Line Arrays for Live Sound

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Line array systems are now the forerunner in large scale live sound reinforcement. This report describes why they have become so accepted and widely-used over the last two decades, explores different arrangements of arrays and why these are necessary, the benefits they have over more traditional horizontally clustered systems in both directionality and high frequency throw and how these are achieved. It also illustrates practical advantages, disadvantages, cabinet design and techniques for setup, configuration and touring.

1 Background

In the 60s and 70s, sound reinforcement systems used in popular music concerts were often not sufficient to compete with the high levels of cheering, clapping and screaming from the audience. It was necessary to begin using an increasing number of speaker cabinets to provide the sound pressure level required, which were usually horizontally arrayed in clusters with a ‘point and shoot’ philosophy and stacked on the side of stage [Webb 2003, 1]. There were some inherent difficulties with this system.

- There was often an irregular frequency response due to destructive interference from the closely stacked cabinets; also added to by the lack of HF coupling and the relative abundance of LF coupling.
- Systems were generally short throw, again due to the lack of HF coupling, requiring the use of delay stacks at regular intervals.

- Significant floor or stage space was required to stack such a large number of physically large cabinets.

These systems started to be superseded by line array systems in the 80s and 90s. These feature a vertical arrangement of specially designed loudspeakers that produce a highly directional sound beam in the vertical plane. They were developed from earlier designs, also known as column loudspeakers, which comprise a tall cabinet with a number of equally spaced, identical drivers, and were historically installed in reverberant environments, such as churches or railway stations to aid vocal clarity for announcements.

Among the advantages of line arrays are their increased directivity in the vertical plane allowing HF to be projected further, a more consistent frequency response, improved direct to reverberant ratio and the convenience of a modular package that can easily be flown above the stage [Webb 2003, 1-2] [Klepper 1963, 198].

2 The importance of distance

It is important when considering line arrays to define the difference between near field and far field, as this characteristic provides the extended HF throw [Webb 2003, 2]. The far field is identified by a sound pressure level which decreases at 6dB for every doubling of distance. In the near field the sound pressure level undulates and decreases nominally at 3dB per doubling of distance [Ureda 2001, 6].

This is an oversimplification however. It has been suggested in the past that the array creates a cylindrical wave front in the near field, providing the 3dB drop off per doubling of distance, and transforms to a spherical one at some point. However, it is more accurate to consider the near field as an interference field. A point on the line array outputs a signal which will not be in phase with another point on the line, creating destructive interference. This is more prominent at high frequencies because they create more interference than low frequencies, due to the shorter wavelengths. When the far-field boundary is crossed, the interference has diminished enough for the SPL to decay as normal [Button 2002, 2].

There are many different opinions of when the far field starts. One source states: "The far field typically begins at a distance about 8 or 10 times the longest dimension of the array, and the critical distance (the transition point from near field to far field) is frequency dependant" [Eargle 2000, 3]. Mark Ureda however shows it slightly more mathematically, stating "The transition point can be estimated if we set as a criterion that the far field is reached when the distance to P from the center [sic] point of a line array is within a quarter-wavelength of the distance to P from the endpoint of the array” [Ureda 2001, 6].

This can be shown geometrically in Figure 1 and mathematically as such:

$$r = r' - \frac{\lambda}{4} \quad \textit{(Eq 2.1)}$$

where r = distance to far point from line centre

r' = distance to far point from line end

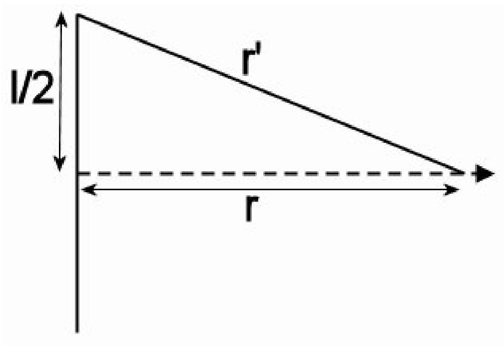


Figure 1 - *The far field starts when* $r' - r \le \frac{\lambda}{4}$ [Ureda 2001, 6]

To solve this gives:

$$r' = \sqrt{\left(\frac{l}{2}\right)^2 + r^2} \quad \textit{(Eq 2.2)}$$

For the distance to the far field *r*, we combine and rewrite this equation as such:

$$r = \frac{l^2}{2\lambda} - \frac{\lambda}{8} \text{ where } l \ge \frac{\lambda}{2} \quad \textit{(Eq 2.3)}$$

This can be converted to a more useful equation using frequency quite simply:

$$r = \frac{l^2 f}{664} - \frac{82}{2f} \text{ where } f \ge \frac{166}{l} \quad \textit{(Eq 2.4)}$$

The $\frac{\lambda}{8}$ or $\frac{82}{2f}$ term can be dismissed in cases where $\lambda \le \frac{l}{2}$ as it becomes insignificant [Ureda 2001, 6-7].

Plotting this equation for various values of *l* (figure 2), shows that the distance to the far field increases with increasing frequency (as stated by Eargle), and also with the length of array. To take an example, for a 4m line array, we get transitions to far field at about 2m at 100Hz, 24m at 1kHz and 242m at 10kHz, while these are more like 10m at 100Hz, 100m at 1kHz and 1000m at 10kHz for an 8m long line.

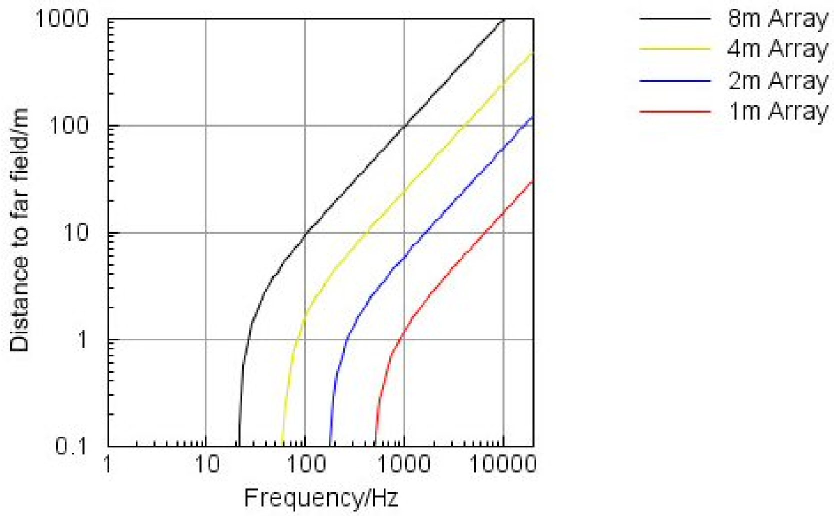


Figure 2 – Distances to far field for lengths of line array 1m, 2m , 4m and 8m

The transition point has also been estimated by a similar procedure, but stating the difference between *r* and *r'* should be within a half-wavelength instead of a quarter-wavelength [Kinsler 1982, 187-188].

There are a number of ways of estimating where the far field may start, but the most important thing is to consider that it's frequency dependant.

3 Directivity

Increased directivity in the vertical plane is a great advantage of line arrays, and is covered by Mark Ureda in great detail in several AES publications, as well as in well-documented and referenced acoustics theory from 70 years ago.

3.1 Problems with multiple point source systems

A horizontally arrayed loudspeaker cluster could be considered as a linearly arranged combination of point sources. Wolff and Malter show that the equation for calculating the polar pattern in the far field is:

$$R_\alpha = \frac{\sin \frac{n\pi d}{\lambda} \sin \alpha}{n \sin(\frac{n\pi d}{\lambda} \sin \alpha)} \quad \textit{(Eq 3.1)}$$

where n = number of sources

d = distance between sources

α = the angle the line from the source to the distant point makes with the normal to the line joining the two sources [Wolff 1930, 201-241].

Plotting this for fixed n=2 and variable $\frac{d}{\lambda}$ (figure 3) shows that there are severe lobes produced when $\frac{d}{\lambda} > 0.5$. Note that these lobes are of equal level to the on-axis lobe, and for $\frac{d}{\lambda} \geq 1$, are much wider [Olson 1947, 31-32].

Plotting the same variable for fixed n=5 (figure 4) shows the same effect, but more pronounced.

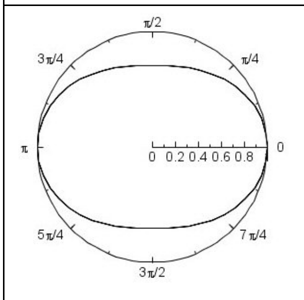
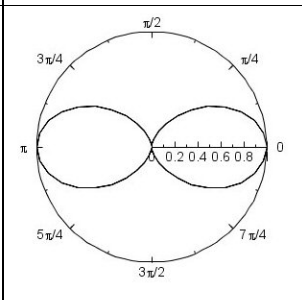
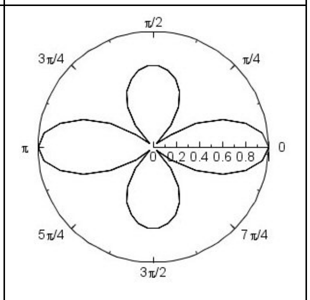
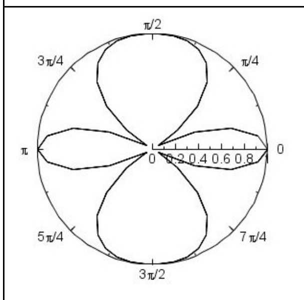
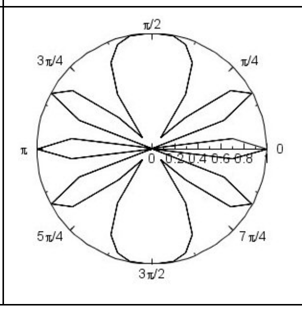
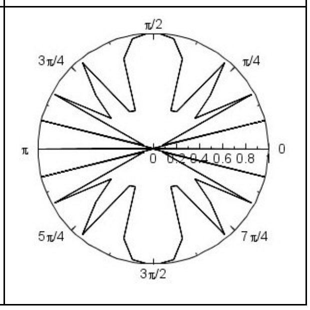
$\frac{d}{\lambda} = 0.25$	$\frac{d}{\lambda} = 0.5$	$\frac{d}{\lambda} = 0.75$
		
$\frac{d}{\lambda} = 1$	$\frac{d}{\lambda} = 2$	$\frac{d}{\lambda} = 4$
		

Figure 3 – Varying values of $\frac{d}{\lambda}$ for 2 point sources arranged in a line.

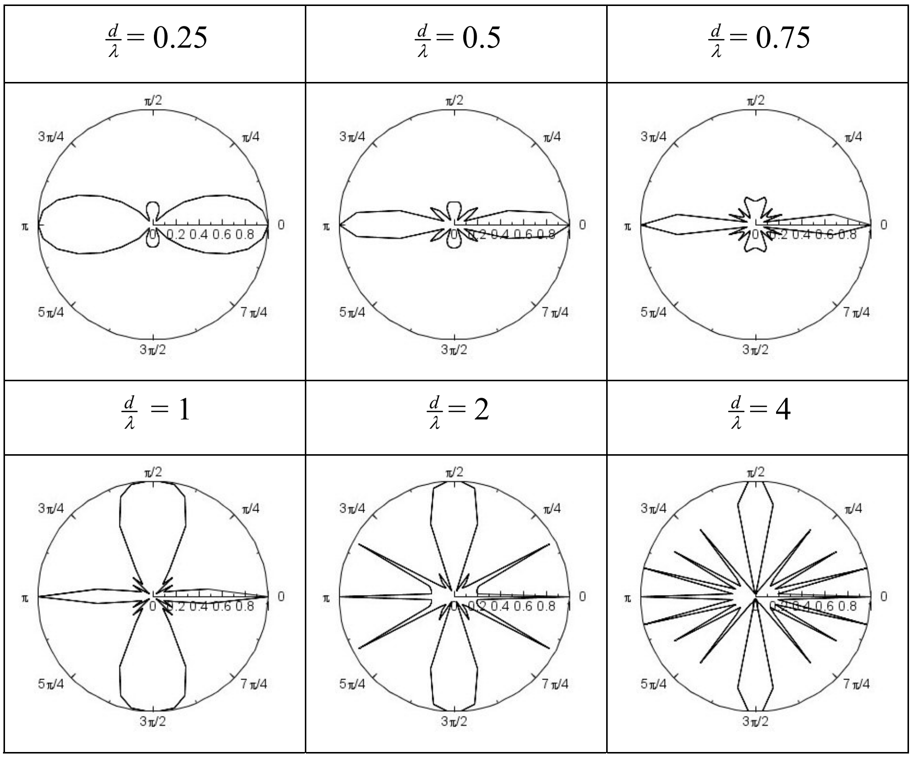


Figure 4 - Varying values of $\frac{d}{\lambda}$ for 5 point sources arranged in a line.

3.2.1 Directivity of a uniform line array system

When the polar pattern of a loudspeaker or other sound source is considered, it is understood that the calculations are based in the far field, so that the sound pressure decreases linearly with distance [Beranek 1954, 100]. This must be taken into account when calculating the directivity of a uniform line array, and it also makes the calculations much simpler.

To analyse the on-axis pressure response of a uniform array, which means it has equal phase and amplitude at all points along the line, the physical arrangement can be shown in Figure 5:

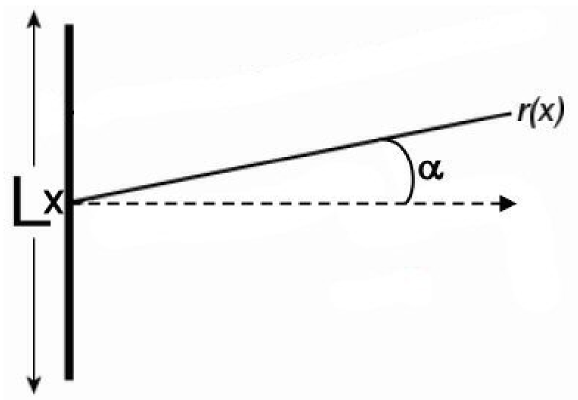


Figure 5 - *A straight line source with length L, with the path r(x) from point x on the line array to the observation point P(r) (not shown)*

The equation for calculating pressure is:

$$P(r) = \int_{\frac{-L}{2}}^{\frac{L}{2}} \frac{A(x)e^{-j(kr(x)+\Phi(x))}}{r(x)} dx \quad (Eq.\ 3.2)$$

where *P(r)* = sound pressure at distant point

L = the length of the array

r(x) = the distance to the far point

A(x) = the amplitude function

$\Phi(x)$ = the phase function

k = the wave number

As stated, considering the observation point, where the pressure is *P(r)*, to be a great distance away compared to the length of the array simplifies the equation, because if we were to move *x* to a different point along the line source, *r(x)* changes insignificantly. Therefore:

$$\frac{1}{r(x)} \approx \frac{1}{r(\frac{L}{2})} \approx \frac{1}{r(\frac{-L}{2})} \approx \frac{1}{r} \quad (Eq.\ 3.3)$$

However, the difference in distances between *r(x)* at different points along the array is significant compared to a wavelength, therefore it must be taken into consideration. Figure 6 shows *x* repositioned along L, and the extra bit of distance that needs accounting for.

$$r(x) = x \sin \alpha \quad (Eq.\ 3.4)$$

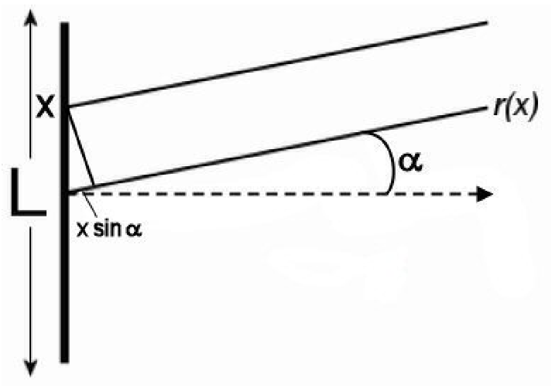


Figure 6 - $x \sin \alpha$ represents the extra distance to a distant point from 2 parallel lines

Substituting equations 3.3 and 3.4 into equation 3.2, we get the far-field pressure at angle α :

$$P(\alpha) = \frac{1}{r}\int_{\frac{-L}{2}}^{\frac{L}{2}} A(x)e^{-j(kx\sin\alpha + \Phi(x))}dx \quad \textit{(Eq. 3.5)}$$

The directivity function $R(\alpha)$ is defined as:

$$R(\alpha) = \frac{|P(r)|}{|P_{\max}|} \quad \textit{(Eq. 3.6)}$$

$P_{\max}$, the maximum radiated pressure, occurs when all segments along the line radiate in phase. This is given as:

$$P_{\max} = \frac{1}{r}\int_{\frac{-L}{2}}^{\frac{L}{2}} A(x)dx \quad \textit{(Eq. 3.7)}$$

Therefore:

$$R(\alpha) = \frac{\left|\int_{\frac{-L}{2}}^{\frac{L}{2}} A(x)e^{-j(kx\sin\alpha + \Phi(x))}dx\right|}{\left|\int_{\frac{-L}{2}}^{\frac{L}{2}} A(x)dx\right|} \quad \textit{(Eq. 3.8)}$$

As we are considering a uniform array, we can set *A(x)* to 1 (as amplitude is equal and unity) and $\Phi(x)$ to 0 (as phase is equal), and we get the following:

$$R(\alpha) = \left|\int_{\frac{-L}{2}}^{\frac{L}{2}} e^{-jkx\sin\alpha}dx\right| \quad \textit{(Eq. 3.9)}$$

To solve the integral gives the most commonly used expression for directivity of a line array:

$$R(\alpha) = \left|\frac{\sin(\frac{kl}{2}\sin\alpha)}{\frac{kl}{2}\sin\alpha}\right| \quad \textit{(Eq. 3.10)}$$

Finally, to substitute in the equation for wave number ($k = \frac{2\pi}{\lambda}$) gives:

$$R(\alpha) = \left| \frac{\sin(\frac{\pi l}{\lambda}\sin\alpha)}{\frac{\pi l}{\lambda}\sin\alpha} \right| \textit{(Eq. 3.11)}$$

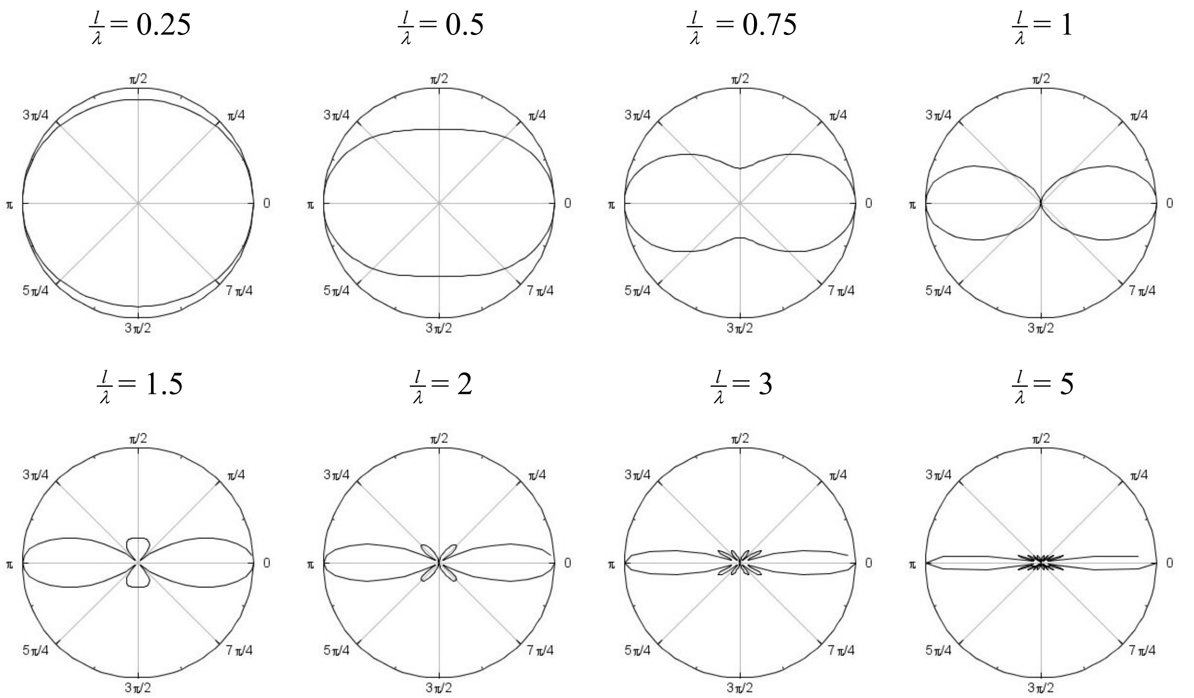


Figure 7 - The relationship between $\frac{l}{\lambda}$ and the directivity of a uniform line source. This table shows that if the array stays a constant length, the directivity pattern narrows and creates side lobes at higher frequencies.

Plotting this equation for changing ratios of $\frac{l}{\lambda}$, as in figure 7, shows that as the length of the array increases, a constant frequency will get more directional. Also, as the wavelength decreases (*i.e.* the frequency increases) for a given array length, the beam-width gets tighter [Ureda 2001, 2-3].

Note also that the secondary lobes are significantly reduced from that of a multiple point source model, and are considerably lower level than the primary lobe. This occurs because an infinite amount of points can never be completely in phase, other than directly on-axis. The effect is lessened at lower frequencies. Nonetheless, this does not mean that the lobes are small enough to be negligible [Wolff 1930, 210-211].

The increased directionality for high frequencies is one of the main benefits of line array systems. However, for a straight line array, this size can become far too narrow to be of any use, as there will be a very slight position where the frequency response is just right, which is far too small to cover a reasonable size audience.

Also, a straight line array would not be very useful in a multi-layer auditorium, as to achieve a satisfactory frequency response at all positions in the venue, it would need to extend from floor to ceiling in order to benefit the people sitting at the front as well as the people sitting higher up. [Webb 2003: 1].

3.2.2 Straight line array lobes

To determine the -6dB point of a uniform array, we can take the general term of equation 3.11 and set it to 0.5:

$$\frac{\sin u}{u} = 0.5 \quad \textit{(Eq. 3.12)}$$

This can be solved to find $u = 1.895$ with a numerical method. Entering this into the equation for *u* gives

$$u = \frac{\pi l}{\lambda} \sin \alpha \quad \textit{(Eq. 3.13)}$$

Because we're finding the angle between 2 -6dB points, and the pattern is symmetrical about 0°:

$$\theta_{-6dB} = 2\alpha \quad \textit{(Eq. 3.14)}$$

Rearranging equations 3.13 and 3.14 gives the following:

$$\theta_{-6dB} = 2\sin^{-1}\frac{0.6\lambda}{l} \quad \textit{(Eq. 3.15)}$$

This is plotted in figure 8, and can be seen to have narrow quarter power angles at high $\frac{l}{\lambda}$ and large angles for low $\frac{l}{\lambda}$. This is unsurprising as we've already shown that the directivity beam gets narrower as the frequency gets higher.

If we consider that $\sin u \approx u$ for small angles, equation 3.15 can be simplified to:

$$\theta_{-6dB} = \frac{1.2\lambda}{l} \quad \textit{(Eq. 3.16)}$$

Using degrees instead of radians and frequency instead of wavelength provides the following approximate equation:

$$\theta_{-6dB} = \frac{24000}{fl} \quad \textit{(Eg. 3.17)}$$

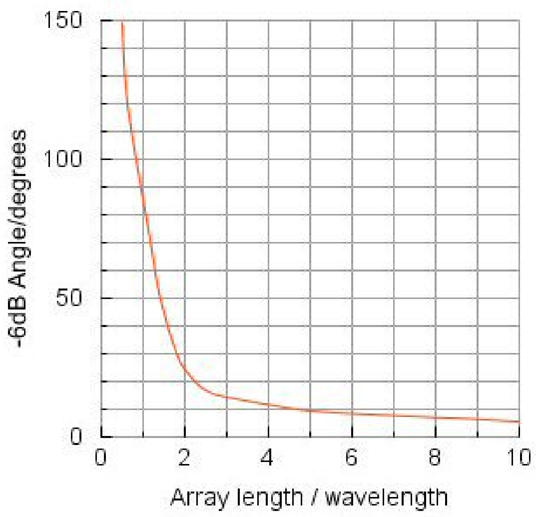


Figure 8 – A graph of θ_{-6dB} against $\frac{l}{\lambda}$ [Ureda 2001, 4]

This can be plotted to show frequency against quarter power angle with different array lengths. You can see from figure 9 that at 10kHz, the -6dB point is only around 1° wide for up to 8m long arrays and gets smaller for longer arrays. This is a very small angle, and is practically unusable except for very specific applications [Ureda 2001, 4].

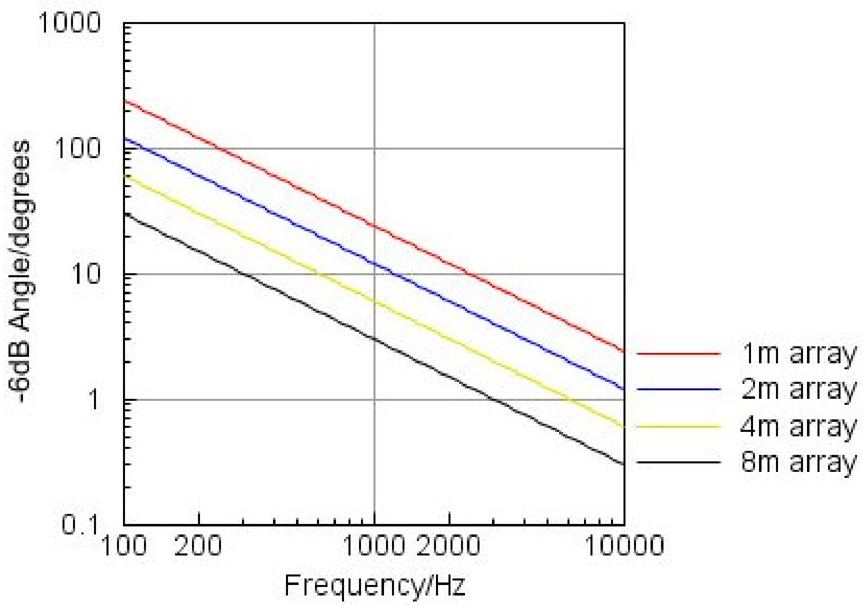


Figure 9 – Directivity response of 1, 2, 4 and 8m long line arrays [Ureda 2001, 4]

3.3 Curved line arrays

The next step in enhancing the use of a line array is to curve it. This provides the small secondary lobe benefits of a line array, while widening the main on-axis lobe to a more practical beam-width.

The process for deriving an equation for a curved array is similar to that for a straight line array, the main difference being able to compensate for the small change of distance caused by moving the point *x* along the array. This becomes more complex, and the arrangement is shown in figure 10.

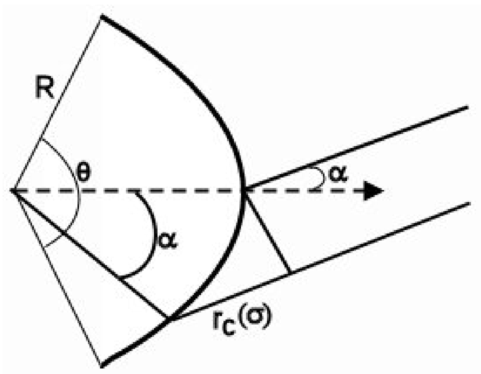


Figure 10 – The physical arrangement of a curved source array [Ureda 2001, 3]

$$r_c(\sigma) = 2R\sin\left(\frac{\sigma}{2}\right)\sin\left(\frac{\sigma}{2}+\alpha\right) \quad \textit{(Eq. 3.18)}$$

We can then state the far field pressure at angle α as:

$$P(r) = \int_{\frac{-\theta}{2}}^{\frac{\theta}{2}} A(\sigma)e^{-j(kr_c(\sigma)+\Phi(\sigma))}d\sigma \quad \textit{(Eq. 3.19)}$$

Again, the far field directivity follows as such:

$$R_{curved}(\alpha) = \left| \frac{\int_{\frac{-\theta}{2}}^{\frac{\theta}{2}} A(\sigma)e^{-j(kr_c(\sigma)+\Phi(\sigma))}d\sigma}{\int_{\frac{-\theta}{2}}^{\frac{\theta}{2}} A(\sigma)d\sigma} \right| \quad \textit{(Eq. 3.20)}$$

Assuming uniform amplitude and phase gives:

$$R_{curved}(\alpha) = \frac{1}{\theta}\left|\int_{\frac{-\theta}{2}}^{\frac{\theta}{2}} e^{-jkr_c(\sigma)} d\sigma\right| \quad \textit{(Eq. 3.21)}$$

This can not be simplified any more as the straight line source was. [Ureda 2001, 3-4]. It also unfortunately doesn't lend itself easily to graph plotting. However, I have included plots from Mark Ureda's paper *'J' and 'Spiral' Arrays* in figure 11, which clearly show that the beam-width has increased for high values of $\frac{d}{\lambda}$, while the secondary maxima are still low.

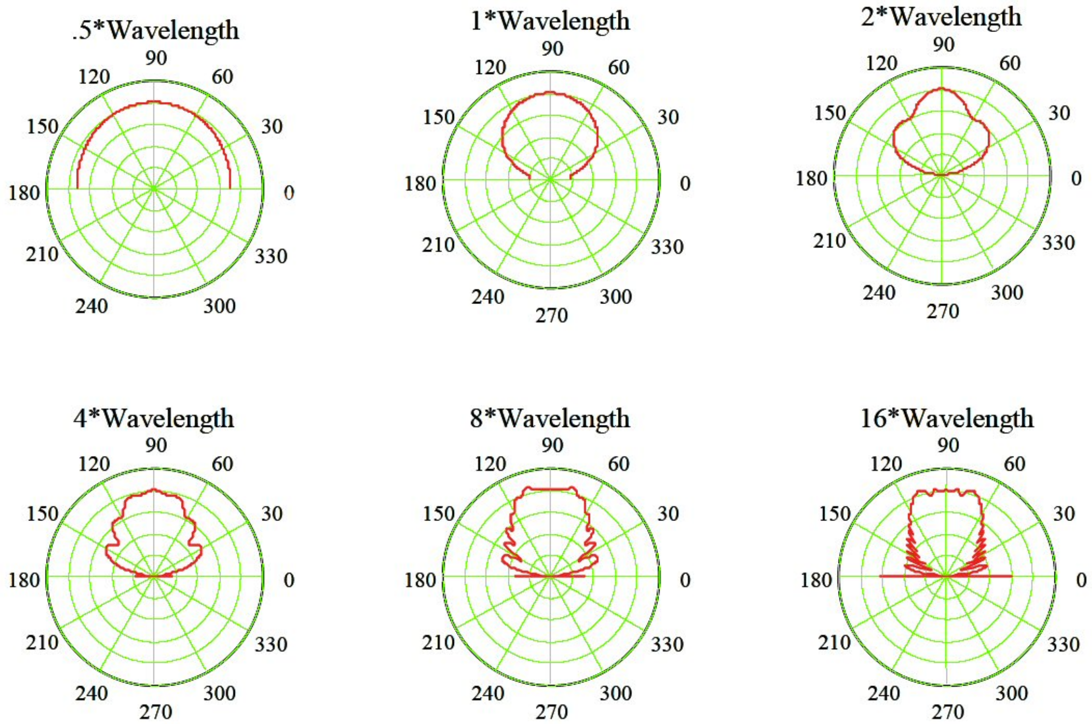


Figure 11 – The polar plots of a curved source array for varying values of $\frac{d}{\lambda}$ [Ureda 2001, 3-4]

3.4 'J' Arrays

The problem with curved arrays is that they are not very well suited to the average auditorium. While the bottom half will be angled down to provide extra coverage at locations close to the front of stage, the top half will be angled upwards at the ceiling. Also, as we saw earlier, the problem with straight line arrays is that the beam is far too narrow at high frequencies.

A solution to utilise the best features of both arrays is to use a 'J' array. This is made up of a straight line portion and a curved portion, normally at the bottom. This provides a long throw straight line component for people relatively far away, while the curve at the bottom acts as an in-fill for the area underneath the array that would otherwise be neglected [Ureda 2001, 5].

Figure 12 shows a geometric representation of a J-array. To calculate the directivity, we can sum the two components.

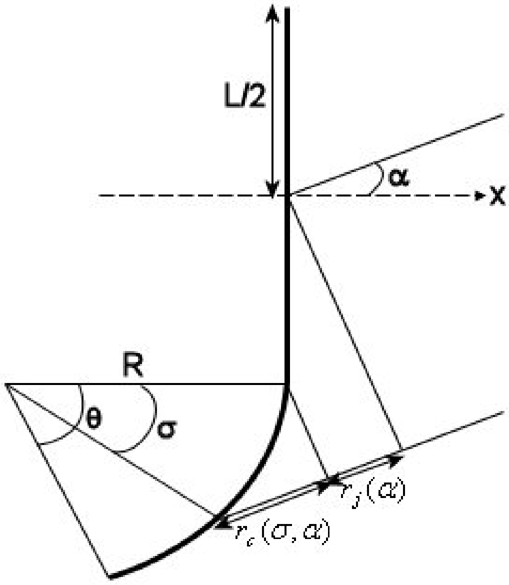


Figure 12 – Geometric representation of a 'J' array.

The straight line component is the same as before:

$$R_{line}(\alpha) = \left| \frac{1}{L} \int_{\frac{-L}{2}}^{\frac{L}{2}} e^{-jkr_L(x)} dx \right| \textit{(Eq. 3.22)}$$

where:

$$r_L(x) = x \sin \alpha \textit{ (Eq. 3.23)}$$

The equation for the circular portion is also the same, but the limits of integration must be changed as it is rotated. So we get:

$$R_{curved}(\alpha) = \int_0^{\theta} e^{-jkr_c(\sigma)} d\sigma \textit{ (Eq. 3.24)}$$

where:

$$r_c(\sigma) = 2R \sin\left(\frac{\sigma}{2}\right) \sin\left(\frac{\sigma}{2} + \alpha\right) \textit{(Eq. 3.25)}$$

The directivity function of a J-array is then:

$$R_J(\alpha) = \frac{1}{A_L L + A_C R\theta}\left| A_L \int_{\frac{-L}{2}}^{\frac{L}{2}} e^{-jkr_L(\alpha)} dx + A_C R \int_0^{\theta} e^{-j(kr_c(\sigma)+r_J(\sigma))} d\sigma \right| \quad \textit{(Eq. 3.20)}$$

where A_L = the amplitude-per-unit length of the straight segment

A_C = the amplitude-per-unit length of the curved segment

[Ureda 2001, 4-5]

Again, this pattern does not lend itself easily to plotting, although if we compare the pattern from a line, curved and J source of a 2 metre long array with a 60° curved source with a radius of 1 metre (figure 13), the differences are quite clear. The J-Array has an asymmetric plot, with a slightly narrower pattern than the curved source. Therefore, not only does a J-array provide a more useful distribution pattern, it has a more practical directivity pattern.

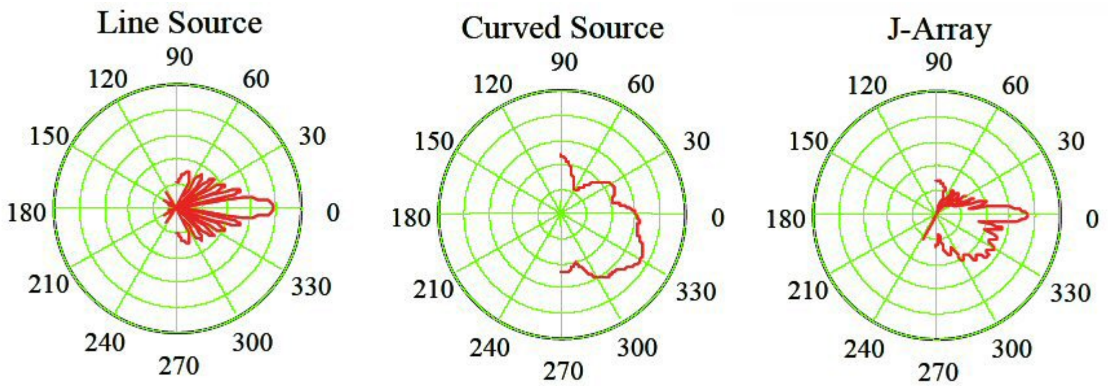


Figure 13 – Response curves of a line source, curved source and J-array with line length 2m, curve of 60° and radius of 1m [Ureda 2001, 4-5]

3.5 Spiral Arrays

Spiral arrays are the next development from J-arrays, and have a superior frequency response due to their similar polar pattern at shifting frequencies, while still retain the long throw and in-fill benefits that J-arrays provide.

The concept is that spiral arrays are curved all the way along the array, but the curve is progressive. This means that the top of the array is almost straight with angles of 1° between boxes, and increase at the bottom to 6° up to about 10°.

A well designed spiral array could have an almost constant directivity pattern with frequency, with some small lobes exhibited at low frequencies [Ureda 2001, 8-9].

4 Practical use of line arrays

4.1 Planning

While line arrays would appear to be a step up from earlier sound reinforcement systems, there is one big problem with them, which is that you can't just stack your cabinets, aim them in the general direction and expect them to perform well. There will have to be some planning done beforehand to determine how many cabinets are needed, how to array them, where they will be hung from, where they will be pointed and angle of curvature. This is a greater problem on tour where you are presented with a new venue each day, rather than a single installation [Bailey 2003].

Fortunately, most companies provide software that will estimate the characteristics of different systems (manufacturer specific), such as JBL's line array calculator (LAC) designed for their VerTec range. This software helps the sound designer build the optimum rig based on input of venue dimensions, seating planes, number of cabinets and it will display the expected response from this input [JBL VerTec 4889 Owner's Manual, Chapter 9].

This could help with planning a tour, as based on venue information received beforehand, you can work out exactly what you need to take to each venue, and work everything out before you get there.

4.2 The effect of atmosphere

Air absorption can be a major problem in sound reinforcement systems designed for long throw, especially outdoors where they are also subject to adverse weather conditions. The effect is that there will be a significant HF loss; progressively more so the further back from the system you listen from.

A simple but effective way of overcoming this is to take advantage of the straight and curved regions in a J or spiral array and their different purposes. The output from the front-of-house drive equipment is split into typically 3 parts with progressively more HF gain, with the most HF fed to the top long throw portion and the least fed to the bottom in-fill curve.

The consequence is that people near the front don't hear excessive HF gain, while the people at the back will hear it as it's meant to sound [Webb 2003, 7-8].

4.3 On-site deployment

After researching current line array systems on the market, it is evident that they are designed for minimal effort on behalf of the riggers. They are arrayed on the floor on wheel boards and hoisted by chain motors so don't need to be lifted at any point requiring only 2 or 3 people for assembly. They are also light which is not only good for the riggers but also for hanging a large number of boxes off of 1 or 2 rigging points and simple truck packing is considered in the design [JBL VerTec 4889 Owner's Manual, Chapter 11].

4.4 Cabinet design

Line array cabinets are built trapezoid shaped so that they can be hinged at the front for curving. This prevents any gaps which would be unavoidable with rectangular boxes and highly undesirable as it would ruin the approximation of a continuous line source. Taking the JBL VerTec as an example, they have a maximum hinge of 10° (the trapezoids are 5° off rectangular), providing enough angle for a typical J or spiral array.

The cabinets are generally 2 or 3 way and designed to be driven by multiple amplifiers fed by an active crossover. For full bandwidth reproduction, it is often necessary to use large sub-bass cabinets as well. However, due to the omni-directional nature of extreme LF, these may be clustered on or beneath the stage out of sight and will provide a good performance sonically.

One of the most important aspects of line array design is maintaining the line characteristic and preventing each driver from becoming a separate point source. As it is impossible to create a satisfactory full-range reproduction with 1 driver, 2 or 3 different types are required, which must have different radiuses to reproduce the desired frequency range, for example, the Renkus-Heinz STXLA/9 line array module features 12" woofers for low frequencies, 6.5" cones for mid frequencies and 2.5" drivers for HF.

In order to preserve line characteristics at all frequency bands, the drivers must be arranged in such a way that they create individual sub-lines. Therefore, a typical line array loudspeaker module may have 2 LF drivers, horizontally spaced, 4 mid frequency drivers arrayed 2 high and 2 across and 3 HF drivers mounted in a vertical line in the middle, as in Figure 14.

In this configuration, when they are stacked, they create vertical lines of drivers as closely spaced as possible to provide the most constructive summing and increased coupling. Also, the closer all drivers are together, the better the output due to constructive summing [Webb 2003, 2].

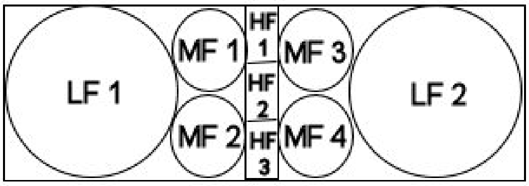


Figure 14 – An example line array module with 2 LF drivers, 4 MF drivers and 3 HF drivers (example based on JBL VerTec 4889).

5.1 Conclusion

The advantages of using high quality, carefully designed and implemented line array systems over horizontal clusters and other types of speaker arrangement are many.

First of all, we can expect a higher perceived direct to reverberant ratio due to the directional nature of the system. Of course, the reverberant level of the auditorium will still be the same, but by directing as much sound energy as possible so as a member of the audience will hear it before any reverb is desirable to achieve this effect. Preventing side lobes which would direct sound towards the walls and create more reverberation also greatly adds to this feature [Wolff 1930, 202-203].

Another consequence of the increased directionality is increased feedback rejection. With correct microphone placement, which will usually be behind and to the side of the array, the SPL radiated will be lower than with horizontally clustered sound reinforcement stacks [Klepper 1963, 1].

Due to the increased HF throw of the system, the need for delay stacks is eliminated or reduced (dependant on the venue). There is also a more even sound intensity over the entire field, as the system doesn't need to be worked exceptionally hard to get the level needed at the back of the field. This is helpful for the front-of-house sound engineer who will get a better impression of what's happening in other areas of the venue.

It's my opinion that the line array is a superior method of sound reinforcement for large scale reproduction, although they would be much less useful in a smaller venue where a short throw solution would be much more practical. They require more planning and possibly unavailable rigging points if a particular system is not floor-mountable.

While the line array system may be more complex than simpler 'point and shoot' systems, there are tools available for precise deployment, meaning an enhanced audio experience and a rightful position as the leading force in sound reinforcement systems.

5.2 Further work

I would be interested to do some research on frequency response of line arrays, as it will change over the field due to far field characteristics, although probably in a predictable manner.

Also, most of the work I have done has been theoretical, and it would be interesting to see how these theories hold out in practice, particularly the directivity patterns.

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