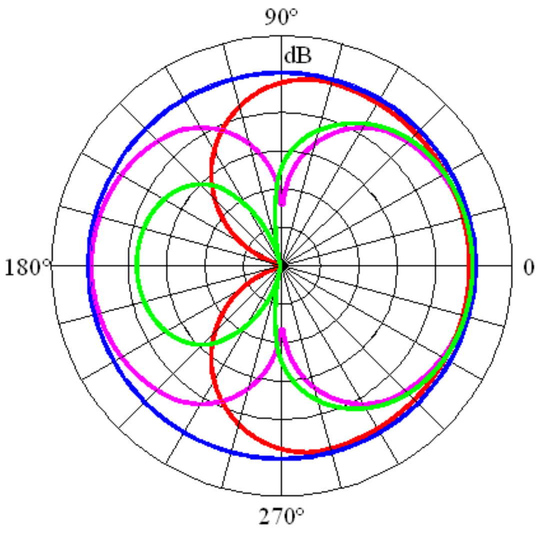

Directivity Control Part 1: A Survey of Loudspeaker Systems

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If the sound radiated from the loudspeaker is primarily directed at the listener(s) with a reasonably constant beam width pattern (unidirectional), then the room related reflection colorations will be minimized and spatial distortion will be low. Sound exists in space and has 3-dimensional properties. For a loudspeaker to have both flat on-axis magnitude response and flat power response, then the directivity must be constant with respect to variation of frequency within the audio band. There really are no loudspeakers that realize both; however, some systems do a much better job than others and a few systems come close. While many manufacturers and hobbyists alike don't seem to care.

A loudspeaker with the unidirectional characteristics stated above will be relatively placement friendly with regards to the listening room. Then such a loudspeaker could be considered a candidate for a high performance monitor of audio program material.

I. TERMINOLOGY & METHODOLOGY

Figure 1 below contains polar plots of various generalized radiation patterns. These plots establish terminology for classes of loudspeaker radiation. Independently measured and manufacturer provided loudspeaker polar and directivity contour plots will be presented later on that contain similar radiation patterns and perturbations of the same.

FIGURE 1. GENERALIZED POLAR PLOTS OF SEVERAL RADIATION PATTERNS WITH THE RESPECTIVE DIRECTIVITY INDEX

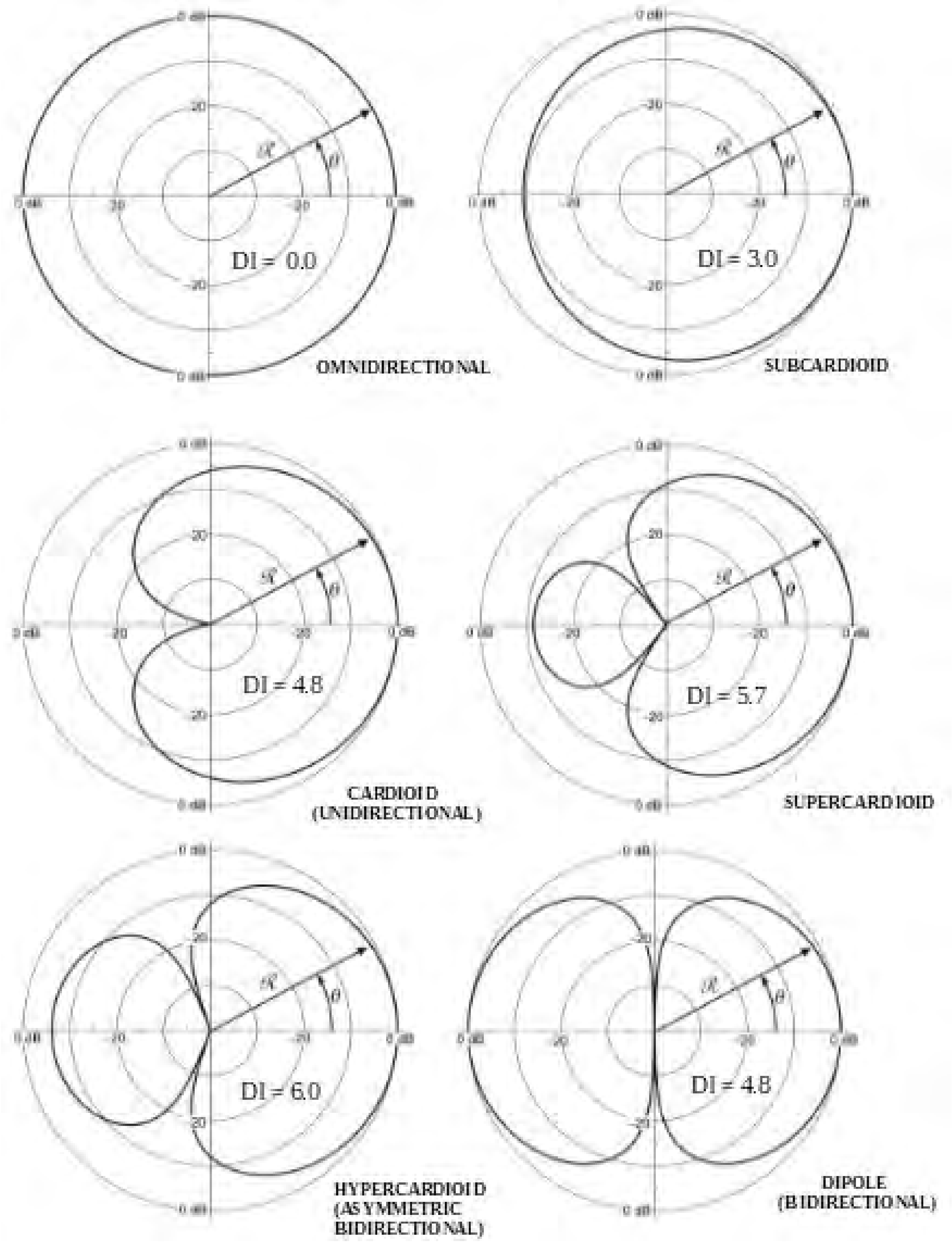
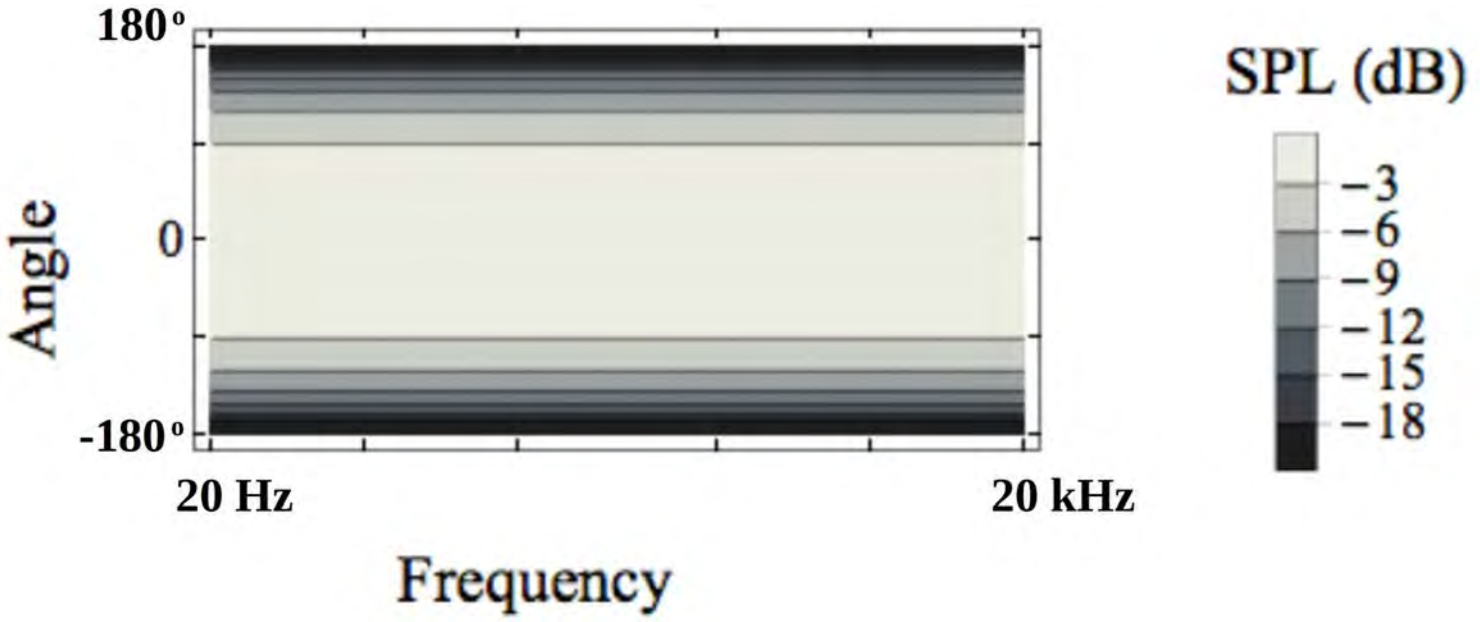


Figure 1 above shows the classes of radiation with the respective directivity index, DI. Note that Cardioid and Dipole have the same DI and Super and Hypercardiod have the highest DI.

Terms such as "controlled directivity", "constant directivity" and "point source" are misleading. There are no loudspeakers with constant directivity. There are loudspeakers that maintain reasonably consistent directivity over a limited band. This is sometimes called controlled directivity and is best illustrated by polar or directivity contour plots. **Here's a link to a technical discussion of the metrics for constant directivity from Princeton University researchers.**

Figure 2 below shows a theoretical ideal constant directivity plot taken from the Princeton Study, which is unidirectional regardless of frequency. Whereas, ideal constant directivity expressed in a polar plot would map into Cardioid radiation.

FIGURE 2. A THEORETICAL IDEAL CONSTANT DIRECTIVITY PLOT



A brief summary of typical loudspeaker direcivity control methodology is contained below.

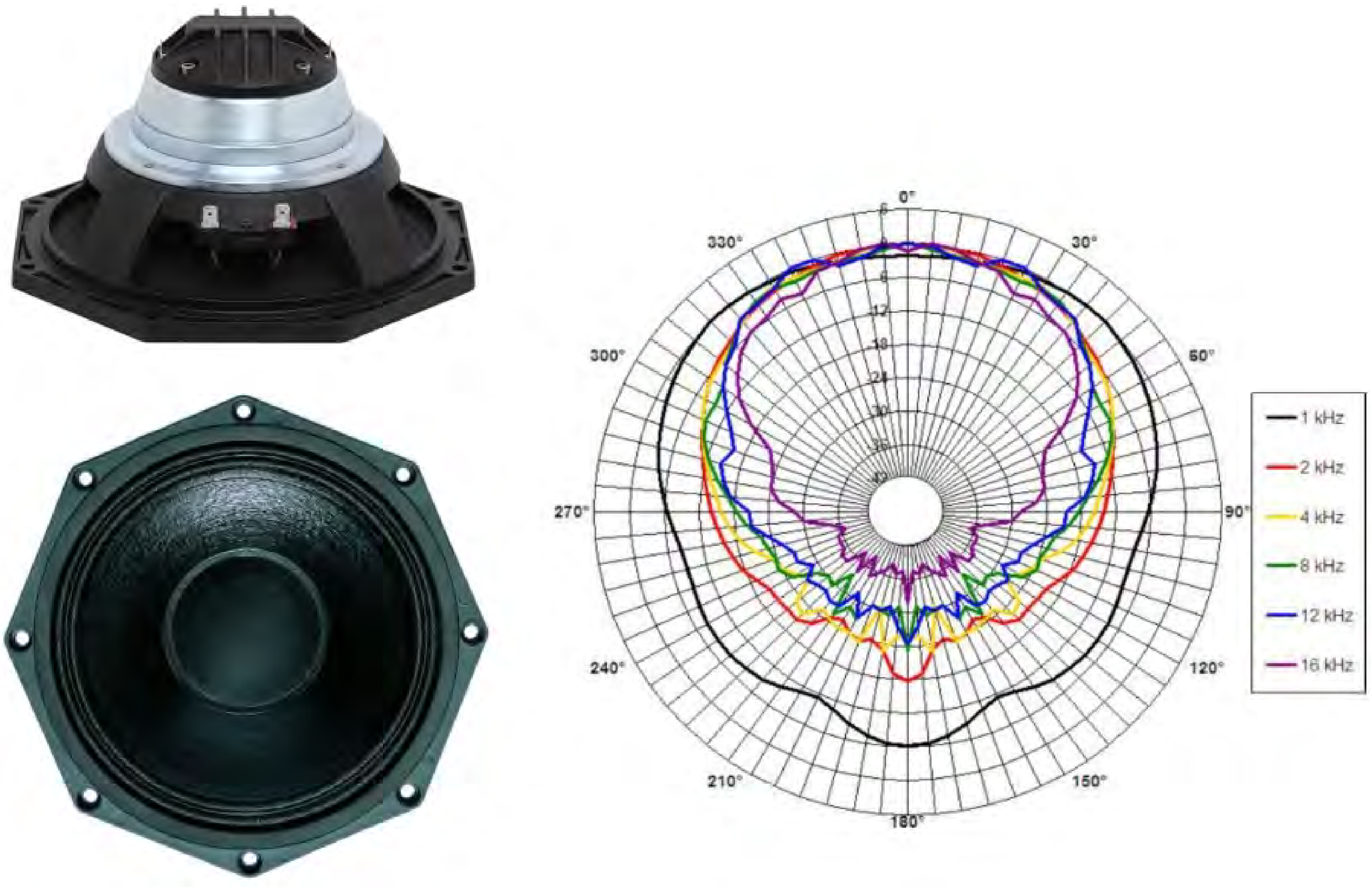
A. WAVEGUIDES

Waveguides are an effective method of controlling directivity above their cutoff. **Early waveguide work was was performed by Paul W. Klipsch in the forties.** Subsequently, **Don Keele introduced the first "Constant**

Directivity Waveguide" while working at EV in the seventies. However, in practice a waveguide's bandwidth is limited by practical size constraints. The larger the waveguide the lower in frequency the directivity control extends.

Coaxial 2-way transducer arrays are a special case where the low frequency transducer diaphragm also functions as a waveguide for the high frequency transducer. Figure 3 contains pictures of a B&C 8CXN51 coaxial driver along with the manufacturer's polar plot. It can be observed that the radiation pattern tends to unidirectional and reasonably constant above 1.5 kHz without beaming and/or side lobes. Later on, measured 360 degree polar plots of loudspeakers that contain waveguides and/or mid/tweeter coaxial transducer array examples will be presented.

FIGURE 3. B&C 8CXN51 COAXIAL 2-WAY TRANSDUCER WITH MANUFACTURER'S POLAR PLOT



B. TRANSDUCER ARRAYS

Transducer arrays including but not limited to level shaded CBT's and the classic MTM'scan control directivity over a band as a result of the effective source size and effective source geometry. Don Keele's Constant Beamwidth Transducer R&D is summarized in two (2) US Patents, US 7826622 and US 7684574 that are assigned to Harman. The CBT's and the Linkwitz Lab LX521 have interesting radiation characteristics but are both bidirectional loudspeakers.

Figure 4 below contains a picture of a prototype of the BeoLab 90 mid and high frequency array topology. Then with DSP implemented delays, quasi-spherical cap (unidirectional) sources can be approximated. Each BeoLab 90 has seven (7) tweeters and seven (7) mids in its top array module.

FIGURE 4. BEOLAB 90 MID AND HIGH FREQUENCY TRANSDUCER ARRAY MODULE PROTOTYPE

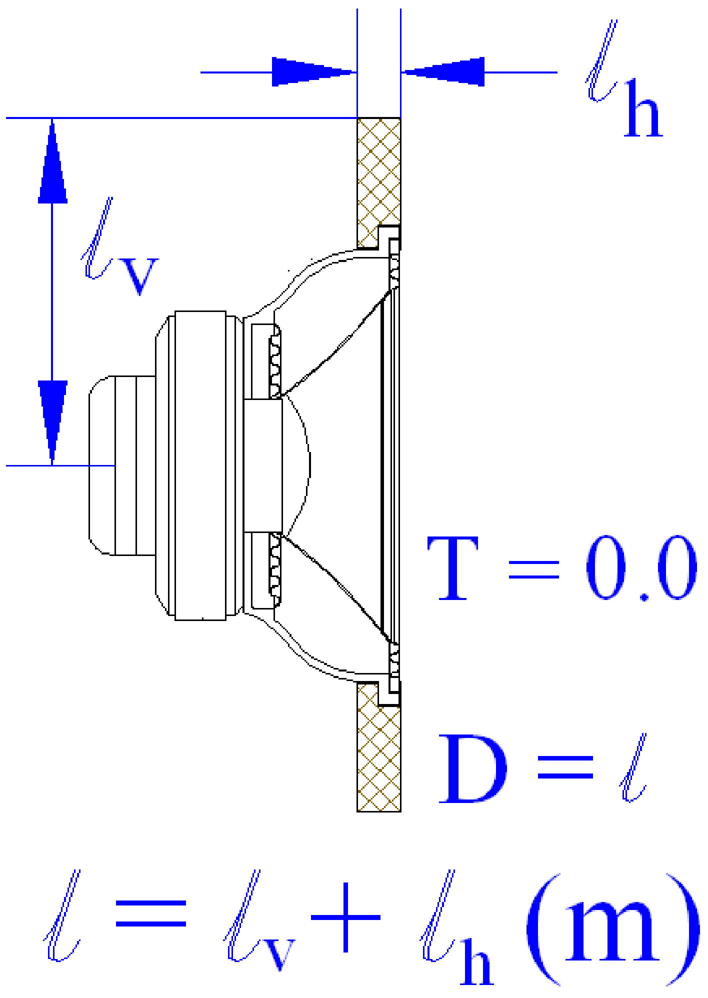
Bang & Olufsen was granted US9942659B2 *Loudspeaker transducer arrangement for directivity control*, filed February 6, 2014.

A question arises in that the entire BeoLab 90 array can be replaced by a simple midbass/tweeter coaxial array with an inherent similar coincident radiation pattern; however, the radiation from the coaxial array will be fixed. An active array allows the user to vary the radiation pattern.

C. GRADIENT SOURCES

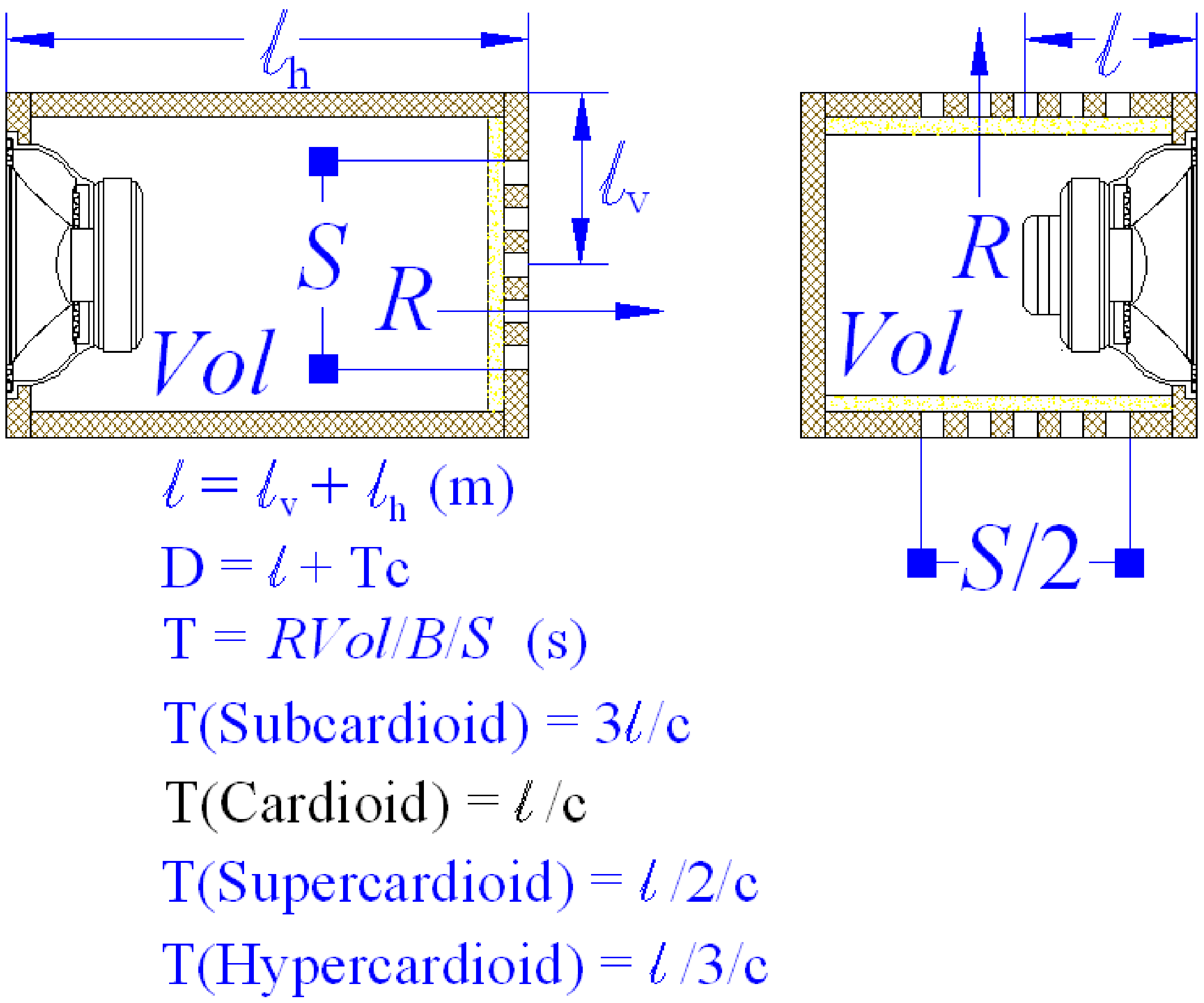
Gradient sources implement directivity buy reducing the acoustic power output of loudspeaker as a result of pressure wave cancellations. **Open baffle** or **dipole baffle** exhibits bidirectional radiation with typically two nulls are formed at the sides of the loudspeaker baffle from front to back cancellation. The baffle width plays an important role in the frequency related radiation patterns. It seems reasonable that dipole is considered the 'fastest' of the radiator types, where less is more. Figure 5 below contains a generalized illustration of an open baffle implementation where ℓ is the minimum front to back path length (m) and D is the effective difference in source positions including physical distance and time delay (m). Notice that the delay, T, is zero and $D = \ell$.

FIGURE 5. GENERALIZED OPEN BAFFLE EXAMPLE ILLUSTRATION



Acoustic resistance enclosure or sometimes referred to as a leaky sealed box, can be an alternative to open baffle. The acoustic resistance enclosure can be implemented with filter like material that is porous with air flow resistance. Then the ratio of acoustic resistance of the vents, R (Ns/m^3) relative to the acoustic stiffness of the box, K (N/m^3) will add delay, T, where $T = R/K$ (s). So in theory, the out of phase acoustic AC pressure from the back of the transducer diaphragm is delayed and leaked from the enclosure such that the rear directed sound pressure is cancelled. This sometimes referred to as passive noise control. Figure 6 below contains generalized illustrations of rear and side vented acoustic resistance enclosure examples. Where ***R*** is the acoustic resistance (Ns/m^3 or MKS rayl); ***ℓ*** is the minimum front to back or back to front path length (m); ***S*** is the total exit area of the vents (m^2); ***Vol*** is the internal volume of the enclosure (m^3); and ***B*** is the adiabatic bulk modulus of air, **142,000** (N/m^2 or Pa), then ***K*** = ***BS/Vol*** (N/m^3). Energy is dissipated in the vents et al.; thus the leaked radiation is attenuated and damping is increased.

FIGURE 6. GENERALIZED ACOUSTIC RESISTANCE ENCLOSURES WITH REAR AND SIDE VENT IMPLEMENTATION EXAMPLES



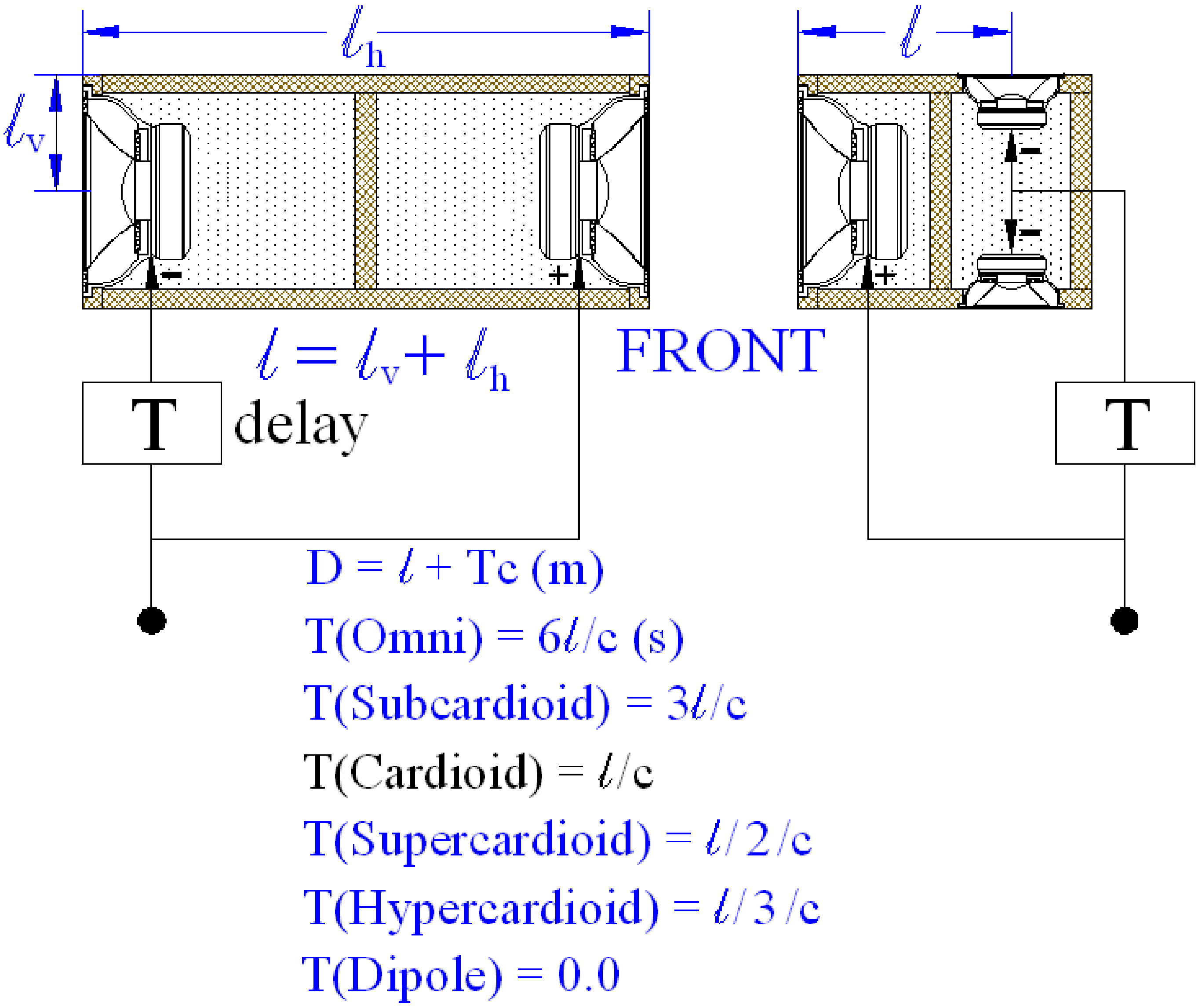
There are a few US Patents relating to the acoustic resistance enclosure. How many times can one claim an invention for the same idea? The answer appears to be at least four (4) times to date in this case.

1. **US 3,722,616, *DIRECTIONAL LOUDSPEAKER SYSTEM,* filed Dec. 14, 1970 by LTW Altec**
2. **US 3,739,096, *LOUDSPEAKER SYSTEM HAVING A CARDIOID DIRECTIONAL RESPONSE PATTERN,* filed Jan. 12, 1971 by US Philips Corp.**
3. **US 6,665,412, *SPEAKER DEVICE,* filed Jan. 10, 1997 by SONY Corp.**
4. **US 10,123,111 *PASSIVE CARDIOID SPEAKER,* filed Jun. 3, 2016 by Fulcrum Acoustic**

Here are some **DIY loudspeaker examples** with acoustic resistance enclosures for both mid and low frequency applications.

Active noise control (**ANC**), also known as **active noise reduction** (**ANR**), is a method for reducing unwanted sound by the addition of a second sound source specifically designed to cancel the first. The typical loudspeaker implementation requires an active system with signal processing. The resultant radiation pattern can be **cardioid (unidirectional) under certain conditions.** There are only a handful of loudspeaker manufacturers that utilize active noise control to control directivity. The fact is that more of the active directivity controlled loudspeaker designs are a result of DIY projects. Figure 7 below illustrates examples of ANC applied to loudspeakers.

FIGURE 7. GENERALIZED ACTIVE NOISE CONTROL IMPLEMENTATION EXAMPLES

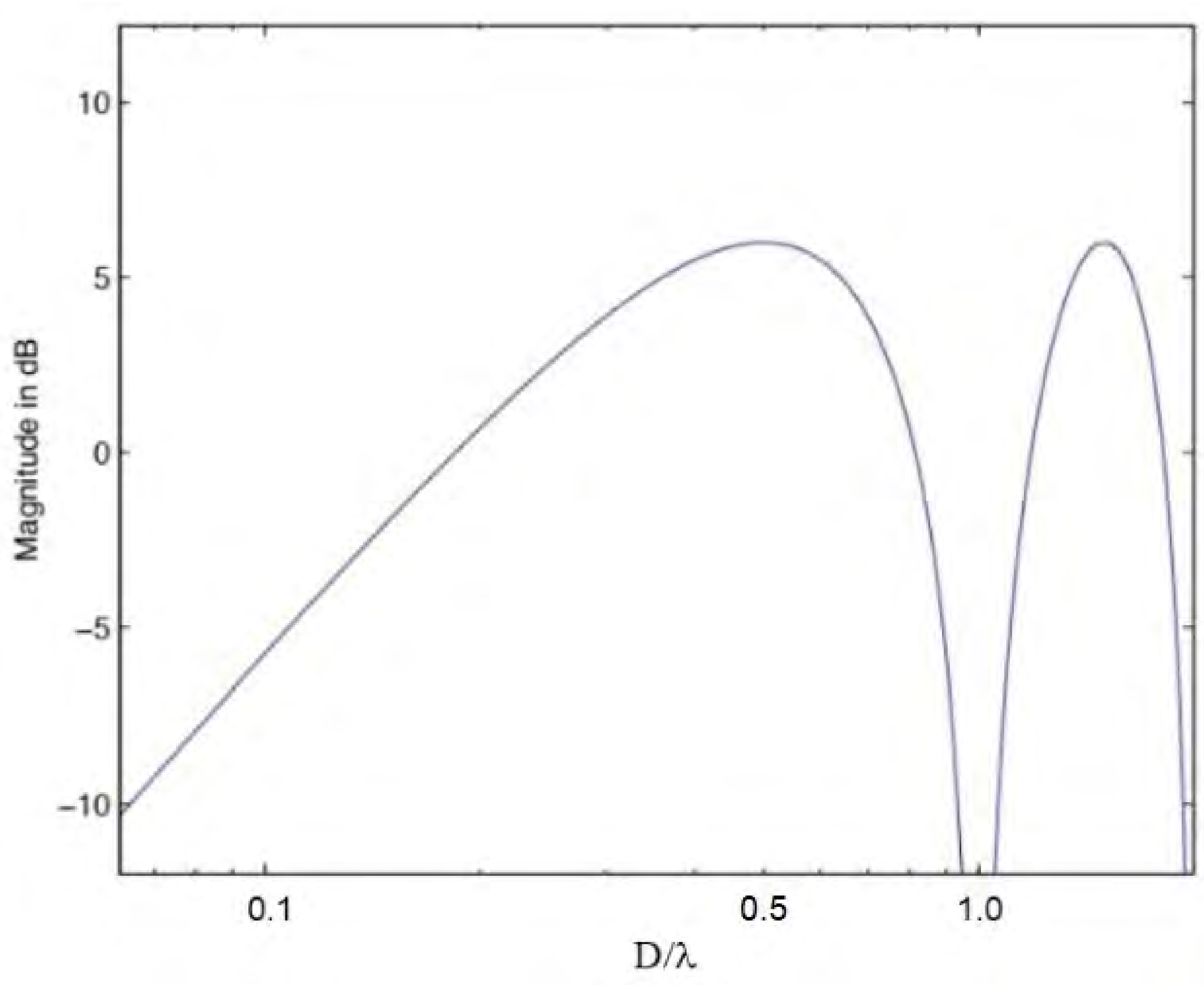


Note that for cardioid condition, when T is decreased, D is decreased, such that D = ℓ + Tc. Likewise, as T is increased, D is increased. With active directivity control, the delays and gains can be selected with the computer mouse within the DSP software GUI. The downsides are the increased system complexity, cost, and package size. Anti-transducers require equivalent sized enclosures to primary transducers.

Here's a link to a technical paper that contains simulations of gradient sources. LE BOT'S GRADIENT SOURCE

The first order bidirectional and unidirectional gradient sources presented achieve their radiation patterns with cancellation of AC acoustic pressure in space. This results in a first order high pass characteristic of on-axis magnitude response below $D/\lambda = 0.5$, with the high - 3 dB cutoff at $D/\lambda = \sim 0.71$ and where $\lambda = c/f$ (m). Figure 8 contains a magnitude plot that was also presented by Olson in 1972 in his AES paper *Gradient Loudspeakers*.

FIGURE 8. GENERALIZED ON-AXIS MAGNITUDE PLOT FOR UNIDIRECTIONAL (D = 2ℓ, T = ℓ/c) OR BIDIRECTIONAL (D = ℓ, T = 0) FIRST ORDER GRADIENT SOURCES



Olson observed that cardioid and dipole sources share the same on-axis first order high pass like characteristic. This is the price for directivity. Although, first order gradient sources both dipole and cardioid have the same on-axis magnitude response, the radiation patterns are quite different. Thus they tend to sound different in the listening room. In practice, first order gradient sources must be equalized to correct the 6 dB / octave high-pass characteristic. The correction requires power and volume displacement. This is the same issue faced by the Linkwitz Lab LX521 dipole loudspeaker et al.

The following two (2) discussion sections present information related to ten (10) loudspeakers that have interesting directivity, beginning with an example of full bandwidth active directivity control and ending with an acoustic dipole.

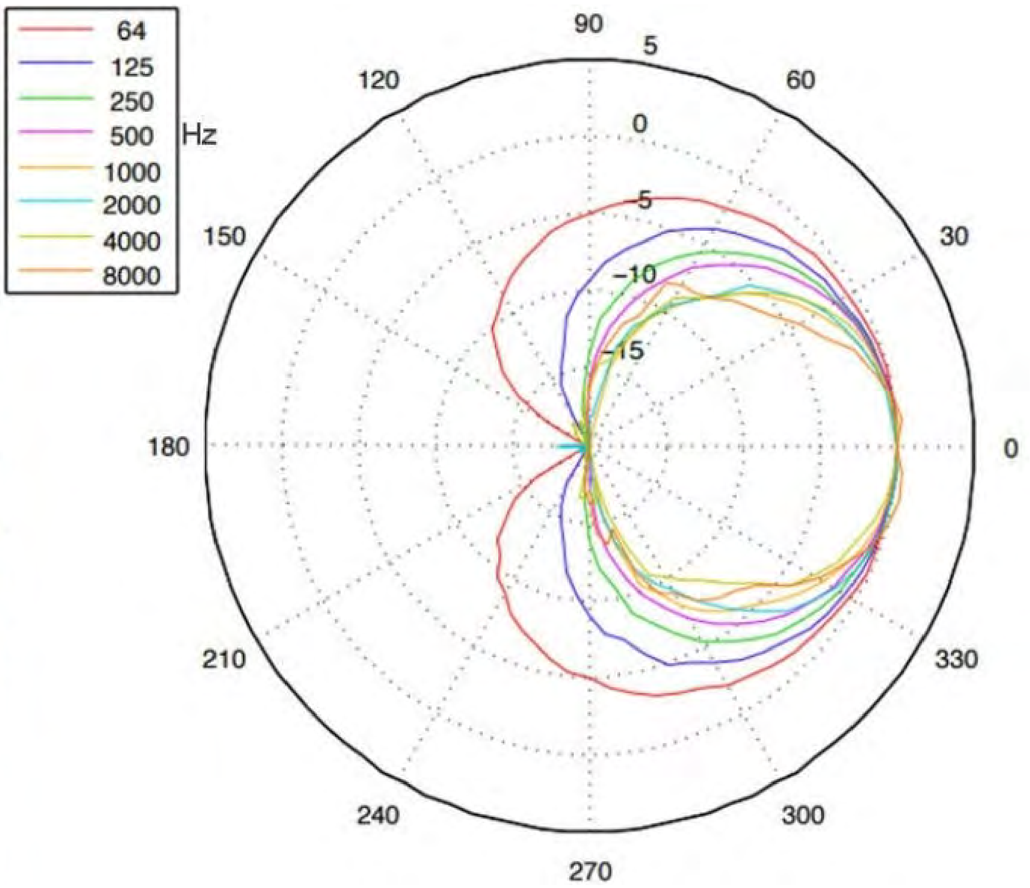
II. MANUFACTURER SUPPLIED PLOT REVIEWS

1. B&O

The **Beolab 90** at ~US$85,000 / pair allows directivity to be varied by the user with a standard size remote control. See figure 9 below.

FIGURE 9. BANG & OLUFSEN BEOLAB 90 PICTURE AND MANUFACTURER'S HORIZONTAL POLAR PLOTS

WITH NARROW AND WIDE BEAM SETTINGS RESPECTIVELY



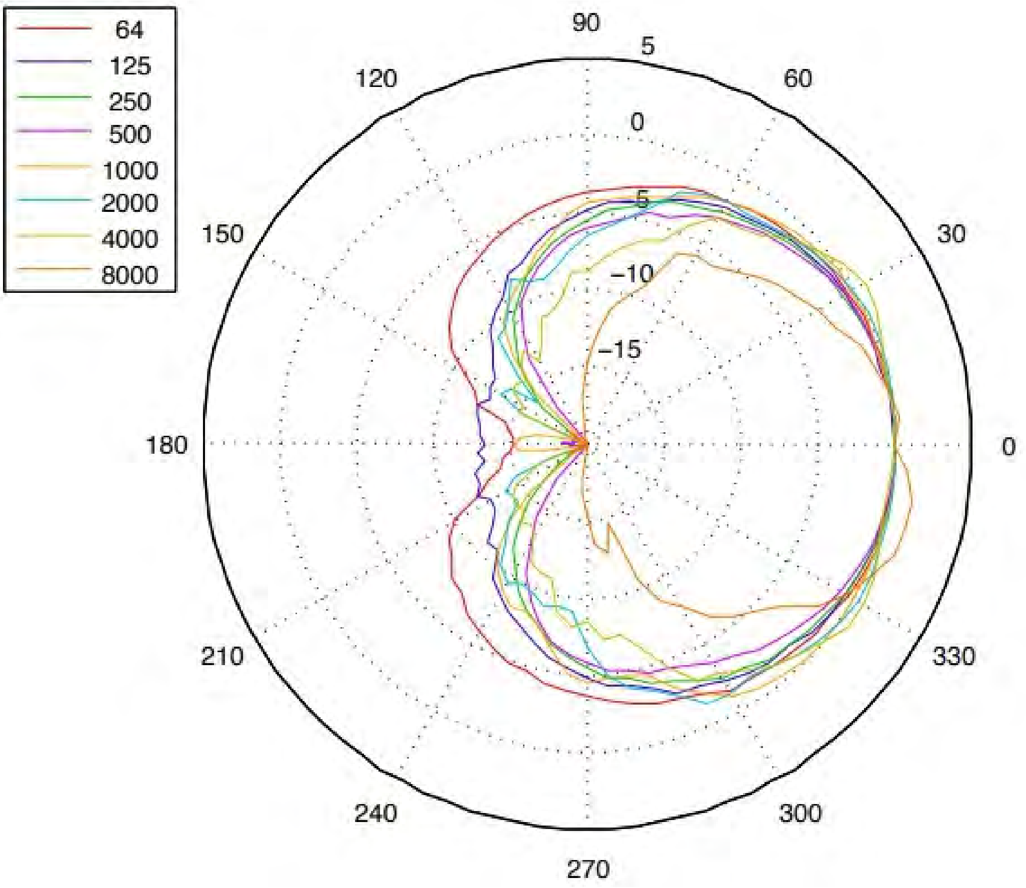
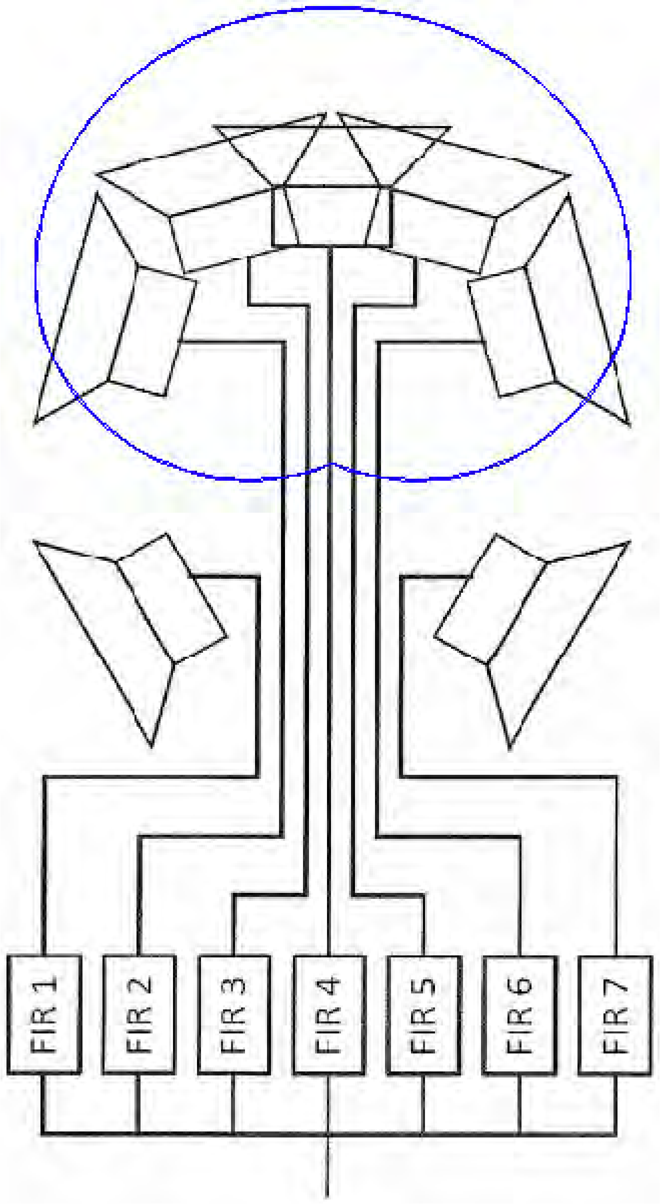


FIGURE 10. ILLUSTRATION OF THE MID ARRAY

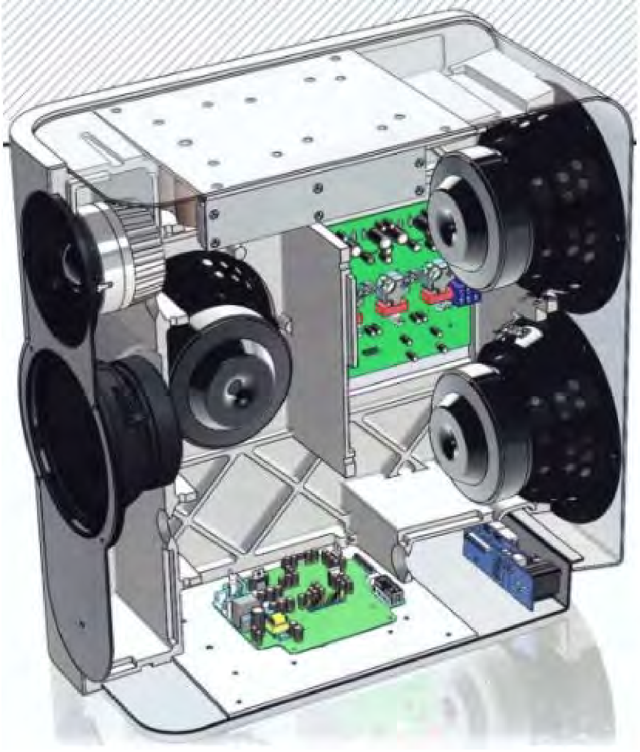
The **Beolab 90** is a complex loudspeaker implementation. 'Arrays of transducer arrays' are utilized. Active directivity control is utilized for low, mid, and high frequencies using FIR digital filters. Figure 10 contains the midrange system block diagram. The radiation is true full band cardioid and directed at the listener(s). The **BeoLab 90** sets the standard for loudspeaker directivity control but some folks find them a bit ugly! There is the question of the audibility of all that signal processing.

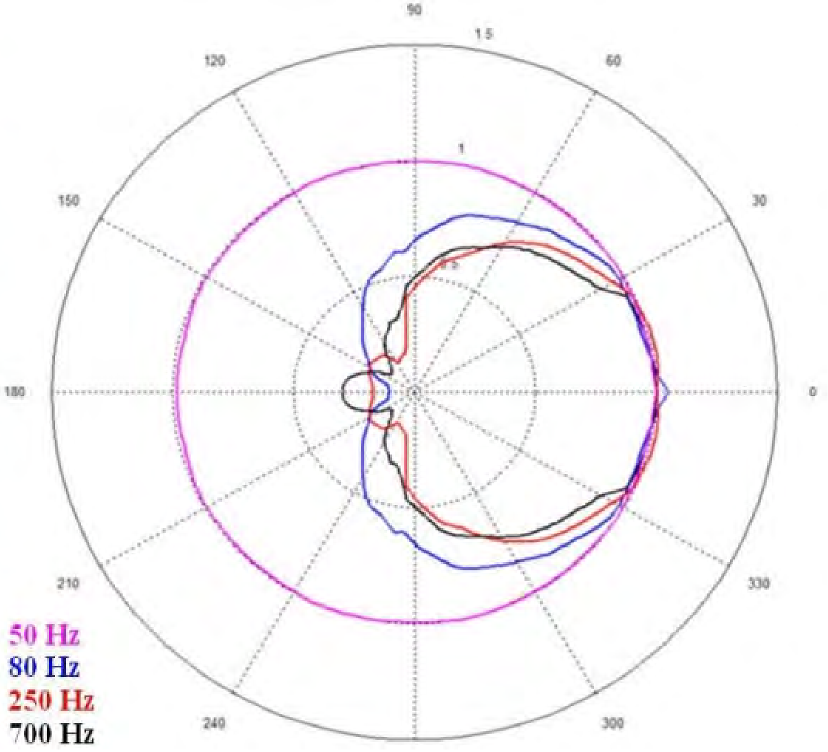


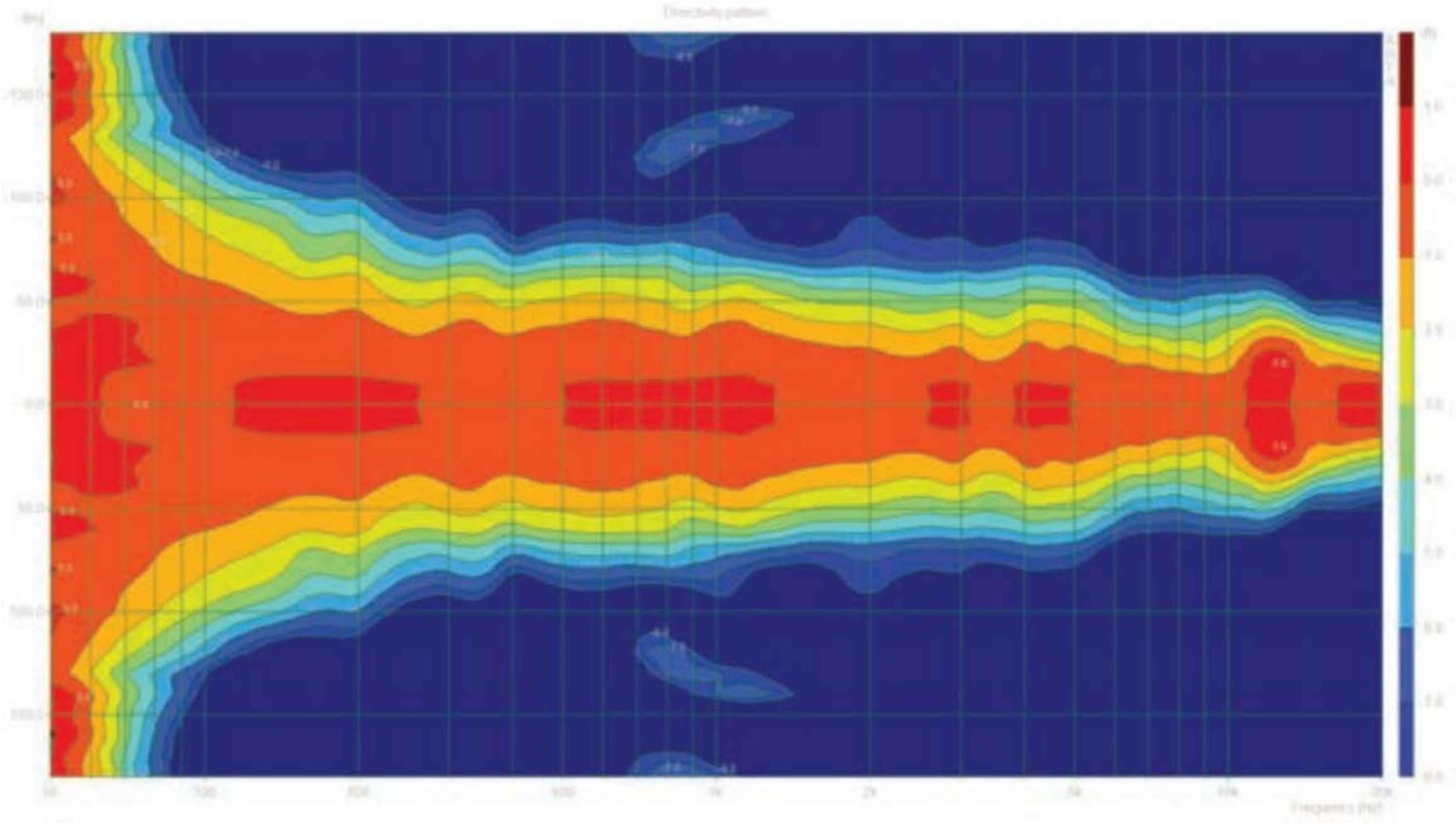
2. Kii

A simplified active directivity control loudspeaker implementation is the **Kii Audio Three**. The high frequency directivity control is passive. The popular **SEAS tweeter with DXT waveguide** is utilized. The mid and low frequency directivity is controlled actively. The polar plot illustrates the active directivity control at 250 and 700 Hz. The retail for the **Kii Three** is ~US$15,000 / pair. See figure 11 below.

FIGURE 11. Kii THREE ACTIVE LOUDSPEAKER ILLUSTRATION WITH MANUFACTURER'S PLOTS

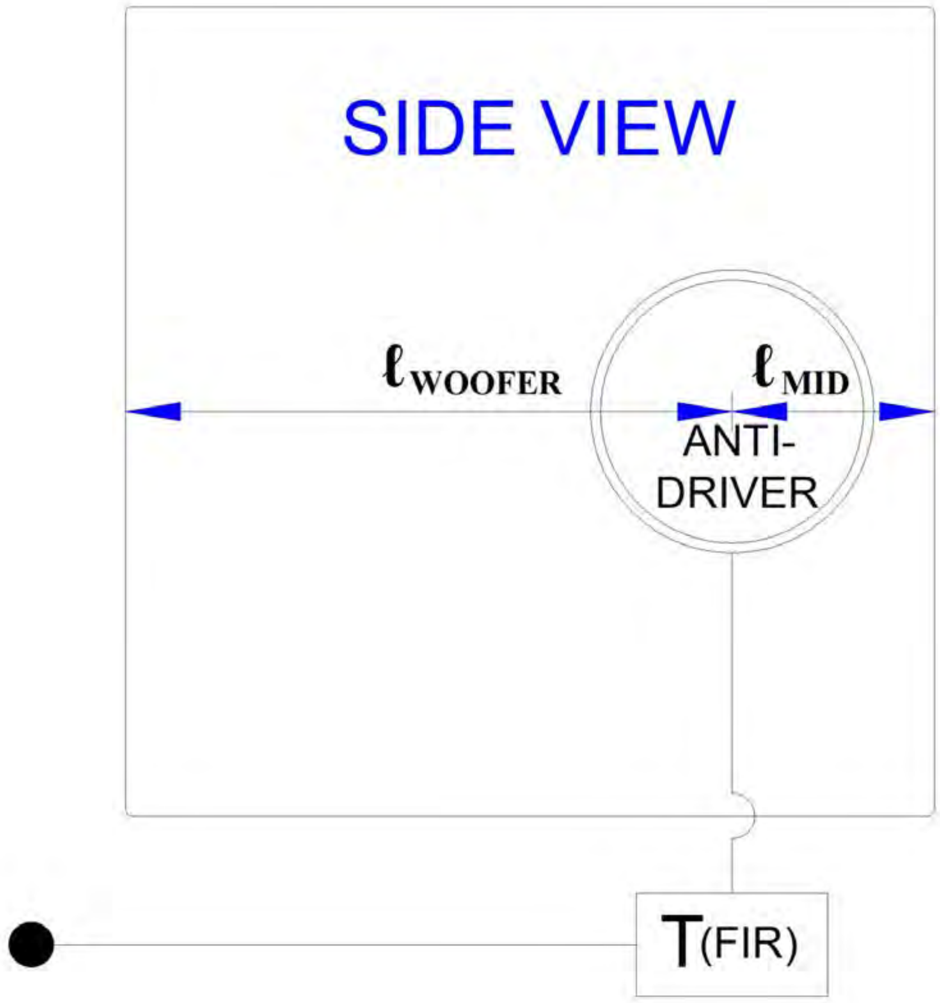






The guess as to the active directivity control function based on transducer positioning is that the side mounted anti-transducers actively controls the directivity of the front midrange below about 1.7 kHz and the woofers below 220 Hz. In this way there is a mid ι and a woofer ι along with an FIR filter that increase the anti-transducer delay, τ, with decreasing frequency. This topology is illustrated in figure 12 below. Highly innovative implementation, yet there seems to be no Patent Application. **Crossover frequencies are believed to be 220 Hz and 2.5 kHz.**

FIGURE 12. Kii THREE ACTIVE NOISE CONTROL TOPOLOGY



Here's a link to a detailed review of the Kii Three system.

There is a concern regarding the woofers' reverse roll surrounds. The narrow reverse roll surround has a potential for manufacturing QC issues and typically mechanically constrains linear displacement; however, they look good! In figure 14, the transducer baskets appear to be stamped steel and the magnets are ferrite. The poly/metal enclosure looks great but this is what **John Atkinson** had to say in Stereophile, "... listening to the panels with a stethoscope as I swept a sinewave up and down in frequency revealed very strong resonant modes at 150 and 225 Hz on all surfaces, and that the enclosure was generally lively between 280 and 400 Hz. The metal panel that surrounds the two woofers on the speaker's rear also vibrated very strongly." However, it looks good!

The retail price of the **Kii Three** is about $15,000 per pair.

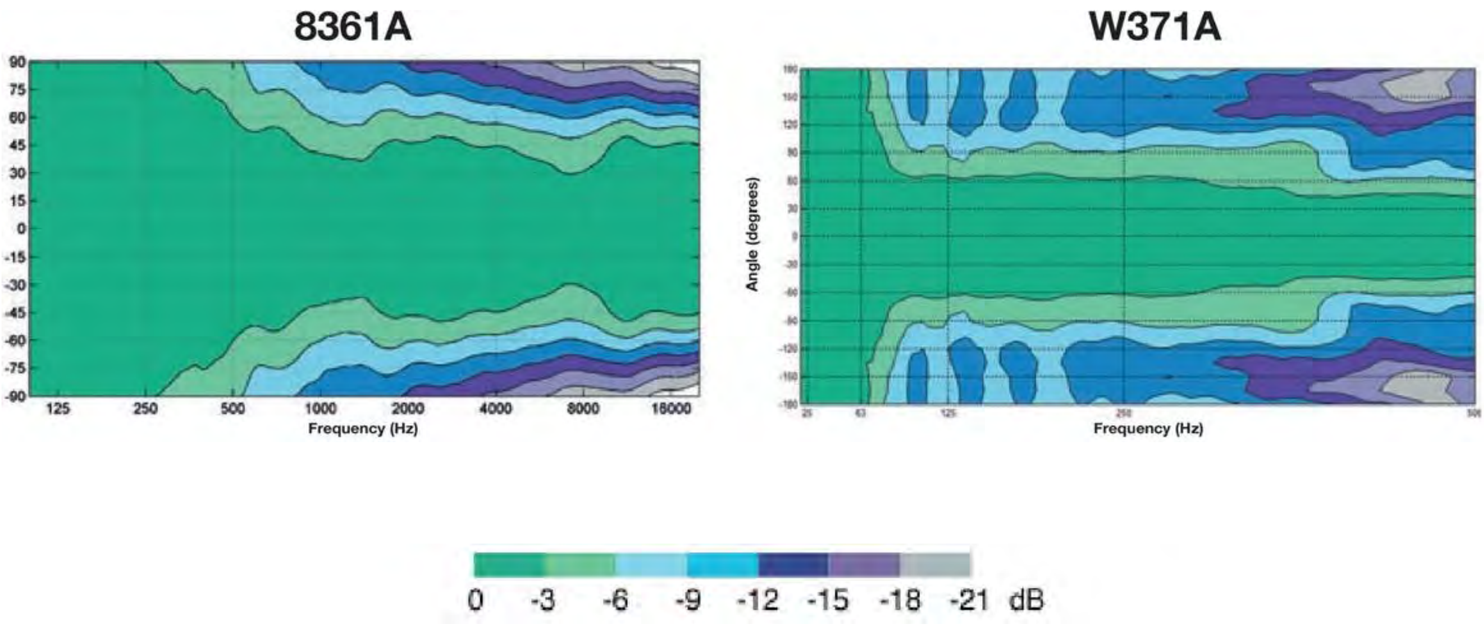
3. GENELEC OY

The **8361A** is GENELEC's flagship of the ONES series of active monitor loudspeakers. The front baffle is integrated into a "**Directivity Control Waveguide**" for a proprietary **5 in. / 1 in. coaxial transducer array**. **The enclosure is a robust die cast Industrial Engineered implementation**. While the **W371A** is a active noise control woofer implementation. Figure 13 below contains a picture of the **GENELEC 8361A** and the **W371A**.

FIGURE 13. PICTURE OF THE GENELEC 8361A AND W371A LOUDSPEAKERS

Figure 14 below contains the manufacture's horizontal directivity contours of the 8361A and W371A respectively.

FIGURE 14. DIRECTIVITY CONTOUR PLOTS OF THE GENELEC 8361A AND W371A RESPECTIVELY



Now the **W371A** is not a subwoofer for the **8361A**. Rather the **W371A** replaces the hidden racetrack woofers within the **8361A**. The **8361A**'s woofers tend to omnidirectional below 500 Hz, while the **W371A** is a unidirectional source from 500 Hz to below 100 Hz. A smaller version of the **8361A** is the **8351A** with a reduced size waveguide. Polar plots from the Princeton Study are shown later on in figure 19.

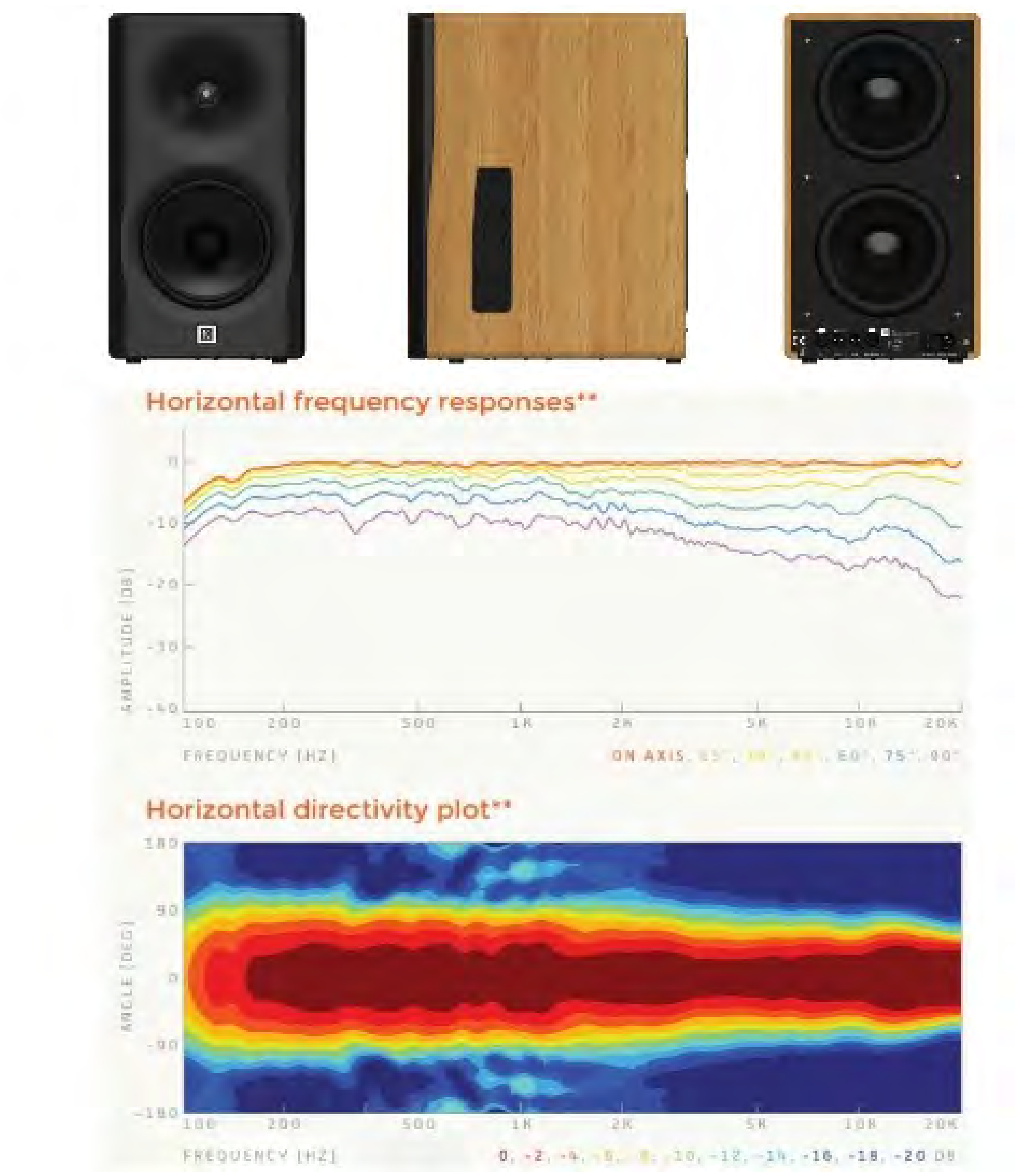
The retail price for one pair of **8361A** and one pair of **W371A** is about $28,000.

4. DUTCH & DUTCH

Figure 15 below contains pictures and manufacturer's plots of a **Dutch & Dutch 8c** active loudspeaker with DSP. It seems that the **8c** has its roots in a **DIY Project** and evolved from open baffle experiments. The **8c** uses only passive directivity control, just a waveguide and an acoustic resistance enclosure. Crossovers are 4th order L/R at 100 Hz and 1.25 kHz. There is a 1.0 in. dome tweeter with an integral baffle/waveguide along with an 8 in. midbass on the front baffle. There are also two 8 in. subwoofers on the rear baffle. All diaphragms are light alloy metal foil. Dutch & Dutch is located in the Netherlands. The design scheme seems to use a waveguide to control directivity from 1.25 kHz - up, with a well designed acoustic resistance midbass from 100 Hz to 1.25 kHz. Below 100

Hz the radiation is from the 2 x 8 in. woofers in an equalized sealed box and becomes omnidirectional. Notice the large surround roll on the rear woofers.

FIGURE 15. DUTCH & DUTCH 8c



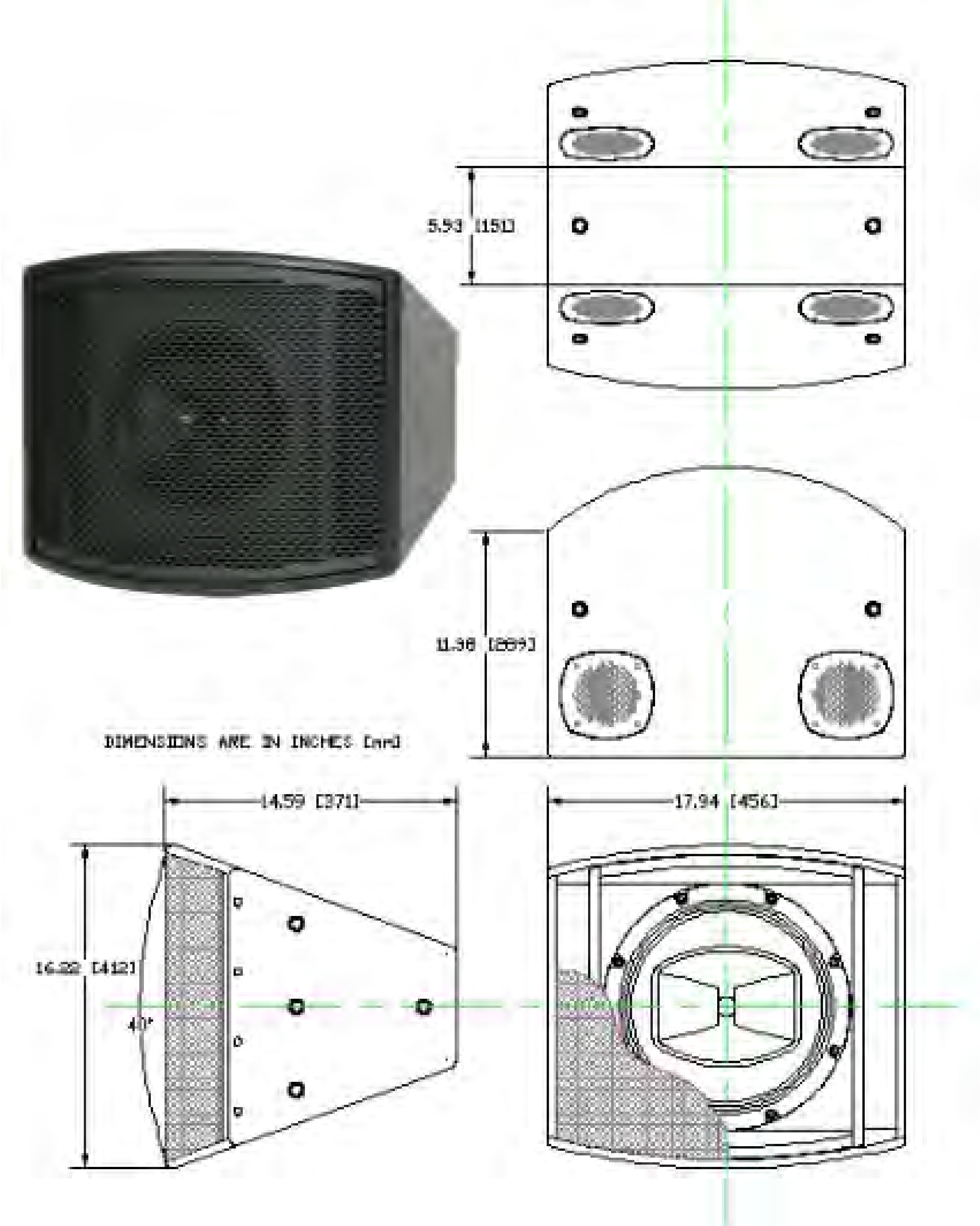
The design of the 8c is nothing less than amazing, essentially constant directivity down to 150 Hz using only passive directivity control methodology and active equalization. All of that in a compact and robust package. Another highly innovative loudspeaker implementation without any Patent Applications.

The retail price is about $14,900 / pair.

The **Fulcum Acoustic CCX 1295** is an interesting example where it is an upgrade from the **Fulcum Acoustic CX 1295**. In both cases, there is a high frequency driver with a separate waveguide mounted concentrically with a 12 in. midbass. The upgrade is a modification to the sealed box enclosure such that an internal baffle and **Variovent** like vents, two (2) on the top side and two (2) on the bottom side are added. Figure 16 below contains a mechanical drawing and the manufacture's polar plots for the **Fulcum Acoustic CCX 1295** passive 2-way subcardioid loudspeaker, which is equivalent to the **Fulcum Acoustic CX1295** except for the vents and internal baffle.

Although this loudspeaker seems less than moderately innovative at best, there was a US Patent Application, US 2017/0353787.

FIGURE 16. FULCRUM ACOUSTIC CCX1295 LOUDSPEAKER DRAWING WITH POLAR PLOTS



Horizontal Polar Response (30 dB Scale, 6 dB per Major Division)

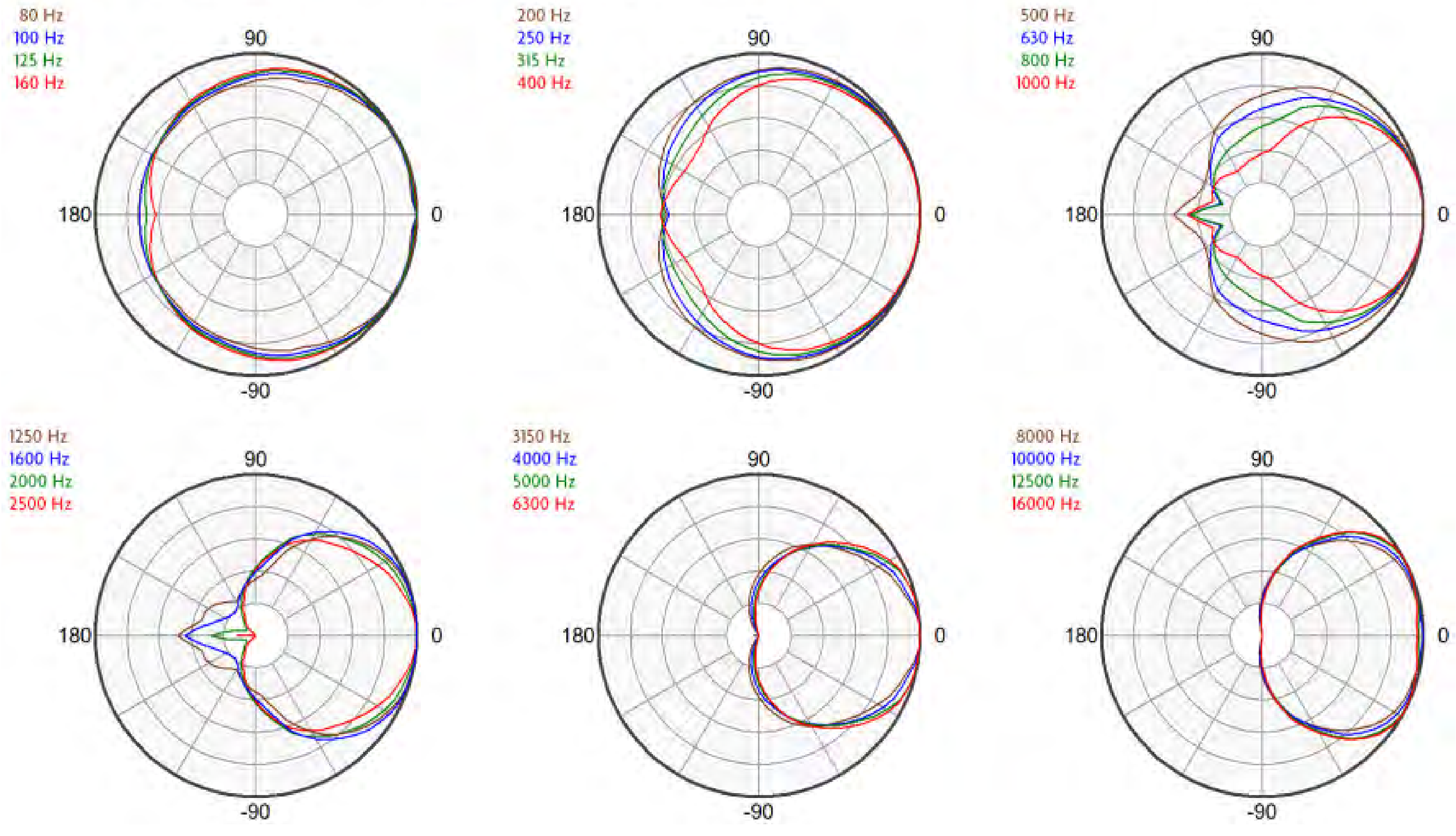
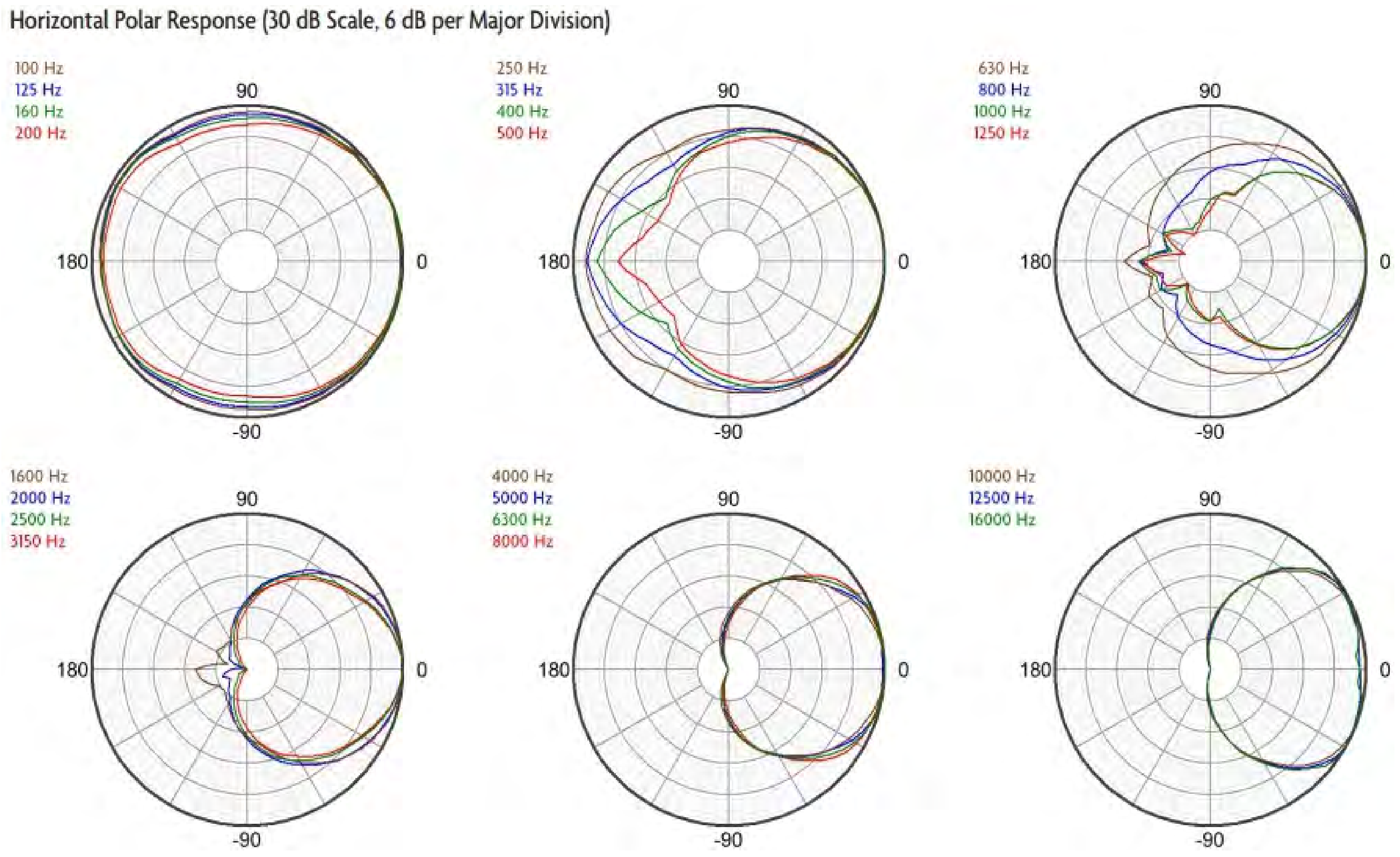


Figure 17 below contains the manufacturer's polor plots of a CX1295 loudspeaker for comparison.

FIGURE 17. FULCRUM ACOUSTIC CX1295 LOUDSPEAKER POLAR PLOTS



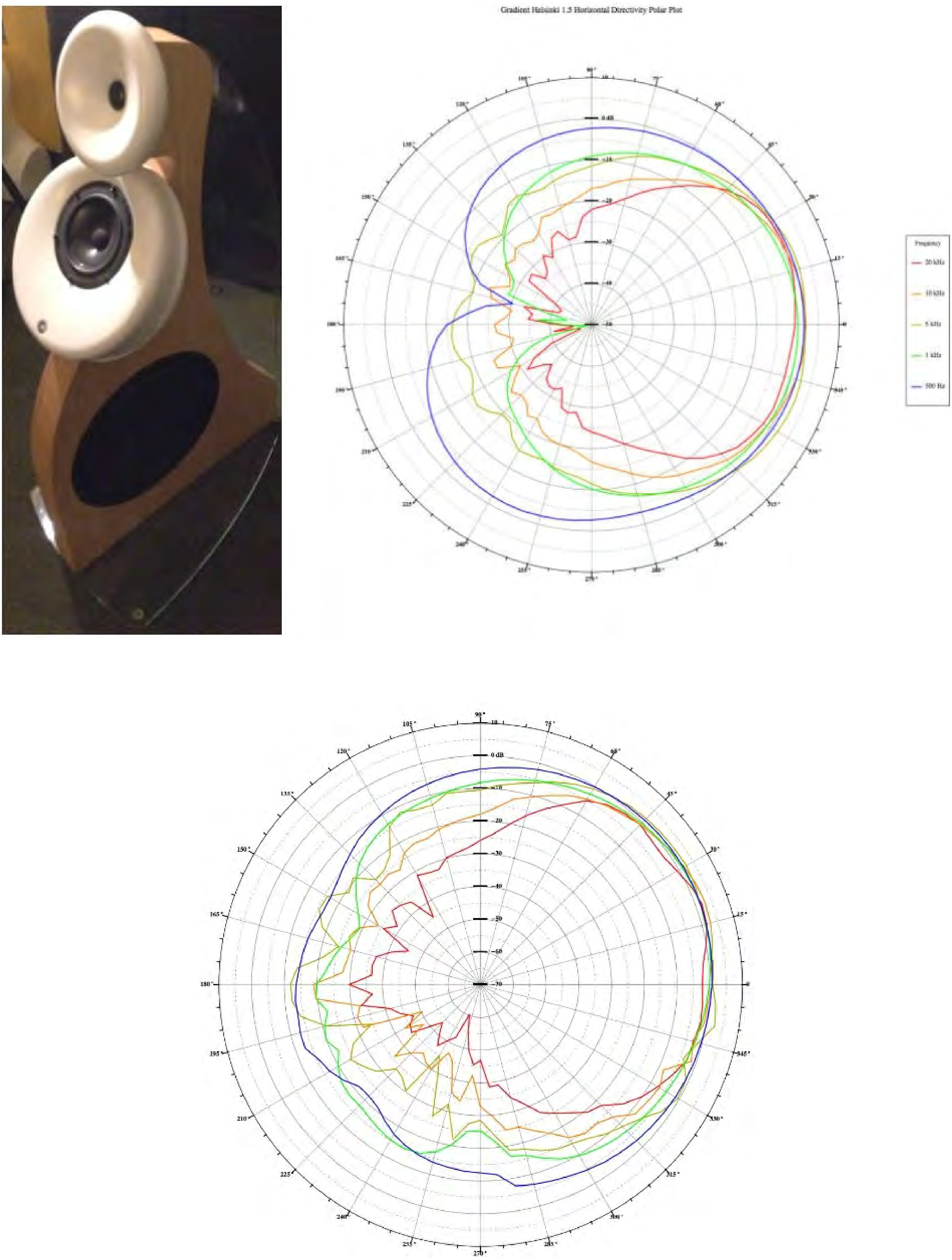
Retail price information was not available (GOOGLE could not find it).

III. PRINCETON UNIVERSITY DIRECTIVITY STUDY POLAR PLOT REVIEWS

6. GRADIENT LABS

Gradient Labs offers an interesting 3-way passive loudspeaker with a 0.75 in. tweeter with waveguide, a 6.5 in. mid in a resistance enclosure, and an open baffle 12 in. woofer. Note that Gradient is located in Finland. For a country of only 5.5 million people, there seems to be a focus on directivity controlled loudspeaker R&D as this discussion will imply. Figure 18 below contains a picture and polar plots of a **Helsinki 1.5**.

FIGURE 18. PICTURE WITH HORIZONTAL AND VERTICAL POLAR PLOTS OF THE GRADIENT HELSINKI 1.5 RESPECTIVELY



The 6.5 in. midbass is eccentrically mounted off center in a circular acoustic resistance enclosure that results in

geometry asymmetry depending on angle, ϕ, where $\ell(\phi)$ and where $D(\phi) = \ell(\phi) + Tc$. Most likely the objective is to extend the unidirectional bandwidth. The 6.5 in. midbass is used from 200 Hz to 2.2 kHz.

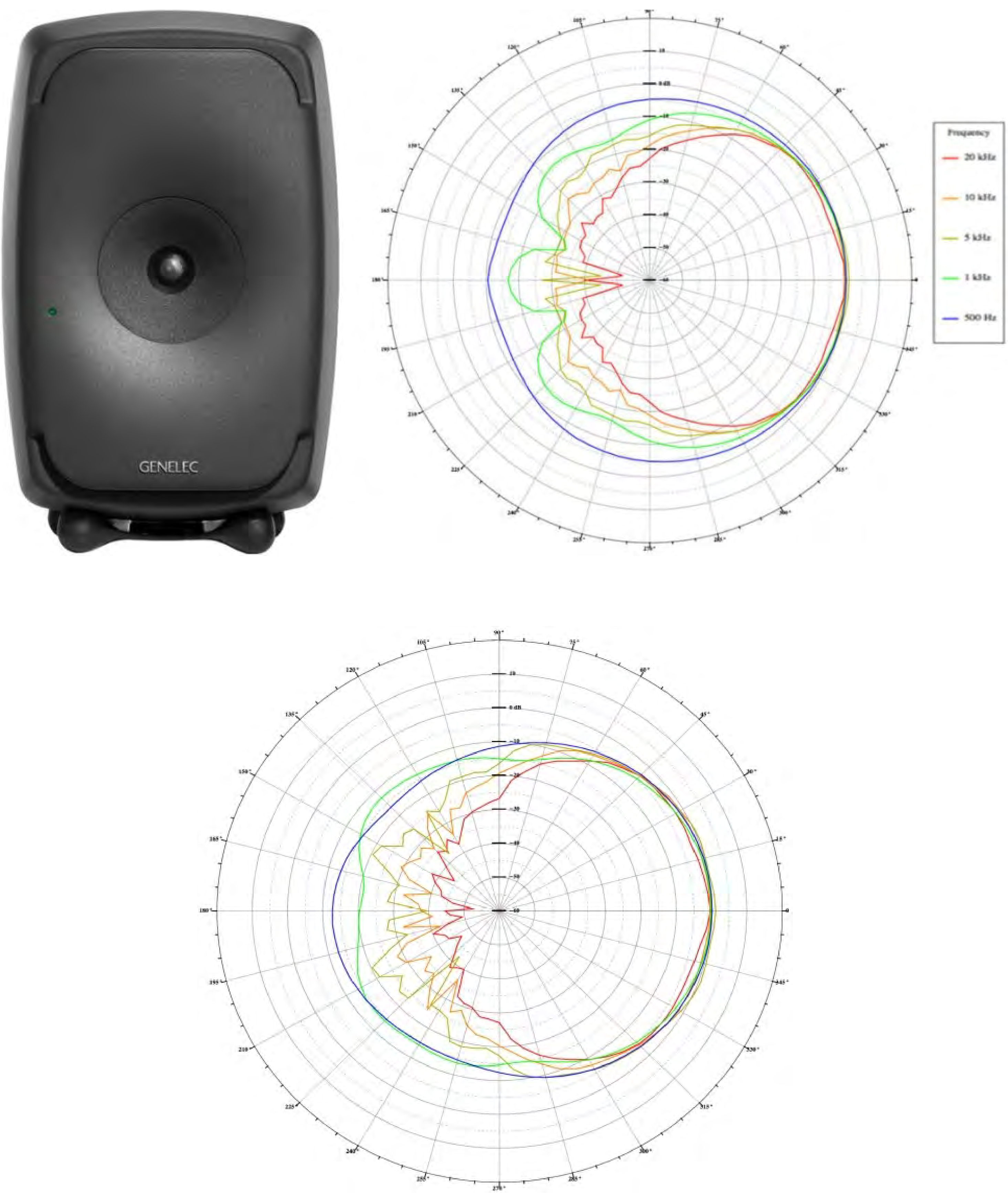
The retail price is approximately $9,000 / pair.

7. GENELEC 8351A

The late founder of GENELEC once said that "Directivity is everything".

Figure 19 below contains a front view and polar plots of the GENELEC 8351A. The 8351A is a 3-way coincident source active loudspeaker with DSP onboard; however, there is no active directivity control. The 0.75 in. / 5.0 in. coaxial array plus the integral baffle/waveguide along with active EQ provides cardioid like radiation from 1.2 kHz up with less variation than the Helsinki 1.5. At 500 Hz the 8351A radiation is subcardioid but tending to omnidirectional with 2 x 8.5 in. x 4.0 in. racetrack woofers in a ported box. The entire front baffle is integrated into a waveguide that loads both the tweeter and the mid. The 8351A crossover frequencies are at 490 Hz and 2.6 kHz. The retail price is approximately US$8,000 / pair. Note that Genelec is also located in Finland!

FIGURE 19. PICTURE WITH HORIZONTAL AND VERTICAL POLAR PLOTS OF THE GENELEC 8351A ACTIVE LOUDSPEAKER RESPECTIVELY



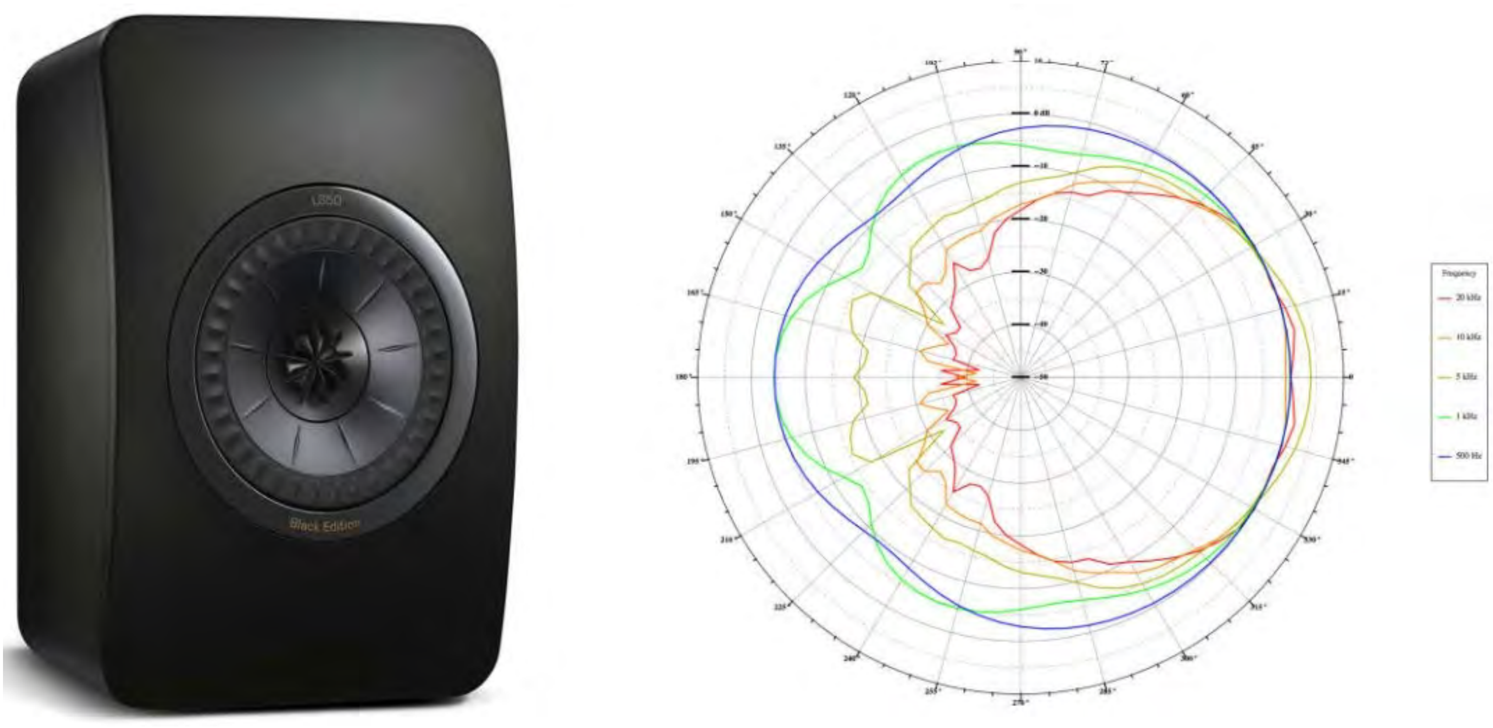
Note that the vertical directivity is a bit more constant than the horizontal. **Some studio installations utilize vertical mounting at ear level.** This is a result of the woofer / coaxial / woofer array topology. From 490 Hz up, the **8351A** had the most constant horizontal directivity above the baffle frequency of all the loudspeakers in the Princeton University Study but is still constrained by waveguide/baffle size. The Industrial

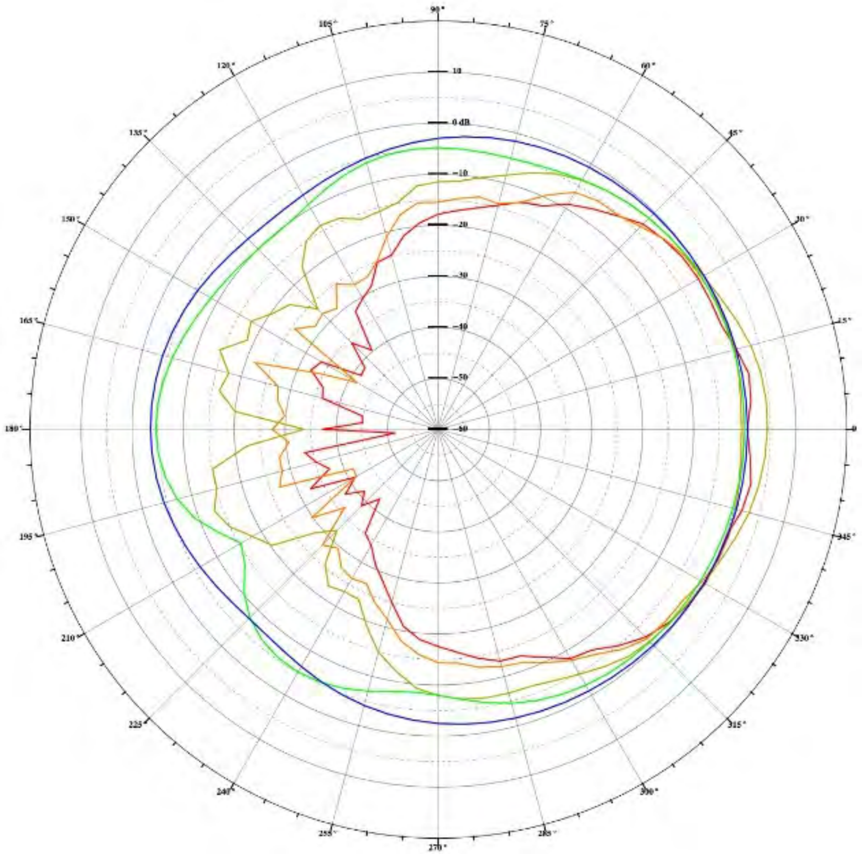
Engineering of the enclosure is certainly appealing; however, could the integral baffle/waveguide be approximated by simply using a larger coaxial driver and/or a larger flat baffle? Compare figure 2 to figure 19.

8. KEF Uni-Q

Figure 20 below contains a front view of the KEF LS50, a passive 2-way coincident source loudspeaker ($1300 / pair) along with a horizontal polar plot. The crossover frequency is 2.2 kHz and the radiation is cardioid like from 1.7 kHz up. Below 500 Hz the radiation becomes omnidirectional.

FIGURE 20. PICTURE OF KEF LS50 WITH HORIZONTAL AND VERTICAL POLAR PLOTS RESPECTIVELY



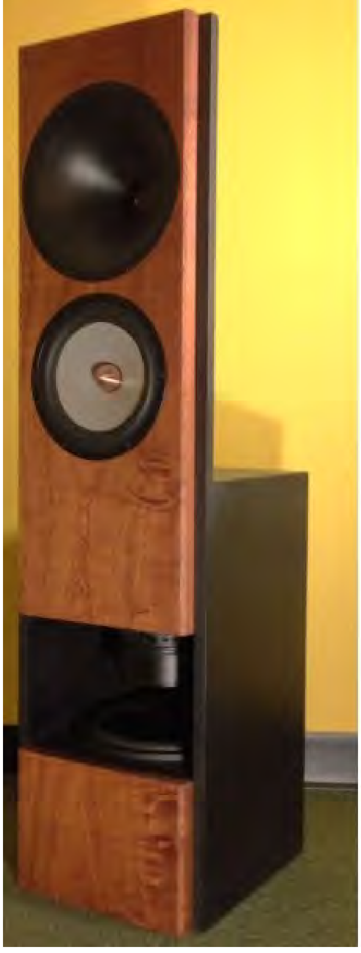


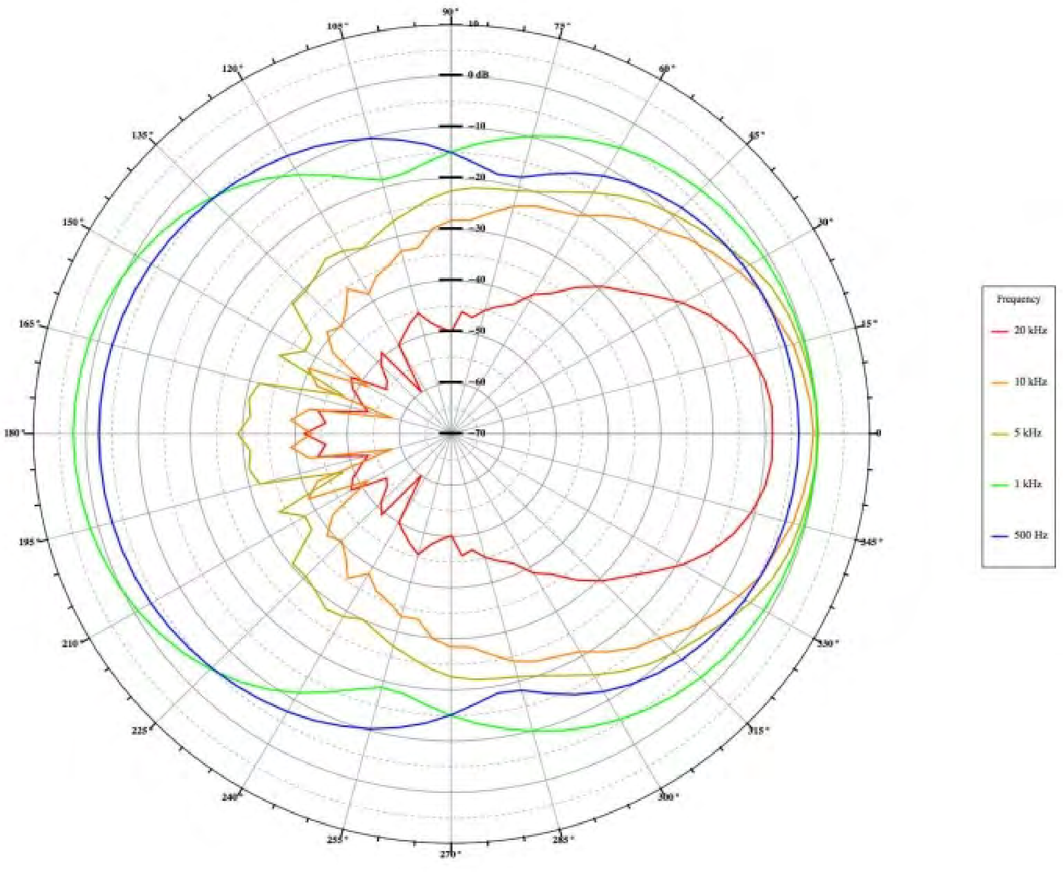
The directivity of the 1.0 in. Al alloy dome tweeter (2.5 kHz up) is cardioid like with good consistency. However the 5 in. midbase directivity could be increased by simply using a larger diameter transducer. KEF also offers the cost effective Q350 with a 6.5 in. midbase and 1.0 in. coaxial tweeter ($700 / pair).

The retail price of the LS50 is $1,300 / pair.

9. GAINPHILE

FIGURE 21. PICTURE OF GAINPHILE R16 WITH HORIZONTAL POLAR PLOT





The **Gainphile R16** shown in figure 21 above is essentially a **Linkwitz Lab Orion** clone with lower cost 2 x Peerless XLS 10 in. subwoofers substituted for the SEAS 10 in. subs and a waveguide with a 10 in. mouth and a 1.0 in. Dayton Audio compression driver rather than the 2 x SEAS 1.0 in. dome tweeters, while the Seas 8 in. remains unchanged. The radiation from the waveguide is unidirectional while the radiation from the Seas 8 in. open baffle is bidirectional figure-8 like but almost semi-omni. It's the waveguide that prevents any lobbing above the 1.5 kHz crossover frequency. Although, the claim is of constant directivity, the Princeton U polar plot represents the least constant directivity over the test band of 500 Hz to 20 kHz in five (5) steps, of all the previous loudspeakers discussed. The rear output of the **Gainphile R16** is actually higher than the front output at 500 Hz and 1.0 kHz. Note that all the loudspeakers with acoustic resistance enclosed drivers reviewed outperformed this open baffle SEAS 8 in. with respect to directivity control.

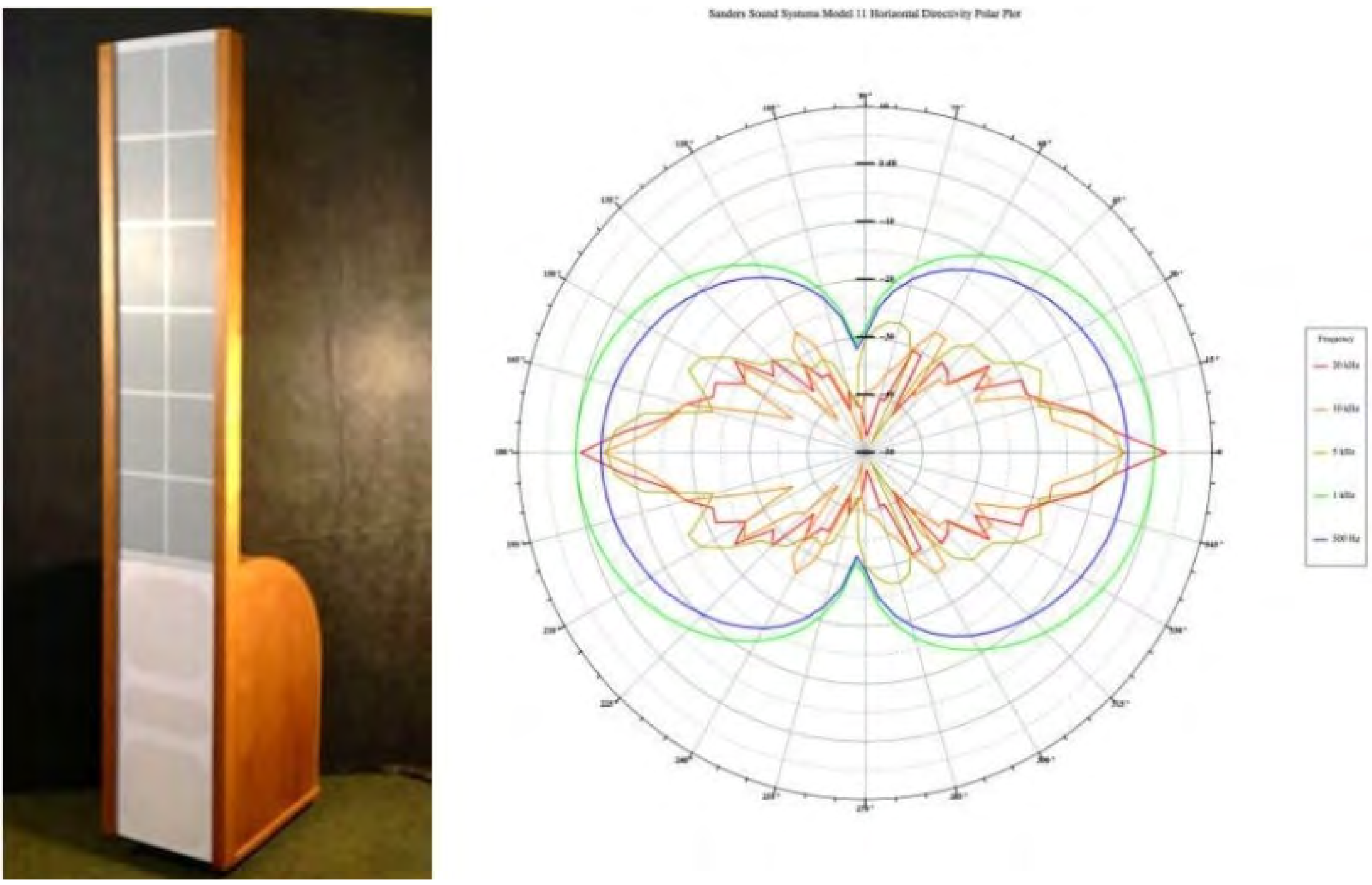
Only the last loudspeaker system below has less constant directivity, the **Sanders Model 11 ESL**.

The **Gainphile R16** was a DIY project and is not commercially available.

10. SANDERS SOUND SYSTEMS ESL

The **Sanders Model 11** is a simple example of geometry related dipole lobbing and beaming. The fixed 11 in. wide front baffle/diaphragm is a directivity nightmare. The **Model 11** is a dipole with D/λ(10 kHz) ≈ 4. Lobbing will begin when $D/\lambda > 0.9$. See figure 8. Figure 22 below is taken from the Princeton University Directivity Study.

FIGURE 22. PICTURE AND HORIZONTAL POLAR PLOT OF THE SANDERS MODEL 11



The retail price is about $12,000 per pair with crossover but without amplifiers.

The author could only find four (4) of the systems discussed that are unidirectional to below the typical room **Schroeder frequency**. Note that all are powered systems with DSP capabilities.

1. **B&O BEOLAB 90** - 4-way: full active control.
2. **Kii Three** - 3-way: tweeter waveguide with mid and low frequency active control.
3. **GENELEC 8361A + W371A** - 3-way: coaxial tweeter / mid with integrated baffle waveguide and low frequency active control system.
4. **DUTCH & DUTCH 8c** - 3-way: tweeter waveguide and midbase acoustic resistance enclosure with omnidirectional subs below 100 Hz.