

S O U N D P R O J E C T S

THE MAGIC OF A LINE-ARRAY EXPLAINED

The introduction of Sound Projects Wave-Shape-Transformer™

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The advantages of a true line-source in sound reinforcement are convincing:

* Room influence (echo/reverb) is reduced to minimum

* High SPL levels can be obtained at distant audience areas with relatively small systems

* More uniform horizontal coverage can be obtained from large clusters.

Abstract: In this paper a short summary is given of the criteria involved in line-array design theory. It should bring the reader up to date on the issues involved in "real life" applications of line-array systems. Different types of acoustical sources, such as the true line-source, curved line-source, "real life" line-arrays and arrays with horn-type elements are compared. In an appendix, attached to this paper, some simulations (in EASE) and polar response plots are presented to visualize the differences in acoustical behaviour between these sources.



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Sound waves

All the sounds we hear are actually pressure waves in air.

The human ear has a frequency range of approximately 50 Hz-16 kHz. Its sensitivity has a "hill"-like shape with its top at 2kHz and a small extra spike around 4kHz. Not by coincidence it closely resembles the opposite of the well-known Fletcher& Munson curve.

By the superposition principal of physics, **every sound at an arbitrary point in space can be decomposed as a sum of pressure waves**. These waves may differ in frequency (or wavelength), amplitudes and relative phase. The difference between amplitudes, relative phase and/or different path lengths between separate sound sources inevitably creates complex interference patterns. In sound reinforcement these interferences are virtually always undesirable.

Another consequence of the superposition principle is; that **every source can be thought of as if it has been made up out of single infinitely small Omni-directional radiating sources** with a certain geometrical configuration. The radiated sound field of these sources is the interference sum (integral) of all the infinitely small sources.

The point-source

Physically one can speak of a point source when a sound source is smaller than half the radiated wavelength.

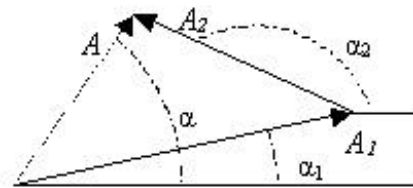
A point source radiates an omni-directional pattern for every frequency; this means it radiates equal amplitude in every direction. Because of this, the radiated acoustical energy of the point source is distributed equally over a spherical surface resulting in energy density dependence, which is proportional to the inverse square of the distance.

Therefore, the Sound Pressure Level ("SPL") decreases with 6dB per doubling of distance.

With a line source several variables are introduced, as we will see on the next page.

By Fourier theory, every signal of any shape can be decomposed in to a sum of sines with different periods (frequencies). This spectrum of amplitudes as a function of frequency is often called Fourier- or Power spectrum (used in analysing programs such as MLSSA or SMAART).

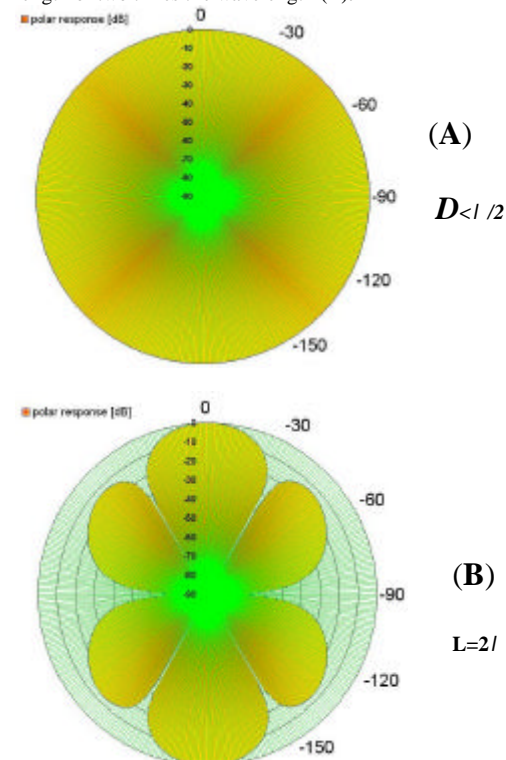
Interference of different signals can then be monitored on frequency level: per frequency, the amplitudes have to be summed according to their phase differences. This is similar to adding vectors (amplitude (A) is the length and the phase (α) the angle with the horizontal-axis).



The amplitude of N waves with the same frequency is given by:

$$A^2 = \sum_{i=1}^N A_{0i}^2 + 2 \sum_{j>i}^N \sum_{i=1}^N A_{0i} A_{0j} \cos(\alpha_j - \alpha_i)$$

Vertical and horizontal polar response of a point source (A) and, as a contrast, a vertical polar response of a line-segment with a length of two times the wavelength (B).



SPL as a function of distance of a point-source:

$$SPL_{ps} = 10 \cdot 10 \log \left(\frac{I_0}{I_d} \right) = 10 \cdot 10 \log \left(\frac{1}{d^2} \right)$$

The line-source

A true line-source is a straight line radiating with constant amplitude and phase along its length.

True line-sources are a rare event in nature. Physically it can be represented by infinitely small omni-directional radiating sources, infinitely close together and oriented along a straight line.

The response of the line-source for an arbitrary point in space is represented by the interference integral of all the infinitely small sources.

In the horizontal plane, the line-source radiates in the same way as the point source.

The vertical plane however is a more complicated story. With respect to the horizontal distance to the source (assuming its length is oriented vertically), space can be divided in two parts. A near field, in which for every frequency the vertical quarter power splay angle is zero, and a far field, in which the splay angle is a function of frequency.

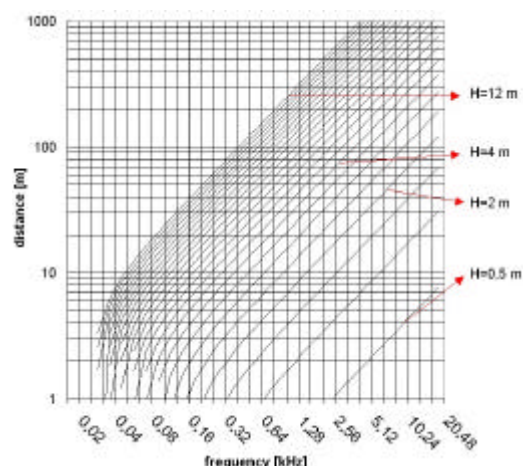
The border between the two fields is given by a border distance d_b , which is dependent on frequency, length of the source and the vertical position relative to the main axis (off-axis the border distance will be larger). The frequency dependence of the vertical splay angle in the far field correlates directly to the width of the main lobe in the polar response plots.

A line-source will have a SPL, which is proportional to -3dB per doubling of distance in the near field and -6dB per doubling of distance in the far field. The vertical directivity of a straight line-source is extreme in the near field (a beam), and a constant angle per frequency in the far field. The SPL in the near field shows small interference "wrinkles" which increase in size with growing distance until they vanish in the far field. Because their amplitude is only 3dB and their position in space depends on frequency this will hardly be hear able. The far field/near field border distance d_b depends on distance frequency and array shape. If it is not properly considered, this can mean a non-coherent listening image specifically in the balance between higher and lower frequencies,.

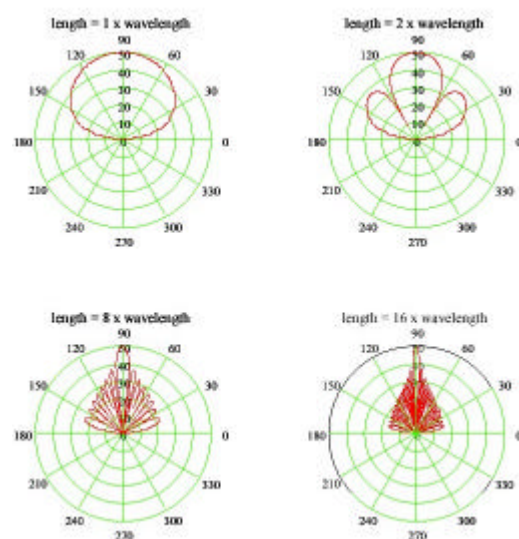
As we will see hereafter, curving a line-array even has additional benefits and reduces most of the practical disadvantages of a straight array (Like the extremely narrow splay for high frequencies or the small interference "wrinkles" in the near field).

$$d_b \approx \frac{H^2}{2\lambda} \sqrt{1 - \frac{1}{(H/\lambda)^2}}$$

A good approximation for the border distance (on axis) for a straight line-source is given by the above formula [1], where λ is the wavelength of the sound and H the height of the source. Below it is plotted as a function of frequency and source height, each curve represents an increase of height of 0,5m, starting at the lower right to the upper left corner of the graph.



Vertical polar response plots, of a straight line-source. Note that in general polar response plots like these are only valid when the distance becomes large compared to the dimensions of the source. At close distances, interference is often more complicated and mostly a function of distance.



Curved line source

A curved line source is similar to a normal line source only now the line is not straight but curved in some manner. Two practical “curve shapes” are the constant curvature source and the spiral source.

The constant curvature source or curved source as we will call it from now, has a remarkable homogeneous interference pattern. Almost independent of frequency; the vertical splay for the radiated sound is just defined by the top and bottom angles, provided the vertical dimensions of the source are large enough.

It seems that the array emulates one huge horn with constant vertical directivity properties!

In addition these conditions are in real life easy to meet for frequencies of approximately 500 Hz and higher. **It immediately follows, that a *straight* line-source is often much trickier to handle with respect to frequency responses at various distances.** The curved line-source has none of these troubles and can therefore be regarded as preferential in mid- and close- range sound reinforcement.

The curved source has also a near and far field, with a 3dB and 6dB *reduction* in SPL per doubling of distance, just like the straight line-source. However, the transition between the two fields is at larger distances and much more gradual. In fact for the high frequencies the far field might be never reached. This is the main reason many nasty frequency dependences a straight line-array has, are removed. In addition the small interference “wrinkles” in the near field are suppressed.

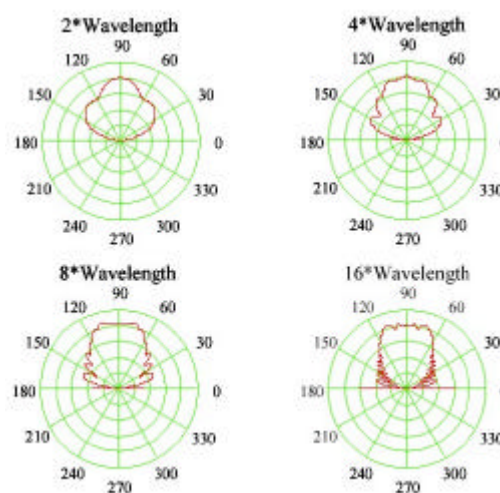
Spiral line source

Instead of a constant curvature, the spiral source has a gradual increasing curvature from top to bottom. **Due to the relatively low curvature at the top, this shape combines the long throw of a straight-line-source with the homogeneous polar pattern and other consequential advantages of the curved array.**

Due to the properties explained above, both the curved and spiral array design is the most practical in use of sound reinforcement.

Vertical polar response plots, of a curved line-source) [2].

In this case, as can be illustrated with a Fresnel analysis, the general shape of the polar response plots appears also to be valid at close distances.



Point-source array

As stated on page three, a “line-source” now a day often is emulated by arraying multiple point sources in a straight line. However, a line of point sources can only perform as a line source if a distance smaller than half the radiated wavelength separates all the individual point sources.

When the distance between adjacent sources is larger, severe side lobing will occur; meaning sound is radiated towards undesirable and/or non-audience areas (Appendix). This will result in a loss of on axis energy and thus SPL. In addition, the point-source array will suffer from more destructive interference in the near field and extreme destructive interference patterns in the far field with respect to a true line-source.

Array of horns

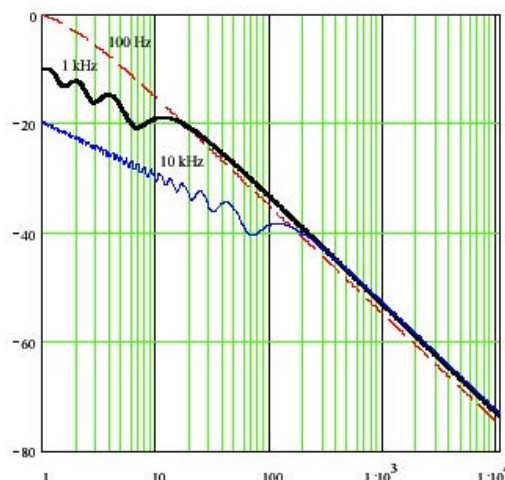
An array of horns is similar to a point-source array with the only difference that the interference pattern is subject to the quarter power (-6 dB) angle of the horns. Therefore, the side lobes of the point-source array are being suppressed as long as they fall outside the quarter power angle of the individual horns.

One might think an array of horns is a proper line-array then. It can be a functional and pragmatic compromise to facilitate the best of both worlds (as successfully demonstrated by Sound Projects 4 Diamond series)

But the reason that a line-array works as it does, is the fact that all parts (or at least large adjacent parts) of the array are able to radiate freely to every point in space. The sound waves of all the source parts interfere and thus build up the typical line-array polar response patterns.

Placing horns on the individual components of the array will have an effective decoupling effect with the rest of the array and will cause different interference mostly in the mid/high frequency range.

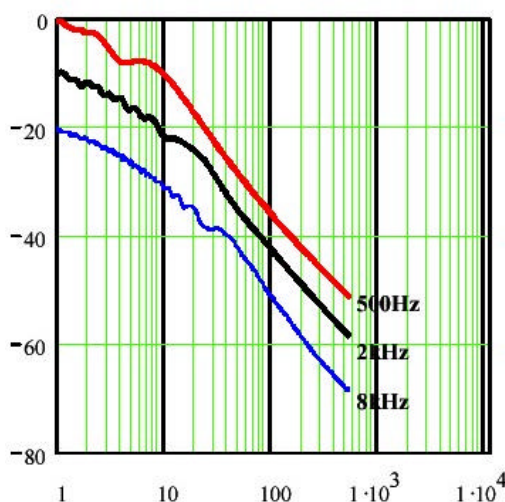
It might be tempting to think when the splay angle of the horns is small enough side lobes can be avoided. However, trying to compress the sound waves in a beam will have, due to the physics of wave propagation, the opposite effect on the quarter power angle. The only way to overcome this is to make a large enough horn or coherent source, hence: to build a line array!



Above: On axis pressure response (dB) of a 4m long straight line-source as a function of distance at 100 Hz, 1 kHz and 10 kHz, [4].

The 1 and 10 kHz curves are offset by -10 and -20 dB respectively.

Below: On axis pressure response (dB) of a curved line-source with a splay angle of 60 degrees and a curvature radius of 4m at 500 Hz, 2 kHz and 8 kHz, [3]. The 2 and 8 kHz curves are offset by -10 and -20 dB respectively.



Line-arrays

A Line-array is an array of full range speakers, which as a whole radiate sound as if it were a true line-source.

To summarize all the physical properties a line-array component must have, for the array to work as a true line-source, a number of criteria have to be fulfilled:

- 1) *The spacing between adjacent sound sources is less than half a wavelength of the highest operating frequency.*
- 2) *At least 80% of the vertical height of the array is covered with a flat wave front radiating area. This wave front must deviate less from flat than one fourth of the wavelength of the highest operating frequency (is 5 mm for 16KHz).*

Due to these criteria it is not possible in "real life" to construct a full range line-source by simply arraying separate drivers. The most obvious obstacle is one of dimensions. The minimum source separation is the diameter of the driver itself, which shall remain smaller than half the wavelength.

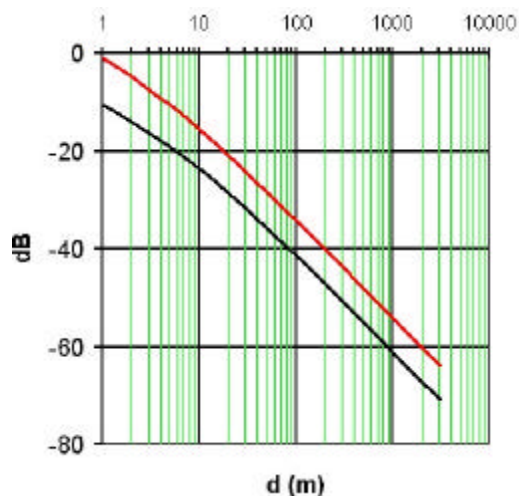
Since most high frequency drivers (e.g. compression drivers) have a diameter of 4-6 inches, an array of them would only work as a true line-source up to 1-1.7 kHz. The construction of a line-array up to 16 kHz would require HF-drivers with a maximum diameter of 1cm or 2/5 inch.

Therefore, to design and build a "working" line source, immense restrictions are imposed on loudspeaker engineering. Only a selected group of manufacturers, like Sound Projects, have actually overcome these limits and make a true line-array system. It is interesting for the reader to note that many manufacturers unrightfully claim they have.

As can be observed from the curve for the SPL dependence on distance of a straight line-source (on the previous page), it is possible to let the curves coincide (meaning a flat frequency response) either in the far field or in the near field depending on e.g. controller settings.

In practice, this effect has to be carefully considered when employing a straight line-source. A flat response in near field conditions for the whole frequency range, will result at further distance in a -3dB decay per *half the* frequency, for the frequencies which have entered far field conditions at that distance (like the graph without the offsets). A flat frequency response in the far field will result in 3dB decay per *doubling* of frequency at closer distances, for the frequencies, which are still in near field conditions at that point (like the with offsets). As can be seen from the curve for the SPL dependence on distance for a curved line-source, the curved line-source has no such problems, because the curved line-source has a vertical splay angle virtually independent of frequency and distance. A reasonable approximation for the on axis SPL versus distance can be given by the following formula, where d is the distance to the source, R the curvature radius and I_0 the total acoustical power of the whole source:

$$SPL(dB) = 10 \cdot 10 \log \left(\frac{I_0}{d} \frac{R}{R + d} \right)$$



Approximate SPL versus distance as given by the formula on the previous page, for a curved line-array with a curvature radius of 4 meters and 8 meters, the latter has a -10 dB offset.

The Sound Projects Wave-Shape-Transformer™

In fact diameters of low and mid frequency drivers, which put restraints on the minimum cabinet height, imply that an individual line-array component itself must contain a true line-source for the high frequency section.

To accomplish this with common HF drivers, a wave-guide has to be developed, which "guides" the sound from the high frequency driver into a narrow vertical slit (ribbon).

This alone however is not enough. The wave-guide has to work in such away that the sound emanating from the slit has a constant amplitude and phase along the slit.

The latter can be accomplished by making every possible path from the beginning of the wave-guide to the slit the same length. In addition, to properly perform as a line source building block, the slit must have a length of at least 80% of the height of the individual line-array component.

Sound Projects Sigma series is equipped with a specially developed and patented wave-guide, which exactly meets the above requirements.

Most manufacturers employ long horns to reduce spherical bending of the sound wave.

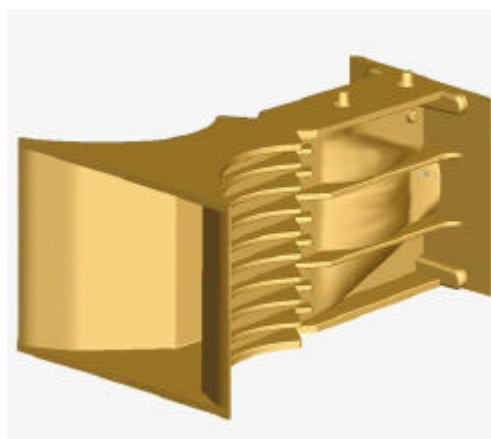
As the pictures in the appendix to this paper will illustrate, arraying components which radiate in a spherical manner, (any common HF-driver without a proper corrective wave-guide does) has dramatic effects due to the strong interference. Such a system is inferior to a stack of horn-loaded speakers, which are oriented under angles, to take into account the coverage angles of the individual horns.

The frequency range for which the curved array has all those fortunate properties can be approximated by the following formula, which actually represents the frequency range for which a far field is never reachable. At closer distances, the frequency range even becomes larger as more frequencies are in near field conditions. Again, R is the curvature radius and l the wavelength; α is half the splay angle of the curved source.

The last part is a use full expression for actual line-arrays. It is in terms of frequency f , array element height h and the angel between to neighbouring elements a . The expression is valid as long as R is relatively large compared to a .

$$1 - \cos \theta \geq \frac{\lambda}{2R} \approx \frac{3\alpha}{fh}$$

Let us say we take 12 line-array elements like for instance SOUND PROJECTS SP20-Sigma, which has a height of approximately 0,35 cm and a maximum angle setting of 5 degrees, making the total splay angle of the array 60 degrees. From the formula it follows the array works properly at 320 Hz and higher frequencies.



SOUND PROJECTS patented Wave-shape-transformer™, designed to operate in multiples to create a vertical ribbon of sound. SOUND PROJECTS S-series is equipped with the Wave-shape-transformer™. The SP10-S, SP20-S and SP30-S are equipped with 1, 2 and 3 Wave-shape-transformers™ respectively.

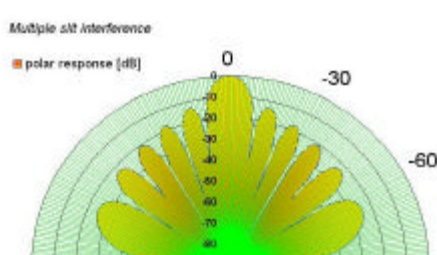
References

- [1] M. Urban, C. Heil and P. Bauman, "Wavefront sculpture technology", presented on the 111th AES convention, New York/USA, sep 21-24, 2001.
- [2] M.S. Ureda, "J and Spiral line arrays", presented on the 111th AES convention, New York/USA, sep 21-24, 2001.
- [3] M.S. Ureda, "Pressure response of line sources", paper 5649, presented on the 113th AES convention, Los Angeles/USA, Oct 5-8, 2002.
- [4] M.S. Ureda, "Line arrays: theory and applications", presented on the 110th AES convention, Amsterdam/The Netherlands, May 12-15, 2001.
- [5] F.L. Pedrotti, S.J. and L.S. Pedrotti, "Introduction to Optics", 2nd ed, Prentice-Hall International, USA, 1993.

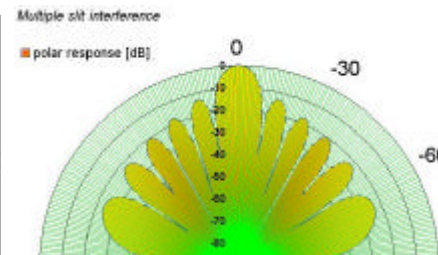
Appendix.

Below the theoretical vertical polar responses are plotted of; a “real-life” line-array (like an array of 6 SOUND PROJECTS SP20-sigma's, which radiate a flat wave front for 80% of the vertical height), a true line-source and an array of close packed 4-inch compression drivers with an exit size of 1,5 inch. All sources are of the same height. Note that at one kHz the compression drivers are separated less than half the wavelength.

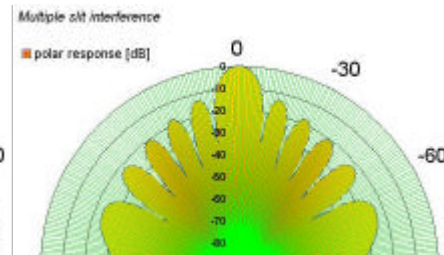
Notice how the secondary lobes of an, according to the line-array criteria proper line-array, stay well under -12 dB. The array of compression drivers has secondary lobes, which are well above this level. The first secondary lobes are even all most as loud as the main on axis lobe.



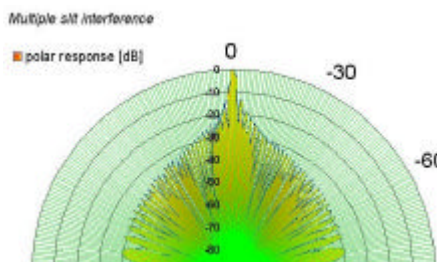
Line-source; 1kHz



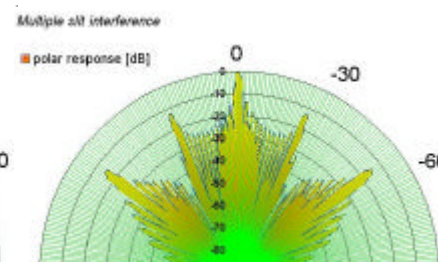
Line-array; 1kHz



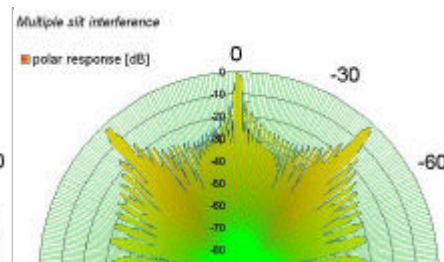
Driver-array; 1kHz



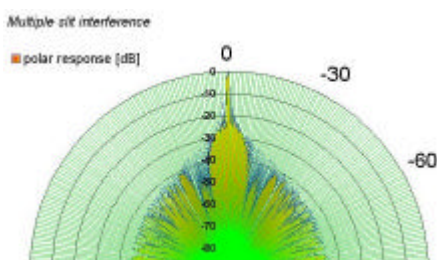
Line-source; 5kHz



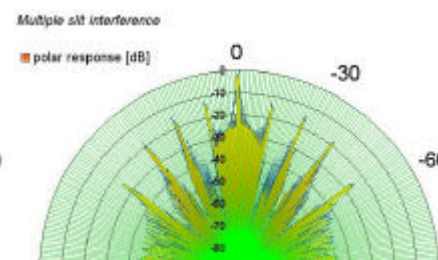
Line-array; 5kHz



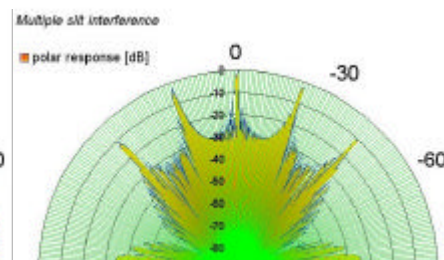
Driver-array; 5kHz



Line-source; 10kHz



Line-array; 10kHz

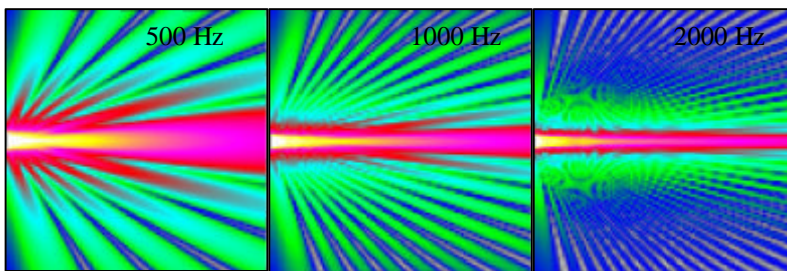


Driver-array; 10kHz

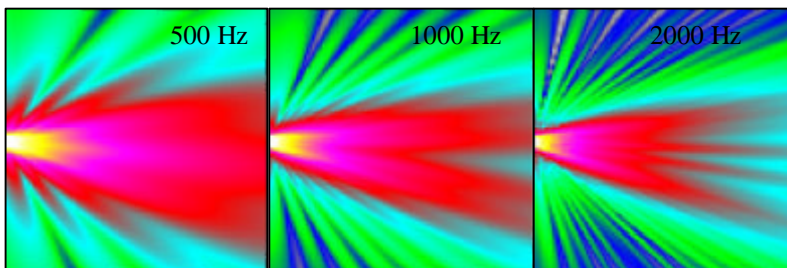
Below the simulations (in EASE) of a straight and curved array are presented. The plots are a vertical plane of a 100 x 100 meters.

The upper pictures are of an array of 64-point sources, with a total length of 4 meters. It should simulate a true line-source up to 2,7 kHz. The second row of pictures is from a curved source with a splay angle of approximately 30 degrees. The array is again constructed with 64 point sources over a total height of 4 meters.

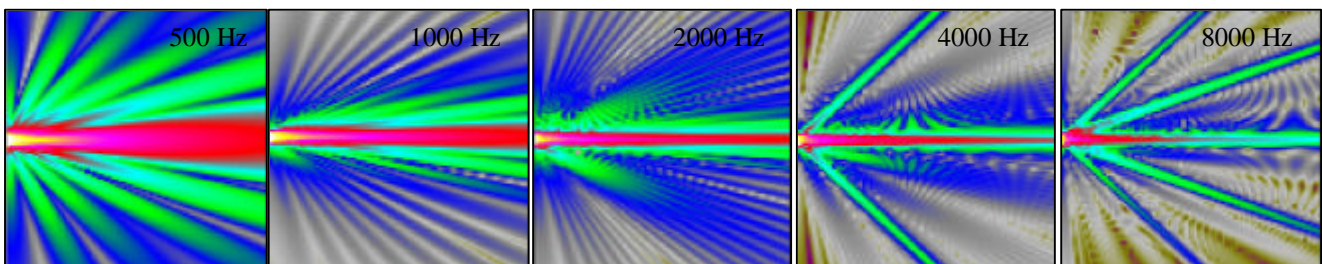
The third and fourth rows represent a straight and a curved array of the same dimensions, but now constructed out of 32 sources with vertical quarter power angles of 30 degrees. Due to their separation (about 5 inch) they should start to give side lobes around 1,3 kHz. This is indeed observed: the lobing continuous for higher frequencies. Notice how the on axis SPL divers with respect to a true line-source.



Above to the left: Straight array of point sources all separated by approximately 2 inch (64 in 4 meters). The total height of the array is 4 meters.



Below to the left: Curved array of point sources all separated by approximately 2 inch (64 in 4 meters). The total height of the array is 4 meters.



Above: Straight array of horns all separated by approximately 5 inch (32 in 4 meters). The total height of the array is 4 meters. The horns have a quarter power angle of 30 degrees.

Below: Curved array of horns. The total height of the array is 4 meters, again constructed with 32 horns. The horns have a quarter power angle of 30 degrees.

