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## Design and Implementation of a Constant-Directivity Two-Way 12" Woofer Wedge Loudspeaker System

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### ABSTRACT

This paper describes the design and implementation of a two-way constant-directivity wedge loudspeaker system that houses a single 12" woofer and eight 2" drivers in a 20° circular arc mounted on a solid curved baffle that covers the LF driver. The curved baffle is open on either side so that the acoustic output of the LF driver and ports can escape to the outside. An individual system comprises a 20° wedge box with a four-channel plate amplifier with two bridged channels driving the woofer, and the two other channels individually driving each half of the eight-driver array. This basic wedge box is then used in multiples to form larger circular-arc arrays of one up to six boxes making arrays that provide various vertical beamwidths in the range of 15° to 90°. Appropriate amplifier gains are chosen to smooth the polar coverage for each array size.

### 1 Introduction

This paper goes into detail on the design and implementation of a two-way 20° wedge loudspeaker system that essentially forms a point-source coax design. The system is composed of an eight-driver segmented circular-arc high frequency array composed of multiple 50.8 mm (2") full-range drivers mounted on a wide curved baffle covering a 300 mm (12") 800 W woofer.

The cabinet is vented and tuned to about 48 Hz by four front-mounted circular ports.

This basic wedge box can be used to form larger circular-arc arrays with one up to six boxes forming arrays of 20° up to 120° which provide vertical beamwidths in the range of about 15° up to 90°.

A built-in DSP four-channel plate amplifier is used to power the system. Two channels are bridged to drive the woofer and the remaining two channels drive the tweeters with the top four tweeters on one channel and the bottom four tweeters on the other.

### 2 Detailed System Description

The system is comprised of an eight-driver segmented circular-arc high frequency array

composed of multiple 50 mm (2") full-range drivers. The full-range drivers are mounted on a wide curved baffle which just covers a 305 mm (12") woofer.

The woofer's acoustic output flows out and around the HF driver array mounted on its curved baffle forming a closely coupled assembly. The system is crossed over quite low at about 400 Hz which avoids any frequency-response anomalies due to essentially hiding the woofer behind the baffled HF array.

The box dimensions are about 0.5 x 0.5 x 0.4 m (19.85" x 19.75" x 15") (H x W x D) and has a loaded weight of about 29.5 kg (65 lbs.). The net internal box volume is about 0.045 cu m (1.6 cu ft.). The 12" driver sports a 4" diameter voice coil.

The woofer cabinet is a vented design with four 2" diameter by 9" long ports on the front of the cabinet in each of the four corners. The vented-box tuning is a relatively low 48 Hz, that maintains strong acoustic output down to 42 Hz, which is the frequency of the open "E" string of an electric bass guitar. The top and bottom of the box are angled at 10° from the horizontal forming a 20° wedge box while the box sides are straight.

The sides of the box contain cabinet handles and pin-locked stacking hardware that allow cabinets to

be stacked and also attached to subwoofer cabinets for increased LF output below 50 Hz.

The unique shape and contour of the circular-arc tweeter array on the front of the box insures that when the boxes are used in multiples, that the tweeters form a larger seamless and perfect segmented circular-arc array. This insures uniformity of vertical coverage for all the array sizes provided various vertical beamwidths in the range of  $15^\circ$  to  $90^\circ$ . The horizontal beamwidth of all the arrays is wide at about  $150^\circ$  which is maintained up to about 10 kHz.

### 3 System Implementation

This section describes the design of the high-frequency (HF) array (sub-section 3.1) and the wedge enclosure itself which houses the 300 mm (12") woofer driver, and the HF array (sub-section 3.2). The HF array is oriented vertically and centrally located over the 300 mm woofer.

#### 3.1 High-Frequency Array Design

The HF array is composed of eight 50.8 mm (2") full-range drivers (actual OD of driver is 55.9 mm or 2.2"). A circular-arc angle of  $20^\circ$  was chosen which matches the wedge angle of the low-frequency (LF) cabinet.

It is noted that multiple boxes from two up to six can be attached with pin-loaded rigging hardware to form larger arrays with circular-arc angles of  $40^\circ$  to  $120^\circ$  providing vertical beamwidths of  $30^\circ$  up to  $90^\circ$ .

The HF assembly housing 8 drivers is shown via 3D CAD in Fig. 1. The total array height is about 504.2 mm (19.85").

The design of the  $20^\circ$  array was chosen so that when multiple HF units are stacked in a circular arc that total array maintains constant center-to-center spacing among all the HF drivers. Effectively when boxes are stacked, the array is just simply larger and maintains seamless transitions between each single cabinet and the next.

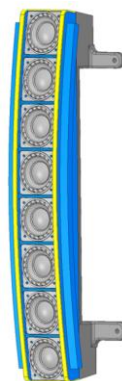


Fig. 1. 3D CAD image of an assembly of eight 50.8 mm (2") full-range drivers in a  $20^\circ$  circular-arc. This array is mounted over a 305 mm (12") woofer forming essentially a pseudo-coaxial design.

#### 3.2 Enclosure Design

The following subsections describe details of the wedge cabinet which houses the low-frequency driver, high-frequency array, a plate amplifier, along with various other miscellaneous items like handles, and rigging hardware, etc.

##### 3.2.1 3D CAD Images of Cabinet

This subsection displays several 3D CAD images of the system including a front view, oblique view, and inside view.

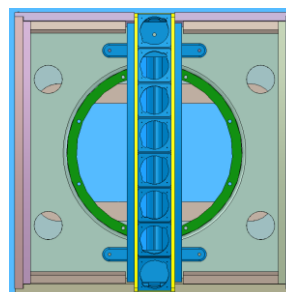


Fig. 2. CAD image of cabinet front view with eight-driver array in place over woofer driver and four front-located corner ports. No curved baffle on either side of the HF driver array is shown.

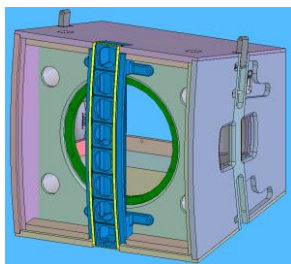


Fig. 3. Oblique 3D CAD view of cabinet with eight-driver array in place, four front-mounted ports, and details of the side handles and pin-loaded cabinet stacking hardware. Again, no curved baffle on either side of the HF driver array is shown.

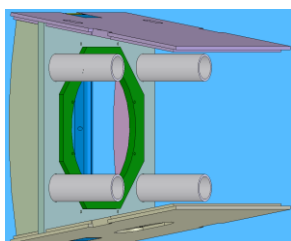


Fig. 4. Inside CAD view of cabinet with sides and rear hidden showing the four front-mounted circular ports. Each of the four ports are 50.8 mm (2”) in diameter and 228.6 mm (9”) long.

**3.2.2 Prototype Cabinet Photos**

This subsection displays three photos of the prototype system including a front view and two oblique views.



Fig. 5. Front view of prototype cabinet constructed of 19 mm Baltic Birch plywood. This photo was taken before the ports were added to the front of the enclosure.



Fig. 6. Oblique view of prototype cabinet before ports were added on the front.



Fig. 7. Oblique view of prototype cabinet with four front-mounted circular ports located in each corner of the front. The cabinet includes a curved-front metal baffle that covers the whole front of the cabinet. The metal baffle is solid for roughly 127 mm (5”) on either side of the HF array and perforated the rest of the way so that the acoustic output of the LF driver and ports can escape to the outside.

**3.2.3 Port Implementation**

One of the most difficult problems to solve was where to locate the vented-box ports to minimize windage and air-chuffing noises. Several locations were tried including rear and side and the best result was achieved with four 50.8 mm (2”) circular ports located on the front panel.

Locating the ports on the front is an excellent choice that insures all sound issues from the front of the cabinet and allows great flexibility in locating the cabinet so the side or rear ports are not covered up. The previous Fig. 4 shows an inside view of the cabinet with the four 228.6 mm (9”) long ports in place.

**3.2.4 Box Splay or Wedge Angle**

The box splay or wedge angle was chosen so that that a single box would have a beamwidth of about 15°. This implies that the box’s circular-arc angle must be about 20° because the beamwidth of a shaded array is about 75% of the array’s circular arc angle [1].

Unfortunately as pointed out later in the array shading section, it was not possible to provide any shading for the single eight-driver array because of amplifier hookup and thus the beamwidth of a single box was roughly 20° (see later sub section 6.1 and the simulated polar results in Appendix B).

**3.2.5 Stacking Hardware**

Simple side-mounted pin-locked stacking hardware was chosen to attach cabinets together in an array. The hardware also allowed the arrays to attach to subwoofer enclosures to extend the low-frequency response of an array below 50 Hz.

The next two figures show CAD images of two boxes attached together (Fig. 8) and also show how a four cabinet array can be hung below two subwoofer cabinets (Fig. 9).

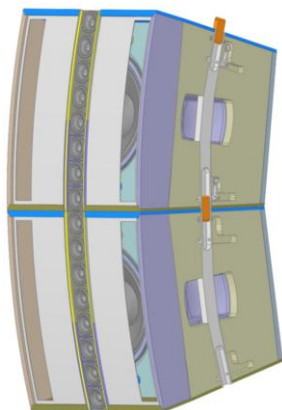


Fig. 8. CAD image of two wedge array cabinets attached together with side-mounted stacking hardware forming essentially a single 40° array box. Note how the two 20° eight-driver arrays seamlessly combine to form a single 40° circular-arc array.

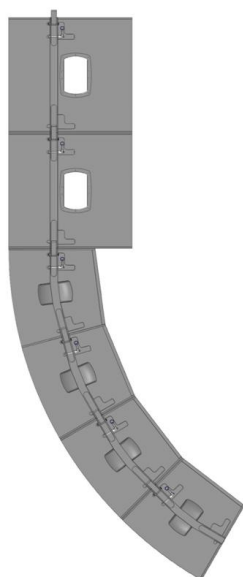


Fig. 9. An example of four 20° wedge boxes mounted to the bottom of two subwoofer cabinets (not described in this paper!). The bottom four cabinets essentially form a single 80° circular-arc system with 32 HF drivers.

#### 4 Amplifier Information

A built-in DSP four-channel 500 W per channel (4 Ohm load) plate amplifier mounted on the rear of the cabinet is used to power the system. Two channels are series bridged to drive the 8 Ohm woofer at 1000 W, while the remaining two 500 W channels (actually 250 W into an 8 Ohm load) drive the

tweeters with the top four tweeters on one channel and the bottom four tweeters on the other. The high power of the built-in amplifier insures that the complete system can reproduce very high peak SPLs.

The amplifiers have very-proficient DSP capabilities including FIR, IIR, parametric EQ, all pass, shelf, high- and low-pass filters, delay, and limiting, etc. Complete networking control capabilities are included with Ethernet or Dante.

#### 5 Array Shading

The gains or weights of the HF driver amplifiers were carefully chosen to maintain smooth and consistent polars for each of the array sizes [1].

Note that all gains are symmetrical up-down with the highest values in the center and the lowest values on the ends.

Each box has two gain values associated with the two amp channels powering the lower and upper tweeters in the array respectively. The following gain values were set for each array size:

1. One box: 0, 0 dB,
2. Two boxes: -6, 0, 0, -6 dB,
3. Three boxes: -7.6, -2.2, 0, 0, -2.2, -7.6 dB,
4. Four Boxes: -8.8, -3.8, -1.2, 0, 0, -1.2, -3.8, -8.8 dB,
5. Five Boxes: -9.5,-4.9, -2.3, -0.7, 0, 0, -0.7, -2.3, -4.9, -9.5 dB, and
6. Six Boxes: -10.1, -5.9, -3.3, -1.6, -0.5, 0, 0, -0.5, -1.6, -3.3, -5.9, -10.1 dB.

As pointed out before in prior research [2], this amplitude tapering or shading goes a long way towards smoothing and minimizing side lobes in the polar response of loudspeaker arrays. The following figure illustrates all the amplifier gain values for each array size.

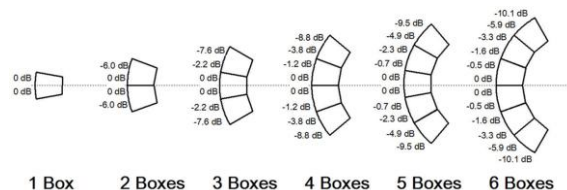


Fig. 10. Illustration of arrays that can be formed with a multiple 20° wedge boxes using from one up to six boxes. Array circular-arc angles range from 20° to 120° with associated vertical beam-widths ranging from 15° to 90°. Each array depiction shows the shading amplitudes for each half of the box.

## 6 Array Simulations

The array simulations shown in Appendix A and B were accomplished with a point-source computer model described in [2, Section 3.1 and Section 6 (Appendix)].

For single and multiple box arrays several simulations were accomplished including: 1) beamwidth, 2) directivity factor and directivity index, 3) power loss, and 4) vertical polars. Although horizontal polars were simulated, these are not shown. All these parameters were calculated at one-third-octave center frequencies.

The simulations include only the upper-frequency portion of cabinet which includes only the small eight wide-range drivers. All simulations assume that each small HF driver is modeled with two point sources making a total of 16 sources per cabinet. No cabinet or baffle diffraction effects were included in the point-source model. The point-source arrays simply operate in free space.

All the simulated data shown in Appendix A and Appendix B of this paper is briefly described in the following subsections:

### 6.1 One Box Array

The single-box array includes eight HF sources modeled with 16 point sources. Remember that due to amplifier restrictions, no shading exists for this box; all HF sources are equally driven with no shading. As a result, the polar simulations of the single box are the poorest of all the multi-box arrays (which do include significant shading).

As pointed out in [3], an unshaded circular-arc array was second only to a shaded circular-arc array but vastly better than an unshaded straight-line array which was ranked in last place.

#### 6.1.1 Beamwidth, Directivity, Power Loss

This information for all the arrays is shown in Appendix A.

This one-box beamwidth data is shown in Appendix A in the first row. The vertical beamwidth essentially stabilizes at about 20° above 6.3 kHz but reaches a midrange dip of about 13° at 5 kHz. This dip is a well known problem of all unshaded circular-arc arrays [3, Fig. 6] and has its origins going back to radial and multi-cellular horns [4, Figs. 6 and 10].

The horizontal beamwidth is 360° for the single box and array and all the remaining arrays because of the omnidirectional point sources used to model all the arrays.

Above 800 Hz the directivity index and factor steadily rise up to 4 kHz where it reaches a peak at about 6.3 kHz and then falls at higher frequencies. This erratic behavior is due to the many lobes exhibited by the vertical polar response (see vertical polars in next subsection).

The power loss steadily falls above 6.3 kHz.

#### 6.1.2 Vertical Polars

The single-box vertical polars shown in the first column in Appendix B illustrate massive off-axis lobes at frequencies above 1 kHz. Again as mentioned before, this is due to the absence of shading! At 12.5 kHz and above, strong off-axis grating lobes appear where the CC source spacing is greater than one-half wavelength.

## 6.2 Two up to Six Box Arrays

As before, this simulated directional information is shown in Appendices A and B. In general, as the number of boxes in an array increases; the shading gets better and better, less granular, and approximates the continuous Legendre shading to a higher degree. This means that all simulated characteristics improve significantly the higher the number of boxes in the array. It's only at 12.5 kHz and above where the data gets rough and chaotic due to the appearance of grating lobes and CC spacing issues.

#### 6.2.1 Beamwidth, Directivity, Power Loss

Appendix A illustrates that all these parameters vastly improve as the number of boxes in the array increases.

As the number of boxes increase, the vertical beamwidth approaches a straight-line with just a slight hint of midrange narrowing. As expected, the vertical beamwidth value increases with the array's circular-arc angle. The indicated beamwidth values are roughly: one box: 20°, two boxes: 30°, three boxes: 45°, four boxes: 60°, five boxes: 75°, and six boxes: 90°.

The directivity above 300 Hz correspondingly gets flatter and better behaved as the number of boxes increase. As expected, the directivity index is lower for the wider angle arrays from 10 dB for a single box to about 2 dB for six boxes.

The power response in turn gets better and better as the number of boxes increases reaching a very smooth rolloff of 3 dB/octave above 300 Hz.



### 6.2.2 Vertical Polars

As expected due to the improvement of shading as the number of boxes in the array increases, the vertical polars shown in Appendix B show vast improvement with increasing array size. At 12.5 kHz the grating lobes actually disappear with increasing array angle. At 16 kHz, all the polars exhibit grating lobes and a chaotic shape!

## 7 Array Measurements

A complete set of polar measurements were gathered on the cabinet with an automated polar measuring setup shown in the following figure. Unfortunately, measurements on a larger number of boxes were not completed because to date (Sept. 7, 2017) only a single prototype box has been constructed.



Fig. 11. Measurement setup for gathering on- and off-axis frequency response measurements. The Four Audio ELF automated loudspeaker measurement system was used for these measurements. Rotation was about the cabinet front with the test microphone 2 m from the front of the box.

### 7.1 Polar Map or Isobar Data for Single Cabinet

The following image (Fig.12) shows a measured polar map of the directional characteristics of a single cabinet. The upper display is the horizontal data while the vertical data is shown in the lower display. Horizontal black lines have been added to each image to show respectively  $\pm 75^\circ$  (horizontal,  $150^\circ$  beamwidth) and  $\pm 20^\circ$  (vertical  $40^\circ$  beamwidth).

Note that the measured vertical data is nearly twice as much as designed, because of the close 2m measurement distance (not far field!) and the fact that rotation was about the front of the box rather than around the circular-arc center of curvature.

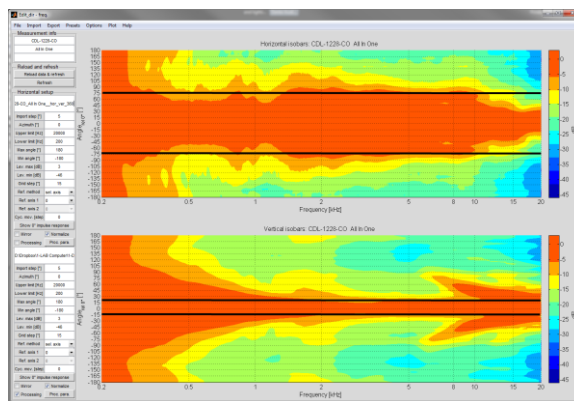


Fig. 12. Polar map (Isobar) data measurement of a single box.

## 8 Conclusions

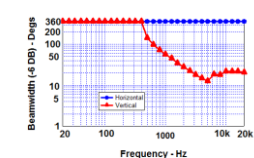
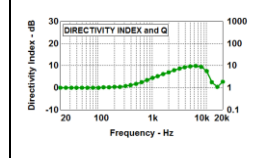
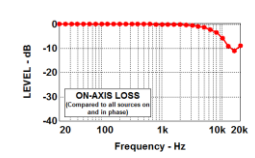
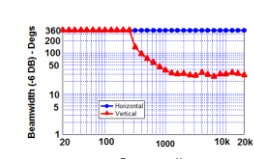
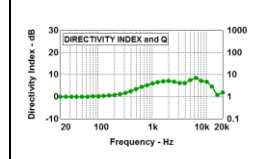
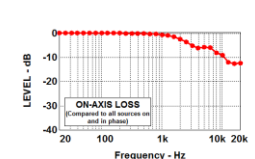
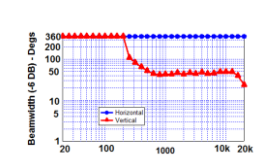
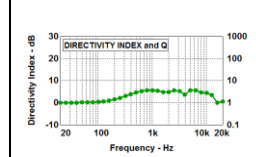
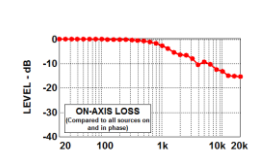
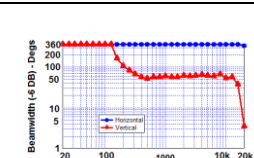
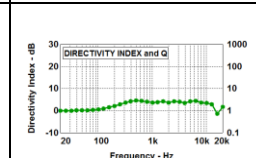
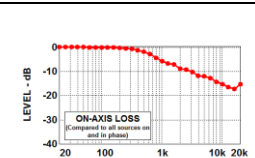
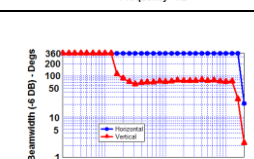
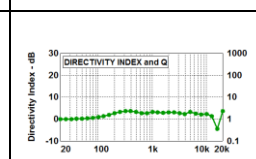
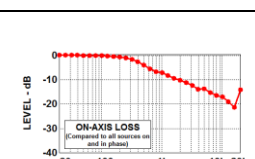
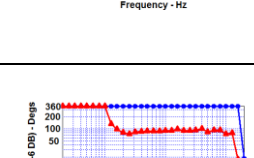
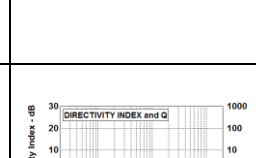
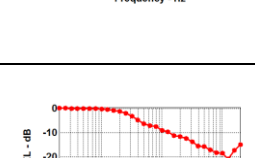
This paper has shown that a very-practical constant-coverage/directivity wide-range wedge loudspeaker system can be designed and constructed that when used to form larger arrays can provide various well-behaved wider coverage patterns with extremely uniform vertical and horizontal coverage.

An individual system is comprised of an eight driver circular-arc high-frequency array covering a 12" driver. The system is in effect a coaxial design providing a very well-controlled vertical pattern with a very-wide horizontal pattern. The overall system provides broadband 45 Hz to 15 kHz response and is very versatile due to its built-in plate amplifier that is controllable via Dante or Ethernet. Side-mounted pin-loaded hardware is included for ease of stacking.

## References

- [1] D. B. Keele, Jr., "Practical Implementation of Constant Beamwidth Transducer (CBT) Loudspeaker Circular-Arc Line Arrays," Presented at the 115th Convention of the Audio Engineering Society (Oct. 2003).
- [2] D. B. Keele, Jr., "The Application of Broadband Constant Beamwidth Transducer (CBT) Theory to Loudspeaker Arrays," 109th Convention of the Audio Engineering Society, Preprint 5216 (Sept. 2000).
- [3] D. B. Keele, Jr., "A Performance Ranking of Seven Different Types of Loudspeaker Line Arrays," Presented at the 129th Convention of the Audio Engineering Society (Nov. 2010).
- [4] D. B. Keele, Jr., "What's So Sacred About Exponential Horns" Presented at the 52nd Convention of the Audio Engineering Society (May. 1975).

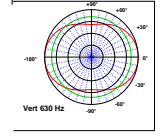
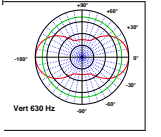
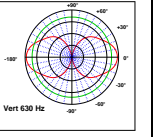
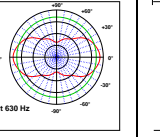
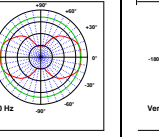
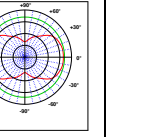
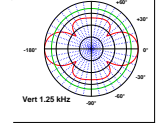
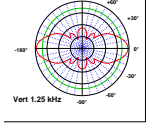
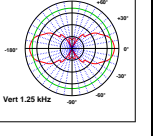
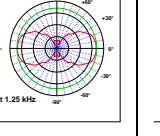
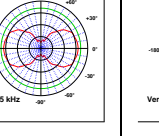
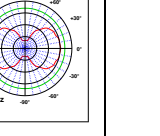
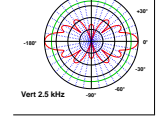
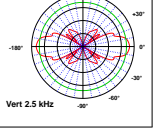
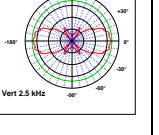
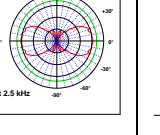
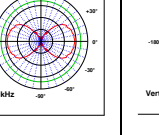
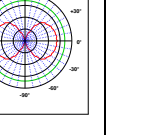
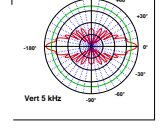
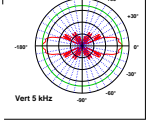
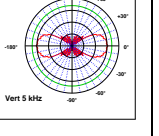
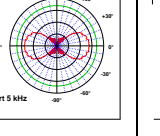
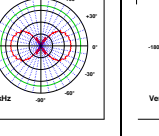
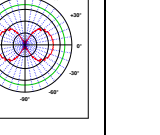
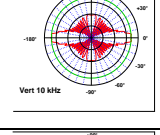
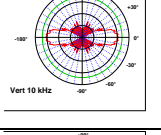
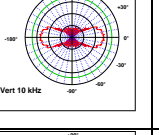
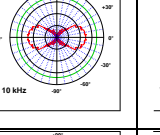
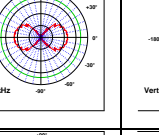
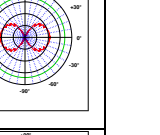
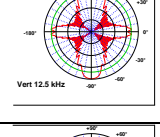
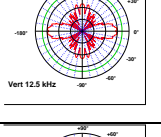
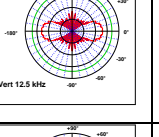
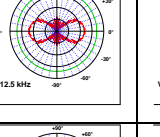
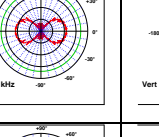
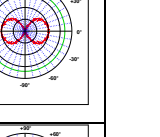
**Appendix A: Table of Simulated Array Beamwidth, Directivity, and Power Loss for Arrays of One up to Six Boxes:**

Number Boxes and Arc Angle	Array (With Box Shading)	Beamwidth vs. Frequency	Directivity vs. Frequency	Power Loss vs. Frequency
1 20°	0 dB 0 dB			
2 40°	-6.0 dB 0 dB 0 dB -6.0 dB			
3 60°	-7.6 dB -2.2 dB 0 dB -2.2 dB -7.6 dB			
4 80°	-8.8 dB -3.8 dB -1.2 dB 0 dB -1.2 dB -3.8 dB -8.8 dB			
5 100°	-9.5 dB -4.9 dB -2.3 dB 0 dB 0 dB -2.3 dB -4.9 dB -9.5 dB			
6 120°	-10.1 dB -5.9 dB -3.3 dB -1.6 dB -0.5 dB 0 dB 0 dB -0.5 dB -1.6 dB -3.3 dB -5.9 dB -10.1 dB			

**Appendix B: Table of Simulated Vertical Polars for Arrays of One up to Six Boxes:**

NOTE! These polars are hard to see at normal page sizes, to view them in detail just expand the page size!

This table shows simulated vertical polars of all six array sizes at octave centers from 630 Hz to 10 kHz, plus the highest-frequency simulated polars at 12.5 kHz and 16 kHz. Array size is plotted across and frequency is plotted down.

Frequency Hz	One Box	Two Boxes	Three Boxes	Four Boxes	Five Boxes	Six Boxes
630 Hz						
1.25 kHz						
2.5 kHz						
5 kHz						
10 kHz						
12.5 kHz						
16 kHz	