of the speaker system as reflected in the acoustic mirrors comprised of the walls, ceiling, and floor surfaces of the listening room. By placing the enclosure in a tight pattern with its reflected images an individual enclosure is multiplied into the equivalent of 20 or more enclosures clustered in free space. This effectively creates a very long array with the listener always located in the nearfield (vs. farfield) at every location in the room. This design is based on the proven method of image analysis that is shared between the fields of optics and acoustics.

I have deliberately made this an open design with all project details fully in the public domain. Everyone is invited to reproduce the design and extend it as suited to their application. While this document gives an overview of the design and the benefits of the corner-line-array, full details sufficient for DIY enthusiasts to reproduce the system are provided online at the project web site located at: http://www.trueaudio.com/array

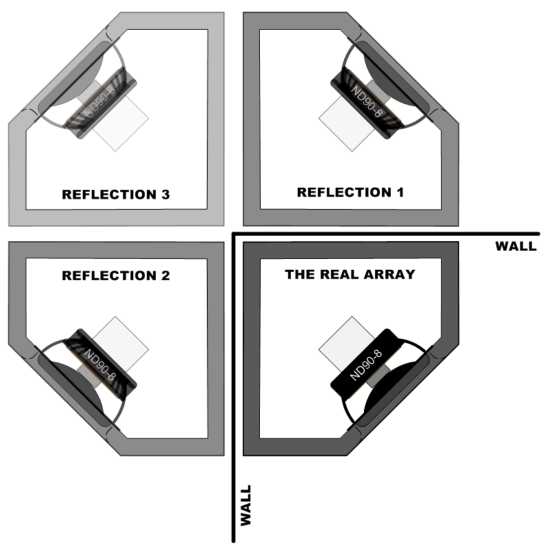


Figure 1.1: Top View of a Single Corner-Line-Array Along With Three Reflected Images

I recommend employing the MCLA wherever a high performance sound playback system is required. Applications for the MCLA include: two-channel home music playback systems, home theater (front corners!), professional studio monitoring, and sound reinforcement systems for small rooms. **There is one basic requirement for the room:** The room must have about an 8 foot ceiling which is parallel to the floor with two corners available for placement of the line arrays. If your listening room conforms to this description then I expect the MCLA will perform in your room very much like it performs in my rooms. This should allow you to benefit from my testing and fine tuning as I voice the system.

Each array employs 25 identical full range drivers in a floor-to-ceiling enclosure specially designed to take full advantage of corner placement. After searching the available drivers I have selected the new Dayton Audio ND90-8. This is a 3.5" driver with solid aluminum cone and 4mm of linear excursion.

2. Design Concepts

Loudspeakers in Rooms

Loudspeakers always seem to be at odds with the room in which they must operate. In order to deal with this designers resort to all sorts of clever tricks. We go to great lengths to either test our speakers in a anechoic chamber or to take quasi-anechoic measurements with fancy test instruments all in an attempt to show what the speaker should sound like...if it weren't for that darn room. But like it or not, virtually all loudspeakers find themselves playing into a room and competing with their own reflections for the listeners attention. The new corner-line-array is an attempt to bring some peace to the war between loudspeakers and rooms. Instead of fighting the room or pretending it's not there, the corner-line-array design joins the loudspeaker with the room in such a way that the performance of the loudspeaker in the room is more predictable and repeatable than with previous point, line or planar type loudspeakers.

Image Analysis

Image analysis is a powerful technique used in the field of acoustics to study reverberation and room reflections. In this analysis method the walls of the room are considered to behave as mirrors allowing the reflected images of sound sources to be readily located using the same ray tracing method familiar from the study of optics.. Before proceeding let's review the image analysis method as it applies to loudspeakers in rooms.

The acoustician/physicist Carl F. Eyring commented on the image method in 1930 as follows:

"This necessary analysis is aided by the method of images. Just as a plane mirror produces an image of a source of light, so also will a reflecting wall with dimensions large as compared with the wave length of the sound wave produce the image of a source of sound. An image will be produced at each reflection. In a rectangular room, the source images will be discretely located through space. This infinity of image sources may replace the walls of the room, for they will produce an energy density at a point in the room just as if they were absent and the walls were present." [2-1]

Here Eyring is saying that the image sound sources can be substituted for the room and the resulting sound field will be the same. The assembly of reflected images is exactly equivalent to the effect of the room. Additional references pertaining to the image method are available at the project web pages.

The simple rule of equal angles of incidence and reflection is shared with the field of optics, a sister field of acoustics falling under the fundamental science we call physics. This shared rule is why acoustical reflections are located in exactly the same positions as the visible images of the sound source that we would see if the walls were mirrored.

In Figure 2-1 below we see an object reflected in a single mirror. If the object in front of the mirror were a sound source that sound source would have a reflected acoustic image at the same apparent location as the optical reflection.

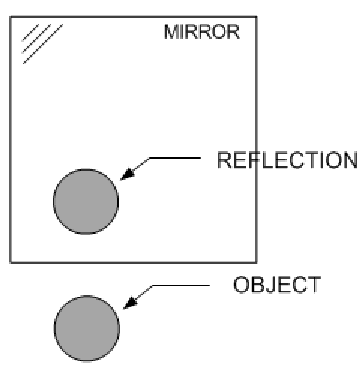


Figure 2-1: An Object Reflected in a Single Mirror

Now let’s consider what happens when viewing an object in two mirrors placed at 90 degrees to one another as in

Figure 2-2 below.

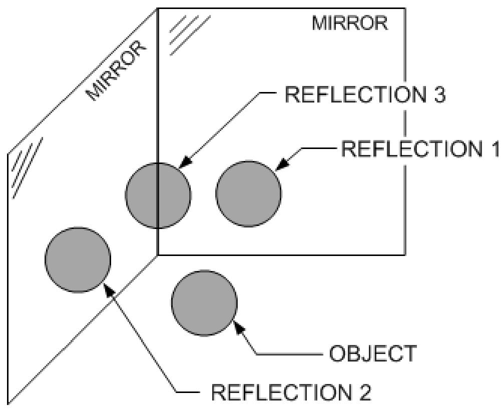


Figure 2-2: An Object Reflected in Two Mirrors

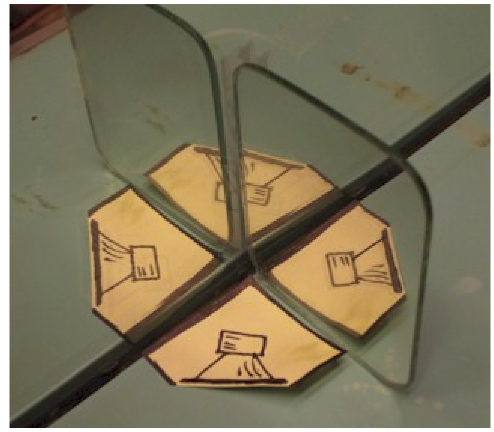


Figure 2-3: Paper Speaker With Three Reflections

The object has acquired not just one, but two more reflections. Reflection 1 is the original reflection. Reflection 2 is a new reflection from the second mirror that corresponds to reflection 1 in the first mirror. The 3rd reflection is best understood by doing the experiment with two regular mirrors. In Figure 2-3 you see a photograph of a simple example with two mirrors placed at right angles similar to two walls of a room. There is only one paper speaker in the photo but you can clearly see all four speakers around the faces of the overall octagon formation.

Back to the Room

In a home listening room the sound reflected from the walls, floor and ceiling creates reflected sound images. "Ray Tracing" is a method used in the study of both optics and acoustics. Ray tracing allows us to precisely locate reflected images using geometric analysis. Rays follow this rule: ***the angle of reflection is equal to the angle of incidence***.

Let's examine how a single reflected image is created in a listening room. In Figure 2-4 below we see "rays" of sound leaving a sound source and arriving at the listener by way of two paths. The ray A-B from sound source A to listener B follows the direct path. There is only one location on the side wall where a reflection occurs such that the incident and reflection angles are equal and that passes through the listening position B. That reflection path is through point C. The sound ray A-C propagates from source A to reflection point C and is then reflected from the wall as ray C-B from the reflection point to the listener. The presence of the wall creates a reflected image at D, just as if the wall was absent and a second sound source was added at that location. The ear is tricked into hearing the sound that arrives via ray path A-C-B just as if the path were straightened out and arrived via the phantom path D-B

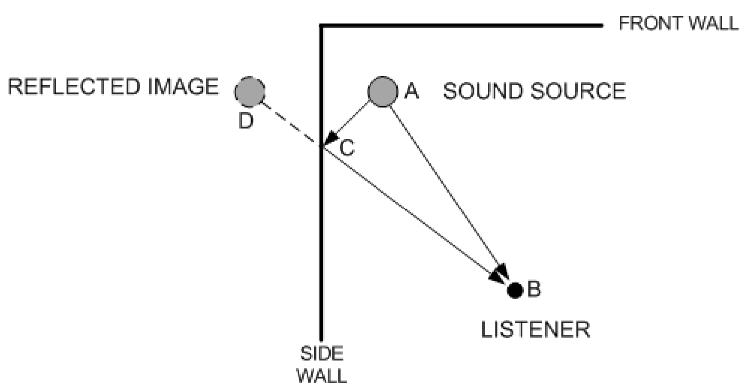


Figure 2-4: Sound Source with a Single Reflected Image

Figure 2-5 shows a pair of point source radiators located against the front wall of the listening room along with their first reflected acoustic images in the floor, ceiling and side walls. Only the first reflections are shown but the array of images actually continues to infinity in all directions...just as regular optical mirrors would show if each wall were mirrored. Each successive reflection grows weaker due to the finite sound absorption of the walls. The listener hears the speakers directly along with all the reflected images. The delay of each image is determined by its path length to the listener. The shortest path to the listener's ears is the direct path from the speakers. Those reflections that follow within 20 -30 milliseconds of the direct sound more or less fuse together into a single perceived sound. Those reflections arriving after 30 milliseconds or so are heard as early reflections and reverberation. As you move away from the speakers and toward the rear of the room the direct sound from the speakers falls compared to the total combined energy of the reflections. Note that the SPL falloff rate for each image is the same as for the direct sound: 6 dB per doubling of distance.

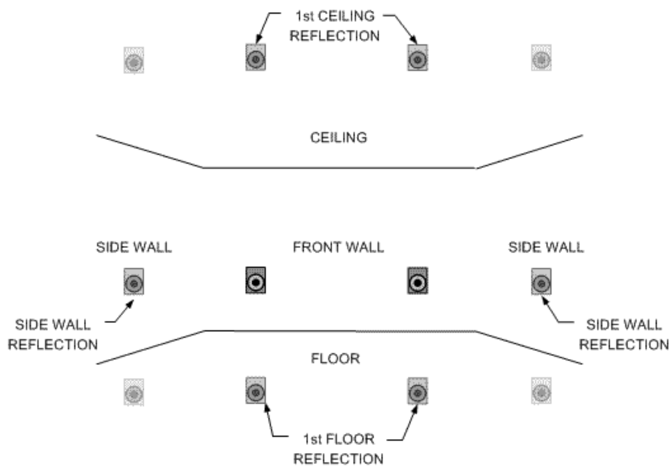


Figure 2-5: A Stereo Pair of Point Source Speakers and Their First Few mages

My goal with the corner-line-array is to include the inevitable room reflections in the design from the start in order to achieve a frequency response that is more consistent throughout the room and from room to room. I would hope that if you reproduce the MCLA's in your room that you would achieve very nearly the same frequency response as I achieve in my own reference system. This is rarely the case with point source speakers for which there is no standardized room location.

Lines in the Room

Consider what happens when we place a line array in a room where the line array spans from floor to ceiling. Note the ceiling and floor reflections shown in Figure 2-6. The first order reflections TRIPLE the effective length of the array. Including the second order reflections we see the height of the array increased FIVE FOLD over the actual speaker. An eight foot long array is reflected into a 40 foot array by consideration of just the first two reflections. A single eight foot array of 25 speakers is transformed into 20 enclosures with 500 sound sources based on just two reflections. In reality the higher order reflections are significant and the array is effectively even longer with more sound sources. The combination of direct and reflected sound sources effectively forms a very long array with the output progressively tapered toward each end. The subjective effect is a reduced drop in sound level as you step away from the speakers.

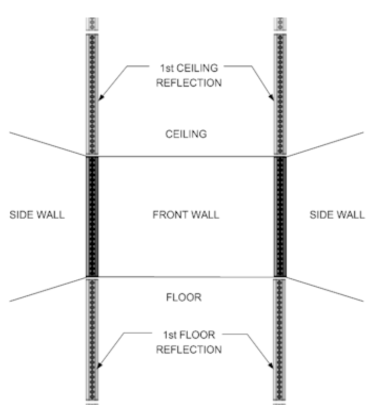


Figure 2-6: Line Arrays with Ceiling and Floor Reflections

Fun With Mirrors

Now let's look at the view from above when a line array is placed in the corner of the room. Figure 2-7 shows the corner-line-array placed in the corner of a room. In light of the front and side wall reflections we now have four arrays tightly packed into the corner.

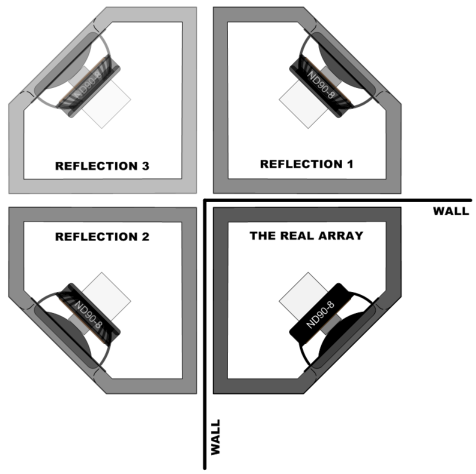


Figure 2-7: Top View of the Single Corner-Line-Array with Three Reflections

Placing the array in the corner causes the front and side wall images to merge with the real line to form an effective acoustic cluster of four arrays. Instead of having one driver every 3.5 inches we effectively have four drivers per 3.5 inches of height. A single physical array near 8 feet in length with 25 drivers integrates with the room to form a new acoustic system consisting of four tightly clustered arrays extending16 feet beyond the ceiling and floor. Figure 2-8 shows a 3D view of one array with its corner reflections and repeating floor reflections.

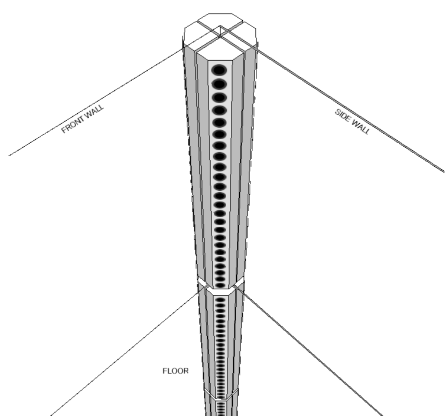


Figure 2-8: 3D View of the Corner-Line-Array with Corner and the First Two Floor Reflections

This net acoustic system now has the power of not just 25 three inch radiators but a total of N = 5 x (25 x 4) = 500 radiators. That's for just one line. With two MCLAs in the room you effectively have about 1000 sound sources configured as long octagonal tubes with speakers on 4 faces of the octagon.

The corner-line-array with its standard speaker placement and well managed reflections appears, in my opinion, to be a superior solution to the overall application of loudspeaker playback systems in home environments.

References:

[2-1] C.F. Eyring, "Reverberation Time in 'Dead' Rooms," *J. Acoust. Soc. Am.*, (1930, Jan.).

3. MCLA Project Details

The Transducers

The MCLA employs the Dayton Audio ND90 3.5 inch full range speaker which is available from Parts Express with pricing as follows:

50+ units: $12.90 each **(this is nearly 35% off the single unit price)**

The MCLA system employs 25 speakers per corner line array enclosure.

The Enclosure

Figure 3-1 shows an overview of the plans for Prototype #2. The detailed plans are available in .pdf form.

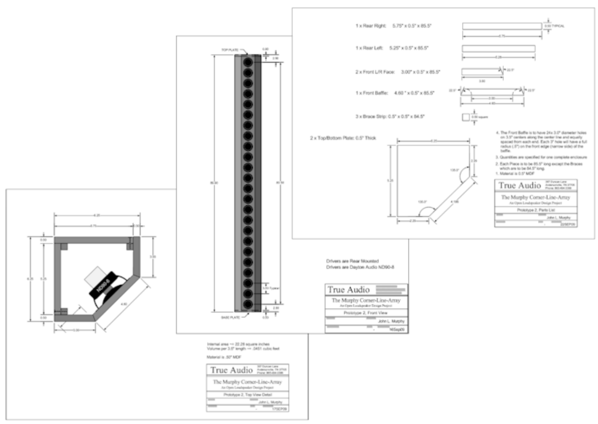


Figure 3-1: The Enclosure Drawings

The Equalizer

I am designing a custom analog EQ to voice the MCLA. For now however, I am using an off-the-shelf digital 1/3rd octave equalizer. I strongly recommend that you use this same EQ in order to directly implement my EQ settings for the MCLA. The equalizer I am using is the Behringer Ultra-Curve Pro DEQ2496 shown in Figure 3-2 below. The equalizer settings I have arrived at for the MCLA systems in my music studio room are available at the project web site.

Figure 3-2: The Behringer Ultra-Curve Pro DEQ2496 Programmable EQ

The EQ settings PDF file can be downloaded from the project site at www.trueaudio.com/array. Each page of the document has the three settings for the Graph Equalizer portion of the Behringer EQ. These settings correspond to:

A: Flat
B: Small-Room X-curve
C: X-curve

4. Single Driver Test Results

Frequency Response

The frequency response of an individual ND90-8 driver was measured using both nearfield and ground plane methods. The nearfield method provides a accurate response up to about 3kHz for this size driver. This upper limit on the nearfield data is a limitation of the nearfield measurement method itself. The nearfield measurement was nicely smooth. Figure 4-1 shows a single unsmoothed nearfield measured response.

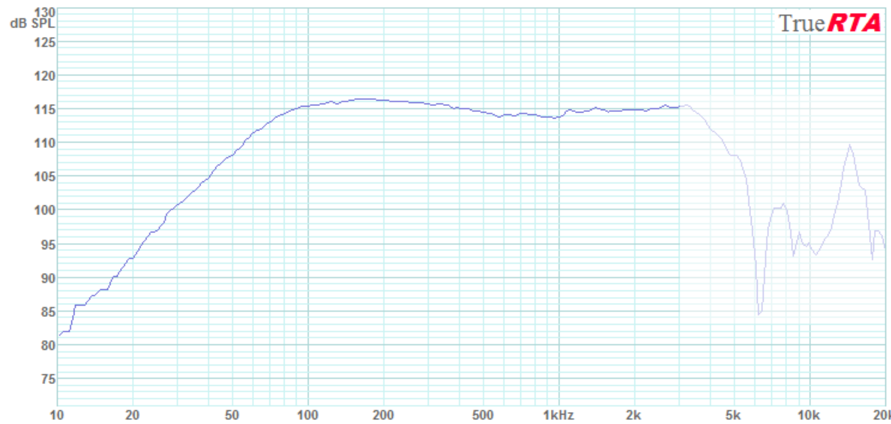


Figure 4-1: ND90-8 Nearfield Frequency Response in 0.1 cubic foot closed box (ignore above 3kHz)

The ground plane frequency response was measured at 1W (2.83 Vrms), 1 meter outdoors. My ground plane measurement setup was not ideal and included some local reflections. The measurement seen below includes the effect of diffraction loss which appears as a 6 dB decrease in response below 2 kHz.

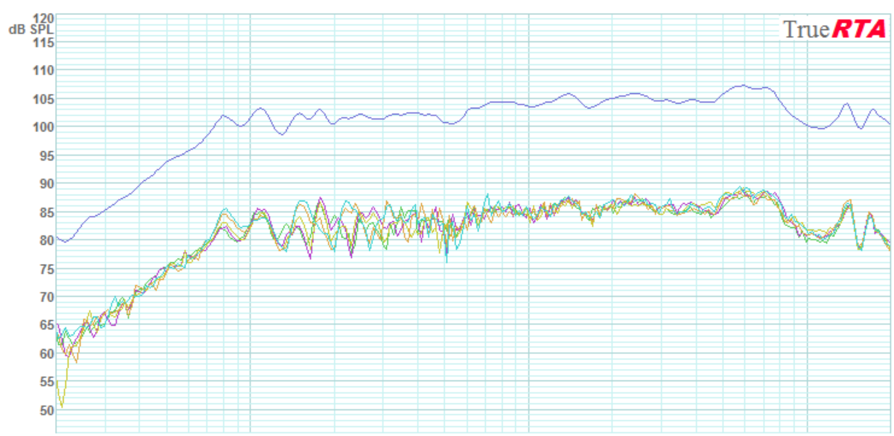


Figure 4-2: ND90 Ground Plane Frequency Response, Closed Box (0.1 cu ft), 1W/1m

The ground plane response shown at the top of Figure 4-2 is an average of the 5 responses below with (slight) 1/6th octave smoothing. The five responses were obtained by varying the outdoor measurement geometry slightly (rotation and/or translation) between measurements in an attempt to average out variations due to local reflections.

In order to create a frequency response that represents the response of the ND90 I combined the nearfield response below 2 kHz with the ground plane response above 2 kHz to get the hybrid response shown in Figure 4-3. This response is representative of the response of the driver in a small closed box with a half-space acoustic load. Note that these frequency responses are displayed in relatively high resolution with minor divisions equal to just 1 dB.

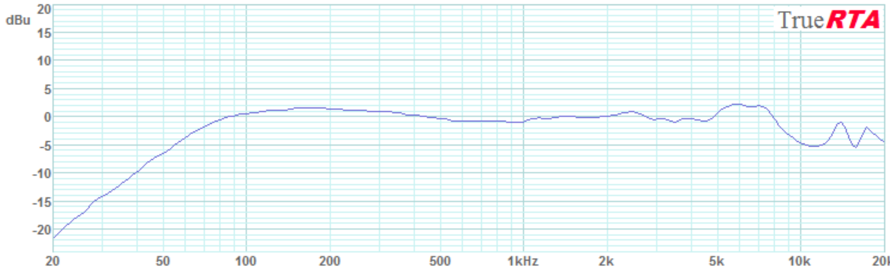


Figure 4-3: ND90 Nearfield/Ground Plane Hybrid Closed Box Response (0.1 cubic foot)

The raw response of the above closed box system is within +/- 2 dB from about 70 Hz to 8.5 kHz. The response is within +/- 4 dB from about 55 Hz to 20 kHz. It is the very wide frequency response range of the driver that makes this project possible.

Distortion Performance

We see the ND90 reproducing 100 Hz in Figure 4-4. The plot shows the 100Hz sine wave at a level of 80 dB SPL with higher harmonics (distortion components) all below 40 dB SPL. Note that the lines at 60, 120 and 680 Hz are components of ambient room noise...the notebook PC primarily. The 2nd harmonic at 200 Hz is at 38 dB SPL versus 80 dB SPL for the fundamental. This puts the 2nd harmonic 42 dB below the fundamental which equates to 0.8% second harmonic distortion. The 3rd harmonic at 300 Hz is down 44 dB from the fundamental for a 3rd harmonic distortion of 0.6%. The 5th harmonic is at -54 dB or 0.2%. The distortion components above the 5th harmonic vanish into the noise floor.

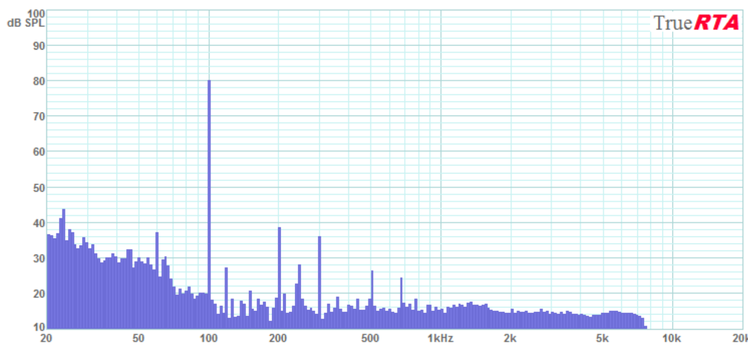


Figure 4-4: The ND90 at 100 Hz, 1Watt, 1 meter

The performance of the ND90 at 1 kHz is shown below in Figure 4-5 where we see that the dominant distortion component is the 3rd harmonic at -49 dB with respect to the fundamental or 0.35%. The 5th harmonic is at -55 dB or 0.18%.

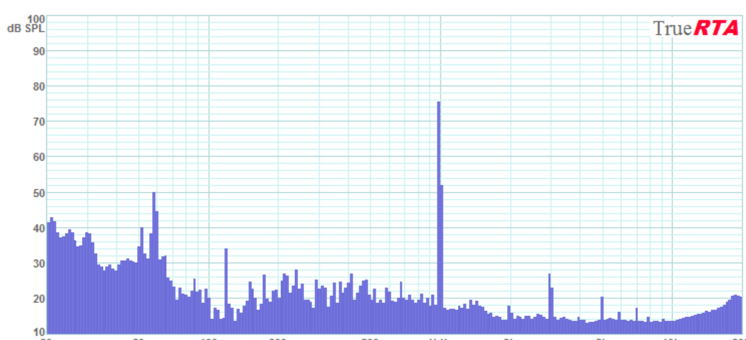


Figure 4-5: The ND90 at 1000 Hz, 1Watt, 1 meter

5. Array Test Results

Equalized In-Room Frequency Response

Each measurement below is an average of the Left and Right systems in-room measured response. Each of the Left and Right measured responses consists of an average of 16 unsmoothed responses measured in the listening area at distances from 1 to 3 meters from each array and at heights from 1 to 2 meters. The final average is smoothed just one time if smoothing is specified. The unsmoothed average is an average of completely unsmoothed data. These responses represent the array with my best equalization to date.

Figure 5-1 shows the MCLA measured spatial average frequency response with 1/3rd octave smoothing. This is what would typically be given as the measured response if this were a commercial loudspeaker. The frequency response is seen to be within +/- 1 dB from 28 Hz to 20 kHz.

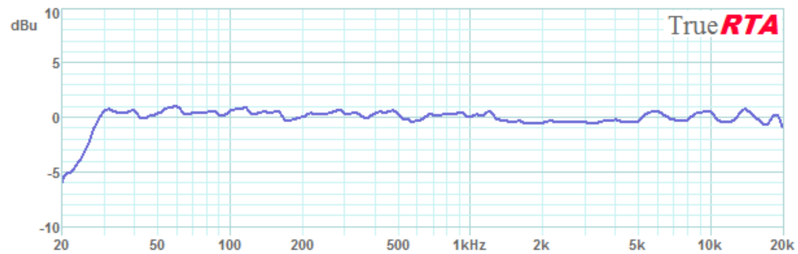


Figure 5-1: The MCLA In-Room Measured Response with 1/3rd Octave Smoothing

Figure 5-2 shows the same measured frequency response as above but this time with more conservative 1/6th octave smoothing. The frequency response is seen to be within +/- 1.5 dB from 28 Hz to 20 kHz. This 1/6th octave smoothed response probably corresponds most closely with what you would actually hear from the system as 1/6th octave corresponds to the "critical bandwidth" of human hearing in the range above 1 kHz. Below 1 kHz the critical bandwidth gets progressively wider as the ear becomes less discerning and greater smoothing could be used without misrepresenting what we would hear. So above 1 kHz we don't want to use any more than 1/6th octave smoothing. Below 1 kHz the 1/3rd octave smoothed response of Figure 5-1 above is more representative of our ear's response.

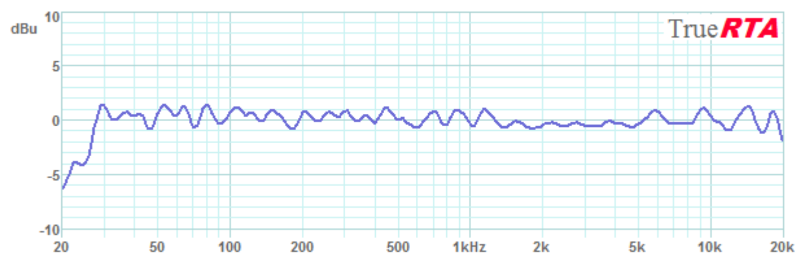


Figure 5-2: The MCLA In-Room Measured Response with 1/6th Octave Smoothing

Figure 5-3 shows the completely unsmoothed spatial average response of the MCLA system. The unsmoothed response is seen to be within about +/- 2.5 dB from 28 Hz to 20 kHz. Keep in mind that loudspeaker manufacturers rarely (if ever) show this high level of detailed data for their commercial loudspeaker systems.

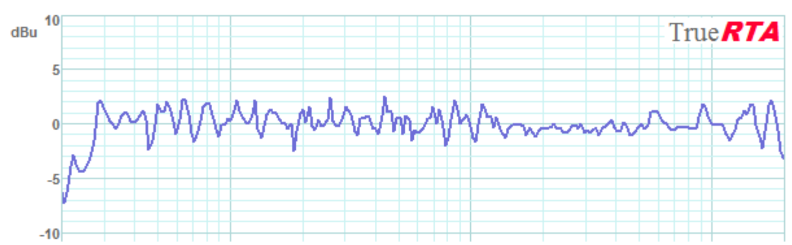


Figure 5-3: The MCLA In-Room Measured Response with No Smoothing

Un-equalized In-Room Frequency Response

The equalized frequency responses shown in the previous section show the arrays with their equalization switched in as they are normally used. In this section I will show the un-equalized frequency responses in order to understand the required components of the corrective equalization.

It is reasonable to ask what frequency response we expect from the arrays. Based on my understanding of line arrays I expect to see the half space response of the driver modified by the -3 dB per octave slope resulting from the effect of array. There will also be some lumps and bumps resulting from the finite spacing of the drivers. The 3 dB per octave boost in the bass from the array effect may not continue all the way to 20 Hz due to the finite length of the array. Remember, the reflections taper off due to finite absorption of the room surfaces so the bass build is expected to be limited. In Figure 5-4 below we see the single driver's hybrid measured response along with a -3 dB per octave reference slope. If we tilt the single driver response the -3 dB per octave we expect the array to add then we should get a response similar to what we expect from the raw (un-equalized) array. Just for fun I'll add the two responses shown here to get some idea of a "predicted" array response.

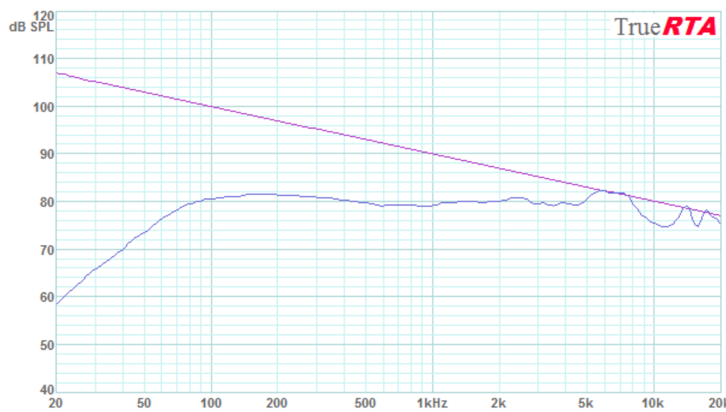


Figure 5-4: The Single Driver Half-Space Response along with a -3 dB/octave Reference

Summing the two responses shown in Figure 5-4 gives the "predicted" response for the array shown in Figure 5-5.

Figure 5-5: Predicted Response of the Array based on the Single Driver Response summed with the -3 dB/octave Reference

In order to restore the flat response of the single driver we would need to equalize the above response with a 3 dB per octave rise. Then, in order to extend the bass response to 30 Hz we would need bass equalization. The bass equalization might take the form of a "Linkwitz Transform" circuit to precisely create a new target response or could be achieved with a general purpose digital EQ such as I am doing.

Finally, here in Figure 5-6 is the un-equalized measured response of the array prototypes. Each array was measured at sixteen locations around the listening area at a distance from 1 to 3 meters. The individual array responses were smoothed at 1/6th octave before the two were averaged. The similarity to the predicted response is notable, especially regarding the overall -3 dB per octave slope of the array. The low frequency corner is expected to be slightly different than the single driver response because the single driver was measured in a 0.1 cubic foot closed box. The array has .045 cubic feet per driver so the array has a higher closed box Q(tc) than the single driver test system.

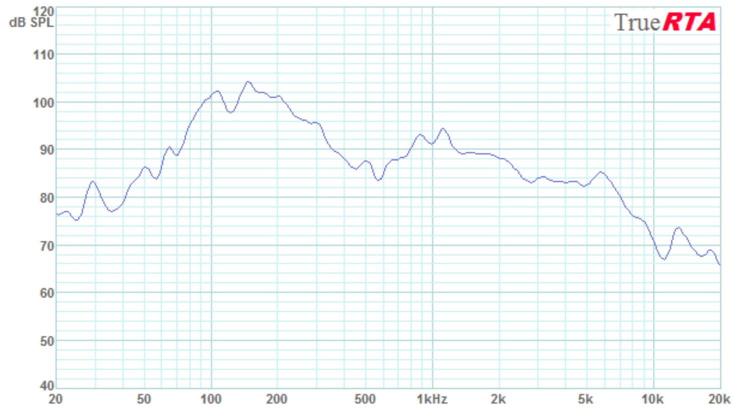


Figure 5-6: The Measured Response of the Un-Equalized Arrays Exhibiting the Expected -3 dB Slope

The frequency response in Figure 5-6 was measured with a drive voltage of 2.309 Vrms which corresponds to 1 Watt into the array's nominal impedance of 5.33 Ohms (proto 1 with 24 drivers). Note the very large build in efficiency in the 100 to 200 octave where the array has an efficiency exceeding 100 dB SPL for 1 Watt over the 1 to 3 meter range. With the array receiving an input of 1 Watt each driver was being driven at 1/24 Watt or .042 Watts. While producing over 100 dB SPL in the 100-200 Hz bass range the drivers are just being tickled a bit with 42 milliwatts of signal. Operating the array at 100 Watts (or just over 4 Watts per driver) would add 20 dB to the above levels. The usual 1W/1meter sensitivity specification of a typical speaker is not appropriate for an array. Instead we would have to indicate sensitivity at a specific frequency or preferably, just show sensitivity a graph as above.

Figure 5-7 shows the measured response along with a -3 dB per octave slope for comparison.

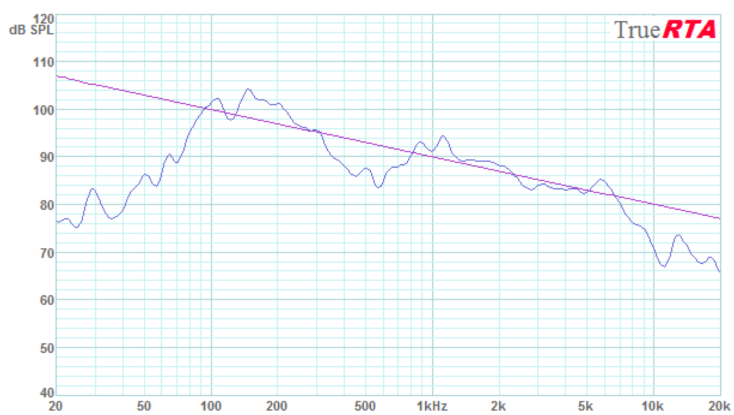


Figure 5-7: The Measured Response, Un-Equalized, along with a Reference -3 dB/octave Slope

The essential components required of the corrective EQ are a 3 dB upward slope (a blue filter) and EQ to extend the bass response. In practice the final EQ is best achieved by a measuring the response and adjusting the EQ a few times in succession until a sufficiently flat response is obtained.

Distortion Performance

The spectrum of the completed array was measured with 1 Watt at 1 meter at key frequencies in order to evaluate its distortion performance. The relatively benign 2nd harmonic dominates the distortion makeup below 1 kHz. Figure 5-8 shows the spectrum from one array driven at 2.31 Vrms (1 Watt into 5.33 Ohms) with a 100 Hz sine wave. The array creates a very efficient 96 dB SPL for 1 Watt/1meter. The 2nd harmonic, 200 Hz is measured at 41 dB below the 100 Hz fundamental for a distortion level of 0.9%. The 3rd harmonic is -51 dB with respect to the fundamental for a level of 0.3%. The 5th harmonic at 500 Hz is even lower at -70 dB or 0.03%.

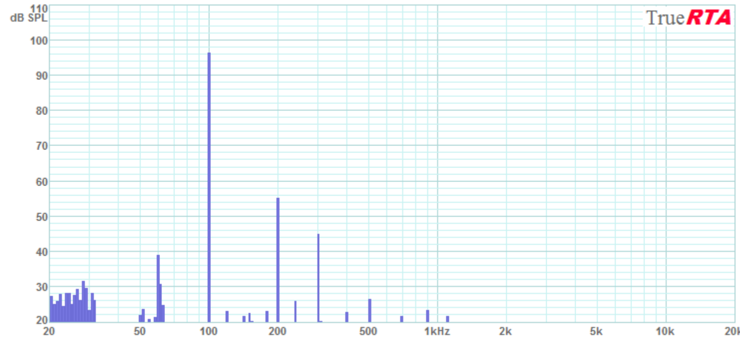


Figure 5-8: The Array's Sine Wave Spectrum at 100 Hz for 1 Watt at 1 meter

Figure 5-9 shows the array at 1 kHz with 1 Watt of input creating 89 dB SPL. The 2nd harmonic is absent with the 3rd harmonic (3 kHz) at -57 dB (0.14% distortion) compared to the fundamental at 1 kHz. The 5th harmonic is at -67 dB or 0.04%. The 7th harmonic pops up to 0.1% but the 9th and higher continue the fall to lower levels.

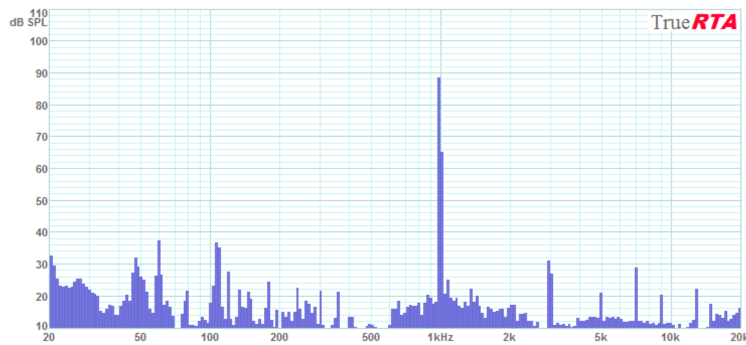


Figure 5-9: The Array's Sine Wave Spectrum at 1000 Hz for 1 Watt at 1 meter

Figure 5-10 below shows the performance at 50 Hz for 1 Watt at 1 meter. The output level is still quite high at 94 dB SPL indicating the strong low frequency boost from the combination of the 24 drivers (prototype 1) and the corner placement. Remember even though the array is putting out 94 dB SPL with 1 Watt it has a power handling capability of 480 Watts or 27 dB greater than the 94 dB SPL we see here. This suggests the array could generate 121 dB SPL at 50 Hz at its max rated power of 240 Watts. There is no shortage of low frequency output capability. At 50 Hz the 2nd harmonic is -41 dB down for 0.9% distortion. The 3rd harmonic increases to -37 dB or 1.4% distortion. Higher harmonics are much lower in level.

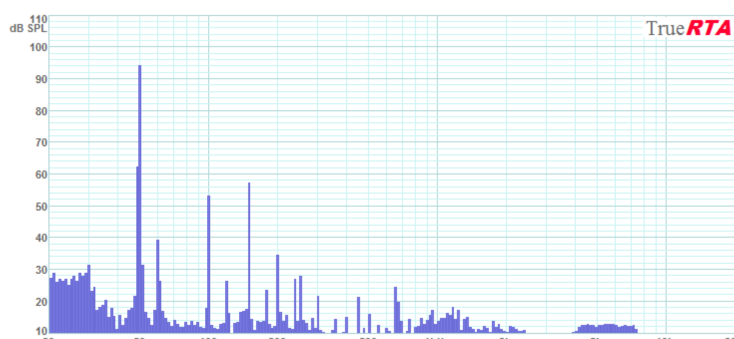


Figure 5-10: The Array's Sine Wave Spectrum at 50 Hz for 1 Watt at 1 meter

The distortion test show a speaker system capable of very high output levels with very low distortion. In all cases the distortion is dominated by the low order harmonics and is frequently dominated by the (relatively benign) 2nd harmonic. Distortion should not be a concern at even the highest sound levels...even for a single enclosure.

In my opinion, the MCLA sounds as great as it measures and delivers unusually accurate sound reproduction.
jlm