Implementation of Straight-Line and Flat-Panel Constant Beamwidth Transducer (CBT) Loudspeaker Arrays Using Signal Delays

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(AES Paper Presented Sept. 2002)

Outline

- Theory
  - Overview of Constant Beamwidth Transducer Theory
    - Originally developed for underwater sound by the military
    - Shaded circular spherical caps
  - Review: Application of CBT theory to curved-surface and line arrays
  - Delay-Derived CBT Arrays
- Overview of 3D Sound Radiation Numeric Simulator
  - Point source arrays
  - Beamwidth, directivity, loss, polars, footprints
- Compare Conventional vs. Delay-Derived CBT Line Arrays
  - Vary vertical coverage angles
- Example: Design Line Array for Flat Off-Axis Response
- Spherical-cap vs. Delay-Derived Circular Flat-panel CBT Arrays
- Conclusions

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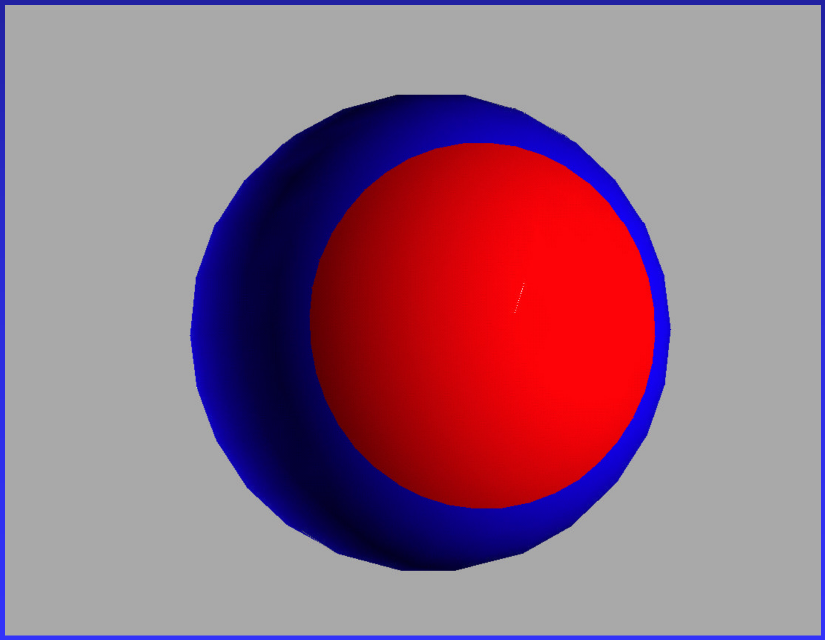
Overview of Constant Beamwidth Transducer Theory

- First formulated in JASA papers published in 1978 and 1983 describing underwater transducers based on shaded spherical caps.
  - P. H. Rogers, and A. L. Van Buren, "New Approach to a Constant Beamwidth Transducer," J. Acous. Soc. Am., vol. 64, no. 1, pp. 38-43 (1978 July).
  - A. L. Van Buren, L. D. Luker, M. D. Jevnager, and A. C. Tims, "Experimental Constant Beamwidth Transducer," J. Acous. Soc. Am., vol. 73, no. 6, pp. 2200-2209 (1983 June).
- Applied to loudspeaker arrays by Keele in 2000
  - D. B. Keele, Jr. "The Application of Broadband Constant Beamwidth Transducer (CBT) Theory to Loudspeaker Arrays," presented at the 109th convention of the Audio Engineering Society (2000 Sept.) preprint 5216.

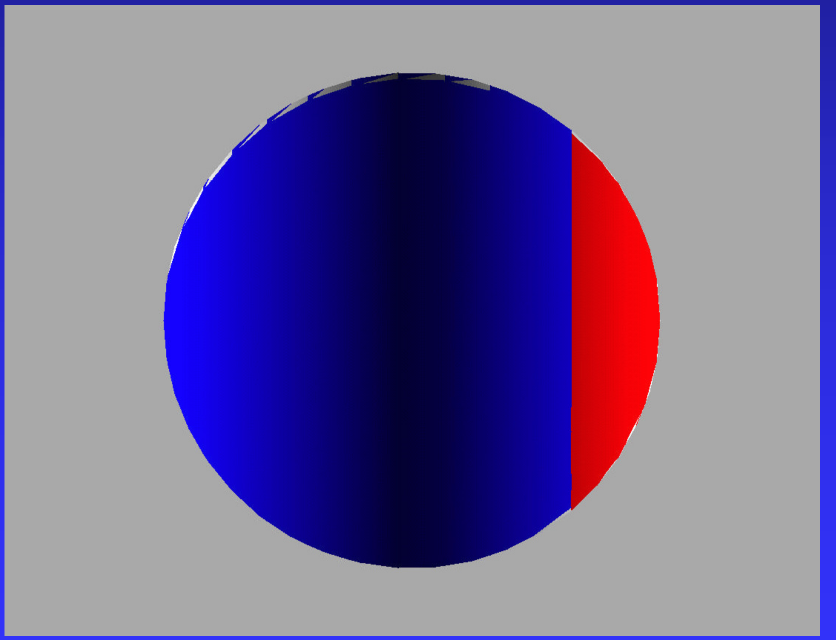
Spherical-Cap CBT Transducers
Overview

100° Circular Spherical Cap

Oblique View



Side View



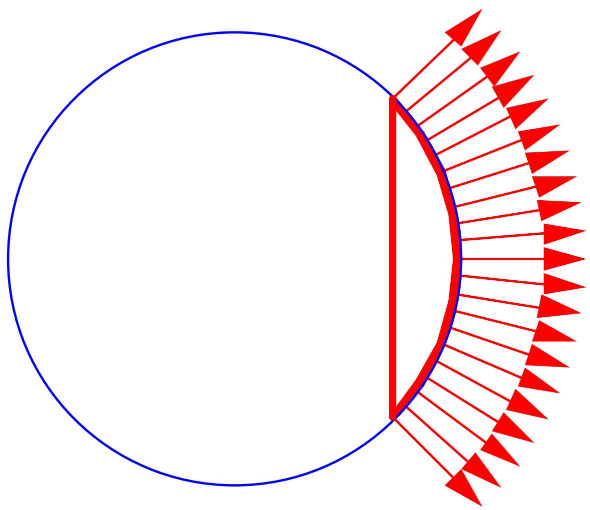
Spherical-Cap CBT Transducers

Overview Cont.:

Legendre Shading of Surface Pressure

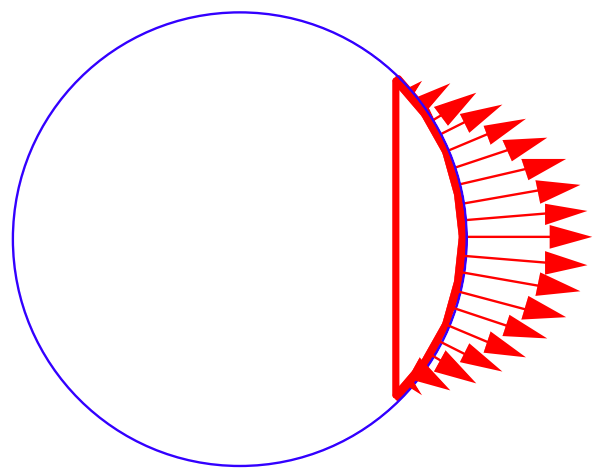
No Shading

$$p(\theta) \square \begin{cases} 1 & \text{for} \quad \theta \le \theta_0 \\ 0 & \text{for} \quad \theta > \theta_0 \end{cases}$$



With Shading

$$p(\theta) \square \begin{cases} P_v(\cos\theta) & \text{for} \quad \theta \le \theta_0 \\ 0 & \text{for} \quad \theta > \theta_0 \end{cases}$$



Spherical-Cap CBT Transducers

Overview Cont.: Legendre Shading

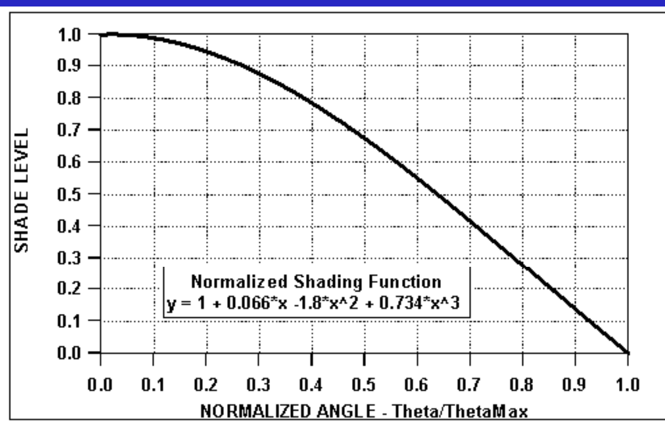
- Power Series Approximation of Legendre Shading Function

$$U(x) \approx \begin{cases} 1 + 0.066x - 1.8x^2 + 0.743x^3 & \text{for} \quad x \le 1 \\ 0 \quad \text{for} \quad x > 1 \end{cases}$$

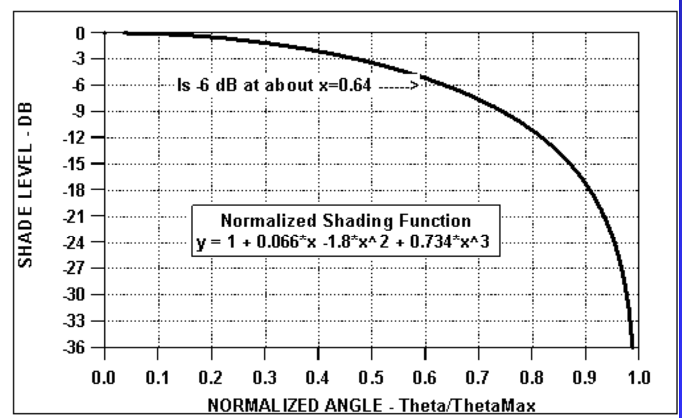
where

$$x = \text{normalized angle} \left(\frac{\theta}{\theta_0} \right)$$

(a)



(b)



Spherical-Cap CBT Transducers
Overview Cont.: Observations

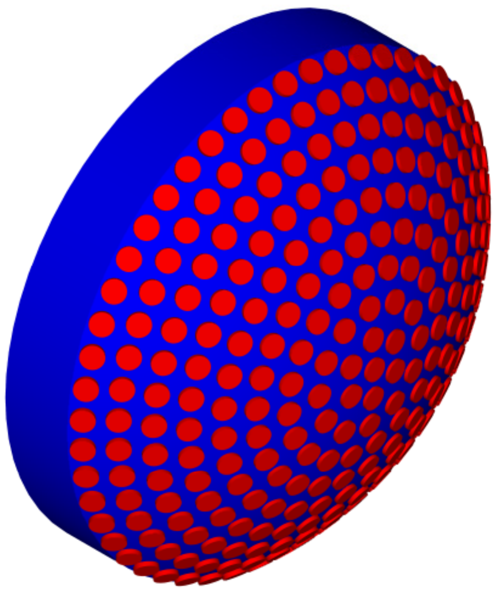
- Provides extremely uniform polars above a certain frequency which are independent of distance
- Beamwidth = 0.64 x Cap Angle
- Surface pressure distribution, nearfield pressure pattern, and farfield pressure pattern are all essentially the same!
- Don’t need the rest of the sphere!

CBT Curved-Surface and Curved-Line Arrays: Review

- Can transform a continuous distribution into a discrete distribution
  - Spherical-cap CBT Arrays
  - Circular wedge curved-line CBT arrays

CBT Curved-Surface and Curved-Line Arrays: Review Cont.

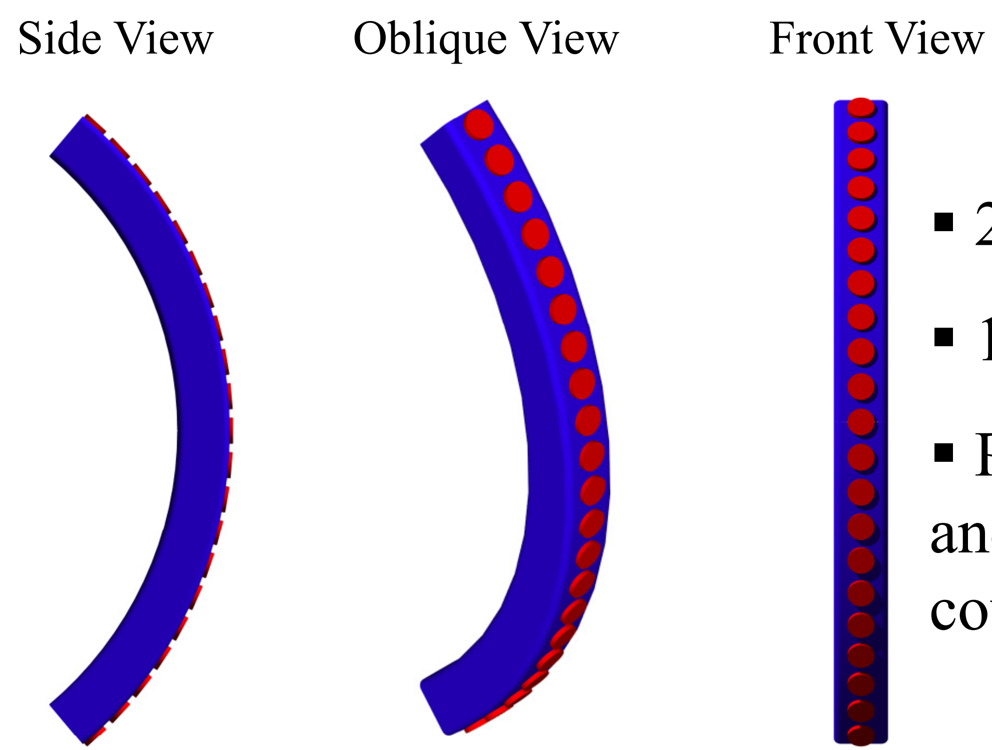
Spherical-cap CBT array example



- 266 wide-range drivers
- 100° cap angle
- Provides 64° symmetrical vertical and horizontal coverage
- 9 rings

CBT Curved-Surface and Curved-Line Arrays: Review Cont.

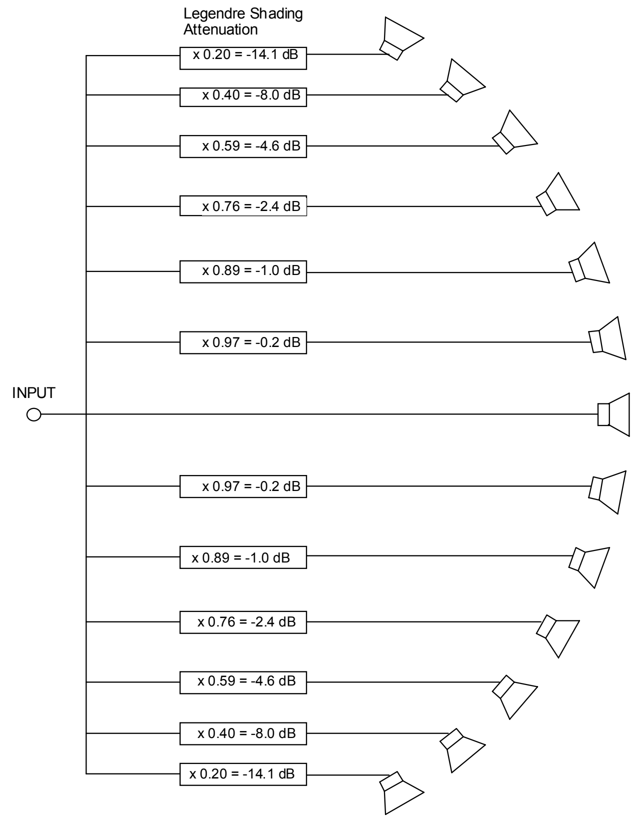
Circular wedge curved-line CBT array example



- 21 wide-range drivers
- 100° wedge angle
- Provides 64° vertical and wide horizontal coverage

CBT Curved-Surface and Curved-Line Arrays: Review Cont.

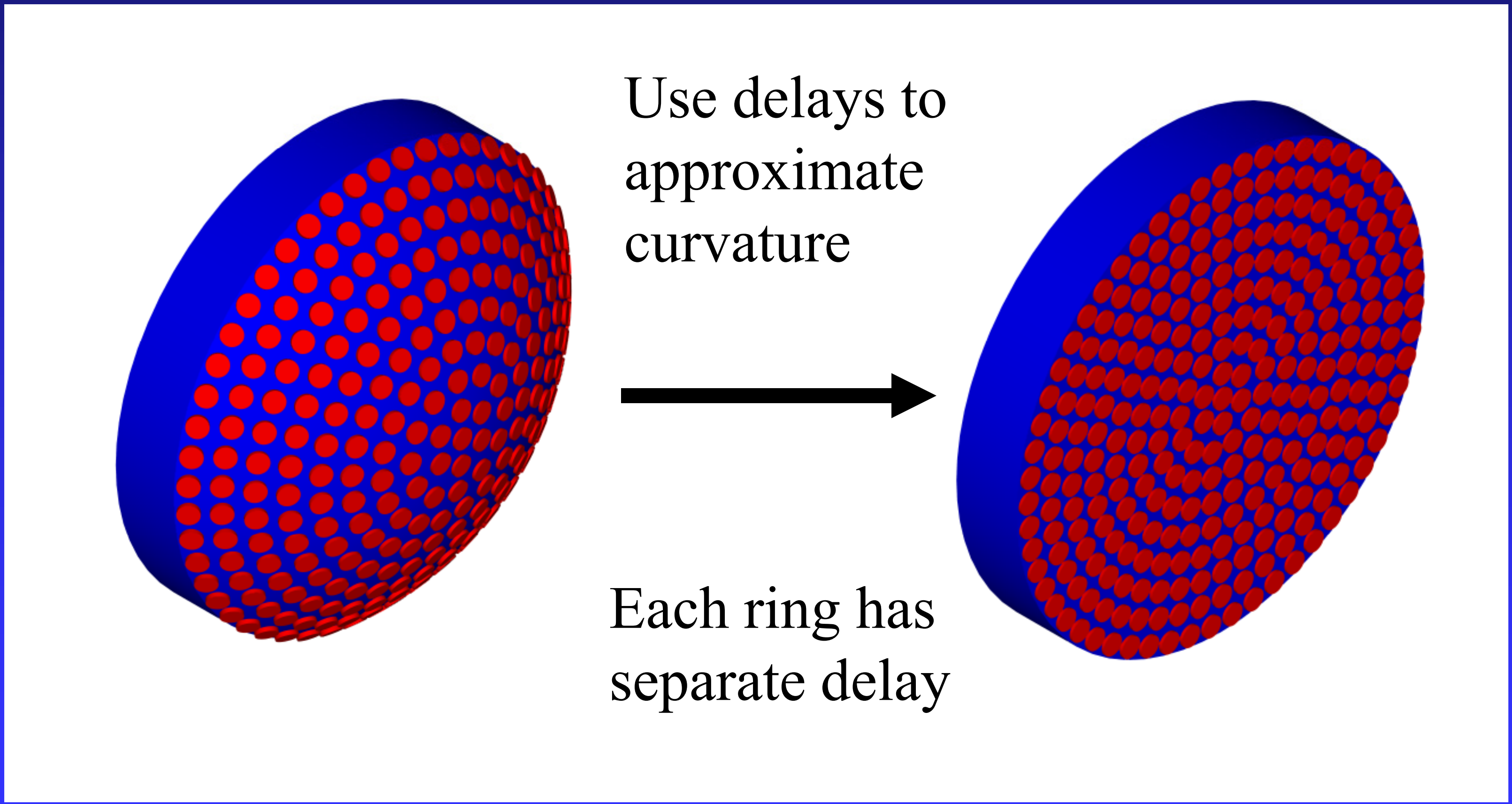
CBT Signal Processing



- Each block sets gain only!
- Implements frequency-independent Legendre shading.
- Can be implemented with or without power amplifiers.

Delay-Derived Flat-Surface and Straight-Line CBT Arrays: Theory

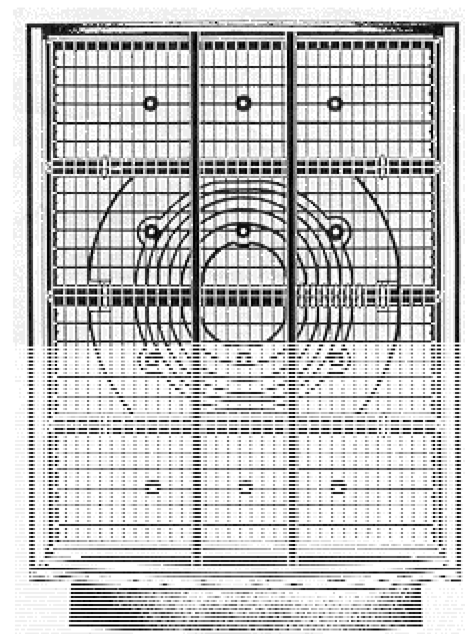
Convert Spherical-Cap to Flat Circular Array



Where'd I see that before?

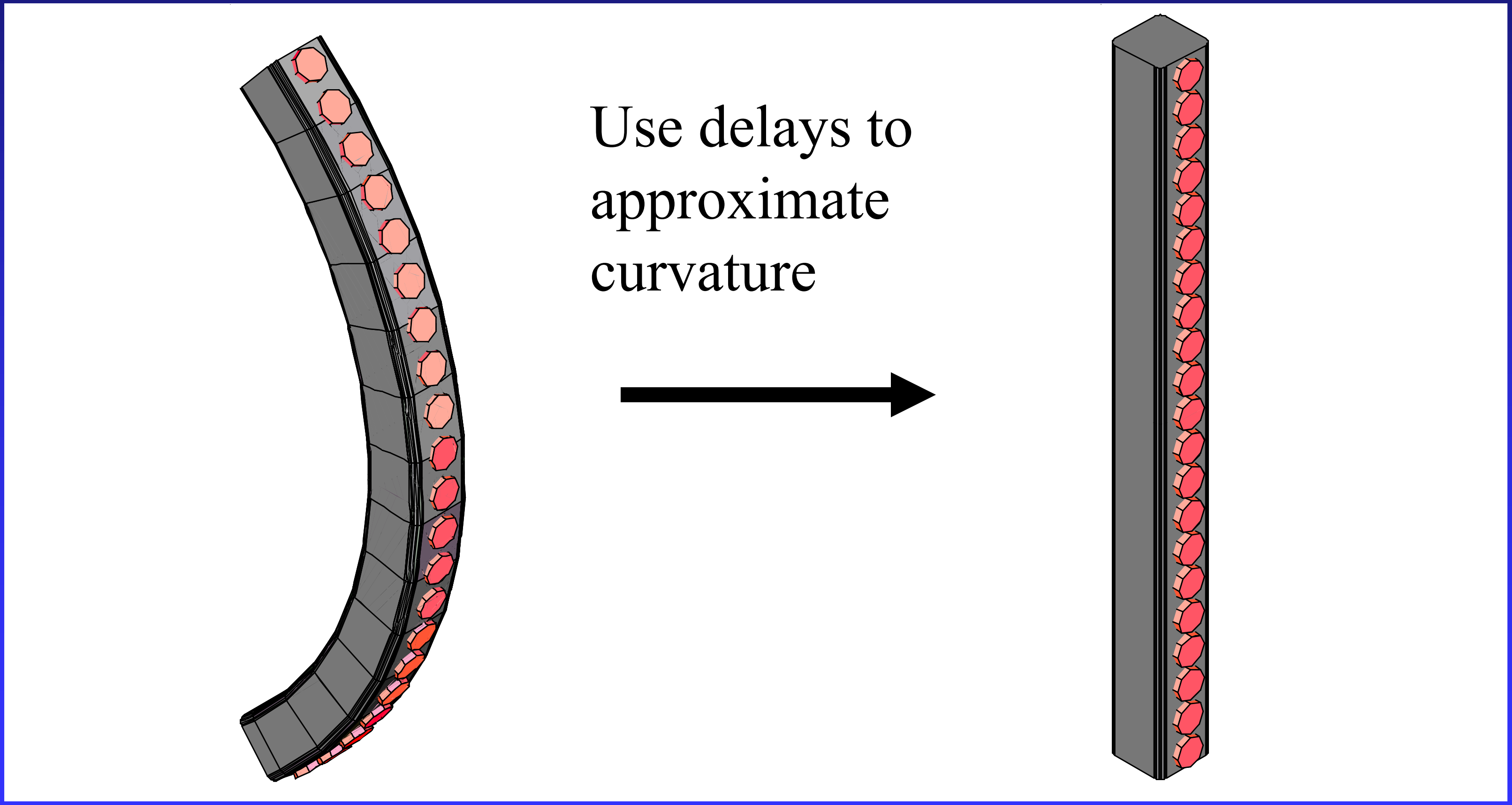
Quad ESL63 Quote: The speaker is divided into regions in the form of concentric rings (see diagram). The audio signal is fed to the concentric rings through a delay line. The signal reaches the innermost ring first and then progresses to the next outer ring. *This technique makes the flat panel radiate a wave front that is similar in geometry to a point source located a short distance behind the speaker.*

Quad ESL63 Diagram



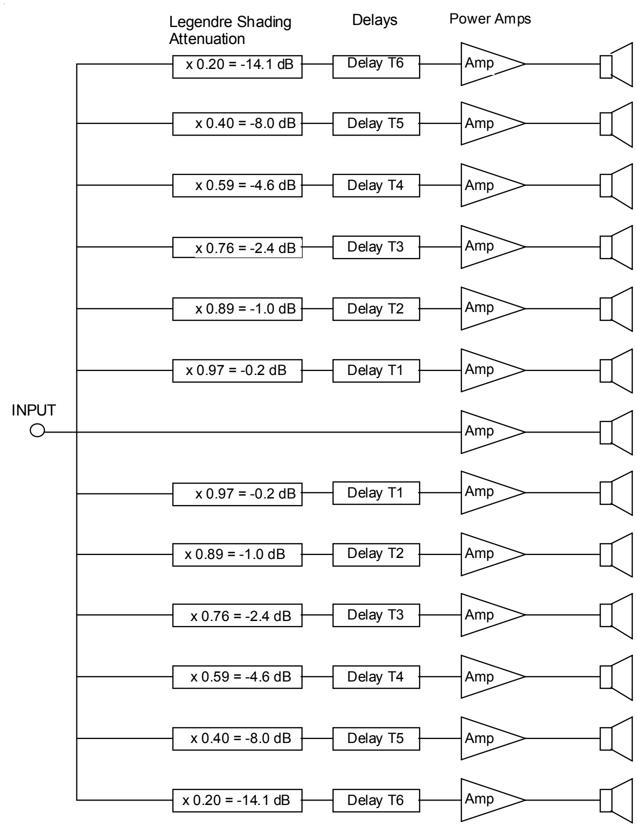
Delay-Derived Flat-Surface and Straight-Line CBT Arrays: Theory

Convert Circular Wedge Curved-Line Array to Straight-Line Array



Delay-Derived Flat-Surface and Straight-Line CBT Arrays: Theory

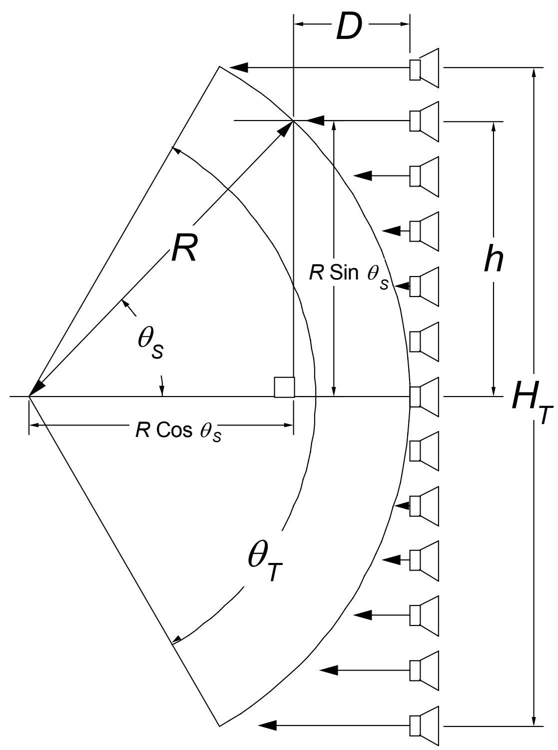
CBT Delay-Derived Signal Processing



- Each channel is composed of a level shift, a pure delay, and a power amplifier.
- Implements Legendre shading followed by a delay.
- Processing is still frequency independent (if an all-pass filter can be described in this way).

Delay-Derived Flat-Surface and Straight-Line CBT Arrays: Theory

Compute Required Delay

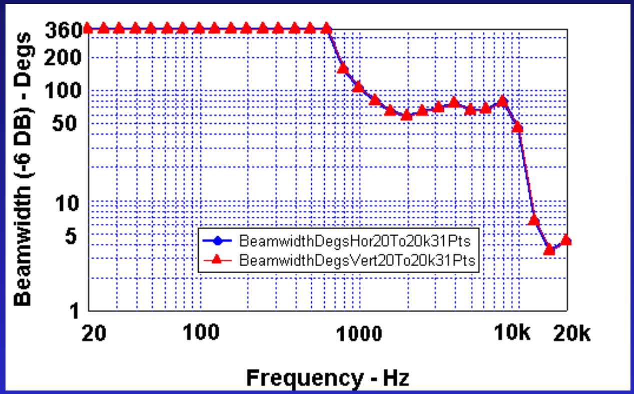


The delay effectively moves the driver from its position on a straight-line or flat surface to a point on a circular arc or on the surface of a sphere.

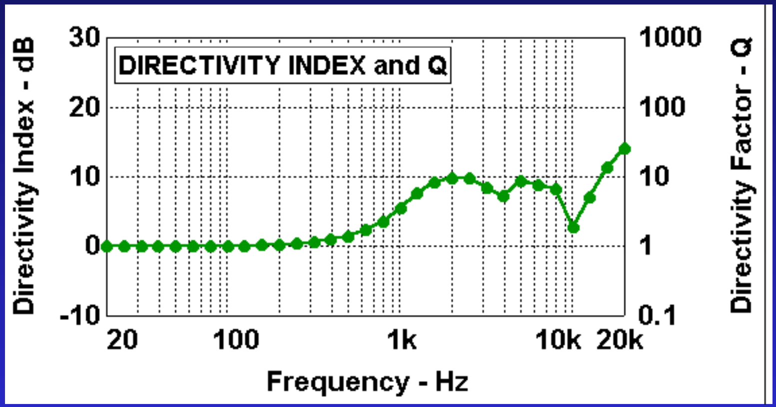
The computations are straightforward, the math's in the paper.

Overview of Point-Source Array 3D Sound Radiation Numeric Simulator

Beamwidth vs. Frequency

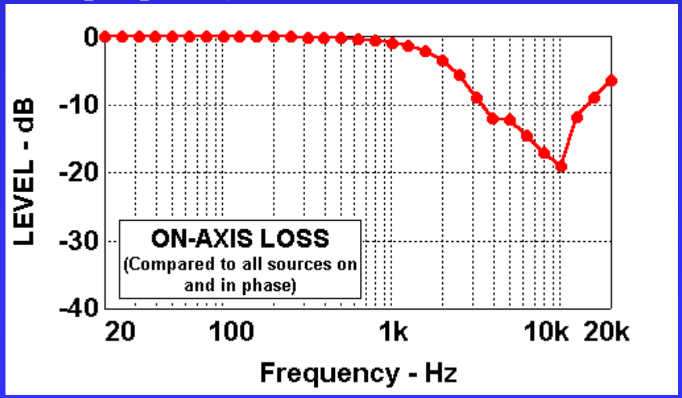


Directivity vs. Frequency

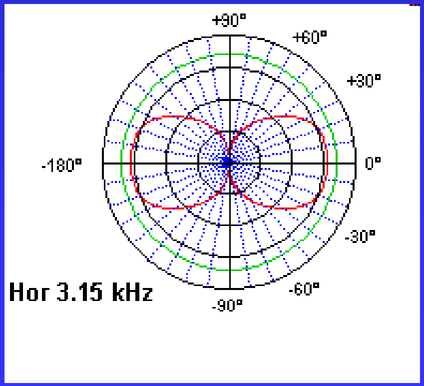


On-Axis Loss vs. Frequency

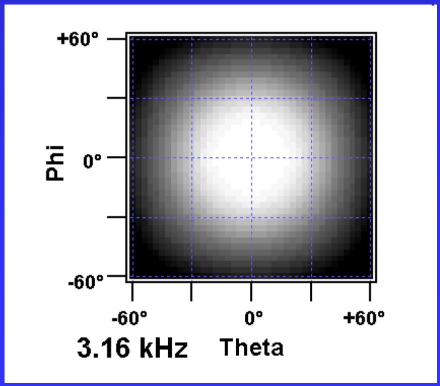
(As compared to all sources on and in phase at sample point.)



Polars



Footprints



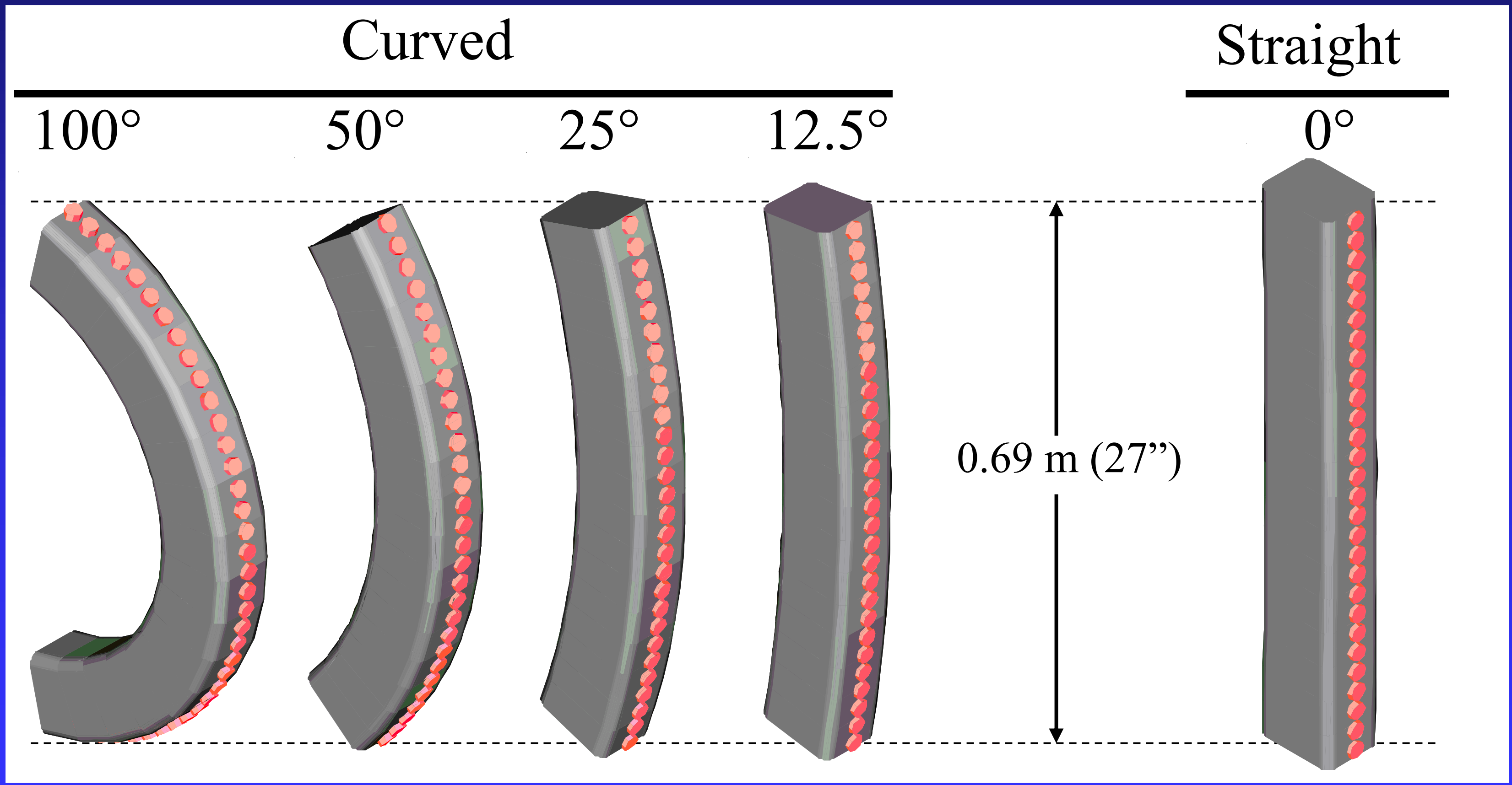
Compare Conventional vs. Delay-Derived CBT Line Arrays

Vary Vertical Coverage Angles

- The coverage of the conventional CBT circular-arc line array was compared to the coverage of a delay-derived CBT straight line array by designing four separate arrays of each type to provide coverage angles (6-dB-down beamwidths) of 12.5°, 25°, 50°, and 100°.
- These coverage's required arc angles of 19.5°, 39°, 78°, and 156° respectively (remember that the coverage angle is approximately 64% of the arc angle).
- All eight arrays were designed to be two wavelengths high at 1 kHz i.e., 27 inches (0.69 m).
- The number of sources in each array was varied so that the center-to-center spacing was about 1 inch (25 mm).

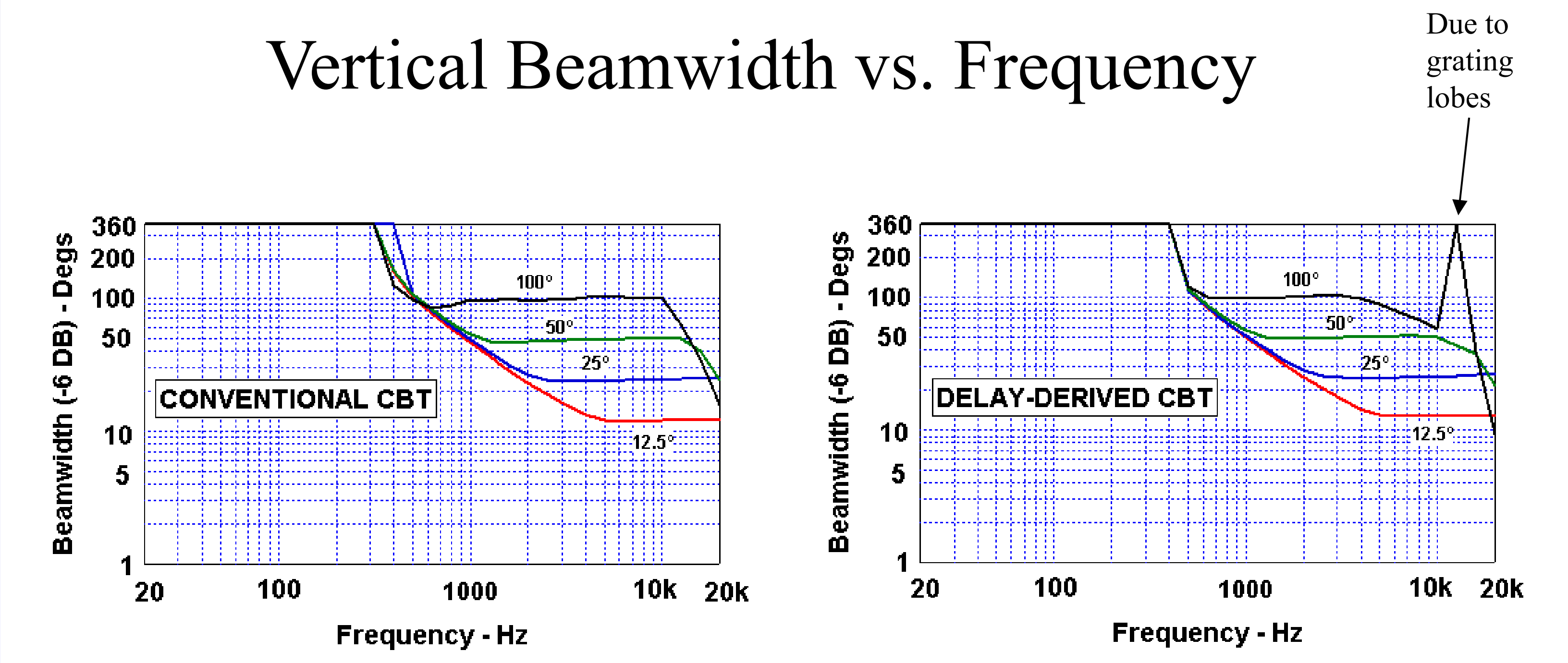
Compare Conventional vs. Delay-Derived CBT Line Arrays

Vary Vertical Coverage Angles: Models



Compare Conventional vs. Delay-Derived CBT Line Arrays

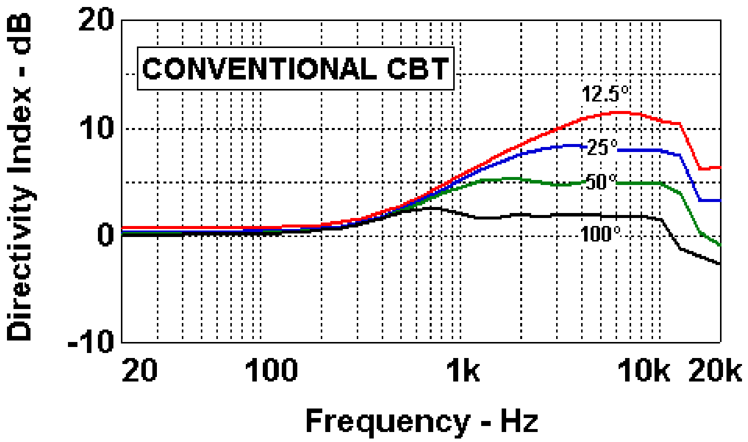
Vary Vertical Coverage Angles: Data

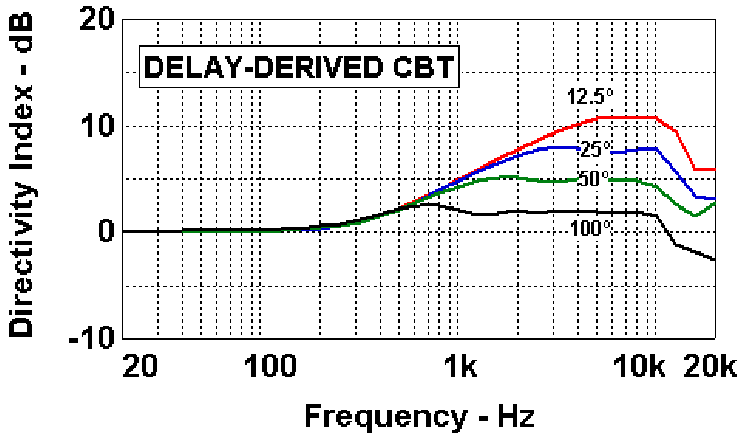


Compare Conventional vs. Delay-Derived CBT Line Arrays

Vary Vertical Coverage Angles: Data

Directivity vs. Frequency

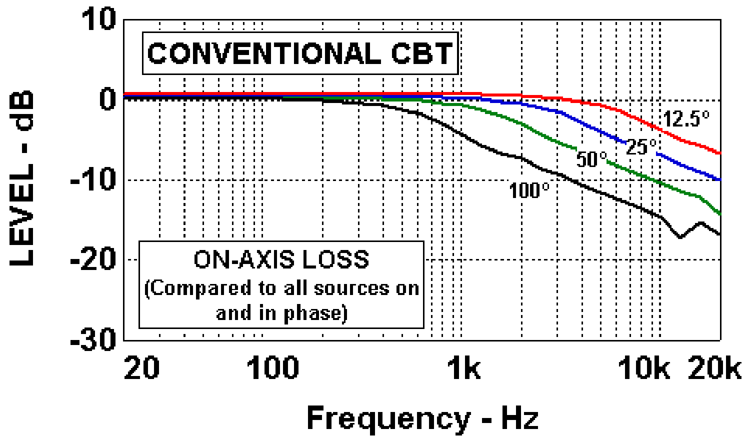


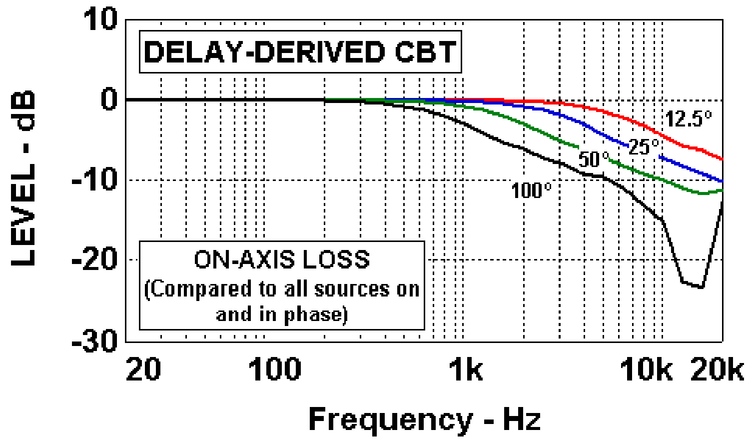


Compare Conventional vs. Delay-Derived CBT Line Arrays

Vary Vertical Coverage Angles: Data

On-Axis (Loss) Frequency Response



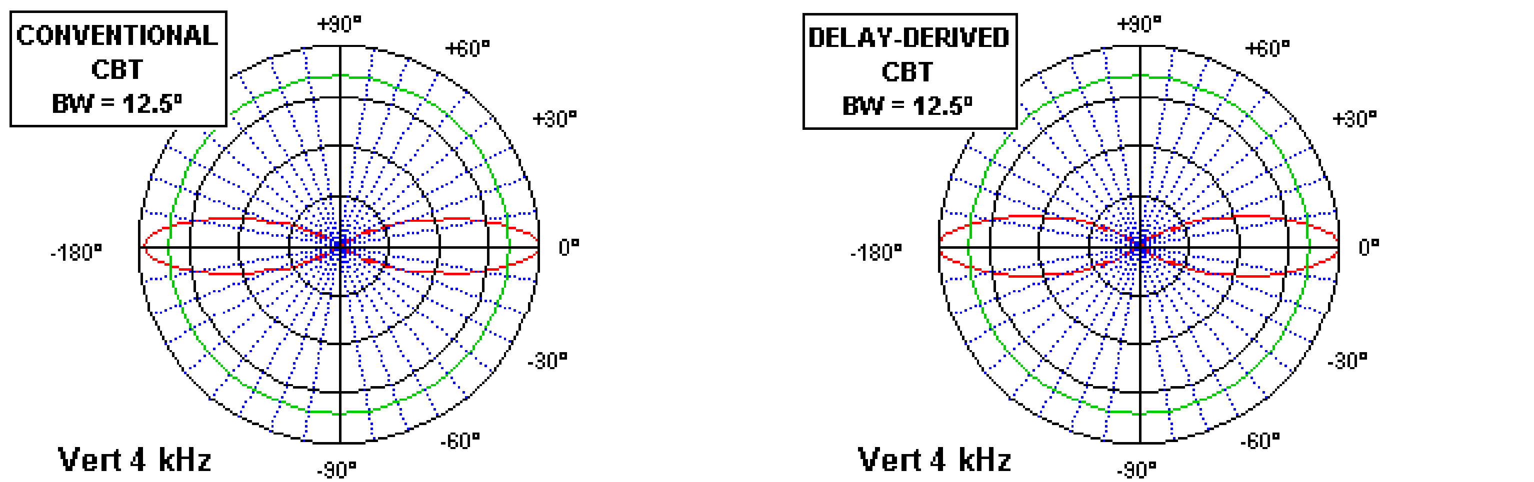


Compare Conventional vs. Delay-Derived CBT Line Arrays

Vary Vertical Coverage Angles: Data

12.5° Vertical Polars at 4 kHz

(*<u>Normalized</u>* to on axis)

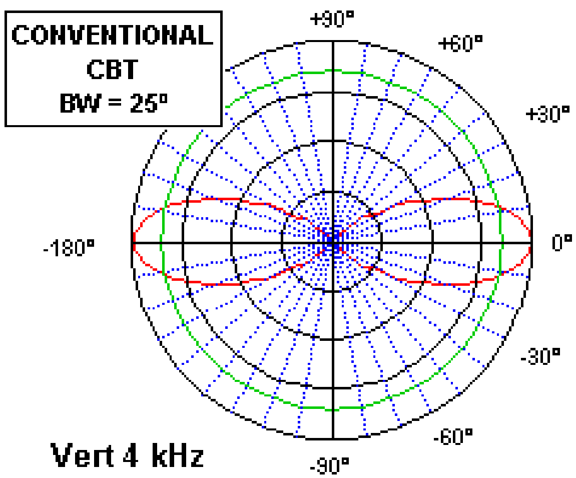


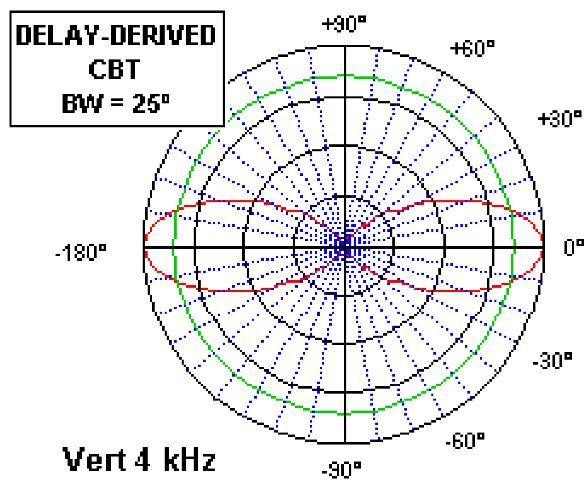
Compare Conventional vs. Delay-Derived CBT Line Arrays

Vary Vertical Coverage Angles: Data

25° Vertical Polars at 4 kHz

(*Normalized* to on axis)



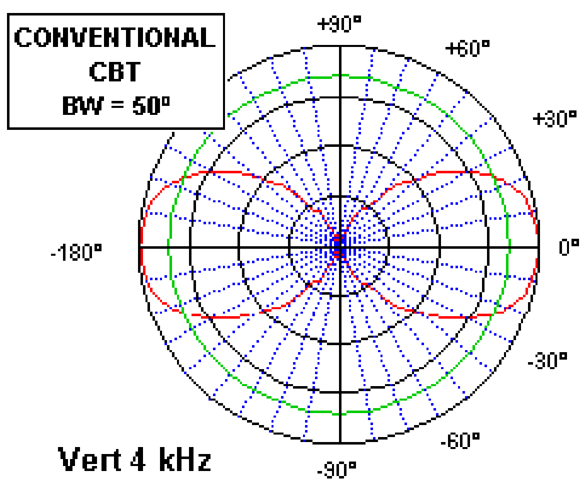


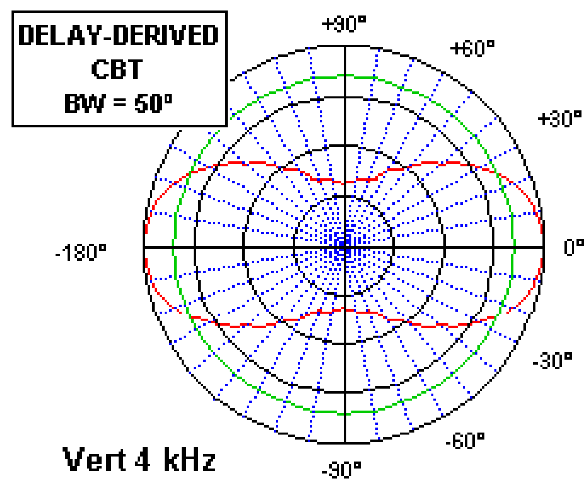
Compare Conventional vs. Delay-Derived CBT Line Arrays

Vary Vertical Coverage Angles: Data

50° Vertical Polars at 4 kHz

(*Normalized* to on axis)



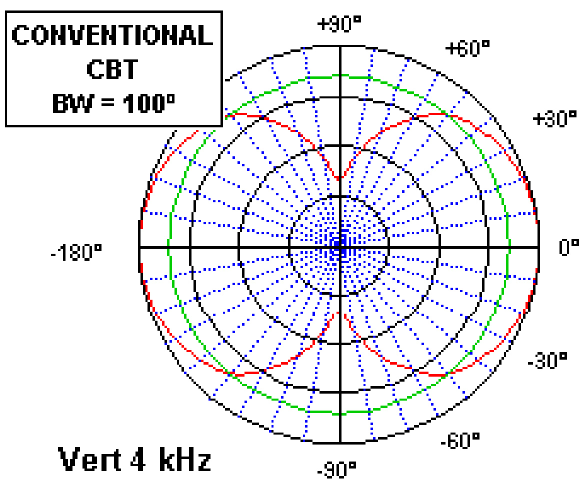


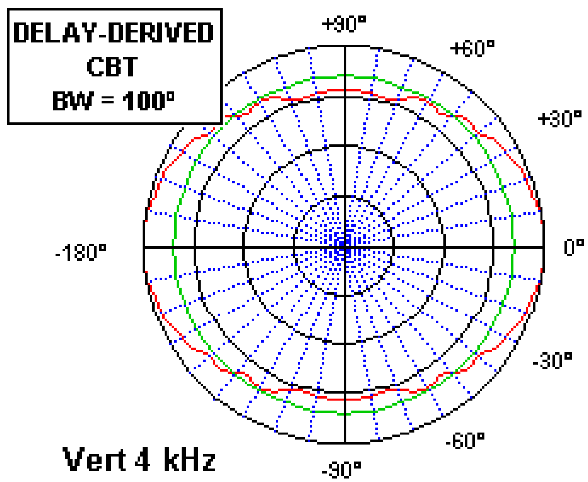
Compare Conventional vs. Delay-Derived CBT Line Arrays

Vary Vertical Coverage Angles: Data

100° Vertical Polars at 4 kHz

(*Normalized* to on axis)



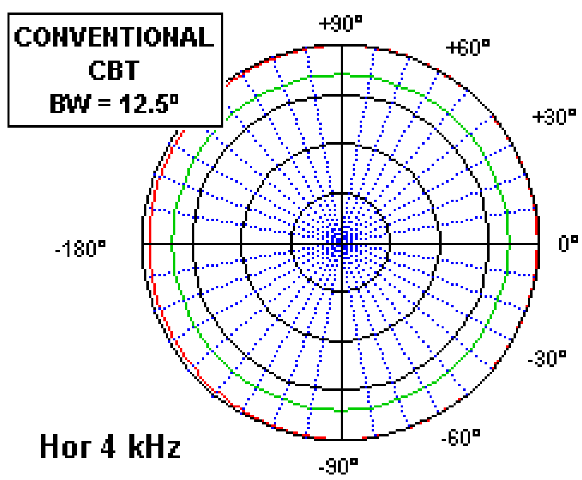


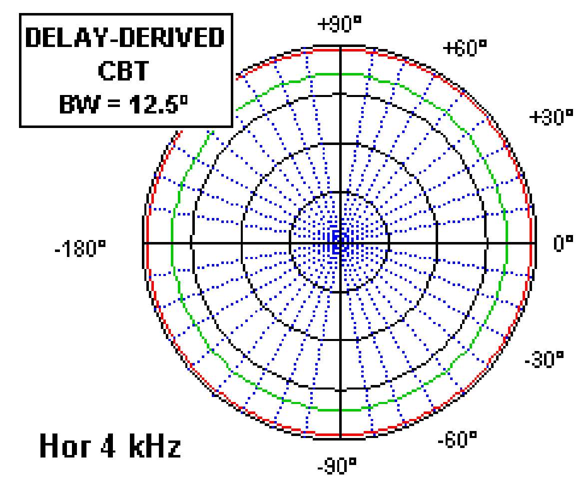
Compare Conventional vs. Delay-Derived CBT Line Arrays

Vary Vertical Coverage Angles: Data

12.5° Horizontal Polars at 4 kHz

(*Not Normalized* to on axis)



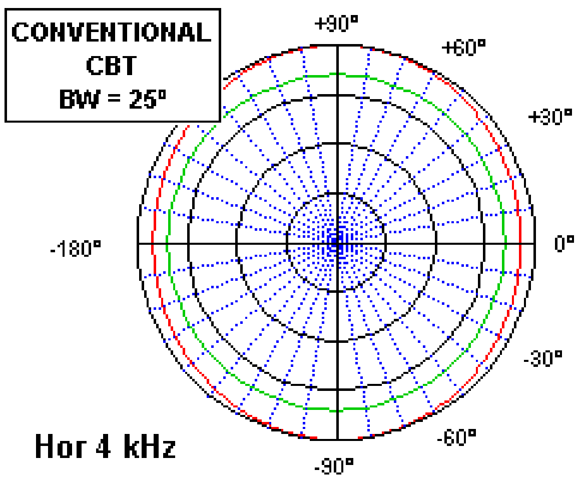


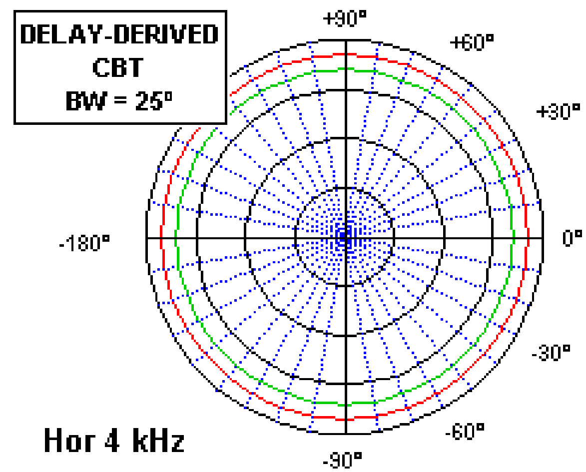
Compare Conventional vs. Delay-Derived CBT Line Arrays

Vary Vertical Coverage Angles: Data

25° Horizontal Polars at 4 kHz (*Not*

(*Not Normalized* to on axis)



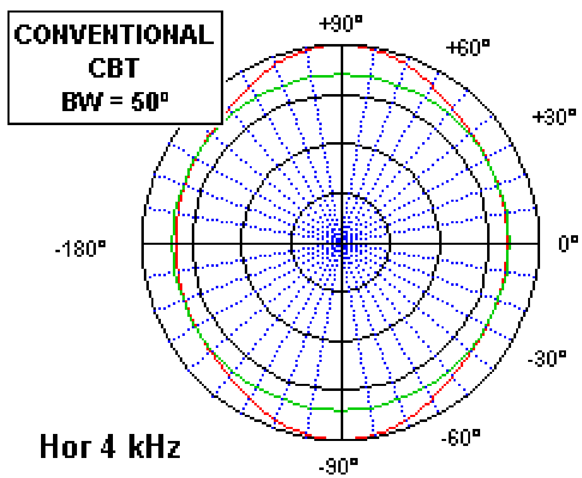


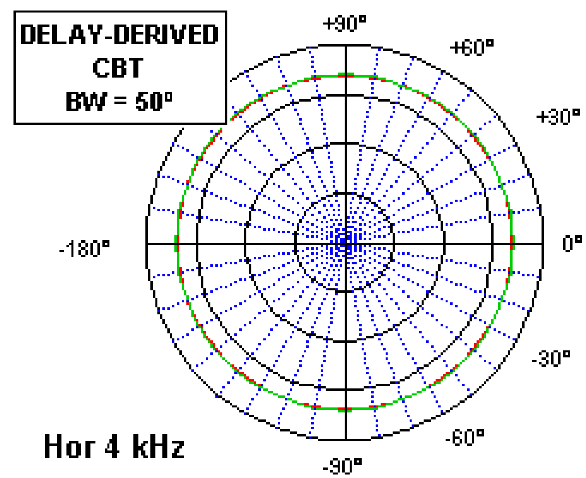
Compare Conventional vs. Delay-Derived CBT Line Arrays

Vary Vertical Coverage Angles: Data

50° Horizontal Polars at 4 kHz (*Not*

(*Not Normalized* to on axis)



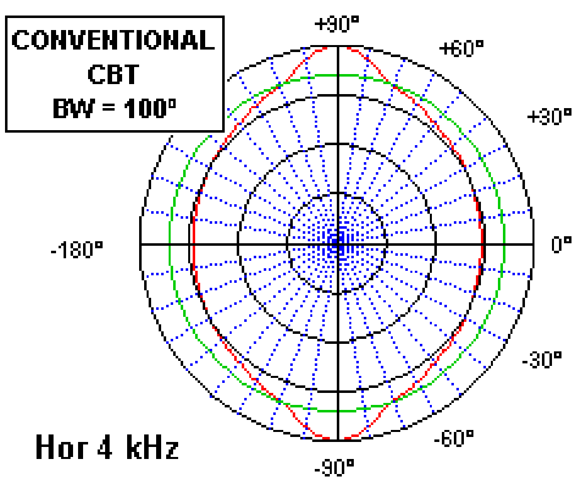


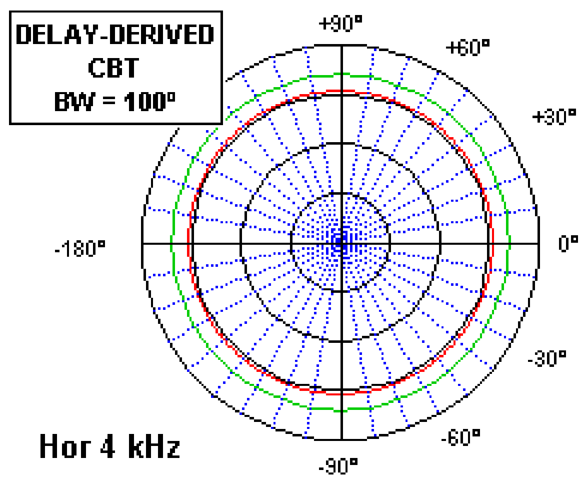
Compare Conventional vs. Delay-Derived CBT Line Arrays

Vary Vertical Coverage Angles: Data

100° Horizontal Polars at 4 kHz

(*Not Normalized* to on axis)

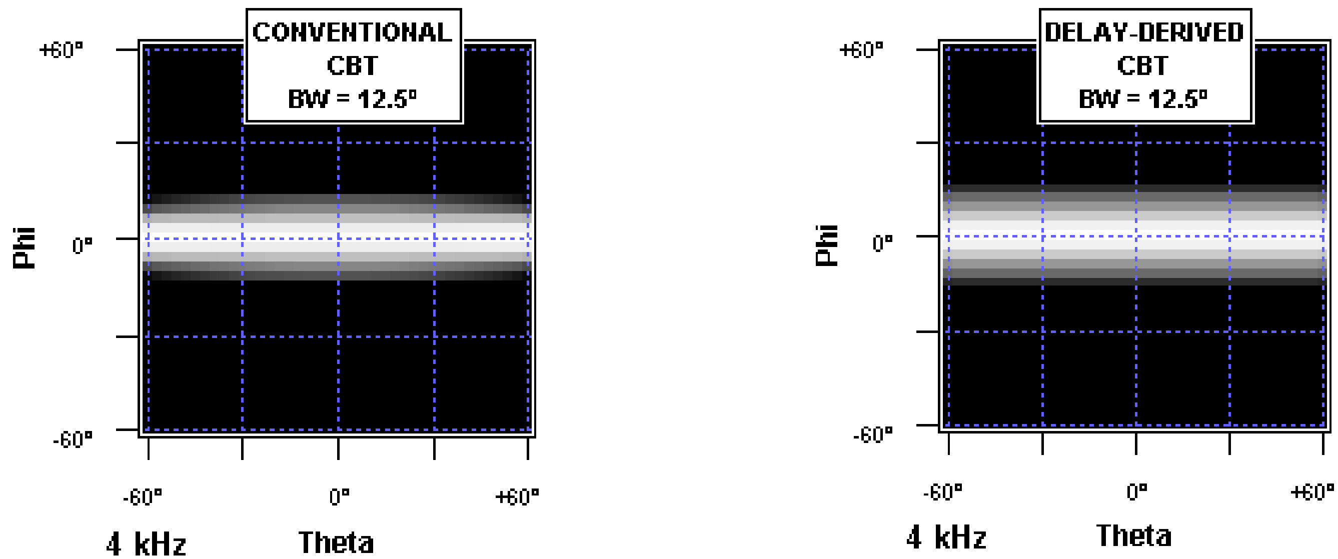




Compare Conventional vs. Delay-Derived CBT Line Arrays

Vary Vertical Coverage Angles: Data

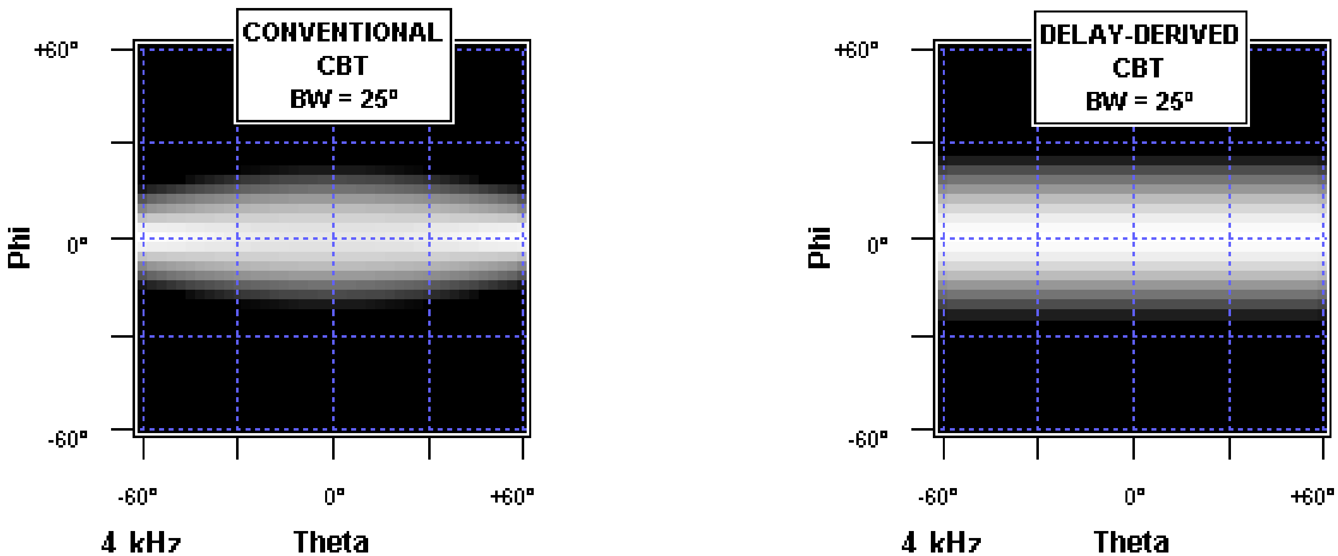
12.5° Footprint at 4 kHz



Compare Conventional vs. Delay-Derived CBT Line Arrays

Vary Vertical Coverage Angles: Data

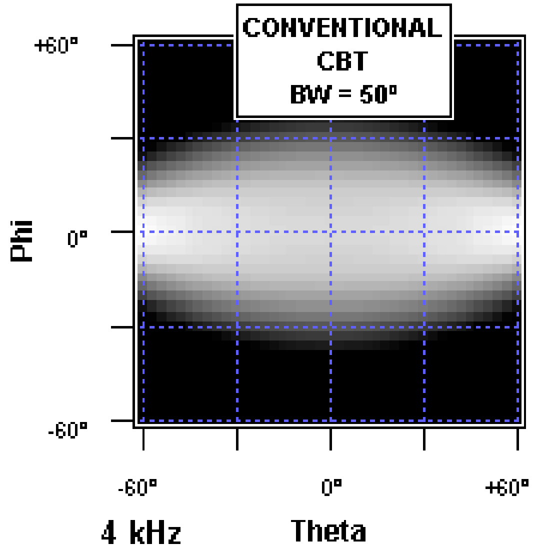
25° Footprint at 4 kHz

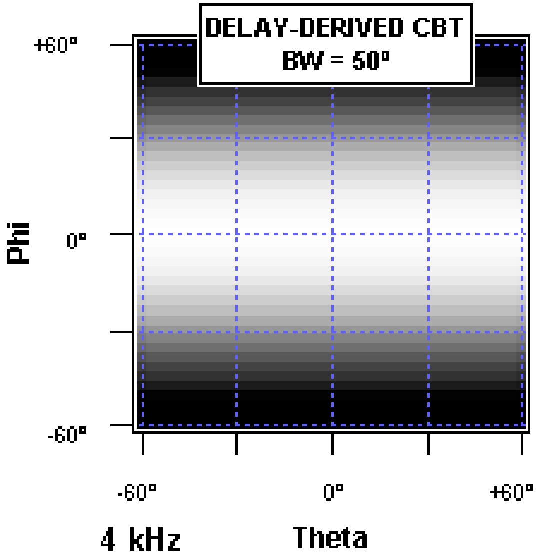


Compare Conventional vs. Delay-Derived CBT Line Arrays

Vary Vertical Coverage Angles: Data

50° Footprint at 4 kHz

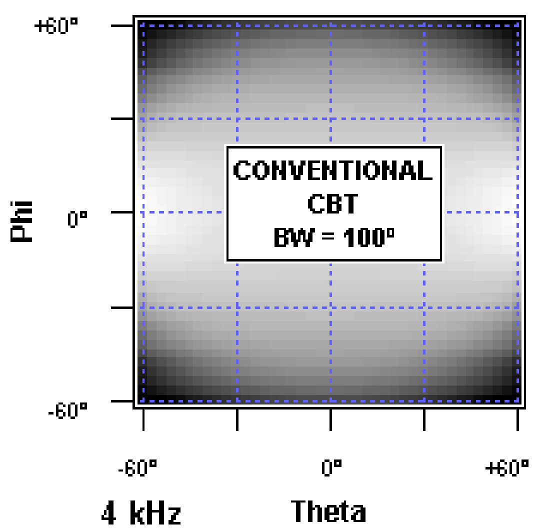


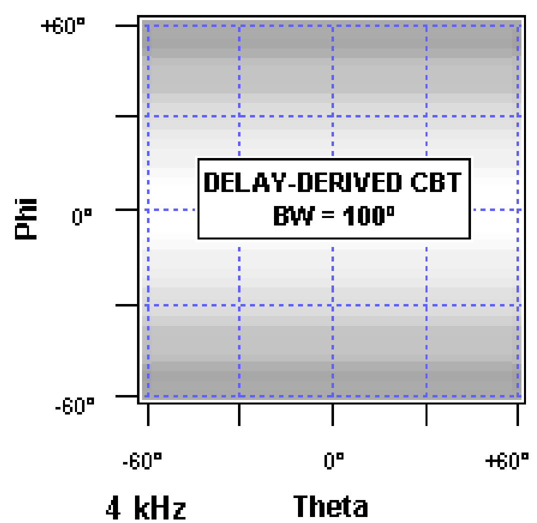


Compare Conventional vs. Delay-Derived CBT Line Arrays

Vary Vertical Coverage Angles: Data

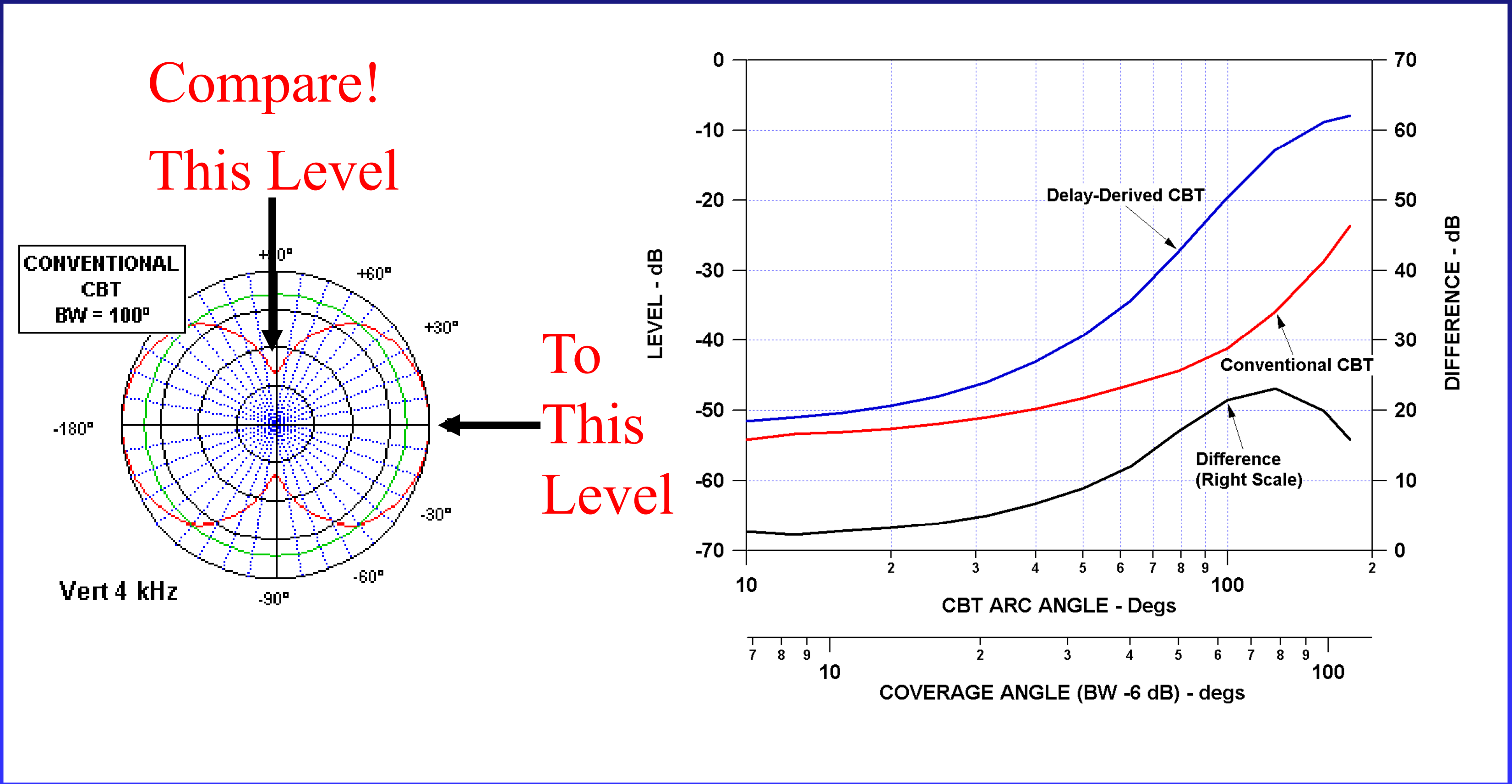
100° Footprint at 4 kHz





Compare Conventional vs. Delay-Derived CBT Line Arrays

±90° Vertical Of-Axis Rejection at 4 kHz vs. Coverage Angle



Design Delay-Derived CBT Array For Flat Off-Axis Response

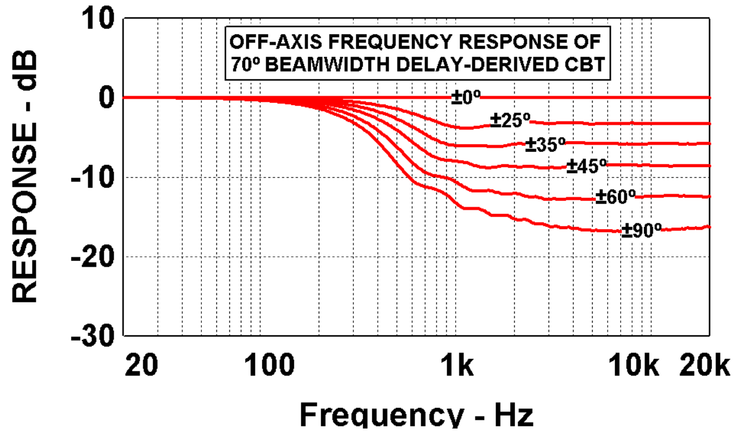
- The widening problem at extreme off-axis angles of the delay-derived CBT array can be used to advantage to flatten the off-axis response of the array for all off-axis angles.
- This essentially trades off-axis rejection for flatness of off-axis response.
- Experimentally it was determined that a 70° coverage-angle delay-derived CBT array with a 110° virtual arc provided just such a condition.

Design Delay-Derived CBT Array For Flat Off-Axis Response

- Design
  - A delay-derived CBT array was simulated with the following characteristics: 70° coverage angle, 110° arc angle, 27 inches (0.69 m) high, and 109 point sources.
  - This high number of sources provides a close source-to-source spacing of only 0.25 inches (6.35 mm) which insures clean operation to beyond 20 kHz.
  - This simulation essentially predicts the response of a continuous source up to 20 kHz.

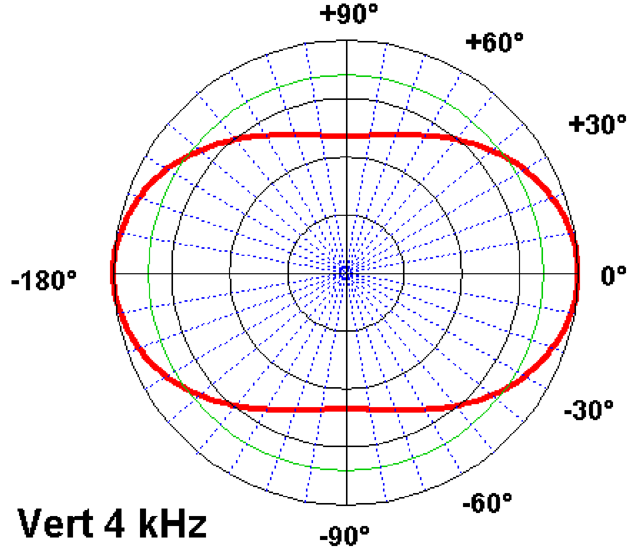
Design Delay-Derived CBT Array For Flat Off-Axis Response

Off-Axis Frequency Response



4 kHz Polar Response

(Typical of all polars above 1 kHz)

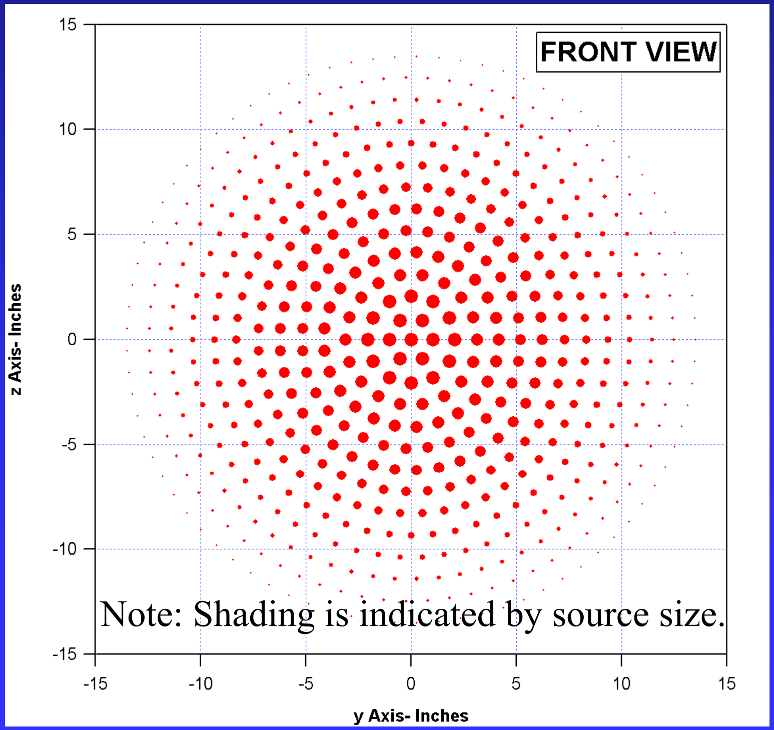


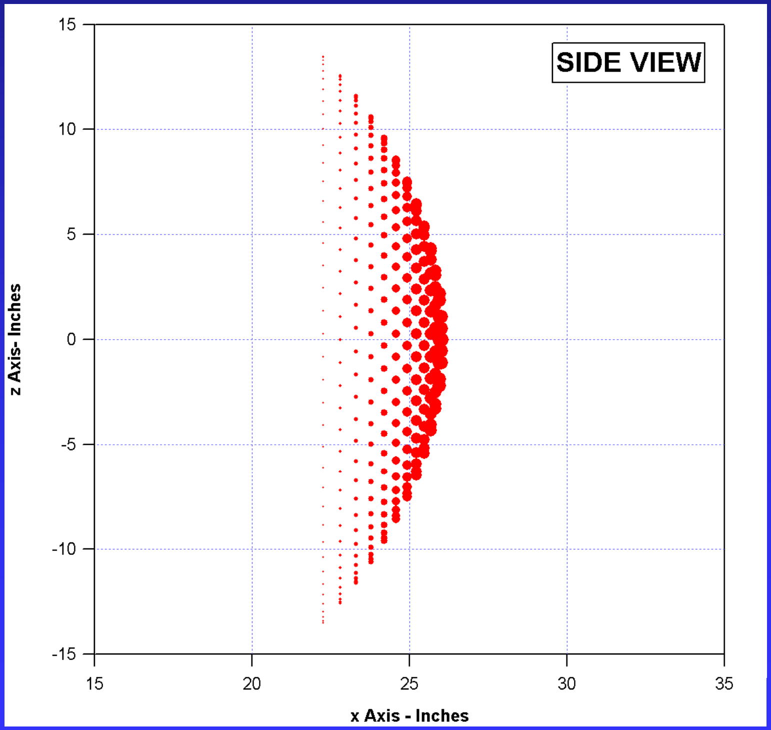
Compare Conventional vs. Delay-Derived CBT Surface Arrays

- Design two 27 inch (0.69 m) diameter CBT surface arrays providing 40° coverage with a 62.5° cap (arc) angle:
  - 1. Conventional spherical-cap curved-surface CBT array.
  - 2. Delay-derived circular flat-panel CBT array.
- Both are designed with 13 radial rings with a single center source and contain roughly 550 point sources. Source spacing is roughly 1 inch (25 mm) which provides proper operation up to 10 kHz.

Compare Conventional vs. Delay-Derived CBT Surface Arrays

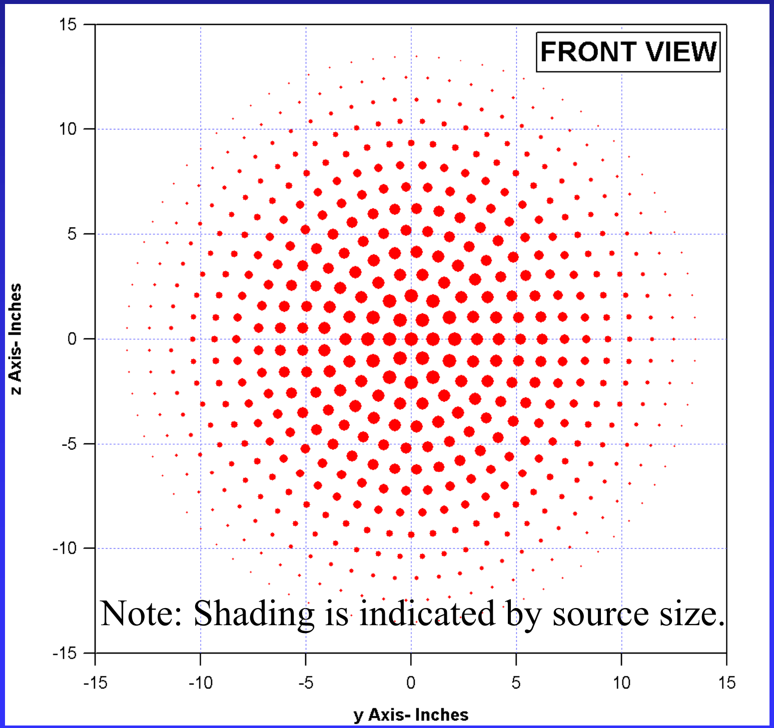
Conventional Spherical-Cap Curved-Surface CBT Array (553 sources)

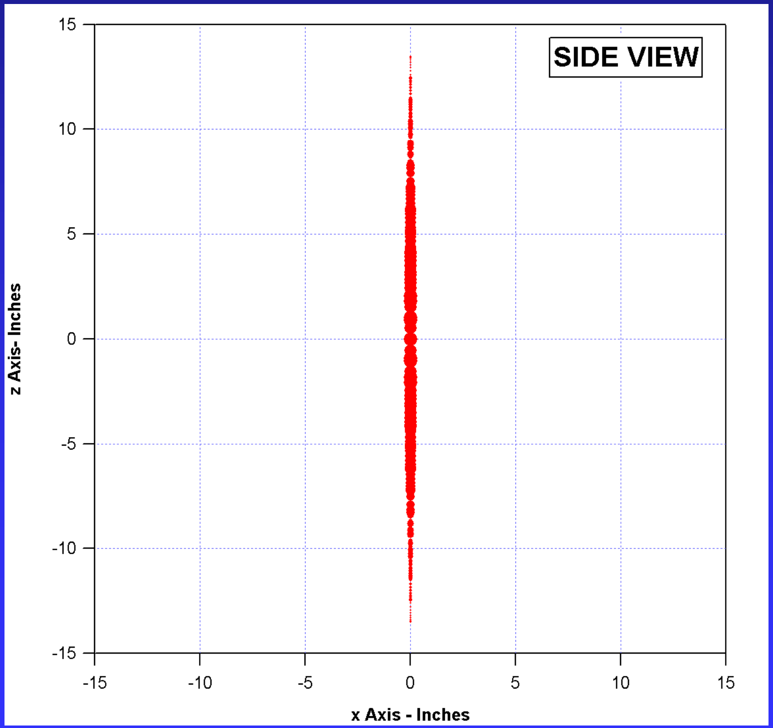




Compare Conventional vs. Delay-Derived CBT Surface Arrays

Delay-Derived Circular Flat-panel
CBT Array (556 sources)





Compare Conventional vs. Delay-Derived CBT Surface Arrays

- A complete set of simulation results for both arrays are in Appendixes 2 and 3 of my paper. (This AES presentation is already to long!!)
- Both sets of simulation data are quite similar except the delay-derived array exhibits:
  - Some widening of polar responses at extreme off axis angles beyond ±60°.
  - Somewhat more off-axis lobing.
  - One-third-octave less high-frequency extension due to grating lobes (8 kHz compared to 10 kHz).

Delay-Derived CBT Arrays: Conclusions:

- This paper has described a method of designing Constant Beamwidth Transducer (CBT) systems that are based on straight-line and flat-surface array configurations, rather than the required circular arcs and curved surfaces of conventional CBT arrays. Unfortunately, the arrays require much more complex processing than that required by the conventional CBT arrays.
- The required processing includes multiple channels of signal delays and power amplifiers. Fortunately, all processing is frequency independent and thus is much easier to implement. The signal delays are used to approximate the required curved lines and surfaces of the conventional CBT array.

Conclusions Cont.:

- Advantages
  - Uniform coverage
    - Provides extremely uniform beamwidth, directivity, and off-axis frequency response over a wide bandwidth (an advantage shared with conventional CBT arrays).
  - Simple construction
    - The array is based on straight-line and flat-panel configurations. These shapes are easier to work with and more convenient from a practical standpoint than the curved lines and surfaces of the conventional CBT array.
  - Change coverage angles easily
    - The coverage angle of the array can be changed by just simply changing delay values.
  - Simple processing
    - All processing is frequency independent (all-pass gain and delay only).

Conclusions Cont.:

- Advantages Cont.
  - Easily steered
    - The array can be steered by simply changing delay values. The delay changes effectively tilt the array in the desired direction.
  - No horizontal polar bulge
    - Does not exhibit the ±90° right-left horizontal polar bulge or pressure build up exhibited by the conventional CBT array.
  - Vertical axis symmetry
    - The polar pattern is symmetrical around the vertical axis of the array.
  - Moderate power rolloff
    - Power rolloff through the operational pass-band is only 3 dB/octave for the straight-line array and 6-dB/octave for the flat-panel array (an advantage in common with conventional CBT arrays).
    - *Note! Traditional variable aperture constant-coverage arrays rolloff respectively at 6 and 12 dB/octave.*

Conclusions Cont.:

- Disadvantages
  - Complex processing
    - Is relatively complex because it requires separate channels of delays and power amplifiers.
  - Polar widening
    - Exhibits widening of polar response at extreme off axis angles as compared to the conventional CBT array. This can be used to advantage in some situations.
  - Requires lots of small wide-band drivers!
    - Requires the use of a large number of small identical wide-band transducers (a disadvantage in common with conventional CBT arrays). Well behaved operation to 10 kHz requires a source spacing of no more that 1 in (25 mm) which implies transducers no larger than about 0.95 in (24mm). This could be a potential advantage when manufacturing economies of scale are considered due to the large number of transducers required.

Thanks for listening!