



Audio Engineering Society Convention Paper

Presented at the 111th Convention
2001 November 30-December 3 New York, NY, USA

This convention paper has been reproduced from the author's advance manuscript, without editing, corrections, or consideration by the Review Board. The AES takes no responsibility for the contents. Additional papers may be obtained by sending request and remittance to Audio Engineering Society, 60 East 42nd Street, New York, New York 10165-2520, USA; also see www.aes.org. All rights reserved. Reproduction of this paper, or any portion thereof, is not permitted without direct permission from the Journal of the Audio Engineering Society.

Directional Radiation Characteristics of Articulating Line Array Loudspeaker Systems

Mark Engebretson
JBL Professional
Northridge, CA USA

ABSTRACT

Directional radiation characteristics of a new form of line array—the articulating line array—are examined. Based upon a single three-way, horizontally symmetrical loudspeaker with variable unit-to-unit vertical splay angles, these components are capable of being configured into straight-line arrays, uniformly and non-uniformly curved arc arrays, progressive arc and J-form arrays. A unique system of suspension hardware provides a continuous baffle surface, and results in rigid array structures that can be flown in any attitude, from one or two points, as required. This paper will compare calculated polar responses and polar measurements for examples of line array systems. Conformance between the calculated and measured performance serves to validate the predictive model, confirming the configuration and arrayability of the radiating elements.

INTRODUCTION

Line arrays are a recent market trend. Not all line arrays are the same, however, and there are widespread misconceptions about how line arrays work and perform. Knowledge of line array behavior is important in understanding the directivity of different array configurations, and the management of array coverage areas. Separating fact from fantasy requires taking acoustic measurements under controlled conditions, and application of scientific principles to interpret the resulting data.

These systems pose unique challenges to sound system owners and operators. The effects of line array summation and box articulation angles can

produce coverage patterns that frequently depart from the intuitive.

Prior experience in the optimization of traditional fan-shaped multi-box arrays does not translate directly to line array systems. Line array deployment and operation is affected by variables in array size, box splay angles, and drive signal processing. It is important that these choices are based upon reliable work that has been scientifically developed. This approach has more validity than assumptions or hearsay.

JBL has developed a software application that allows the accurate prediction of directional

radiation characteristics of its line array system. This enables systems to be deployed with the assurance that the program's predictions will accurately conform to measured performance. Measurements under controlled conditions and listening sessions during system development have shown that computed and measured data correlates well.

HORIZONTAL DIRECTIVITY

A logical configuration for multi-band line arrays finds its genesis in a loudspeaker configuration first suggested by Joseph D'Appolito¹ in 1983. This configuration places the high frequency transducer in the middle of the system, flanked on either side by devices that cover frequencies immediately below. In a three-way system there are 2 more speakers outside the two mid-band drivers flanking the tweeter.

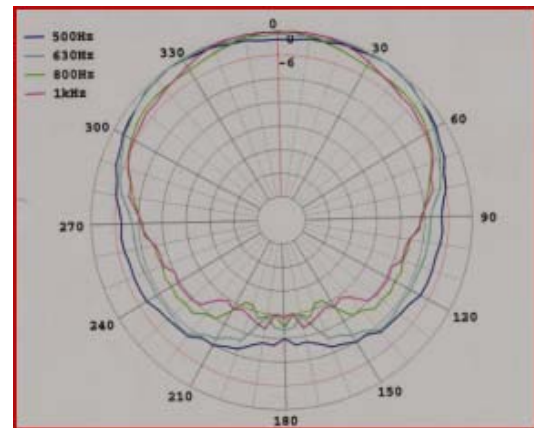
Christian Heil later introduced a variant of the D'Appolito configuration, using compression drivers for high frequencies. An additional twist was the subtle detail of "toeing in" of the midrange devices to reside inside the "wave guide" for the high frequencies. This allows the effective lateral dimension of the midrange devices to be smaller thereby enabling wider horizontal dispersion.

In the JBL line array product, we have adopted the D'Appolito-Heil configuration with the addition of a third compression driver, more powerful transducers and a midrange phasing plug like device, which serves as an improved high-frequency wave guide while also providing a smaller mid-frequency array to maintain wide horizontal dispersion to a higher frequency.

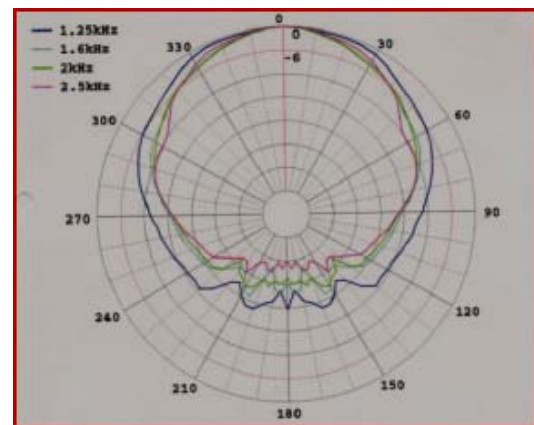


VT4889 LINE ARRAY COMPONENT

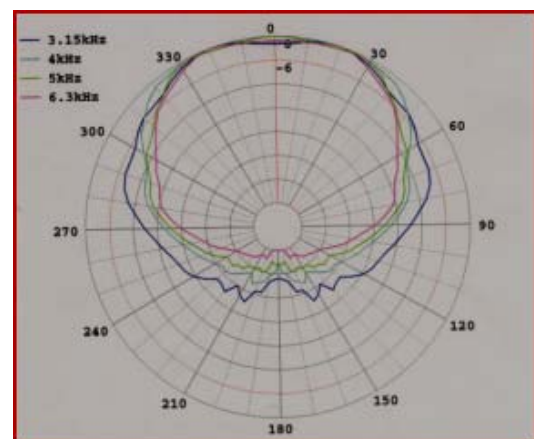
A single VT4889 is shown above. The horizontal directivity of arrays of VT4889s will be that of a single cabinet, and is shown in polar form.



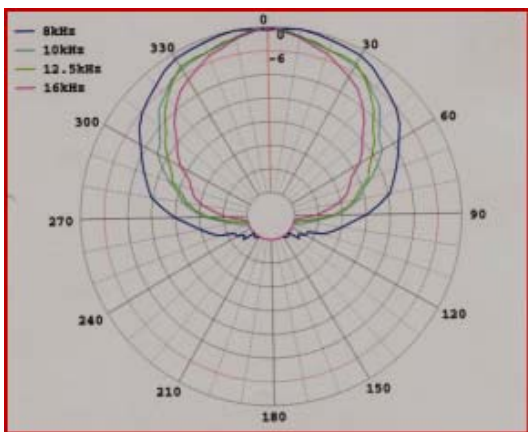
500 Hz – 1 kHz HORIZONTAL POLARS



1.25 kHz – 2.5 kHz HORIZONTAL POLARS



3.15 kHz – 6.3 kHz HORIZONTAL POLARS



8 kHz – 16 kHz HORIZONTAL POLARS

VERTICAL MEASUREMENTS

Vertical directivity data were derived from ground-plane MLSSA impulse measurements taken at 20 meters on 5-degree intervals over 360-degrees. Data gathering took place inside a vacant airplane hangar to prevent wind-borne temperature gradients and other disturbances.



GROUND PLANE MEASUREMENT SETUP

The photo shows an array of eight cabinets configured for ground plane data gathering. The eight boxes are shown set on end, with 5-degree splay angles between adjacent cabinets.

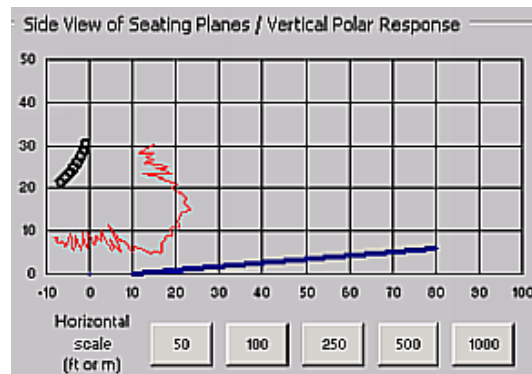
Measurements of one, two, four, six and eight-box arrays at various cabinet-to-cabinet splay angles document different array performance characteristics and validate the software used to predict directivity for arbitrary arrays.

LINE ARRAY CALCULATOR

A Microsoft Excel™ Line Array Calculator program has been designed to predict the vertical directivity of different line arrays and preview the resulting performance characteristics. JBL's Line Array Calculator is not just a hypothetical prediction tool. The algorithms that calculate

array performance and drive the graphic displays have been correlated with actual measurements.

The VERTEC Line Array Calculator allows the design engineer to select the number of array elements and individually adjust the splay angles between adjacent elements. The designer can specify the front-to-back distances as well as the slope of up to three seating planes, all relative to the location of the line array.



PREDICTED 2 kHz VERTICAL POLAR RESPONSE

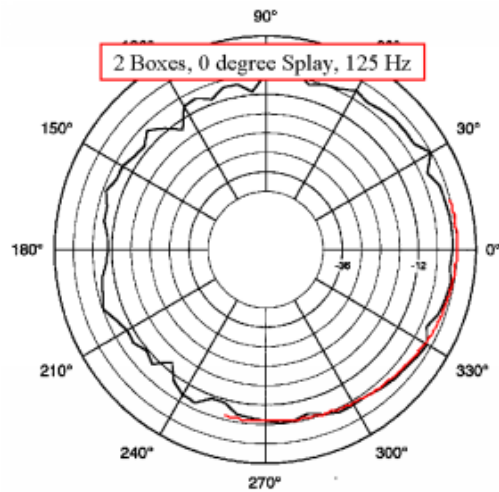
The program asks the user to select an ISO-preferred one-third octave center frequency between 100 Hz to 20 kHz. When the frequency is selected, the program calculates the far-field vertical polar response of the line array on 1-degree increments and projects the directional response onto the selected seating plane to graphically show the front-to-back coverage variation in dB.

Useful mechanical and rigging information, including dimensions, array weight, weight distribution and center-of-gravity is available on a separate rigging page.

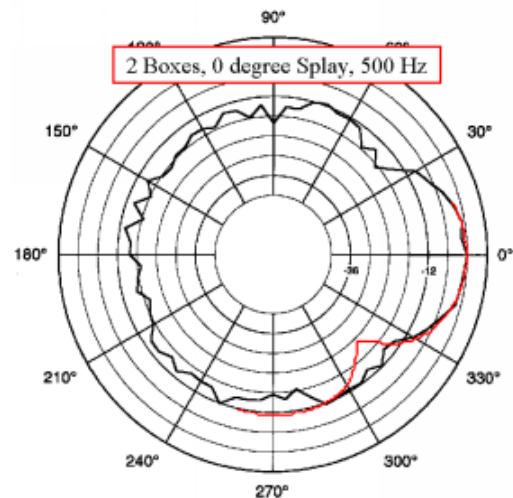
PREDICTIONS vs. MEASUREMENTS

In the following polar charts, predicted vertical polar responses from the line array calculator have been re-scaled and superimposed on the respective measured polar data.

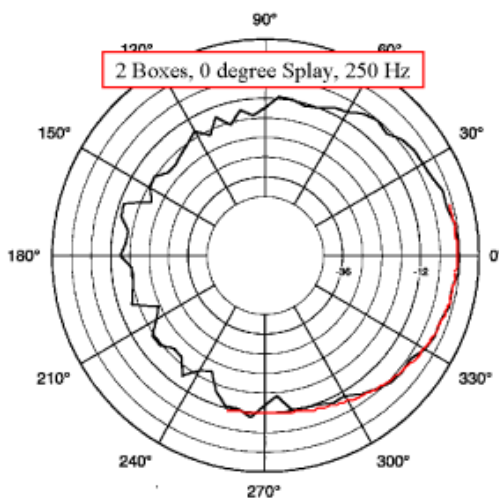
The series of charts on pp. 4-8, showing 2-box, 4-box, 6-box and 8-box arrays splayed at 0 degrees, 5 degrees and 10 degrees over a range of specific frequencies, provide a visual tool for evaluating the correlation of predicted versus measured polar data for the arrays.



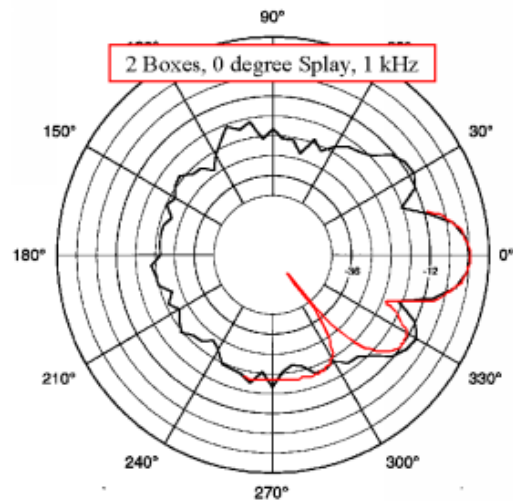
The polar responses are derived from MLSSA data taken on 5-degree intervals, whereas the polar data produced by the Line Array Calculator are computed on one-degree increments. The design program computes the response for the 120° included by 15° above the horizontal and 15° past vertical, independent of the simulated array axis.



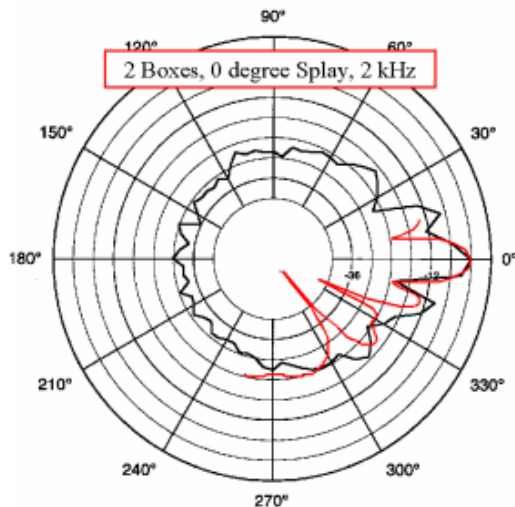
At long wavelengths (i.e. low frequencies), the Line Array Calculator remains accurate over fairly wide angles for small arrays. For the two-cabinet arrays, the calculated polar response shows 120° of radiation with the array aimed straight ahead in the simulation, to show the response immediately below the array.



The calculator does not recognize diffraction or boundary conditions. As such, off-axis accuracy near cabinet boundaries will vary, depending upon array size and frequency.



The correlation between the measured and predicted polar responses can be seen. The 5° measurement intervals are much wider than the calculations, but the lobe and null structure are clearly evident and nearly identical.



between the measured and the predicted is nevertheless evident.

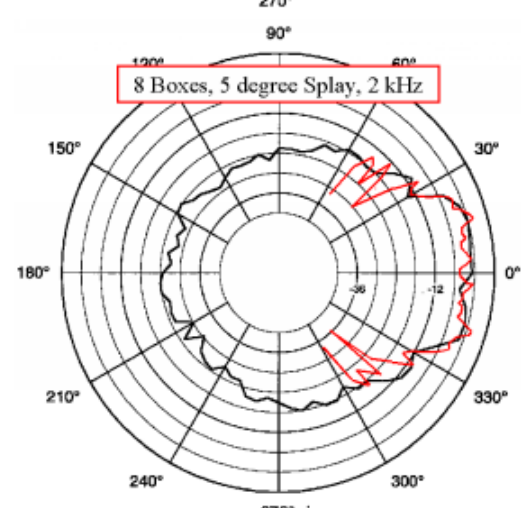
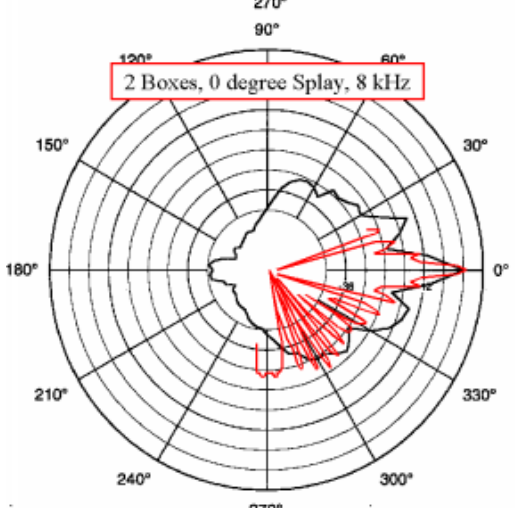
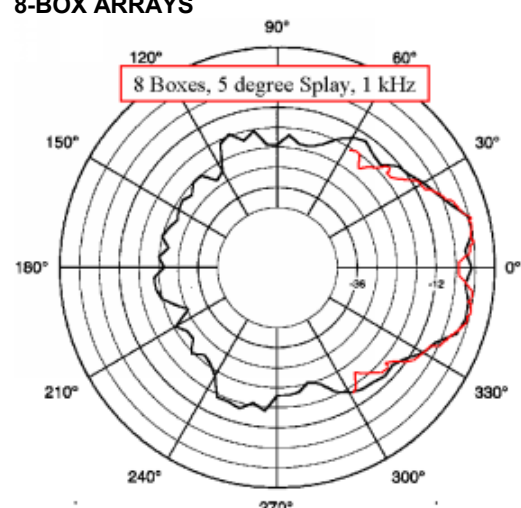
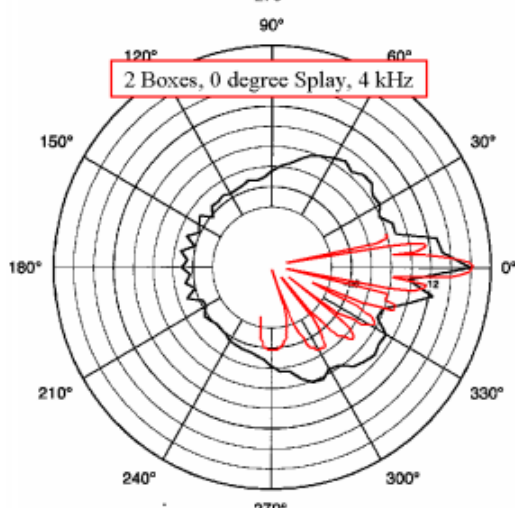
The half-pressure beam width of a straight line array can be estimated by²:

$$\theta_{-6\text{ dB}} = \frac{24,000}{f l} \quad [1]$$

(l in meters, f in Hz)

This indicates the -6 dB beam width at 8 kHz for an array of two cabinets (one meter length) will be approximately 3 degrees, which is consistent with both the measured and calculated results.

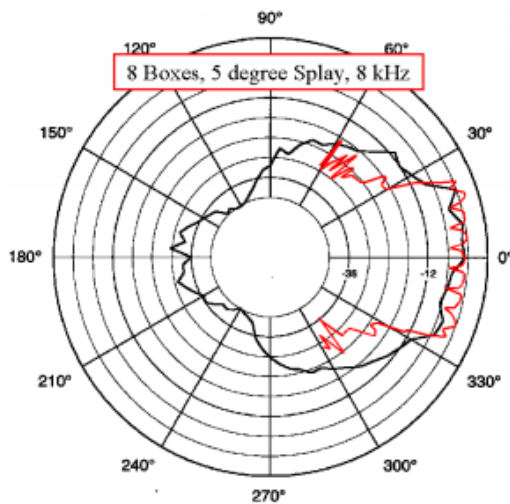
8-BOX ARRAYS



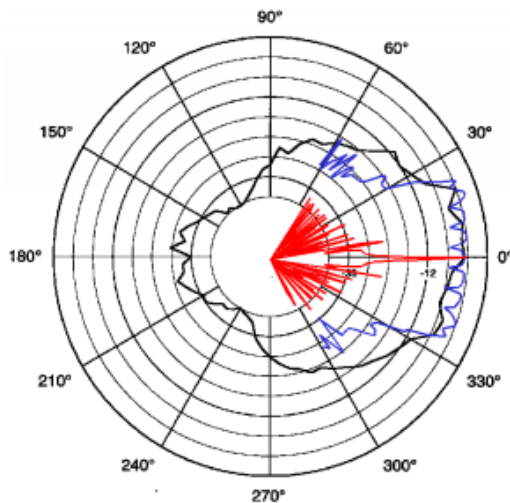
The narrowing of the polar response at high frequencies is shown above. Although the polar narrowing at high frequencies in line arrays will most often exceed that which can be properly resolved by 5° measurements, the consistency

For these 8-element predictions, the simulated loudspeaker array was rotated to calculate the polar response with the axis of radiation centered within the calculator's 120° 'window', then re-rotated to conform to the measurement

convention. The resulting 120° polar response plot is symmetrical to the 0° axis.

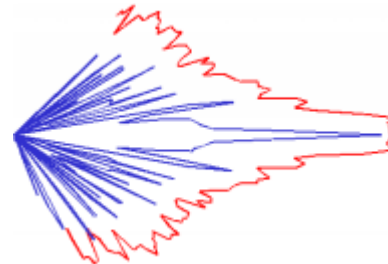


The computed 8 kHz polar response shows about 5 dB lobe-to-null 'fingering' within approximately 40° of vertical coverage between -6 dB points. This is contrasted below with the simulated vertical polar response for 8 cabinets at 0° splay, which results in 0.75- degrees between -6 dB points at 8 kHz.



This clearly shows that large, straight arrays produce extremely narrow quarter-power angles at high frequencies. Such arrays are extremely difficult for operators, and must be aligned with great care and precision. In most cases, straight line arrays are sufficiently narrow in vertical coverage at high frequencies to be of limited practicality.

Comparing the 8 kHz simulated polar responses of an 8-cabinet array having 0° splay between cabinets to the same array with 1° splay angles between cabinets reveals similar polar shapes, but with substantially greater useable energy available from the splayed array.



This suggests that applications that call for 'long throw' elements might be better served by array configurations that employ a modicum of splay between elements.

Contrast this with the opposite extreme, an 8-element array with 10° splay angles between cabinets. The resulting simulated polar response shows 80° included between the outermost -6 dB points, 8 lobes and 7 nulls, having approximately +/- 10 dB ripple at 8 kHz.



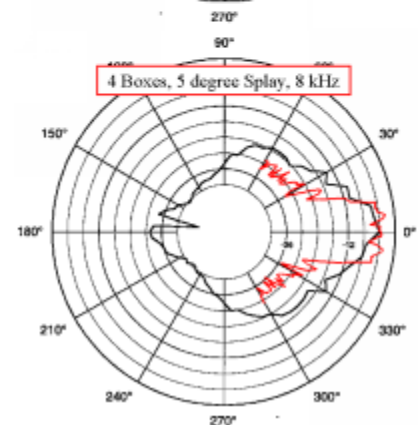
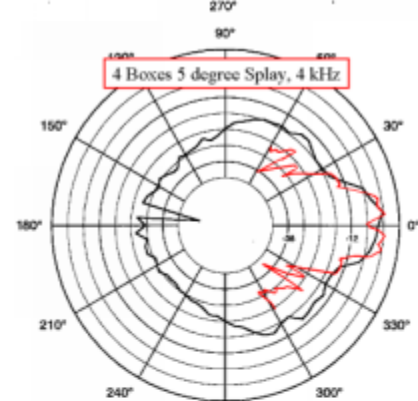
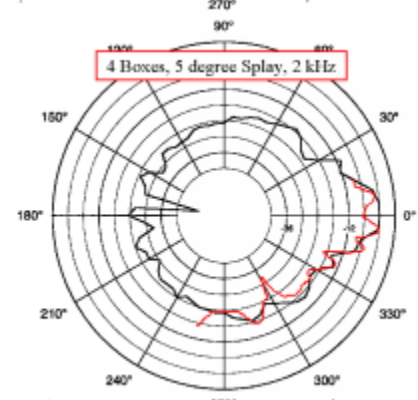
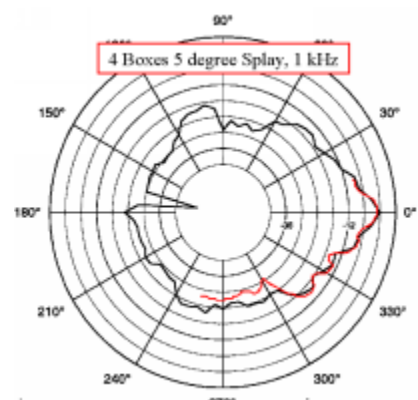
Such an array might be useful in providing wide-angle coverage, although primarily at speech frequencies which would be less affected by the lobes and nulls in the vertical polar response.

The Line Array Calculator simulates polar responses for far field conditions³, found by:

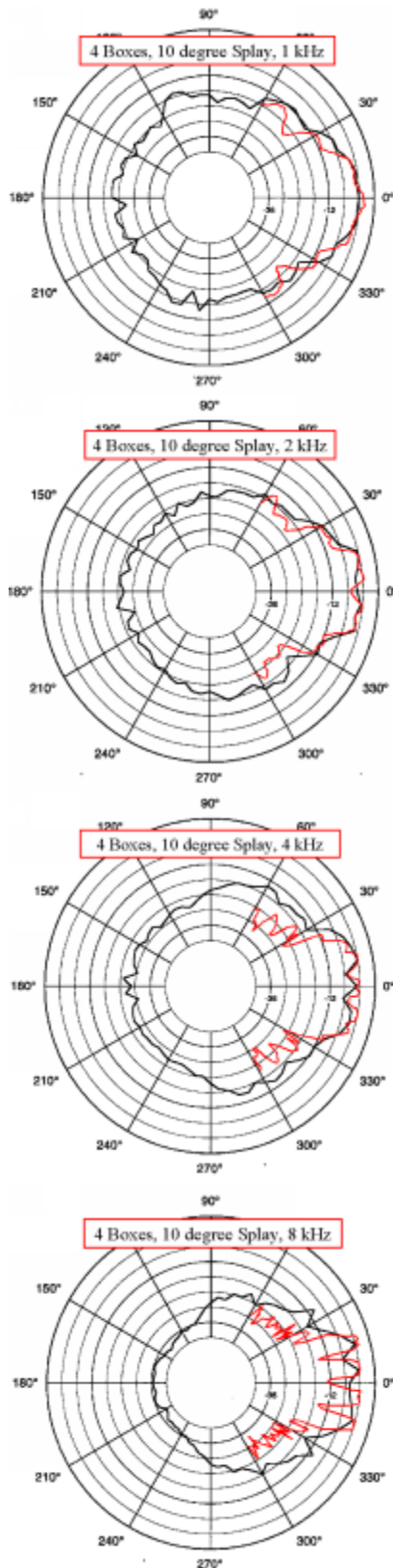
$$r = \frac{l^2 f}{700} \quad [2]$$

(l in meters, f in Hz)

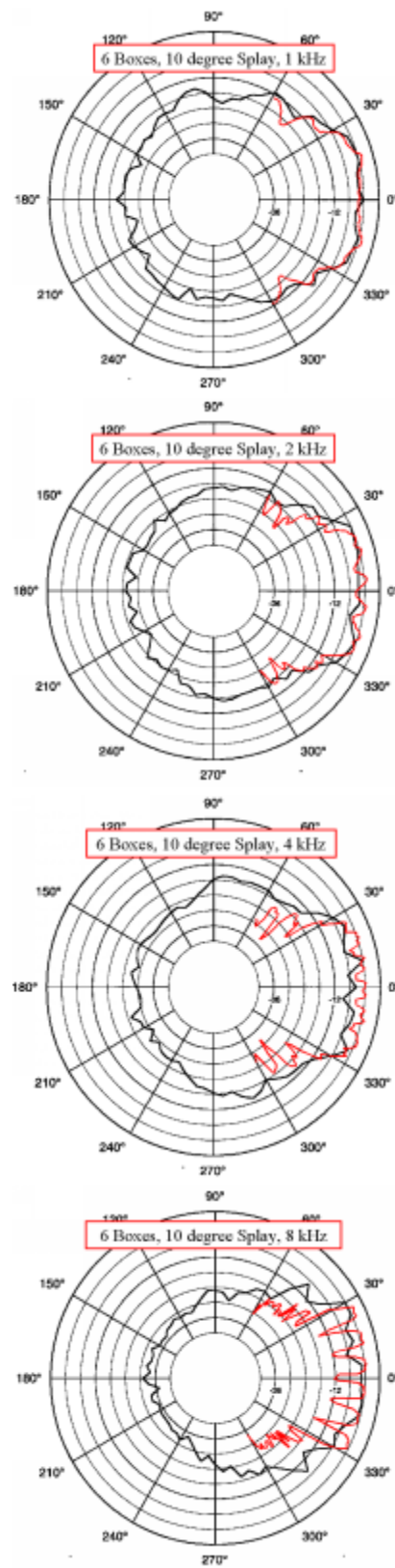
4-BOX 5° SPLAY POLARS



4-BOX 10° SPLAY POLARS



6-BOX 10° SPLAY POLARS



LINE ARRAYS IN-SITU

We have examined line array vertical directivity measurements made under controlled conditions and compared these to simulations produced by the Line Array Calculator. These efforts have resulted in substantial knowledge and several new insights into line array behavior. Reducing this information to a body of practice suitable for recommendation to customers and system users required the installation and operation of many different systems in actual-use environments.

One of the environments selected for systems development was a large Southern California outdoor amphitheater, which was secured for an extended period. Straight, curved, compound J-form and progressive spiral arrays, consisting of from four to eighteen elements, were examined under use-conditions. These investigations proved extremely valuable in establishing cause-and-effect array configuration criteria affecting coverage and sound quality.



8-BOX ARRAY IN-SITU

Another product of the field trials was a family of DSP templates that address the frequency-

directivity characteristics of various array sizes and shapes.

LINE ARRAY SIGNAL PROCESSING

Crossover topology and slopes were derived from electro-acoustic transfer characteristics measured in-situ. In the horizontal direction, VerTec arrays reflect the horizontal polar response characteristics of a single enclosure. Signal processing can affect horizontal coverage, however. The VerTec system geometry places the high frequency elements at the center of the horizontal array, flanked symmetrically by mid-frequency devices, followed by the low-frequency sections at the outside.

The width of the array in each frequency band and choice of crossover frequencies allow nominal 90-degree horizontal coverage to beyond the cross over points. Maintaining uniform on- and off-axis responses requires matching directivities through the crossover region for the mid-to-high frequency transition, and crossing over sufficiently low in frequency as to minimize the directivity disparity in the low-to-middle frequency transition region.

Signal processing affects the vertical coverage. Line array performance predictions often ignore the fact that there are different elements overlapping in the vertical direction, as well as in the horizontal direction. In the mid-to-high frequency crossover region, for example, we have mids and highs operating simultaneously, which produce greater interference in the vertical direction than experienced within the individual sections alone. While specific levels of interference are not quantified in this paper⁴, high-order filters were observed to result in improved vertical coverage uniformity as well as superior subjective sound quality.

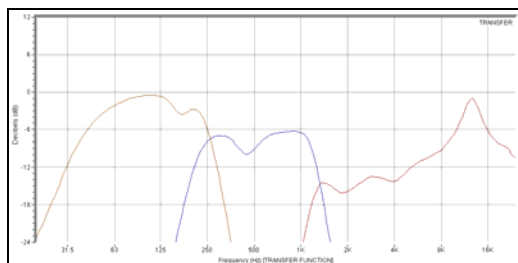
It is important to minimize the frequency overlap region, thereby minimizing imprinting the (larger) dimensions of the lower frequency section above the crossover.

In addition to using 8th-order filters to minimize frequency overlap (hence improving coherency), program equalization filters in the DSP templates were employed to normalize transducer power response, and compensate for directivity changes with different array geometry.

Band-to-band program delay offsets for each supported DSP platform were finalized *after*

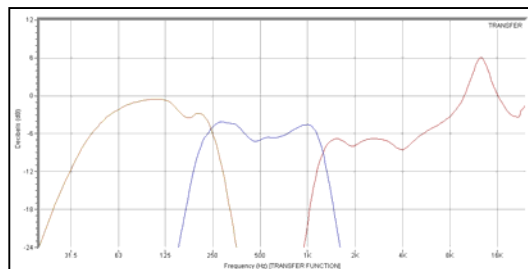
bandpass filter assignments and PEQ, thereby encompassing all filter group delays and DSP platform latencies, which were different for each supported device. This is an iterative process.

Different array shapes (i.e., straight, curved, compound J-shape and progressive spiral) will have different directivity characteristics, especially at high frequencies. As we have seen, the included coverage angle of a straight array will be inversely proportional to frequency. The more straight the array, the more directivity it will have at high frequencies. Straight arrays will require less high frequency equalization than arrays that employ mild-to-moderate splays for a given throw distance.



4-BOX 1° SPLAY MAGNITUDE

Shown above is the transfer magnitude for a small 4-box array having 1° uniform splay angles between cabinets. Below, we see the magnitude required for comparable acoustic response from a 4-box array employing uniform 6° splay angles between cabinets.



4-BOX 6° SPLAY MAGNITUDE

Frequently, the vertical coverage requirements are such that the loudspeakers must cover a wide angle, with loudspeaker-to-listener distance variations approaching 10:1 in certain outdoor venues. This gives rise to the compound, or J-shape line array, wherein a straight (long throw) section is joined to a curved section, to satisfy coverage requirements.

Where atmospheric absorption of high frequencies fortuitously compensates for the

difference in directivity between the short- and long-throw components, a single program equalization template is sufficient, with changes in amplifier gains to 'level-shade' the close-in elements. With larger venues, the throw and coverage requirements may require separate signal processing for short and long throw loudspeaker elements in addition to level adjustments. These are referred to as 'split processed' arrays.

An especially interesting configuration is the 'progressive spiral' array, wherein the splay angles increase from top-to-bottom, as in 1°, 2°, 3°, 4°, etc. These arrays change slowly in directivity, normally requiring only level adjustments to the near-throw components to achieve virtually seamless coverage from front-to-back in all but the largest venue.

THE DSP FILES

JBL has prepared a family DSP template files for 26 different line array configurations for each of three supported DSP platforms. These DSP templates accommodate straight-line arrays, uniformly and non-uniformly curved arc arrays, compound J-form and progressive spiral arrays.

These line array elements can be used in a wide variety of ways. This flexibility, while providing the system user with many array setup options, requires careful selection of DSP template files for optimum acoustical results.

JBL Technical Notes Vol. 1 No. 27 describes⁵ various array shapes that will be encountered during system use and considerations that must be taken into account when using these DSP templates on supported system controllers. The eight-digit file name incorporates information as to array size and shape, single or split processing, and source designation for the file.

CONCLUSION

Line arrays are high-directivity loudspeaker systems. Line array directivity derives from cumulative off-axis losses, rather than from some mysterious cylindrical radiation properties. It has been shown that tools exist to accurately predict the directional radiation characteristics of line array systems. The predictive software tool has been shown to have excellent correlation to controlled acoustic measurements, and these characterizations have been shown to correlate to actual performance in suspended array applications.

REFERENCES

¹ D'Appolito, J., "A Geometric Approach to Eliminating Side Lobing Error in Multiway Loudspeakers", presented at the 74th Convention of the AES, JAES (abstracts), vol. 31, no. 12, p. 968 (Dec. 1983) Preprint #2000.

² Ureda, M., "Line Arrays: Theory and Applications", presented at the 110th convention of the Audio Engineering society, 2001 May 12-15, Amsterdam, the Netherlands, p. 4

³ Ibid, p. 7.

⁴ Wilson, R., Adams, G., Scott, J., "Application of Digital Filters to Loudspeaker Crossover Networks", J. Audio Eng. Soc., Vol. 37, No. 6, pp. 459 – 461, (1989 June).

⁵ JBL Professional, Technical Notes, Vol. 1, No. 27, "Signal Processing Guidelines for VT4889 VerTec™ Line Array Systems", (2001 September).