Line Arrays: Theory, Fact and Myth

Line arrays have enjoyed a surge of popularity in recent years. This revived approach to acoustical control (formerly embodied in the familiar column loudspeaker) now dominates the large-scale touring market, and also has seen rapid growth in markets for smaller venues such as houses of worship.

Alongside a flood of new product introductions, the industry trend toward line arrays has generated some misleading assumptions — often the result of questionable marketing hype. This discussion outlines the basic theory and clarifies some points of possible confusion.

What is a line array?

A line array is a group of omnidirectional radiating elements arrayed in a straight line, closely spaced and operating in phase with equal amplitude. Described by Olson in his classic 1957 text, *Acoustical Engineering*, line arrays are useful in applications where sound must be projected over long distances. This is because line arrays afford very directional vertical coverage and thus project sound effectively.

The MAPP Online *(see sidebar about MAPP Online on page 4)* plots of Figure 1 illustrate the directional characteristics of a line array composed of sixteen omnidirectional sources uniformly spaced 0.5 meters apart. The array is highly directional to 500 Hz, but at higher frequencies the directional characteristic begins to break down. Note the strong rear lobe at low frequencies: all conventional line arrays will exhibit this behavior because they are omnidirectional in this range. (The M3D Line Array loudspeaker is, of course, the notable exception.) This configuration also generates strong vertical lobes at 500 Hz.

The horizontal pattern of this system is independent of the vertical, and is omnidirectional at all frequencies — though a practical system would show horizontal directionality at middle and high frequencies.

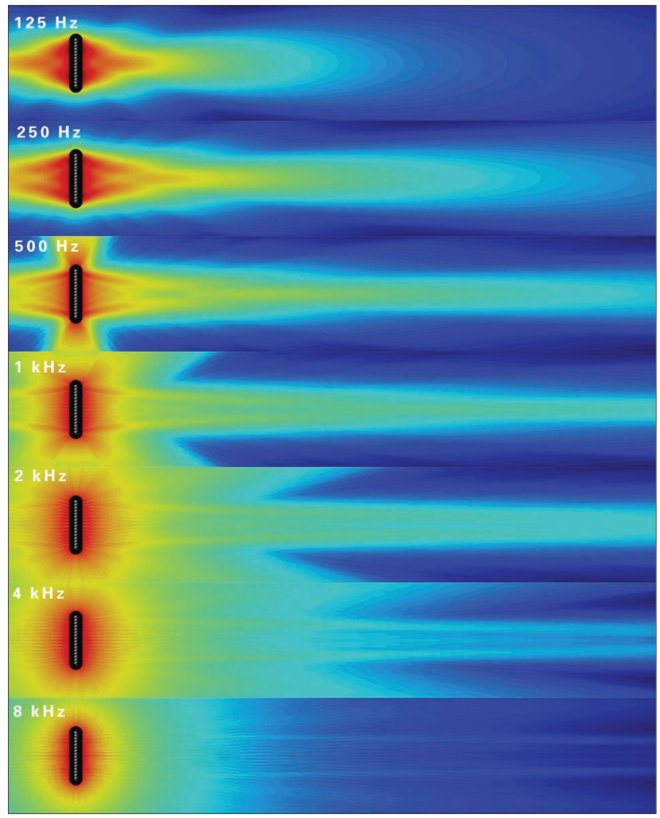

Figure 1: Directional behavior of an eight-meter long array of sixteen omnidirectional sources

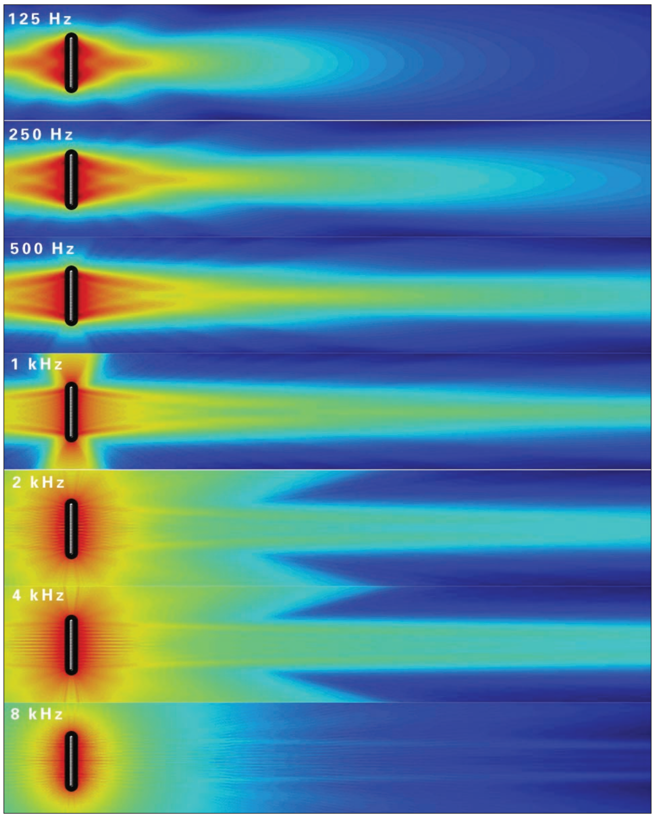

Figure 2: Directional behavior of an eight-meter long array of thirty-two omnidirectional sources

Figure 2 shows a line of thirty-two omnidirectional sources spaced 0.25 meters apart. Notice that this array maintains its directional characteristic to 1 kHz, where the strong vertical lobe appears. This illustrates the fact that directionality at high frequencies requires progressively more closely spaced elements.

How do line arrays work?

Line arrays achieve directivity through constructive and destructive interference. A simple thought experiment illustrates how this occurs.

Consider a single 12” cone radiator in an enclosure. We know from experience that this loudspeaker’s directivity varies with frequency: at low frequencies, it is omnidirectional, but as the sound wavelength grows shorter, its directivity narrows. Above about 2 kHz, it becomes too beamy for most applications. This is why practical system designs employ crossovers and multiple elements to achieve more or less consistent directivity across the audio band.

Stacking two of these loudspeakers one atop the other and driving both with the same signal results in a different radiation pattern. At points on axis of the two there is constructive interference, and the sound pressure increases by 6 dB relative to a single unit. At other points off-axis, path length differences produce cancellation, resulting in a lower sound pressure level. In fact, if you drive both units with a sine wave, there will be points where the cancellation is complete (this is best demonstrated in an anechoic chamber). This is destructive interference, which is often referred to as combing.

A line array is a line of woofers carefully spaced so that constructive interference occurs on axis of the array and destructive interference (combing) is aimed to the sides. While combing has traditionally been considered undesirable, line arrays use combing to work: without combing, there would be no directivity.

Can a line array really form a “cylindrical wave?”

In a word, no.

A common misconception regarding line arrays is that they somehow magically enable sound waves to combine, forming a single “cylindrical wave” with special propagation characteristics. Under linear acoustic theory, however, this is impossible. “Cylindrical wave” is a marketing concept, not a verifiable acoustical reality.

Unlike shallow water waves, which are non-linear and can combine to form new waves, sound waves at the pressures common in sound reinforcement cannot join together: rather, they pass through one another linearly. Even at the high levels present in the throat of compression drivers, sound waves conform to linear theory and pass through one another transparently.

The MAPP Online plot of Figure 3, which shows a cross-fired pair of Meyer Sound MSL-4 loudspeakers, illustrates this point. At the area labeled A, in the crossfire region, there is significant destructive interference in the dark areas. At the area labeled B, however, the output of the corresponding MSL-4 is completely unaffected by the cross-firing unit. Though the waves interfere at A, the interference is local to that area in space, and they still pass through one another unaffected. In fact, you could turn off the cross-firing unit and hear virtually no change whatsoever at B.

But don’t line arrays produce waves that only drop 3 dB with every doubling of the distance from the array?

This simplistic assumption results from a misapplication of classical line array theory to practical systems. Classical line array mathematics assume a line of infinitely small, perfectly omnidirectional sources that is very large compared with the wavelength of the emitted energy. Obviously, practical systems cannot approach these conditions, and their behavior is far more complex than is suggested by this assumption.

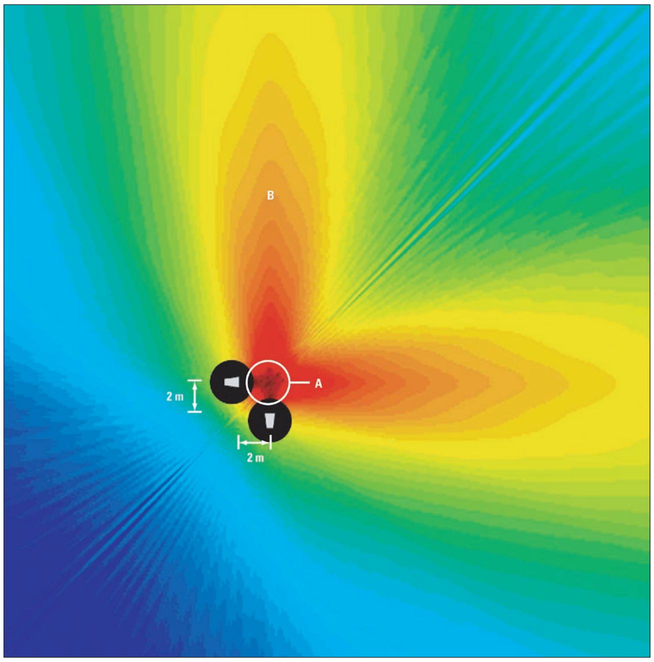

Figure 3: Cross-fired MSL-4 loudspeakers

By modeling the behavior of a 15” woofer with Bessel functions (which describe a piston), Meyer Sound has written custom computer code to model line arrays with various numbers of loudspeakers at various spacings. This computation shows that it is theoretically possible to construct an audio line array that follows the theory at low frequencies. However, the array requires more than 1,000 fifteen-inch drivers, spaced twenty inches center-to-center, to do it!

It is true that a truncated continuous line array will produce waves that drop 3 dB per doubling of distance in the near field, but the extent of the near field depends on the frequency of the sound and the length of the array. Some would have us believe that, for a hybrid cone/waveguide system, the near field extends hundreds of meters at high frequencies. It can be shown mathematically that this is true for a line of 100 small omnidirectional sources spaced an inch apart, but that is hardly a practical system for sound reinforcement and is not a model for the behavior of waveguides.

Nor does the purely theoretical computation reflect the reality of air absorption and its effects at high frequencies. Table 1 shows the attenuation at various distances from an array of 100 1” pistons spaced 1” apart, as modeled using a Bessel function. At 500 Hz and above, it also shows the total attenuation when

	2 meters	4 meters	8 meters	16 meters	32 meters	64 meters	128 meters	256 meters
125 Hz	0	5.5	11	17	23	29	35	41
250 Hz	0	5	11	17	23	29	35	41
500 Hz	0	2.3	7.2	13	19	25	31	37
w/air absorption								38
1 kHz	0	1.3	3.2	8.2	14	20	26	32
w/air absorption					15	21	28	35
2 kHz	0	3	5.2	7	12	18	24	30
w/air absorption				8	13	21	29	41
4 kHz	0	2.7	6.3	9	11	16	21	27
w/air absorption		3.1	7.1	11	14	23	35	59
8 kHz	0	2.8	5	8.6	11	13	18	24
w/air absorption		3.5	6	12	17	25	42	72
16 kHz	0	3.1	6.6	8.2	12	14	16	21
w/air absorption		4.1	8.6	12	20	33	49	88
3 dB per doubling	0	3	6	9	12	15	18	21
6 dB per doubling	0	6	12	18	24	30	36	42

Table 1: Attenuation in decibels for octave frequency bands at various distances from a line array of 100 1” pistons spaced 1” apart

air absorption is included using the calculation given in ANSI Standard S1.26-1995 (the conditions for this table are 20° C ambient temperature and 11% relative humidity). Note that, while at 16 kHz the array as modeled by the Bessel function is approaching 3 dB attenuation per doubling of distance, air absorption makes its actual behavior closer to 6 dB per doubling.

With a practical, real line array of sixteen cabinets (each using 15” low-frequency cones), a slight “cylindrical wave-like” effect can be measured at about 350 Hz, where there is a 3 dB drop between two and four meters from the array. More than four meters from the array, however, the sound spreads spherically, losing 6 dB per distance doubling. This behavior can be confirmed with MAPP using the measured directionality of real loudspeakers.

Meyer Sound’s MAPP Online

MAPP (Multipurpose Acoustical Prediction Program) Online (patent pending) is a cross-platform, Internet-enabled application that accurately predicts the behavior of arrayed Meyer Sound loudspeakers. MAPP Online has two components: a Java applet that runs on the sound system designer’s computer, and a prediction program that runs on a remote server.

Using the Java application, the sound designer configures Meyer Sound products and, optionally, defines the environment in which they operate — including air temperature, pressure and humidity, as well as the location and composition of walls. When the designer requests a prediction, data travel over the Internet to the server, which runs a sophisticated acoustical prediction algorithm using high-resolution, complex (magnitude and phase) polar data. The loudspeaker data used by MAPP are acquired at $1/24^{th}$ octave frequency resolution, and one degree angular resolution, in a calibrated anechoic environment. Predicted data return over the Internet and are displayed in color on the designer's computer.

MAPP Online’s Sound Field display comprises a map of the specified space with loudspeaker(s) installed, and the distribution of sound energy in a specified frequency band. The color spectrum signifies sound pressure level, with reds being the loudest and blues the softest.

MAPP Online is unique in its ability to accurately predict a system’s frequency response at any position in the sound field. Frequency response is a function of Virtual SIM, a mode that simulates measuring the system using SIM System II. MAPP’s frequency response predictions have been verified in an actual performance space using a physically realized sound system, and have been proven to be accurate (within the modeled parameters) to approximately ±1 dB at $1/24^{th}$ octave frequency resolution.

At frequencies below 100 Hz, the drivers in a practical line array will be omnidirectional but the array length will be small compared with the sound wavelength, so the system will not conform to line array theory. Above about 400 Hz the low-frequency cones become directional, again violating the theory’s assumptions. And at high frequencies, all practical systems use directional waveguides whose behavior cannot be described using classical line array theory.

In short, the geometry of real-world audio line arrays is far too complicated to be modeled accurately by “pure” line array theory. Rather, modeling with a useful degree of accuracy requires a computational code that uses a high-resolution measurement of the complex directionality of actual loudspeakers, such as MAPP Online.

That said, practical line array systems remain very useful tools, regardless of whether the continuous line array equation applies. They still achieve effective directional control, and skilled designers can make them behave very well in long-throw applications.

How do practical line array systems handle high frequencies?

Figures 1 and 2 show that line array theory works best for low frequencies. As the sound wavelength decreases, more and more drivers, smaller in size and spaced more closely, are required to maintain directivity. Eventually, however, it becomes impractical to use, for example, hundreds of closely spaced one-inch cones.

Practical line array systems therefore act as line arrays only in the low and mid frequencies. For the high frequencies, some other method must be employed to attain directional characteristics that match those of the lows and mids. The most practical method for reinforcement systems is to use waveguides (horns) coupled to compression drivers.

Rather than using constructive and destructive interference, horns achieve directionality by reflecting sound into a specified coverage pattern. In a properly designed line array system, that pattern should closely match the low-frequency directional characteristic of the array: very narrow vertical coverage and wide horizontal coverage. (Narrow vertical coverage has the benefit that it minimizes multiple arrivals, which would harm intelligibility.) If this is achieved, then the waveguide elements can be integrated into the line array and, with proper equalization and crossovers, the beam from the high frequencies and the constructive interference of the low frequencies can be made to align so that the resulting arrayed system provides consistent coverage.

Can you curve a line array to extend vertical coverage?

In practice, gently curving a line array can aid in covering a wider arc, and thereby extend the coverage area in the vertical plane. In fact, some line array systems such as Meyer Sound's M1D and M2D are termed "Curvilinear Array Loudspeakers" because they are designed specifically to allow curvature and still maintain optimum performance. Radically curving line arrays, however, introduces problems.

First, if the high-frequency section has the narrow vertical pattern that's required to make a straight array work, curving the array can produce hot spots and areas of poor high-frequency coverage. Second, while the curvature can spread high frequencies over a larger area, it does nothing to the low frequencies, which remain directional because the curvature is trivial at long wavelengths.

Figure 4 illustrates these points. On the left is a series of MAPP Online plots for a curved array, and on the right are plots of a straight array. Both arrays are constructed of identical loudspeakers having a 12" cone low-frequency driver and a high-frequency horn with a 45-degree vertical pattern.

Notable in the left-hand plots is that, while the wider horn aids in spreading the high frequencies, it also introduces pronounced lobing due to interference. At 1 kHz and below, the array remains highly directional, following line array theory. In practice, this behavior would produce very uneven coverage, with the frequency response varying substantially across the coverage area and a large proportion of that area receiving almost no low-frequency energy.

The right-hand series of plots reveals that a loudspeaker with a horn having moderately wide vertical coverage for curved arrays behaves poorly in a straight array. While the array is highly directional, pronounced vertical lobing occurs at 1 kHz and above. These strong side lobes divert energy from the intended coverage area and would excite the reverberant field excessively, reducing intelligibility.

In sum, it's unwise to assume that any line array can be radically curved and still provide the desired results. The acoustical properties of the particular system in question must be examined to determine if a curved configuration will give the desired results.

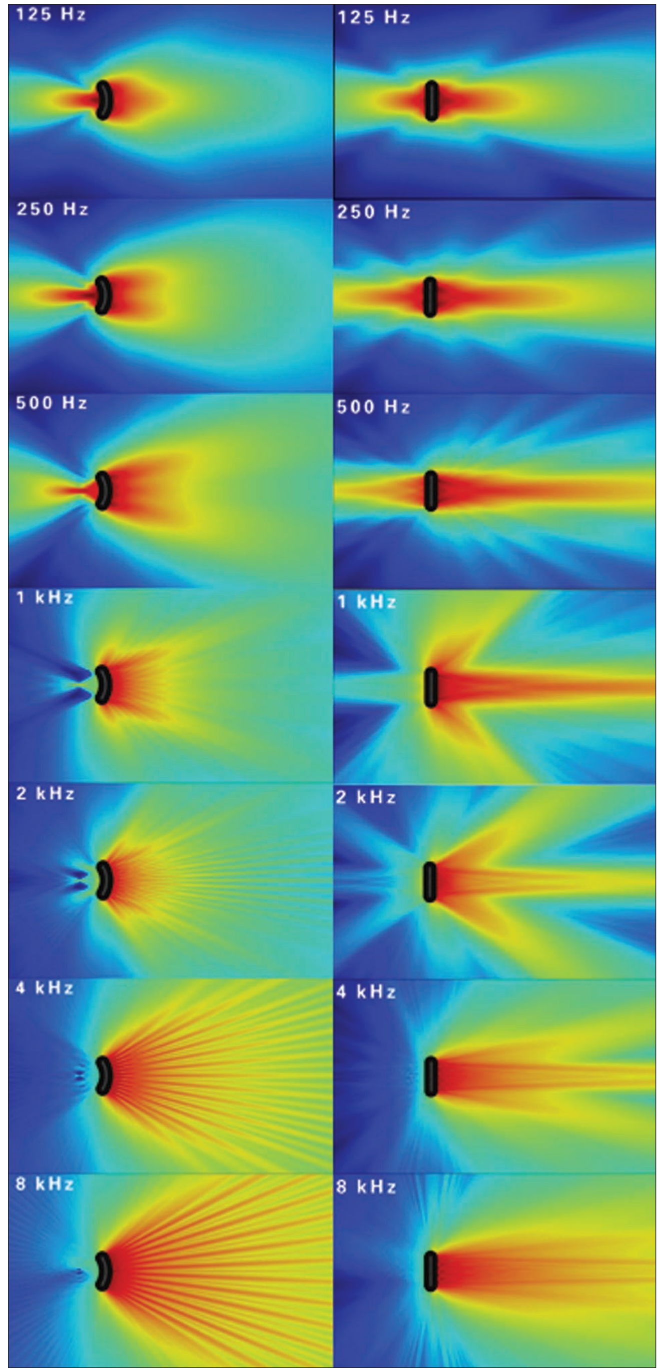

Figure 4: Directional characteristics of a curved (left) and straight (right) line array using a high-frequency horn with a 45-degree vertical pattern

Can you combine line arrays with other types of loudspeakers?

Yes, since sound waves pass unaffected through one another regardless of whether they are created by a direct radiator or a waveguide, it is possible to combine line array systems with other types of loudspeakers as long as their phase response matches. *There is nothing special about the sound waves that line arrays create.* They are merely the output of low-frequency cones, spaced using line array theory, and high-frequency waveguides. Therefore, skilled designers with the proper tools can flexibly integrate other compatible types of loudspeakers to cover short-throw areas.

In practice, larger and smaller versions of similar line arrays can work extremely well together, as a proper design will give the two versions similar coverage patterns. For example, Meyer Sound's M2D Compact Curvilinear Array loudspeaker is designed to work seamlessly as a front fill system underneath an M3D Line Array loudspeaker system.

How do line arrays behave in the near and far field?

As we have seen, practical "line array" systems as used in high-power applications are actually a combination of "classical" line arrays for the low frequencies and highly directional waveguides for the high frequencies. Because of this hybrid nature, it is difficult to apply predictions from classical line array theory across the whole audio spectrum. Nonetheless, line array systems can be made to work reasonably well in both the far field and moderately close to the array.

Seen from the far field, the outputs of the individual sources in a line array combine constructively, and appear to operate as one source. Figure 6 illustrates this concept. The figure shows the far-field frequency response for line arrays of two, four and eight omnidirectional radiators (a single omni response is included for reference) spaced 0.4 meters apart. Notice that each doubling of the number of elements results in a uniform 6 dB level increase across the full frequency range of operation. The high-frequency response is smooth, but reflects a natural rolloff due to air absorption (20 degrees C and 50% relative humidity).

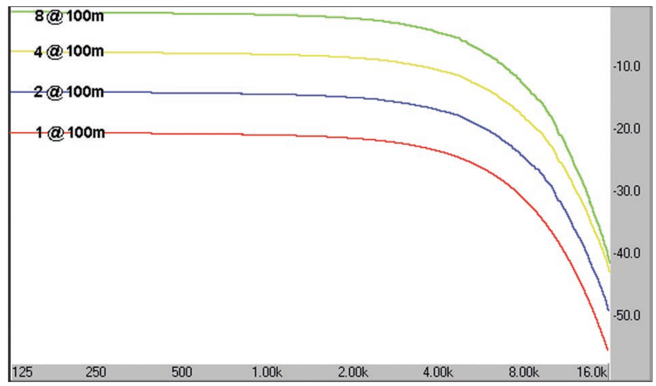

Figure 6: Far-field frequency response for line arrays with various numbers of sources showing high-frequency loss due to air absorption and humidity

The near-field behavior of practical line arrays is more complex. Any given point in the near field is on axis of only one of the very directional high-frequency horns, yet "sees" the low-frequency energy from most of the cabinets in the array. For this reason, adding cabinets to the array boosts the near-field low-frequency energy, but the high frequencies remain the same.

This explains why line array systems need high-frequency boost equalization. In the far field, the equalization effectively compensates for air loss. In the near field, it compensates for the constructive addition of the low frequencies and the proximity to the directional high-frequency waveguide.

How does the M3D compensate for the real-world limitations of line arrays?

Figure 7 illustrates how a low-frequency line array and high-frequency waveguides can be integrated to form a well behaved, consistent system. It shows the directional characteristics of a line array comprising sixteen M3D Line Array loudspeakers. By virtue of the M3D's REM (Ribbon Emulation Manifold) and constant-directivity horn, the high-frequency radiation pattern closely matches that of the low frequencies.

Note, also, the absence of any significant rear lobe at low frequencies. This illustrates the advantages of the M3D's low-frequency directional technology. There is also virtually no vertical lobing at 500 Hz, as was seen in the omni array of Figure 1, because the 15" cone drivers and the high-frequency horn are aligned in this region to work together and suppress off-axis energy.

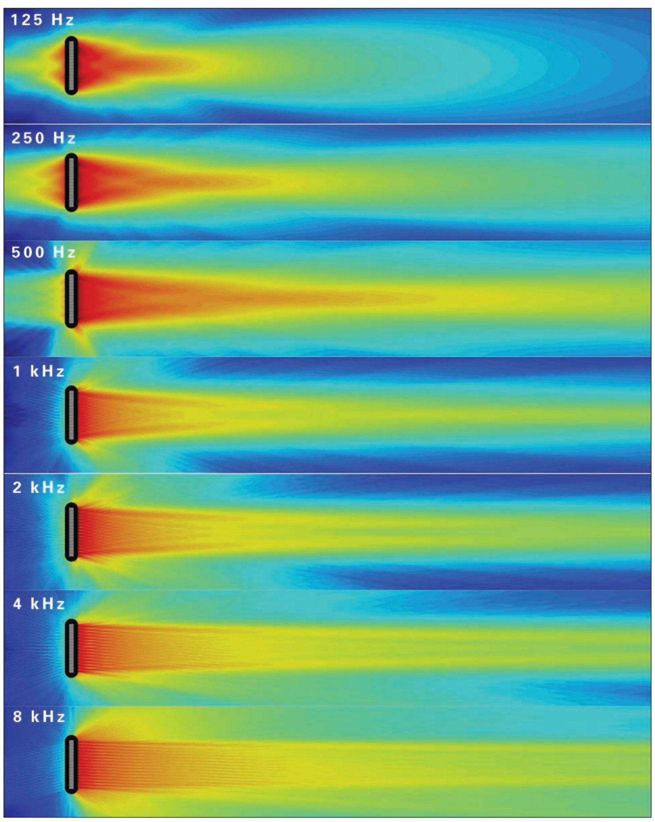

Figure 7: Directional behavior of an eight meter long array of sixteen M3D Line Array Loudspeakers

So, when is a line array the preferred solution?

Though some might suggest that a line array is the ultimate solution in all situations, this is decidedly not the case. In general, the line array is best suited to applications where broad horizontal coverage is desired throughout a given space, combined with long throw and relatively narrow vertical beamwidth. In contrast, for short-throw applications, or other situations where greater vertical beamwidth or narrower horizontal coverage is desired, single cabinets solutions or conventional "cluster" arrays usually provide better results. Also, although smaller line arrays can be used successfully in distributed systems, conventional single cabinets or small clusters generally prove more cost-effective.

MEYER SOUND LABORATORIES INC.
2832 San Pablo Ave.
Berkeley, CA 94702

T: +1.510.486.1166
F: +1.510.486.8356

18.990.158.01