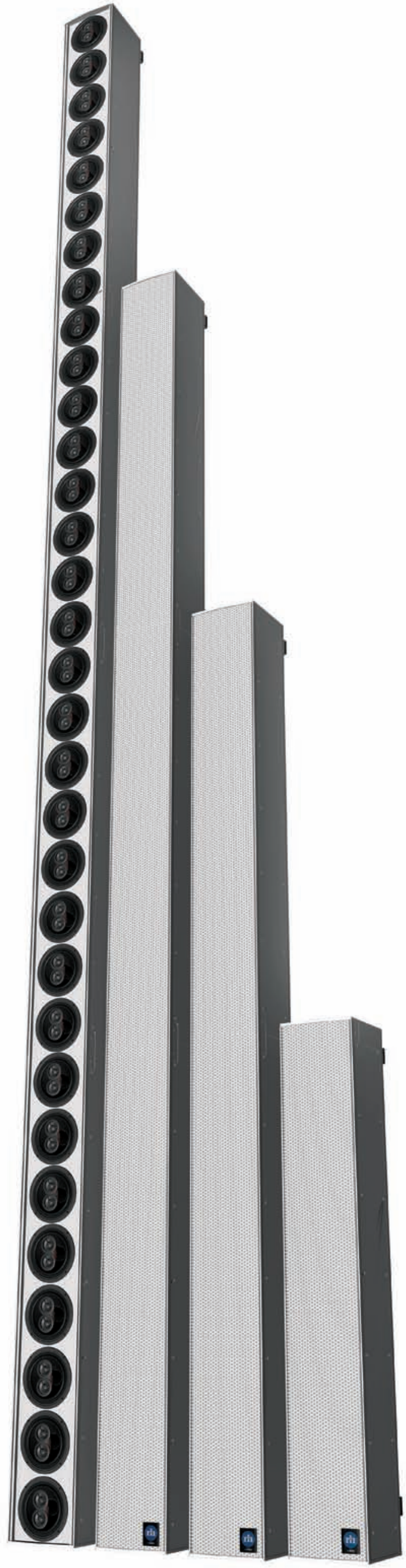
ICONYX



DSP-Driven Vertical Arrays

Acoustical, Electronic & Mechanical Considerations

A Renkus-Heinz
Engineering White Paper

RENKUS-HEINZ

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DSP-Driven Vertical Arrays
Acoustical, Electronic & Mechanical Considerations

This white paper discusses some of the problems involved in the design and deployment of DSP-driven vertical arrays. Practical examples are taken from the new Renkus-Heinz IC Series Iconyx steerable column arrays.

What is Iconyx?

Iconyx is a steerable column array that combines very high directivity with accurate reproduction of source material in a compact and architecturally pleasing package.

Iconyx is the first digital loudspeaker system to deliver both a tightly focused, steerable beam and musical sound quality.

Like every other loudspeaker system, Iconyx is designed to meet the challenges of a specific range of applications. Many of the critical design parameters are, of course, determined by the nature of these target applications. To understand the decisions that have been made during the design process we must start with the particular problems posed by the intended applications.

Steerable Array Applications

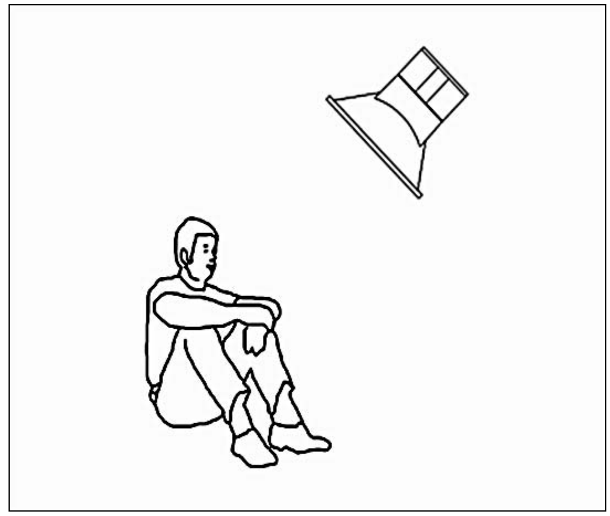
Today's steerable arrays are similar in form to the column speakers that have been used since the 1950's. While they represent a major advance in technology and performance, these systems are most often used in the same kinds of applications. They are typically installed in houses of worship, auditoriums, theaters and other similar venues.

Where column arrays are used for portable sound reinforcement, the audience tends to be under 200 people. Installed systems can be much larger – this type of speaker is often found in cathedrals, passenger terminals for rail networks and airports, and public spaces used by government, such as legislative chambers.

Acoustical Concerns

Acoustically, all of the above venue types share the common characteristic of very long RT60s (reverberation times).

Highly reverberant spaces demand high-Q devices: The direct/reverberant energy ratio must be sufficiently high for the understanding of speech and the appreciation of music to be possible.



Too much of the acoustical output from low-Q devices excites reflective surfaces. Only listeners in the very near field will be able to understand and/or enjoy such a system.

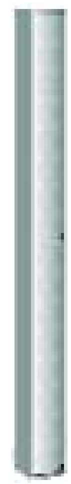
The cost-effective solution is based on a smaller number of high-Q devices, each of which can be located farther away from the listener and can therefore cover a greater area effectively. From a purely acoustical point of view, the technique used to direct the acoustic energy onto the audience and away from the walls, floors and ceilings does not matter. We could, for example, get very similar results in EASE models whether the loudspeaker system included very large horns, or was a curved "line array" of the type so often seen today in concert touring systems.

Architectural Concerns

An acceptable balance of listening quality and overall system cost is typically found when the system uses a small number of high-Q loudspeaker systems. Why then do we not see large horn arrays or line arrays in the highly reverberant spaces mentioned above? The short answer is that architects design buildings with their eyes, not their ears. Horn and/or line arrays of sufficiently high Q to produce acceptable acoustic results will always be larger than most architectural elements of the space in which they are to be installed.

They do not blend in with the shapes and colors of most interior designs. Very few architects or building owners welcome a last-minute disruption of the building's interior on this scale. It is difficult to get approval for hanging one or more large, oddly-shaped objects in the middle of a space that is intended to produce a carefully considered and coherent visual impression on the occupants.

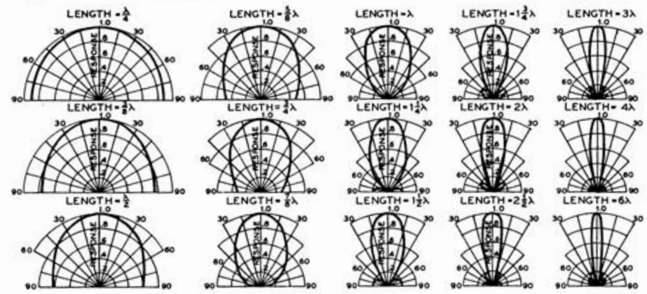
Typical Line Array



Typical Iconyx Column

Column loudspeakers were often the compromise solution even before their performance was advanced by the integration of DSP and individual driver control. The reason for this is that columns are easily concealed within most architectural environments, whether traditional or modern. They are usually mounted flush to the wall and can be painted to match the adjacent surface, making their presence easy to conceal. This is a much more attractive and acceptable solution to the architect. With individual DSP control of the array elements, we can now provide acceptable acoustic performance as well.

Line Arrays are not a new idea
Harry F. Olson did the math and described the directional characteristics of a continuous line source in his classic *Acoustical Engineering*, first published in 1940. Traditional column loudspeakers have always made use of line source directivity. The function of individual driver control and DSP is to make more effective use of this phenomenon. No amount of silicon can get around the laws of acoustical physics.



The directional characteristics of a continuous line source are shown in Fig. 2.4. The directional characteristics are symmetrical about the line

FIG. 2.4. Directional characteristics of a line source as a function of the length and the wavelength. The polar graph depicts the sound pressure, at a large fixed distance, as a function of the angle. The sound pressure for the angle 0° is arbitrarily chosen as unity. The direction corresponding to the angle 0° is perpendicular to the line. The directional characteristics in three dimensions are surfaces of revolution about the line as an axis.

Continuous line source directivity, described in Acoustical Engineering
Harry F. Olson, 1957

The acoustical properties of first-generation "column speakers" are set by the acoustical characteristics of the transducers and the physical characteristics of the package, as shown in this table:

System	Acoustical Performance
Column height	Lowest frequency (longest wavelength) at which the system controls vertical beamwidth
Driver spacing	Highest frequency at which the output is free of "grating" lobes
Driver type (cone, co-axial, etc.) and size	Horizontal dispersion
Driver bandwidth	Frequency response

1. The height of the column determines the lowest frequency at which it exerts any control over the vertical dispersion.

2. The inter-driver spacing determines the highest frequency at which the array acts as a line source rather than a collection of separate sources.

3. Horizontal dispersion is fixed and is typically set when the drivers are selected, because column loudspeakers do not have waveguides (as noted above, the size of even a minimally effective waveguide is too large to satisfy the architectural requirements of the target application).

4. Other driver characteristics such as bandwidth, power handling and sensitivity will determine the equivalent performance characteristics of the system.

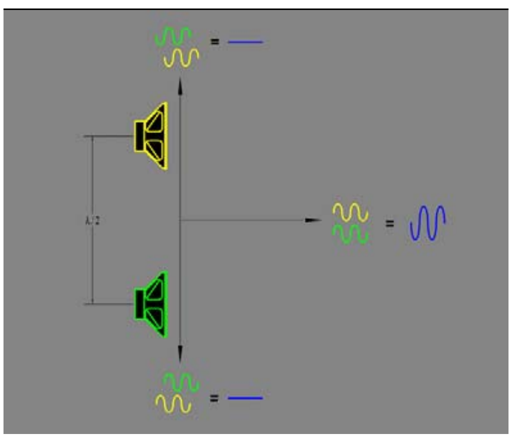
One unfortunate corollary of these characteristics is that the power response of a “conventional” column loudspeaker is not smooth. It will deliver much more low frequency energy into the room and this energy will tend to have a wider vertical dispersion. This can make the critical distance even shorter because the reverberant field contains more low frequency energy, making it even harder for the listener to recognize higher-frequency sounds such as consonants or instrumental attack transients.

To see why the traditional column loudspeaker behaves the way it does, we will briefly review some key concepts of basic line array and steerable array physics.

Point Source Interactions

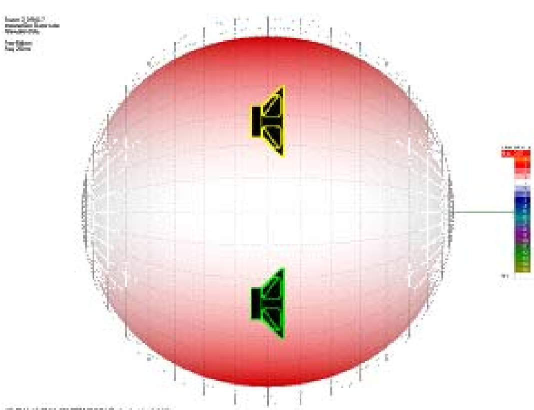
Doublet Source Directivity

These cancel each other’s output directly above and below, because they are spaced ½ wavelength apart in the vertical plane. In the horizontal plane, both sources sum. The overall output therefore looks something like this (see below):



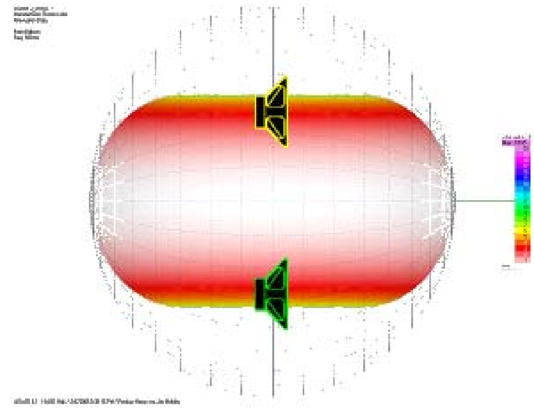
λ/4 (1/4 wavelength)

When two sources are ¼ wavelength apart or less, they behave almost like a single source. There is very slight narrowing in the vertical plane.



λ/2 (1/2 wavelength)

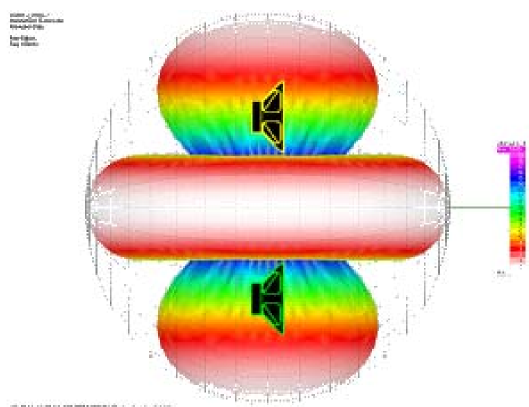
As explained in the diagram on the previous page, there is significant narrowing in the vertical plane at ½ wavelength spacing, because the waveforms cancel each other in the vertical plane, where they are 180° out of phase.



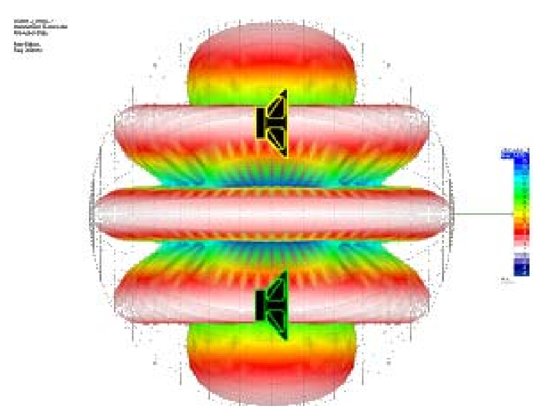
λ (1 wavelength)

At one wavelength spacing the two sources reinforce each other in both the vertical and horizontal directions. This creates two lobes, one vertical and the other horizontal.

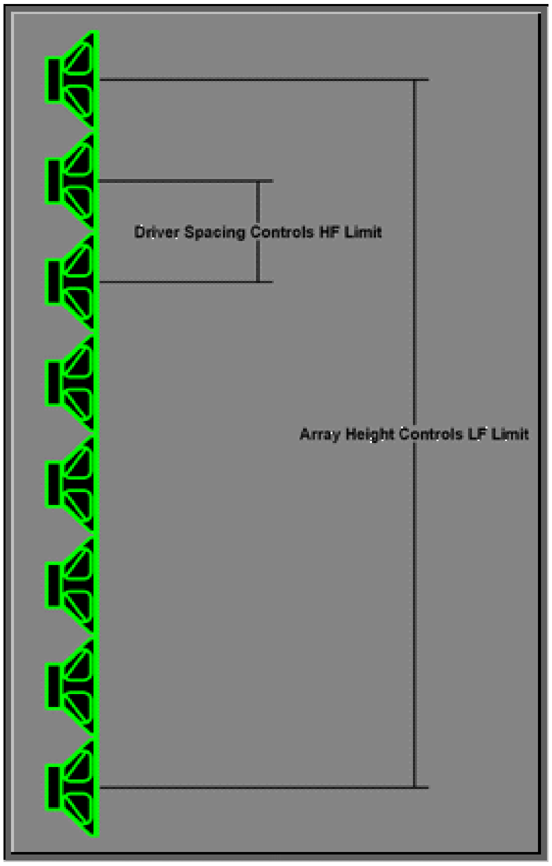
2λ



As the ratio of wavelength to inter-driver spacing increases, so do the number of lobes. With fixed drivers as used in line arrays, the ratio increases as frequency increases ($\lambda = c/f$ where f is the [variable] frequency and c is the [constant] speed of sound).



Line **Source Performance Limits**



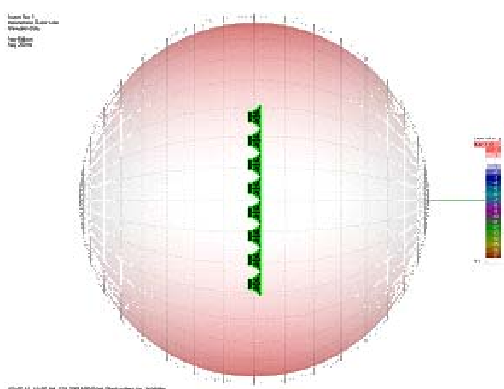
Driver-to-driver spacing sets the highest frequency at which the array operates as a line source.

The total height of the array sets the lowest frequency at which it has any vertical directivity.

Array Height vs. Wavelength (λ)

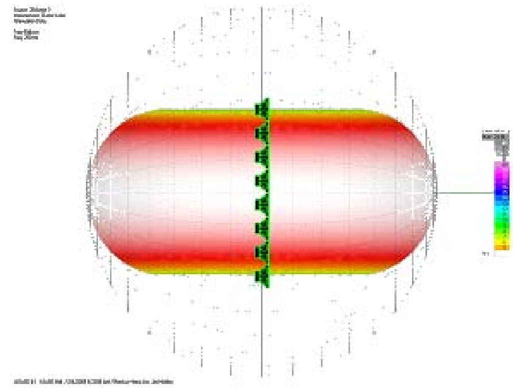
λ/2

At wavelengths of twice the array height, there is no pattern control: the output is that of a single source with very high power handling.



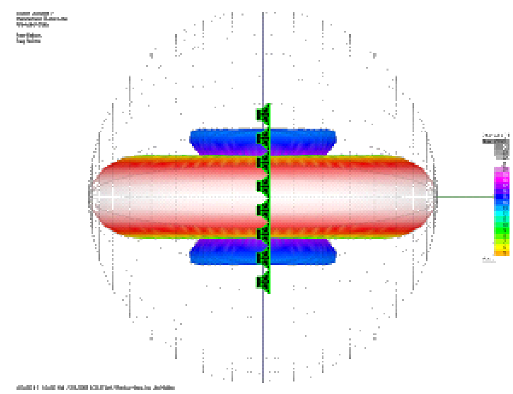
λ

As the frequency rises, wavelength approaches the height of the line. At this point there is substantial control in the vertical plane.



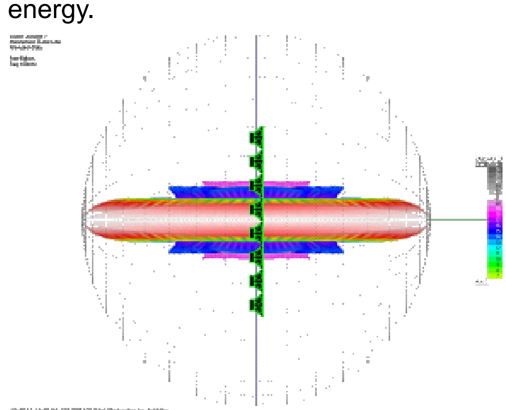
2λ

At higher frequencies the vertical beamwidth continues to narrow. Some side lobes appear but the energy radiated in this direction is not significant compared to the front and back lobes.



4λ

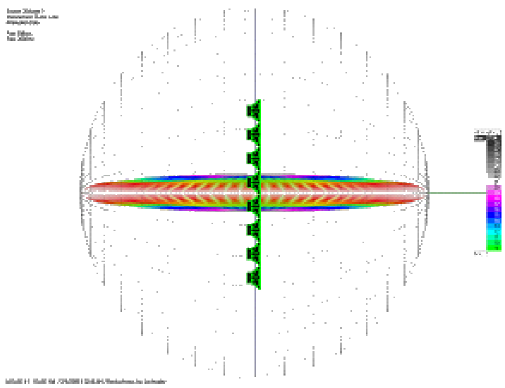
Still further vertical narrowing, with side lobes becoming more complex and somewhat greater in energy.



Inter-Driver Spacing vs. Wavelength (λ)

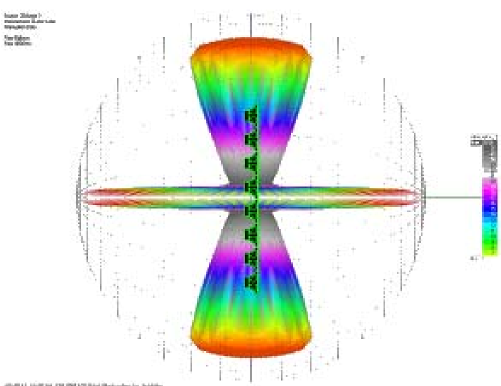
λ/2

When the drivers are spaced no more than ½ wavelength apart, the array produces a tightly directional beam with minimal side lobes.



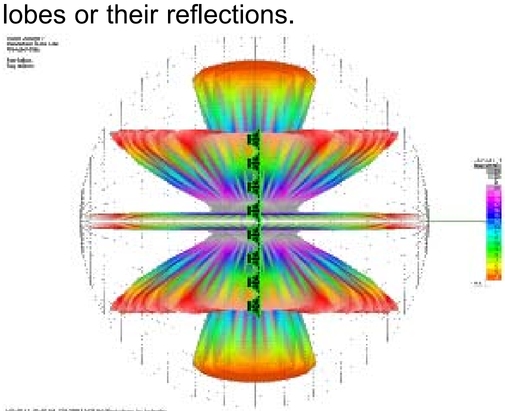
λ

As the frequency rises, wavelength approaches the spacing between drivers. At this point, grating lobes become significant in the measurement. They may not be a problem, if most or all of the audience is located outside these vertical lobes.



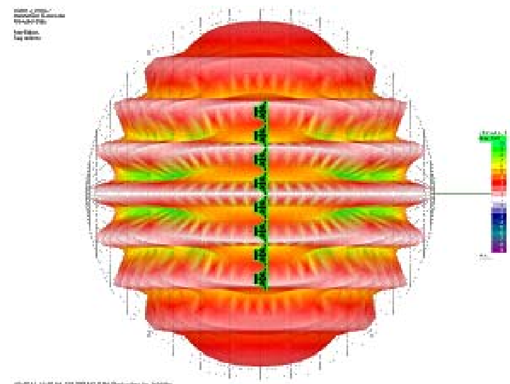
2λ

At still higher frequencies, lobes multiply: it becomes harder to isolate the audience from the lobes or their reflections.



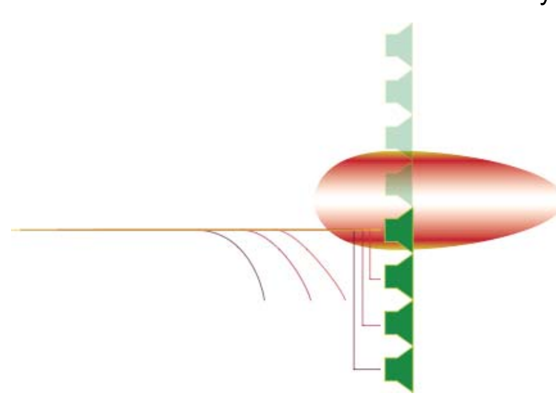
4λ

As inter-driver spacing approaches 4 times the wavelength, the array is generating so many side lobes of such significant energy that its output closely approximates a single point source. We have come "full circle" to where the array's radiated energy is about the same as it was when array height was ½ λ. As shown in the first diagram, this is the high frequency limit of line array directivity.



Multi-Channel DSP Can Control Array Height

The upper limit of a vertical array's pattern control is always set by the inter-driver spacing: the design challenge is to minimize this dimension while optimizing frequency response and maximum output, and do it without imposing excessive cost. Line arrays become increasingly directional as frequency increases: at high frequencies they are too directional to be acoustically useful. However, if we have individual DSP available for each driver, we can use it to make the array acoustically "shorter" as frequency increases – this will keep the vertical directivity more consistent. The technique is conceptually simple: use low-pass filters to attenuate drive level to the transducers at the top and bottom of the array, with steeper filter slopes on the extreme ends and more gradual slopes as we progress to the center. As basic as this technique is, it is practically impossible without devoting one amplifier channel and one DSP channel to each driver in the array.

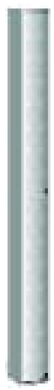


Simplified schematic shows how multi-channel DSP can "shorten" the array as frequency increases. For clarity, only half the processing channels are shown: delays are not diagrammed.

Iconyx: Designing a Next-Generation Digitally Controlled Line Source

Steerable Arrays May Look Like Columns But They Don't Quack…

Simple column loudspeakers provide vertical directivity, but the height of the beam changes with frequency. The overall Q of these loudspeakers is therefore lower than required. Many early designs used small-cone "full range" transducers, and the poor high frequency response of these drivers certainly did nothing to enhance their reputation.



Beam-Steering: Further Proof That Everything Old Is New Again

As Don Davis famously said, "The ancients keep stealing our ideas." Here is another illustration from Harry F. Olson's *Acoustical Engineering*. This one shows how digital delay, applied to a line of individual sound sources, can produce the same effect as tilting the line source. It would be long after 1957 before the cost of this relatively straightforward system became low enough for commercially viable solutions to come to market.

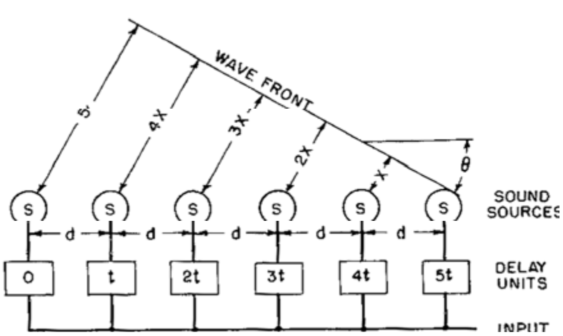


FIG. 2.5. A delay system for tilting the dir tional characteristic of a line of sound sourc

DSP-Driven Arrays Solve Both Acoustical & Architectural Problems

Variable Q

DSP-driven line arrays have variable Q because we can use controlled interference to change the opening angle of the vertical beam. The IC Series can produce 5°, 10°, 15° or 20° opening angles if the array is sufficiently tall (an IC24 is the minimum required for a 5° vertical beam). This vertically narrow beam minimizes excitation of the reverberant field because very little energy is reflected off the ceiling and floor.

Consistent Q with frequency

By controlling each driver individually with DSP and independent amp channels, we can use signal processing to keep directivity constant over a wide operating band. This not only minimizes the reverberant energy in the room, but delivers constant power response. The combination of variable Q, which is much higher than that of an unprocessed vertical array, with consistent Q over a relatively wide operating band, is the reason that DSP-driven Iconyx arrays give acoustical results that are so much more useful.

Ability to steer the acoustic beam independently of enclosure mounting angle

Although beam-steering is relatively trivial from a signal-processing point of view, it is important for the architectural component of the solution. A column mounted flush to the wall can be made nearly invisible, but a down-tilted column is an intrusion on the architectural design. Any DSP-driven array can be "steered." Iconyx also has the ability to change the acoustic center of the array in the vertical plane, and this can be very useful at times.

Applications for Steered Arrays

Houses of Worship

Our Lady of Perpetual Reverberation

Many Catholic cathedrals and churches share architectural characteristics – very high ceilings, boundary surfaces of stone, glass and similarly reflective materials, an absence of any sound-absorbing materials except for the worshippers themselves – that create exceptionally long RT60s and equally low intelligibility. Mosques, temples, synagogues and houses of worship for many Protestant or evangelical churches pose the same set of acoustical and architectural challenges.

Transportation Terminals
The Lost Consonants of Atlanta (Chicago, New York, Dallas/Fort Worth, Denver, etc.)
Airports and train stations often use some of the same materials and space planning as houses of worship to make their architectural statements. Communication is just as important in these spaces: passengers need to know departure and arrival times and last-minute schedule changes, families and guests need to find each other, etc.

Auditoriums, museums, lobbies, etc.
Many buildings that are on a smaller scale than a cathedral or a transportation terminal nevertheless have one or both of the characteristics that make a digitally controlled array the best, and sometimes the only, solution. The two main challenges that a digitally controlled array meets better than any other solution are: long reverb times that make speech intelligibility problematic; and architectural styles that are in conflict with typical systems.

Design Criteria: Meeting Application Challenges

Full range output
The diagrams above make it clear that any line source, even with very sophisticated DSP, can control only a limited range of frequencies. However, we decided early in the design process to use full range co-axial drivers as the line source elements. Providing full range output, we reasoned, could make the overall sound of the system more accurate and natural without seriously compromising the benefits of beam-shaping and steering. In typical program material, most of the energy is within the range of controllable frequencies. Earlier designs radiate only slightly above and below the frequencies that are controllable. Thus much of the program source is sacrificed, without a significant increase in intelligibility.

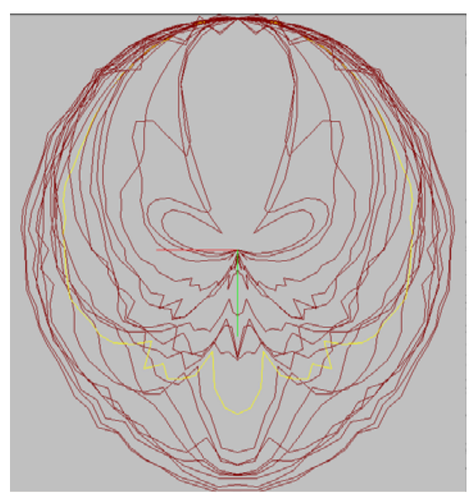
Full control with advanced electronics
To maximize the effectiveness of a digitally controlled line source, it's not enough to start with high-quality transducers. We knew that we also had to enable full control of each element. This was the start of our search for a compact multi-channel amplifier with integral DSP capability. The D2 audio module that we used has the required output, full DSP control and the added advantage of a purely digital signal path option. When PCM data is delivered to the channel via an AES/EBU or CobraNet input, the D2 audio processor/amplifier converts it directly into PWM data that can drive the output stage.

First-generation "digital" amplifiers require that PCM data be converted to analog waveforms and then back to digital PWM data in order to drive their output stages. The added D/A and A/D converters add cost, distortion and latency.

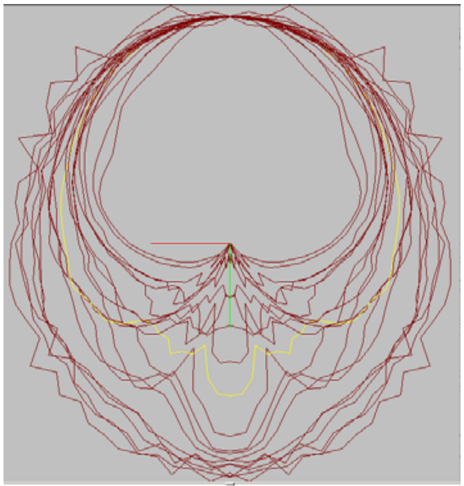
Flexibility
We believe that when accurate, natural reproduction is combined with digital control of the line source, the potential applications are greater than just cathedrals and transportation terminals. Therefore we made flexibility a goal of Iconyx design. We started with a modular concept that allows very tall lines to be built up from smaller modules. Individual modules can be shipped via low-cost carriers such as UPS, then quickly assembled on site. Direct control of each line source element allows multiple lobes to be shaped and aimed from the same array. Acoustic centers of these lobes can be moved independently of the physical location of the array, because inter-driver spacing is constant throughout the full length of the line.

Horizontal Directivity Is Determined By The Array Elements

Like other vertical arrays, Iconyx systems can be steered only in the vertical plane. Horizontal coverage is fixed and we knew it would be determined by the choice of array elements. The transducers used in Iconyx modules have a horizontal dispersion that is consistent over a wide operating band, varying only between 140° and 150° degrees from 100 Hz to 16 kHz. Iconyx has much more consistent horizontal directivity than similar arrays using 4" full range drivers.



Polar response of a full range 4-inch cone: note the progressive narrowing as the frequency increases.



The polar response of the Iconyx co-axial 4-inch driver: high frequency dispersion is much wider. The off-axis narrowing observed in many coaxial transducers is absent, thanks to a time-aligning passive crossover network.

Wider dispersion confers both performance and cost advantages

Wider dispersion, particularly of high frequencies, enables Iconyx systems to deliver more consistent performance and intelligibility, particularly on the edges of the coverage area. In many situations, the wider coverage angle means that fewer devices can be used to produce acceptable results, which translates into cost savings.

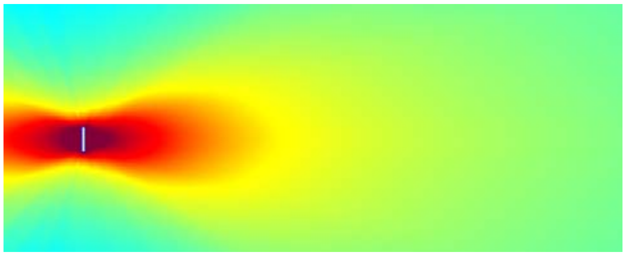
Line Source Performance: Real Driver Interactions

Real drivers are not uniformly directional: as with any source that has physical dimensions (as opposed to a theoretical perfect point) they get more directional with increasing frequency. For instance, the 4 inch diameter co-axial driver used in Iconyx vertical arrays is omni-directional to about 300 Hz and half-hemispherical from 300 Hz to about 1kHz. Over the next decade (1 kHz to 10 kHz) the pattern is conical 140° x 140°.

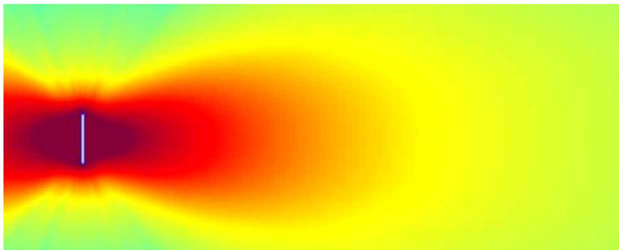
It should be obvious that an array of these sources will behave differently from a line of point sources with perfectly spherical radiation. Measurements confirm this: the rear lobe is much lower in level than the front lobe; off-axis "grating" lobes, when they do occur, are lower in level than the main lobe. In particular, grating lobes at 90° to the main axis of the array are greatly reduced in level.

Iconyx Arrays @ λ (1 wavelength)

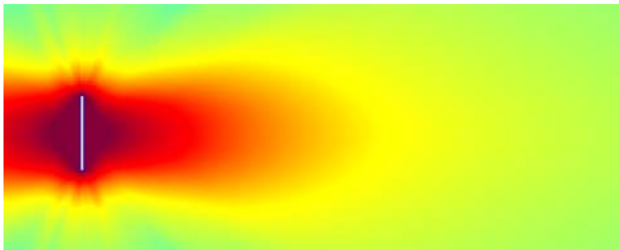
IC8 @ 400 Hz



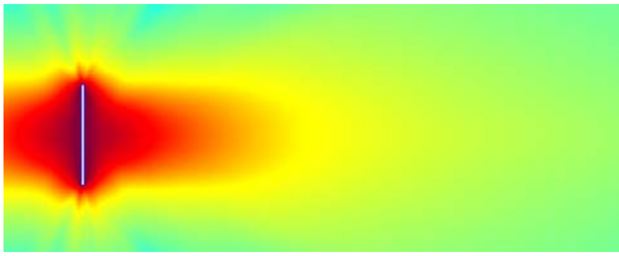
IC16 @ 200 Hz



IC24 @ 125 Hz

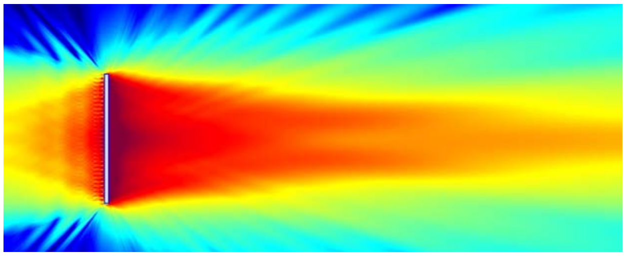


IC32 @ 100 Hz



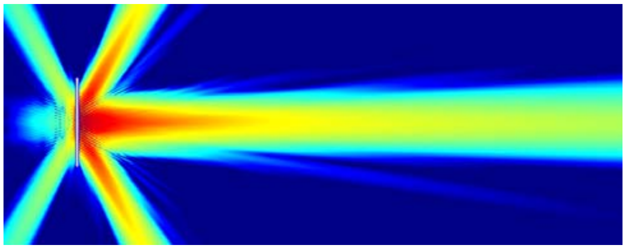
The lobes are similar in shape, although the IC32, which is 4x higher than the IC8, is narrower.

IC32 @ 1.25 kHz



At 1.25 kHz, the IC32 radiates a near-perfect 10° vertical beam. Side lobes are present but their level is well (-9 dB) below that of the main beam.

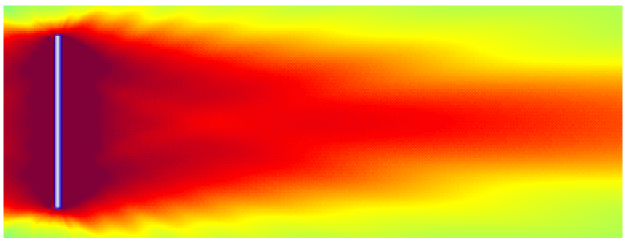
IC32 @ 31λ



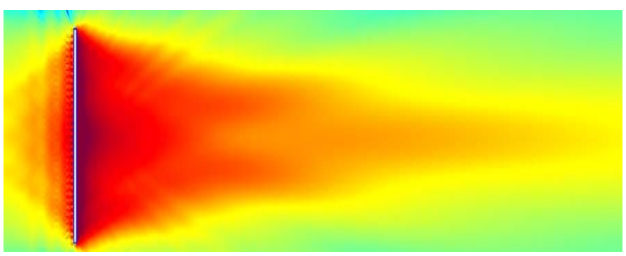
At 3.1 kHz the main lobe is still well focused, but two grating lobes are also present. Because of the wide angle to the main beam, these side lobes do not present practical problems.

Iconyx Directivity Remains Consistent With Changing Frequency

IC32 @ 5λ & 12.5λ



At 500 Hz (5λ), the IC32 shows a 10° lobe that is very consistent with both the 100 Hz and 1.25 kHz measurements.

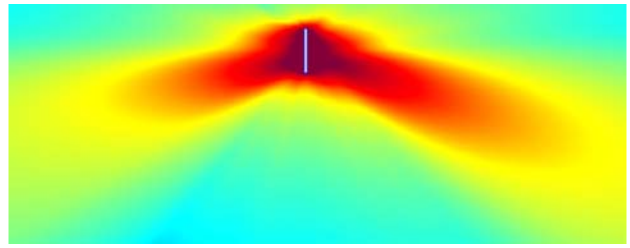


At 1.25 kHz (12.5λ), the 10° lobe radiated by the IC32 is slightly narrower but still consistent.

Steering is Simple–Just Progressively Delay Drivers

If we tilt an array, we move the drivers in time as well as in space. Consider a line array of drivers that is hinged at the top and tilted downward. Tilting moves the bottom drivers further away from the listener in time as well as in space. We can produce the same acoustical effect by applying progressively longer delays to each driver as we move from top to bottom of the array.

Again, steering is not a new idea. It is different from Mechanical Aiming–Front and Rear Lobes Steer the Same Direction.



Beam-steering produces different acoustical results than mechanical aiming because both front and rear lobes are steered in the same direction.

For progressive delay to steer the main lobe, the array must be two wavelengths (2λ) tall

The different model designations in the IC Series refer to the number of co-axial transducers in the vertical array. The different models can be steered effectively down to the following frequencies:

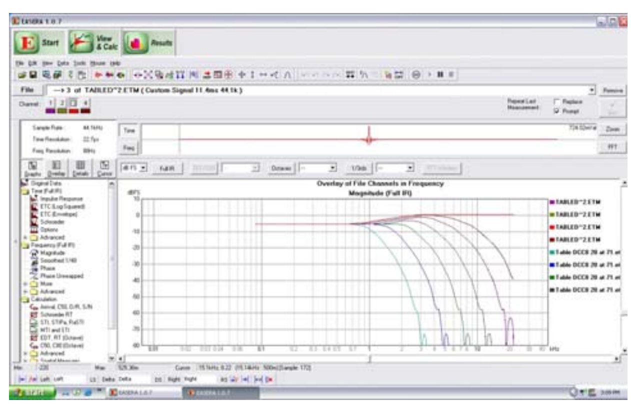
- IC8: 800Hz
- IC16: 400Hz
- IC24: 250Hz
- IC32: 200Hz

BeamWare: The Software That Controls Iconyx Linear Array Systems

The section of this white paper entitled Multi-Channel DSP Can Control Array Height on page 7 discusses how a series of low-pass filters can maintain constant beamwidth over the widest possible frequency range.

The ideas are simple, but for the most basic Iconyx array, the IC16, we must calculate and apply 16 sets of FIR filters, and 16 separate delay times. If we intend to take advantage of constant inter-driver spacing to move the acoustical center of the main lobe above or below the physical center of the array, we must calculate and apply a different set of filters and delays.

Complex low-pass filtering produces a 20° lobe for an IC8 array



Theoretical models are necessary, but as discussed in the section on Line Source Performance: Real Driver Interactions, the behavior of real transducers is more complex than the model. Each of the complex calculations underlying the Iconyx beam-shaping filters were simulated, then verified by measuring actual arrays in our robotic test and measurement facility.

Fortunately, the current generation of laptop and desktop CPUs are up to the task. BeamWare takes user input in graphic form (side section of the audience area, location and mounting angle of the physical array) and provides both a simulation of the array output that can be imported into EASE (v4.0 or higher) and a set of FIR filters that can be downloaded to the Iconyx system via RS422 serial control. The result is a graphical user interface that delivers precise, predictable and repeatable results in real-world acoustical environments.

Iconyx: a next-generation solution

Sound Quality
Iconyx sounds like a Renkus-Heinz loudspeaker, because it has been designed from the start for accurate, natural reproduction of both speech and music. Earlier digitally controlled arrays had restricted bandwidth and sounded more like “tall paging horns.” One of key differences between Iconyx array modules and earlier designs is that Iconyx uses wideband, wide-angle co-axial drivers instead of “full range” cones or separate dome tweeters.

Wider dispersion.
The decision to use high performance co-axial drivers gives Iconyx wider horizontal dispersion, especially at high frequencies. This means more consistent frequency response across the coverage area, and wider dispersion that allows many spaces to be covered properly using fewer devices.

Flexibility
Iconyx modules are vertical arrays of identical co-axial transducers. Because inter-driver spacing is constant, the acoustical center of the lobe can be positioned anywhere on the array. This can be very useful when the physical location of the array is either too high or too low for optimum coverage with a lobe radiating from the center of the array. Modular design allows each Iconyx array to have multiple elements and lobes. Multiple separate lobes can be produced from a single Iconyx array: each lobe can have a different beamwidth and steering angle.

Lower cost
Again thanks to the wider dispersion of the co-axial array elements, each Iconyx array can cover a larger area. Modular design cuts shipping cost because individual modules can be shipped via UPS and similar low-cost carriers.

Main Performance Advantages of the Iconyx Design

More efficient vertical pattern control
Iconyx arrays with similar directivity indices to previous designs are substantially smaller: arrays of similar size are more directional, which means they are more intelligible in reverberant spaces. In addition, the modular design of Iconyx gives the designer and installer more flexibility.

Full bandwidth
Previous designs had restricted bandwidth of 200 Hz – 4khz. Iconyx is a full range system with a frequency response of 120 Hz – 16 kHz. In addition, Iconyx modules are more electrically and acoustically efficient: they are 3 – 4 dB louder than previous designs of similar dimensions. With full range output and greater efficiency, Iconyx sounds like a loudspeaker, not a “tall paging horn.”

Advanced electronics
Each Iconyx array element is driven by its own processor/amplifier. If the optional AES/EBU or CobraNet inputs are used, the signal path is “pure digital.” The DSP amplifier converts the PCM input data directly to PWM data that drives the output stage. First-generation “digital” amplifiers must convert PCM data to analog waveforms and then convert again from analog to PWM. These conversion stages introduce distortion and latency into the signal chain.

Sophisticated DSP algorithms
Developed specifically for Iconyx, the sophisticated DSP algorithms and BeamWare interface make it easy to adapt Iconyx arrays to a wide variety of audience areas. SPL can be made consistent over distances of up to 300 feet. The lobe center can be moved anywhere from the top to the bottom of the array. Multiple lobes with individual beamwidths and steering angles can be produced from a single array. An EASE DLL allows Iconyx arrays to be accurately modeled in EASE 4.0 and higher.

19201 Cook Street, Foothill Ranch, CA 92610, USA . Phone: +1 949 588 9997 . Fax: +1 949 588 9514 . sales@renkus-heinz.com . www.renkus-heinz.com

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