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High Frequency Components for High Output Articulated Line Arrays

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ABSTRACT
The narrow vertical pattern achieved by line arrays has prompted much interest in the method for many forms of sound reinforcement in recent years. The live sound segment of the audio community has used horns and compression drivers for sound reinforcement for several decades. To adopt a line array philosophy, to meet the demands of high level sound reinforcement, requires an approach that allows for the creation of a line source from the output of compression drivers. Additionally it is desired that the line array take on different vertical patterns dependant upon use. This requires the solution to allow for the array to be articulated. Outlined in this work is a waveguide/compression driver combination that is compact and simple in approach and highly suited for articulated arrays.

0. Overview

As long ago as 70 years [1] mathematical models existed for predicting the polar patterns of line sources. In recent years a number of authors have revisited the discussion and created computer models to predict polar coverage from vary complicated vertical arrays [2,3]. Closed form solutions to the problem can be found in these works. However the solutions do not provide the user with an understanding of the actual frequency response at any given point in space. The models focus on the polar patterns. These models are based on the notion that a continuous source is made up of an infinite number of omni directional point sources. Because of the intense computations required the older models required a closed form solution in order to gain useful output. With the vast increase in computers speed available today a more brute force, and intellectually accessible, approach can be undertaken. We can use the same basic underlying ideas and create a line source with a large number of points that are sufficiently close together that they are effectively a continuous source. The solution is to then simply vector sum the sources at any point in space to gain the desired frequency response. The shape of the array can then be modified to any shape and the resultant response calculated.

1. Line and Curved Arrays.

While many would have us believe that line arrays have superior pattern control, the reality is that they are not constant coverage solutions at all. Figure 1 from Olsen [2] shows the narrowing of the beam with increasing frequency of a line source. At the highest frequencies the beam can become so narrow as to be largely useless in covering an audience. The first inclination might be to curve the array to get more consistent coverage. As we can see from Figure 2 from Olson [2] the pattern control vs frequency is also not terribly consistent. This suggests that neither solution is ideal and even if we could create a device with the behavior of a line source further modification through articulation will be required to provide more ideal coverage. It is not within the scope of this paper to discuss the optimization of the articulation as this can be found in other works by Ureda [4]. The purpose of this discussion will be to examine a device that purports to simulate a line source. The proof of it's ability to do so will be though comparison of the modeled frequency response and the measured frequency response of the device in arrays.

2. Near-field/Far-field

Much has been written about the near field and far field nature of line arrays. It has been purported that the line array creates a cylindrical wave front and then at some point in space transitions to a spherical wave. This description of the wavefront behavior of line source is one that many can easily grasp but it is largely an over simplification with some underlying falsehoods. Because a cylindrical wave only drops off at 3 dB per doubling of distance the notion that the sounds is dropping off less in the near filed only tells part of the picture. A more accurate way to describe the near field is that it is an *inference field*. As well, it is important to think of moving toward the source and the notion that the SPL in *only* increasing by 3 dB per doubling of distance at higher frequencies. As show in Figure 3 from Ureda, we see the SPL vs distance of a line source 4 meters tall. From the chart we can see the transition to the near filed at about 100m at 10 kHz and 10 m at 1 kHz and 1 m at 100 Hz. If we move toward the array the SPL doesn't increase as much at higher frequencies. It can clearly be seen that at 1 m there is 20 dB of attenuation at 10Khz vs 100 Hz. This is because the near field is full of destructive interference. While this may be useful to maintain more consistent Sound Pressure Level's (SPL) near the array, the notion that there is some form of gain that projects the near field and the high frequencies is misleading. It is because the interference is diminishing as we move away that the SPL drops off slower. It is not that the high frequencies are being projected further but that they are much reduced in the near field and gain coherency as we move to the far field. The undulations in figure 3 also show that the 3 dB per doubling of distance is only the overall trend, the true variations are easily +/-2 dB from the 3 dB per doubling of distance.

This notion is important as we look at real devices so that we understand the output in the near field may in fact be lower than expected due to the increase in interference.

3. Mathematical Model

To begin the investigation of how our device many or may not represent a true line source element we must first develop a simulation that gives use the predicted performance of a true line source. Because measuring frequency response is often much easier than measuring the polar response it was decided to develop a model beyond those previously demonstrated that showed only polar response. This will give clear insights into the near and far field behaviors vs frequency as well as on and off axis behavior.

The model is a 2D plane on axis in the horizontal and 180 degrees in the vertical. The frequencies response is calculated at discrete frequencies 1/12 of an octave apart. The model uses 1000 points evenly distributed over a line source length of 1.5 meters. This spacing is sufficiently close as to represent a continuous source at 20Khz. The points are assumed to be omni directional. The frequency response calculation at any X,Y point in the vertical plane is made by a vector summation of all points on the line array relative to that observation point at discrete frequencies. The point in the center of the array is taken to have 0 degrees phase and the phase of all points are referenced to that. The vector summation of the real and complex parts for each point results in a complex number for each frequency. The magnitude of this vector is then plotted on a log scale as the frequency response. This requires a grid in Excel of 1000 rows for each point on the line source and 2 columns per frequency (for real and imaginary). At 12 frequencies per octave this creates a grid 1000 by 240 for the full audio spectrum. The computation time for any point in space is far less than a second. From there, multiple pages can be created to compare different shaped arrays and different points in space. While this brute force approach may seem cumbersome it lends itself to easy understanding and the basic idea is not lost in complicated mathematics and is easily implemented.

4. Line array model results

To begin to understand the expected results from our line array first lets look at what the model tells us the theoretical results should be. The first thing of interest is to understand the way the frequency response changes versus distance. Figure 4 shows the frequency response of a 1.5 m tall line source at 1 meter and 2 meters on axis. This is in the near field and should give us an indication of what doubling the distance really does in the near field. As can be seen in figure 4 there is significant attenuation in the high frequencies. As a matter of fact we see nearly 20 dB at 1 m as was suggested by the data from Ureda [3]. At two meters we see the 6dB drop at lower frequencies and what appears to be an "average" of about 3dB at higher frequencies but clearly the drop off is not even with frequency. At about 1500 Hz it is actually louder at 2 meters than 1 meter and around 2 to 2.5 kHz the drop off is greater than 6dB.

This unevenness as we move away from the source would constitute a radical change in the sonic character of the program material. The undulations in the response curve give us a clear picture that this is in fact an "interference field". In Figure 5 the same array at 4 meters and 8 meters is shown. We can see that there is attenuation above 2 kHz suggesting that we are still in the near field at those frequencies. In comparing these two curves we see the same radical difference between curves at a doubling of distance. However, the curve at 8 meters shows much less interference than at 1 m. In this graph it would be hard to find more than just a few frequencies where the two curves differed by 3dB. In this intermediate zone it is clear than the neither the 3dB or 6 dB rules for doubling of distance applies.

Figure 6 shows a comparison of 8 meters with 32 meters. It is clear that by the time we reach 32 meters there is little interference and the curve is nearly flat up to the highest frequencies. What is disturbing is the comparison between the curves in that they are only 2dB different at 10 kHz but 10 dB different at 4 kHz. Examination of figures 4 thru 6 clearly show that any attempt to make the frequency response consistent in this range would be futile. Figure 7 shows 32 meters versus 100 meters. In this scenario the two curves look quite similar (flat) and the extra energy at 100 meters in the high end would probably be offset by air losses. As a tool for providing good bandwidth at a distance the line source seems quite well suited but to expect it to perform well in the near and transition field would be unrealistic.

5. Articulating the array

As we saw from the data from Olson [2] the pure flat line source will have narrowing polars with frequency and we may want to articulate or curve the array. In figure 8 we see the array at 8 meters and 32 meters again but with a 1 degree splay between the upper 1/3rd and the center and then 1 degree splay on the lower 1/3. This is to represent three 0.5 meters hypothetical line sources splayed 1 degree apart. This size is appropriate, as the realizable boxes we will study later will have this configuration. In figure 8 we can see the two curves are not as radically different than with the perfectly straight source. The system will tend to have problems around 6 to 7 kHz but it is more consistent everywhere else. In figure 9 we see 8 meters vs 100 meters with the 1 degree of splay per 1/3rds. In this simulation we see that these two curves only vary in the high frequencies and that the increase in HF at 100 meters would probably be offset by air losses. An important observation of the 100-meter data is that the high frequencies never completely come back. *Once you begin to articulate the array the high end will naturally roll off.* Figure 10 shows the three line sources articulated by 5 degrees at 8 meters and 32 meters. At this point it becomes clear that the two curves are much more alike and it might be more realistic to expect to flatten them out with EQ to be very similar. Figure 11 shows that between 32 and 100 meters the response is nearly identical. While there is clearly substantial attenuation at high frequencies the response could be corrected to be nearly identical throughout the whole distance. No splay between the sources (boxes) appear to have the most problematic variations in frequency response, and at least 1 degree of splay may be mandatory to even hope to have consistent sound within the near field. It is clear that the closer the audience to the array the more articulation that might be required. This turns out to be the case as written about by Ureda[4] where he shows the advantages of a "Spiral" or "Progressive" array. This is an array in which articulation is incrementally increased as one moves closer to the array in the audience plane.

6. Slightly curved wavefronts

Ureda [3] defines a wavefront to be essentially planer if the curvature at the highest expected frequency is less than ¼ of the wavelength. We will now look at curved vs truly flat sources. The wavefront curvature is defined as the difference between the edges of the waveform and the center as in Figure 12. We will model a surface with 9 curved sources that are a total of 1.5 meters high. For our array this curvature is going to be about 0.2" so that it represents a wavefront that would be expected to work to 15kHz based on the Ureda criteria. We will compare flat versus curved wave fronts for three different splays. In figure 13 we see the effect of the curvature of the wavefronts on the frequency response nearing the far field. We show 0.6 inch curvature as compared to 0.2” curvature. It is clear that a curvature of 0.6 inches is way too much as significant high frequencies are lost with this much curvature. The example shows that 0.2 inches is within 1 dB of the truely flat planer curve.

Figure 14 shows the difference between nine point sources, the curved sources, and a true planer source at 2 meters. The point sources show a radical departure from the other two suggesting it should be easy to tell if a device is acting like a group of point sources or something approaching a planer source.

Figure 15 shows the 9 curved sources vs a true planer source at 1 meter. Although there are differences the two are not that different and appear to follow the same basic high frequency roll off in the very near field. Figure 16 shows a comparison at 8 meters where we see the two are nearly identical. Figures 17 and 18, at 32 and 100 meters respectively, also confirm there is little difference between the two as we move away from the array.

Figure 19 shows the array articulated with the top three wavefronts splayed 1 degree along with the bottom three at 4 meters. The two are very similar with subtle differences above 10kHz. In figures 20 and 21, at 16 meters and 100 meters respectively, the two are nearly identical. Figures 22, 23 and 24 show the upper three and lower three wave fronts splayed 5 degrees as compared with the flat planer sources. Shown at 4, 16, and 100 meters there is little difference between the slightly curved wave fronts and the flat ones.

While the above simulation suggest that a slightly curved wavefront appears to behave very similar to the planer one on axis, let’s look at what the simulation predicts off axis. Figure 25 & 26 show the response at 0, 1, and 2 degrees off axis for a 3 degree splay between the three planes for curved and straight wavefronts. The two sets of off axis curves are nearly identical. Figures 27 and 28 show the same comparison on a wider splay of 8 degrees at 0, 3, and 6 degrees off axis. The data suggests that the curved wave fronts might behave a little better as the planer source appears to drop off faster at high frequencies off axis.

7. The 2435 compact maximum efficiency compression driver

Compression drivers are the most effective known devices at converting electrical energy into acoustical energy. A well-designed compression driver may reach a theoretical maximum efficiency of 50 %. Historically compression drivers have been designed to have nearly maximum theoretical efficiencies in the midrange but usually fall short at high frequencies due to excess mass in the assembly. Interestingly, because all large format (3” domes and larger) have break up modes in the usable band it is possibly to have efficiencies greater than the theoretical envelope at high frequencies by designing in resonant behavior [5]. Due to this compression drivers can have wide bandwidth. The resonance’s come with a price, which is very ragged frequency response and ringing or poor time response. In the design of the 2435 it was desired to have both high efficiency but also smooth response and no ringing with pistonic motion to 15Khz.

A model of compression driver response was developed based on the work of Locanthi [5]. The parameters that determine the theoretical curve that a compression driver should have are moving mass, BL product, compression ratio, slot spacing and diaphragm spacing. To maximize the efficiency of the design by manipulating this combination of parameters we developed a Monte Carlo type of modeling program that will search for the combination of parameters that will give maximum efficiency in a specified bandwidth. We chose 3K to 20 kHz as the bandwidth we wished to maximize efficiency in. The resulting optimum solution is realized in the 2435. As well, in this analysis we addressed maximizing energy from 10 to 20 kHz, which pointed toward minimizing the moving mass at all costs. Beryllium is the lightest structural solid so it was chosen as the diaphragm material. We wished for the first break up mode of the diaphragm to be at the very top of the band of audibility. FEA was done on the diaphragm assembly and again beryllium proved to be the best material because of it’s extremely high stiffness to weight ratio. The 2435 has a performance envelop that far surpasses all commercial available compression drivers. In figure 29 we see the plane wave tube response of the 2435 as compared to a popular 3” titanium dome compression driver. Figure 40 shows the laser scan of the 2435 beryllium dome vs a 3 “ titanium dome at 14.5 kHz. It is clear the beryllium dome is still pistonic and the titanium dome is in heavy break up.

Figure 30 shows the cross-section of the compact compression driver. This driver has a 3 inch dome and an outside diameter of only 4.25 inches. Extensive magnetic finite element analysis was done to make the motor as compact as possible. Great care was taken to minimize the outside diameter of the driver so that they could be arrayed very close to each other. The resultant driver weighs only 1 Kg.

8. A physically realized line source

The above discussion has focused on how theoretical line sources behave. While these devices are imperfect and have widely different response in the near field, with small amounts of splay, the inherent lack of horizontal interference from a single source still makes the approach attractive and a realizable solution is desired.

The above simulations suggest that a small amount of curvature in the wavefront imparts no negative effect on the response or off axis behavior. We which to reach 15 kHz, which translates to a curvature of about 0.2 inches. Figure 31 shows a wave guide that is long with a narrow expansion that would yield a curvature of about 0.2 inches when energized from the from the 1.5" aperture of the compression driver. The waveguide is about 12 inches long and 5.3 inches high. Three of these devices can fit into a box that is .5 meters high. As well the outside diameter of the compression driver is small enough to allow a 3.3 degree splay between drivers in each box. This would be desired if the boxes were to be splayed at 10 degrees between boxes. Figure 32 shows the ideal configuration for boxes splayed 10 degrees with splay inside the box. In the same picture the top boxes are splayed 0 degrees.

Unfortunately, this idealized situation is best for large splay but not for narrow ones. With this in mind it was decided that the waveguides would be mounted at no splay within each box as in figure 31, as most use would be with narrow angles. Later on we will look at a simple method for effectively splaying within the box without changing the architecture. But first lets compare the measured results of three boxes with three sources in each box vs the model. In figure 33 we see a measurement taken at 4 meters of the three boxes versus the simulation of the a perfectly straight planer source, 9 slight curved sources, and 9 point sources. We can see than the measured result looks far closer to the planer source or the slightly curved source. The radical swings in the curve expected from the point sources is not seen. It can be debated at to whether the device is acting like a true planer source or slightly curved one but needless to say it is not acting like point sources. Since the planer result and the slightly curved results are so similar it doesn't really matter which one it is acting like, and it is sufficient to say that the overall behavior of an array of these devices *acts like a continuous source* not discrete point sources.

Let's look further into how the measured results compare to the model. In figure 35 we see the response of 9 waveguides on 3 boxes splayed at 0 degrees. In order to prove the array is working like a line source lets look at the performance versus distance. As we saw earlier the line source has a very specific kind of behavior in the changing of the frequency response versus distance. The data was taken at 4, 8 and 32 meters. The data was derived by subtracting the response of a single waveguide from the system response. This will compensate for the assumed flat response device implied in the model. In figure 34 we see the simulation at the same distances. The model includes gaps between the enclosures to insure that we are simulating the actual acoustical radiating surface. In comparing the two graphs, we can see all of the macroscopic features of the responses are identical. Smaller irregularities in the measurements are the result of diffraction effects of the box edges, which create a less than ideal environment. In figures 36 and 37 we see the comparison with the boxes splayed at 1 degree. Again we see very close matching to the macroscopic features of the curves in the model with the relative levels, the peaks and dips matching up nicely. Finally in figures 38 and 39 we see the comparison at 5 degrees of splay. And again, the measurements agree very nicely with the simulation.

9. Splaying beyond 5 degrees

Although the performance with the boxes splayed 5 degrees seems quite good it was desired the boxes be versatile enough to splay to 10 degrees. While it might seems as though we need to splay the waveguide inside each box as discussed earlier a simpler solution is available. Figure 41 shows the cross-section of a box with spacers placed between the compression drivers and the waveguide for the top and bottom driver. By adding this spacer to the outside drivers in each box we can effectively curve the wavefront within the box and splay the boxes to a wider angle. Shown in figures 42 is the raw (rolls off at higher frequencies, not normalized) measured off axis performance without spacers. The data is 1/12 octave at given frequencies. Cleary at high frequencies there is severe lobing. Figure 43 shows the off axis response of the two boxes with the spacers added. At lower frequencies there is little change but the lobing at high frequencies is eliminated within the intended 20-degree coverage pattern. Clearly adding the spacers effectively splaying the devices 3.3 degrees, eliminates the irregularities that are there in the normal configuration. It could also be speculated that, with tweaking, the response could be refined further at any splay angle with the appropriate spacers.

10. Conclusions

The near and intermediate fields created by continuous sources are interference fields and losses at high frequencies increase as one moves toward the source giving the illusion that there is a smaller difference in SPL for great distances covered than might be seen from a smaller radiating device. While this gives the appearance of a cylindrical wave and a 3dB per doubling of distance this is only a loose approximation. Flat planer sources have wildly different response characters in the near and intermediate fields suggesting that a perfectly straight source is largely unusable for consistent sound in these areas. Greater amounts of splay show more uniformity at these closer distances ranges.

A wave guide with a minimized amount of curvature in the wave front at the exit, limited to ¼ the wavelength of the highest intended frequency, does well to approximate a continuous source with a compression driver as the acoustic generator.

Shaping of the wave front by physical adjustment at the origin of the wave (adding a spacer between the driver and waveguide) can do well to improve coverage when splays of 5 degrees or greater are used.

11. Acknowledgments

The author wishes to thank Mark Ureda, Don Keele, Mark Engebretson, and Bernie Werner for their insights about the behavior of line arrays.

12. References

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[2] Olson, H. F., "Elements of Acoustical Engineering", 1st ed., p.25, D. Van Nostrand Company, Inc., New York, 1940.

[3] Ureda, M.S., "Line Arrays: Theory and Applications." Presented at the 110th Convention 2001 May 12–15 Amsterdam, The Netherlands

[4] Ureda, M.S., "J and Sprial Arrays" Presented at the 111th convention of the AES, November 2001, New York, New York.

[5] Locanthi, B et al, "Design of 48-mm Beryllium Diaphragm Compression" 60 th convention of the AES, 1978

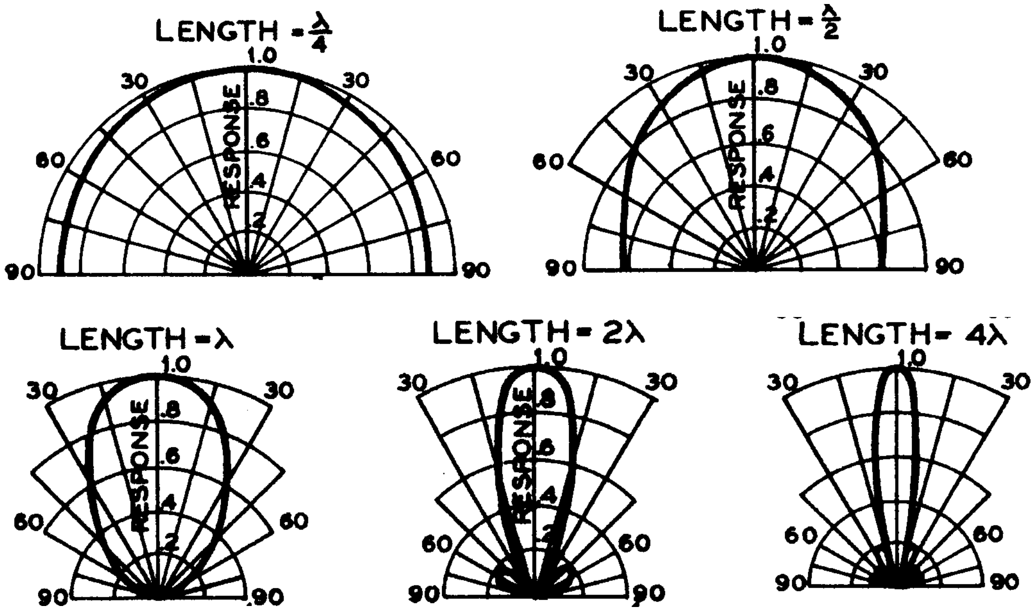


Figure 1. Vertical polar response of a straight planner surface from Olson [5].

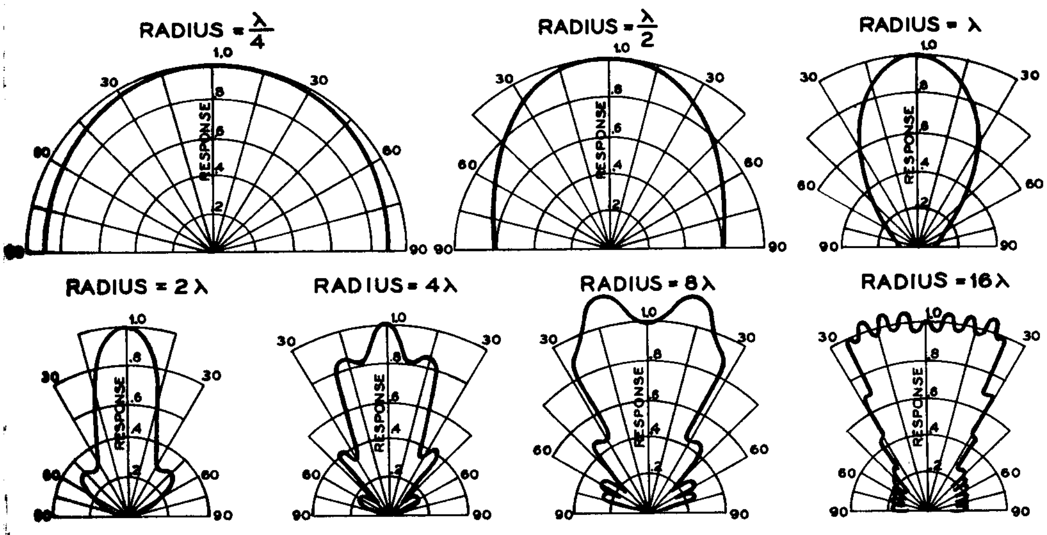


FIG. 2.9. Directional characteristics of a 60° arc as a function of the radius and the

Figure 2. Vertical polar response of a curved surface from Olson [5].

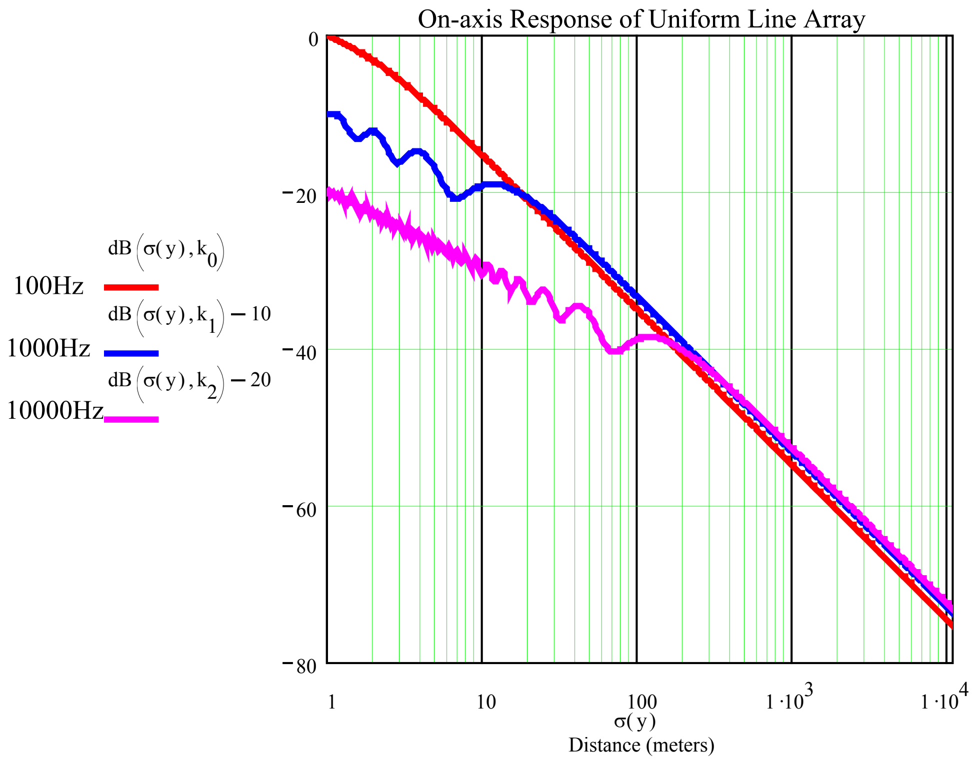


Figure 3. Attenuation vs distance for a uniform line array at 100Hz 1000Kz and 10,000Hz. From Ureda [1].

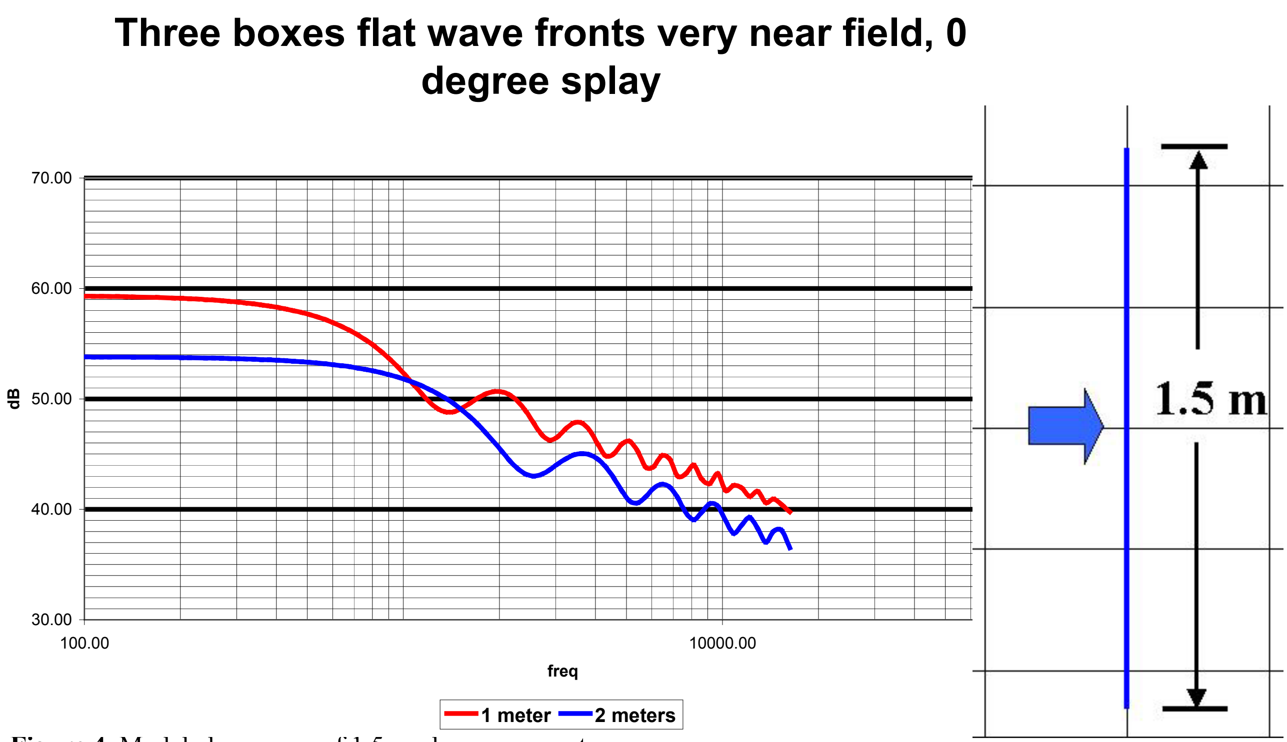


Figure 4. Modeled response of 1.5 m planner array at 1 and 2 meters.

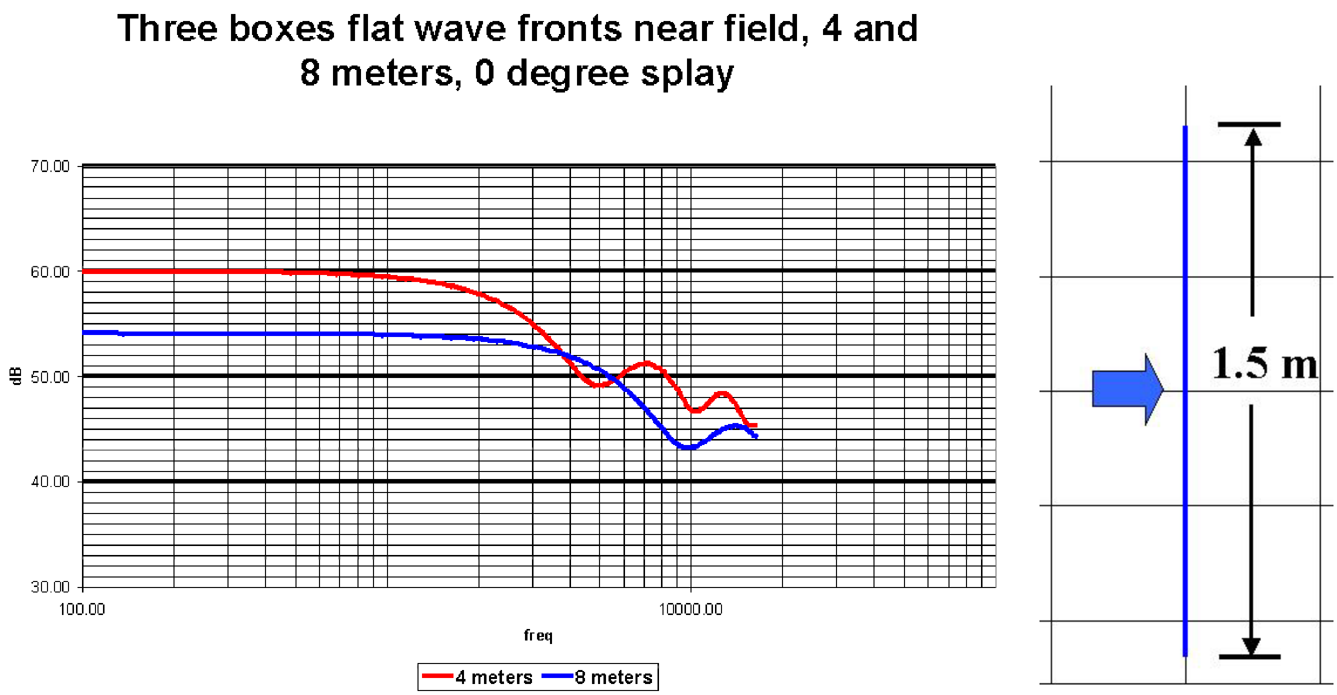


Figure 5. Modeled response of a 1.5m array at 4 and 8 meters.

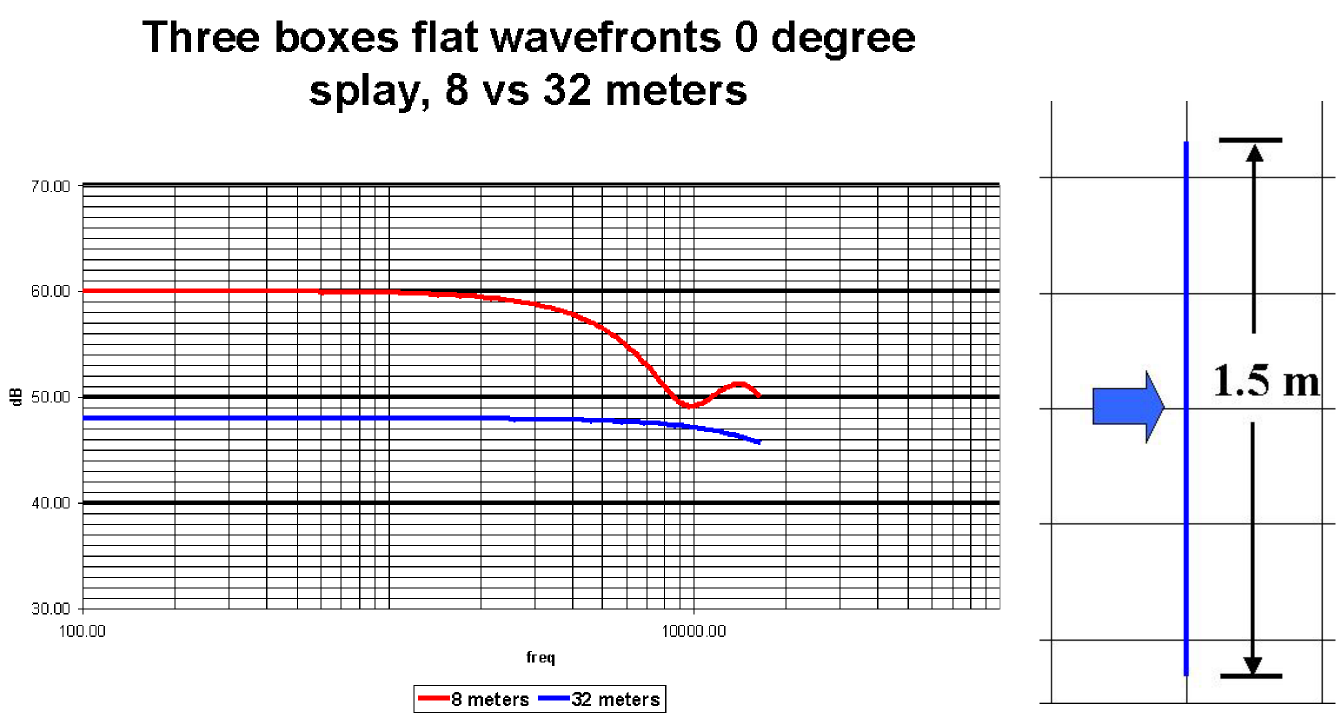


Figure 6. Modeled response of a 1.5 m array at 8 and 32 meters.

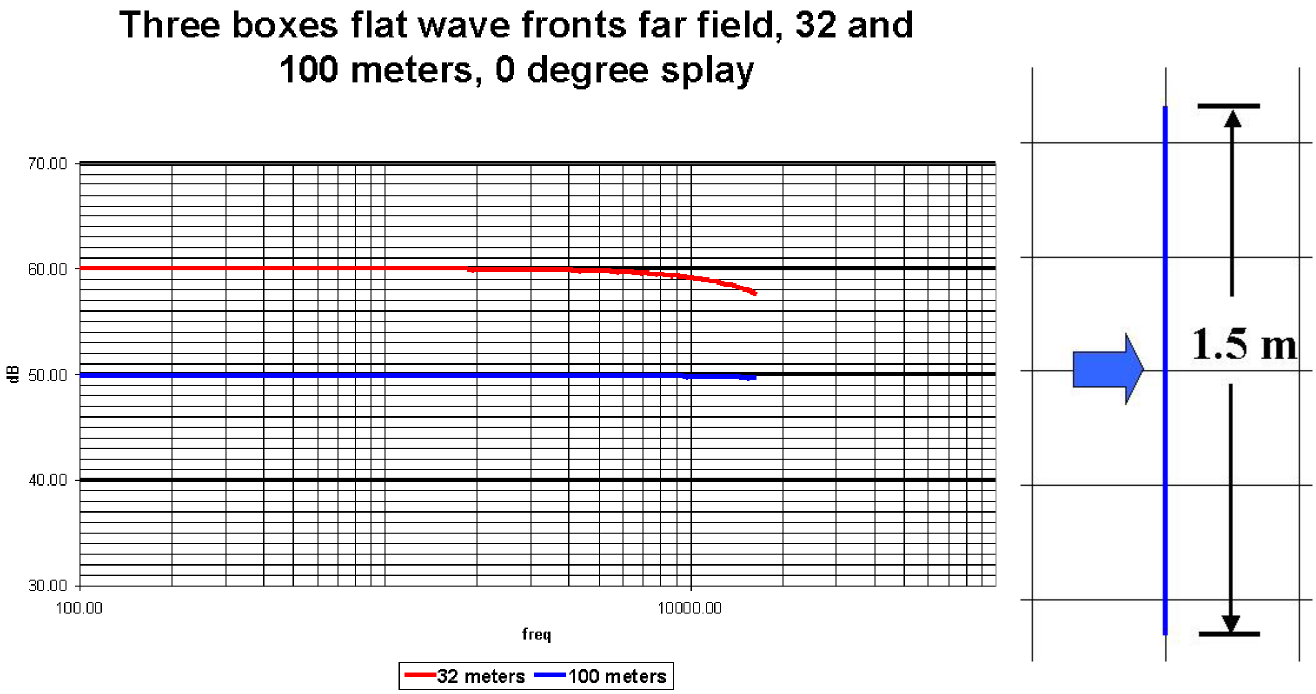


Figure 7. Modeled response of a 1.5 m array at 32 and 100 meters.

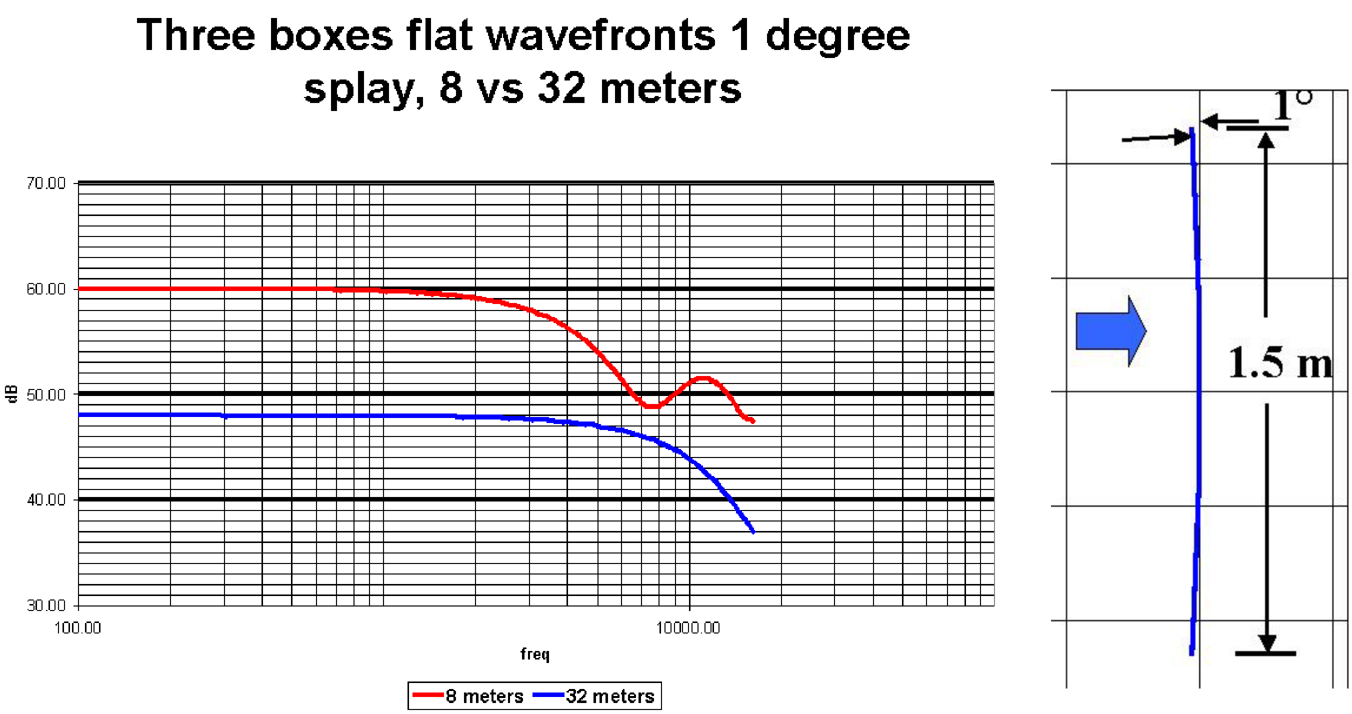


Figure 8. Modeled response of 1.5 m array splayed in 1/3's by 1 degree.

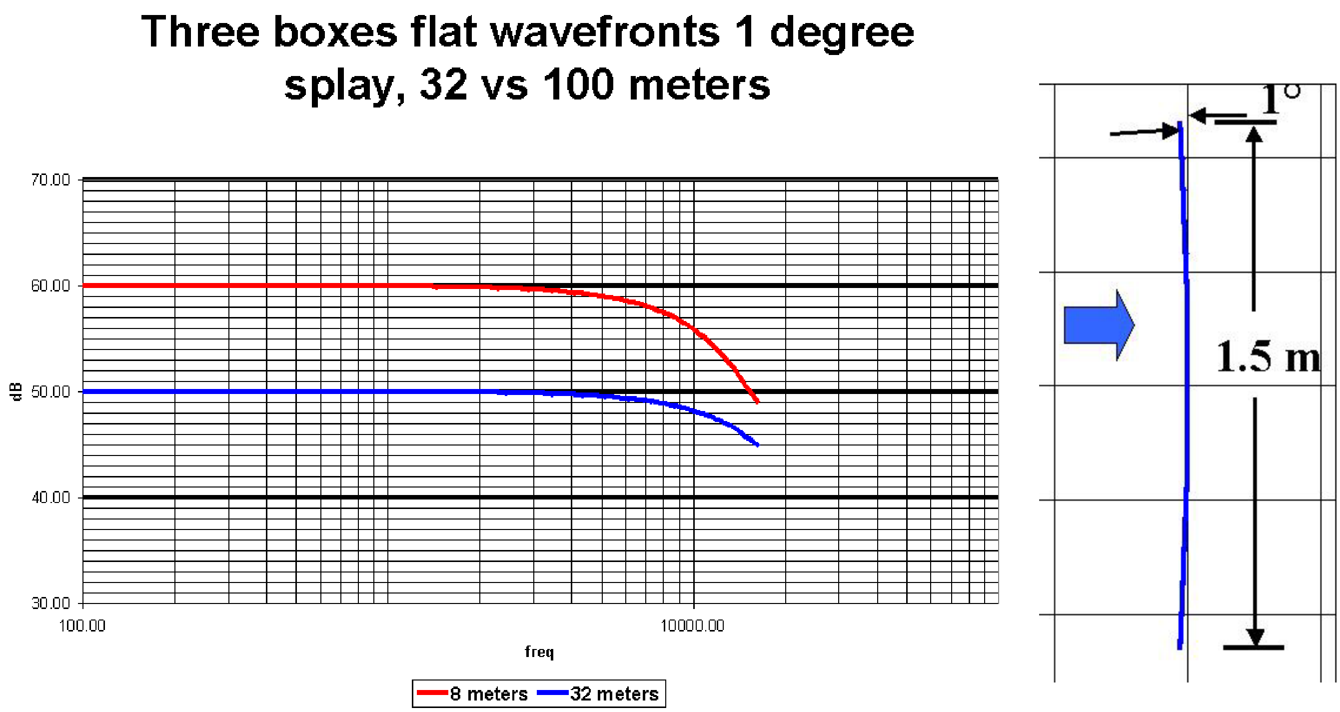


Figure 9. Modeled response of 1.5 m array splayed in 1/3's by 1 degree.

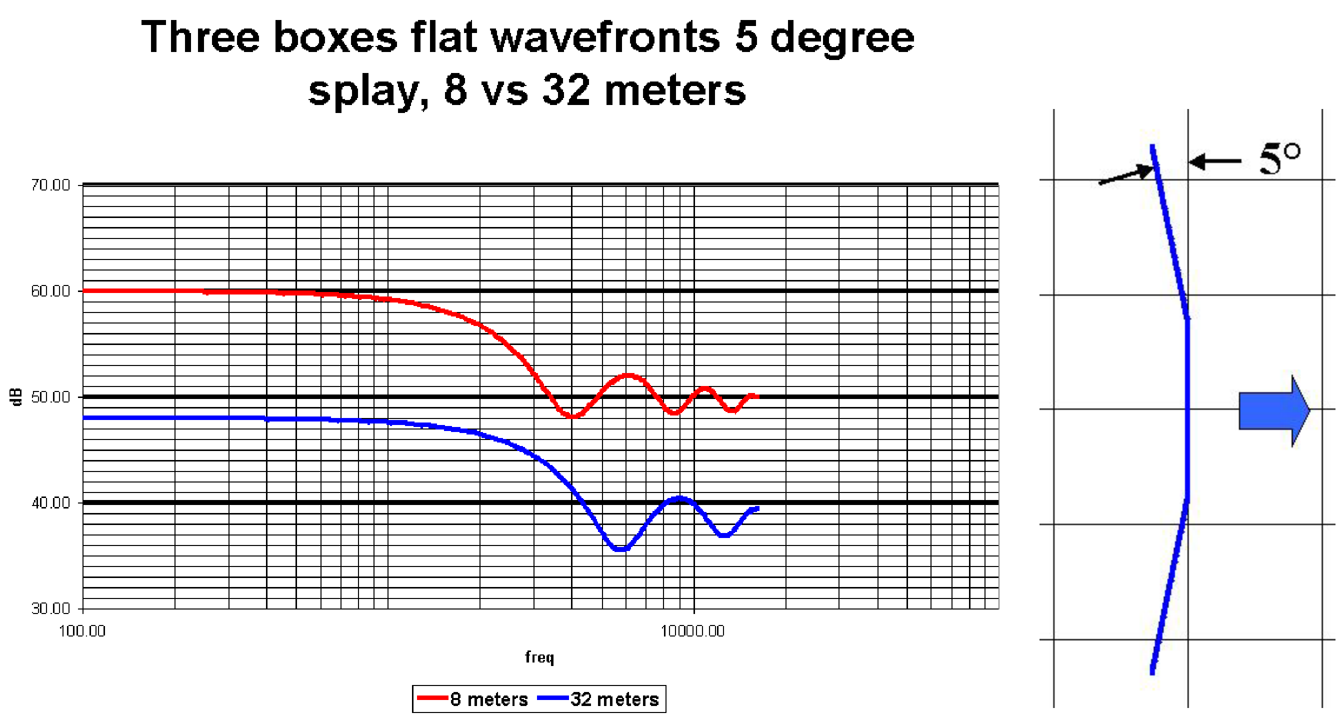


Figure 10. Modeled response of 1.5 m array splayed in 1/3's by 5 degrees.

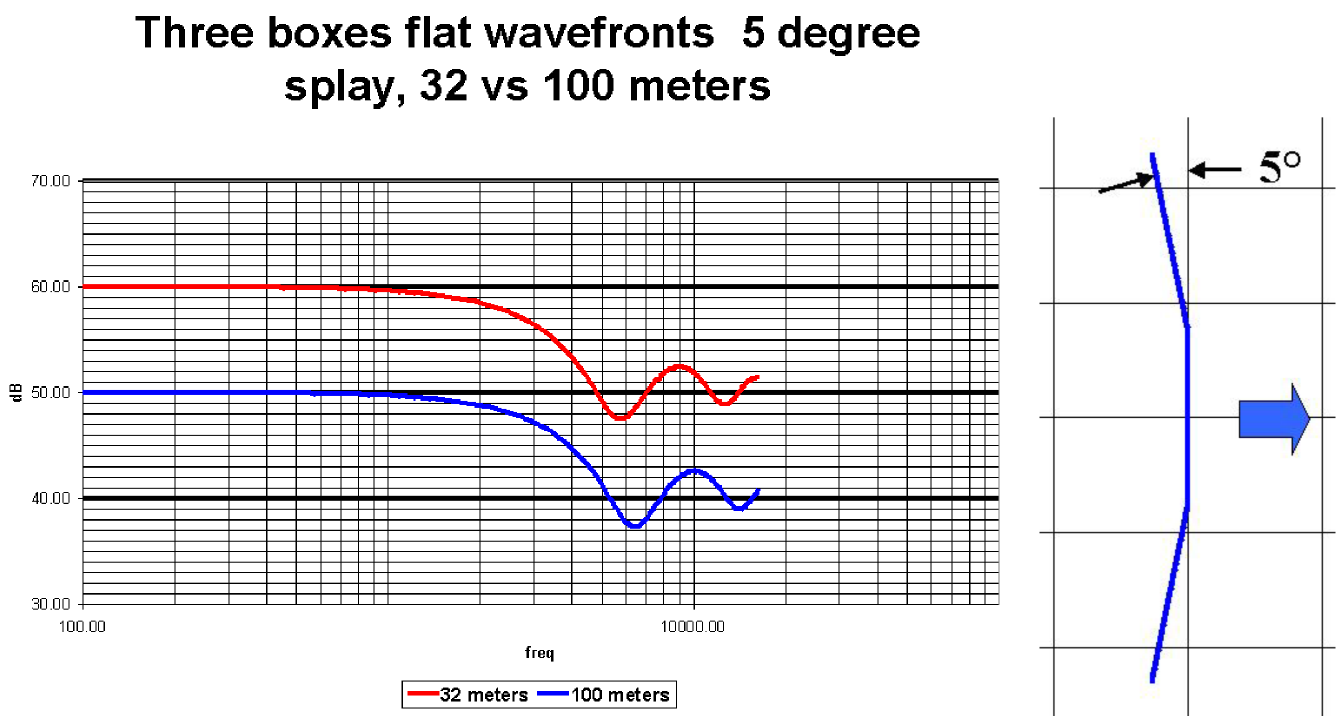


Figure 11. Modeled response of 1.5 m array splayed in 1/3's by 5 degrees.

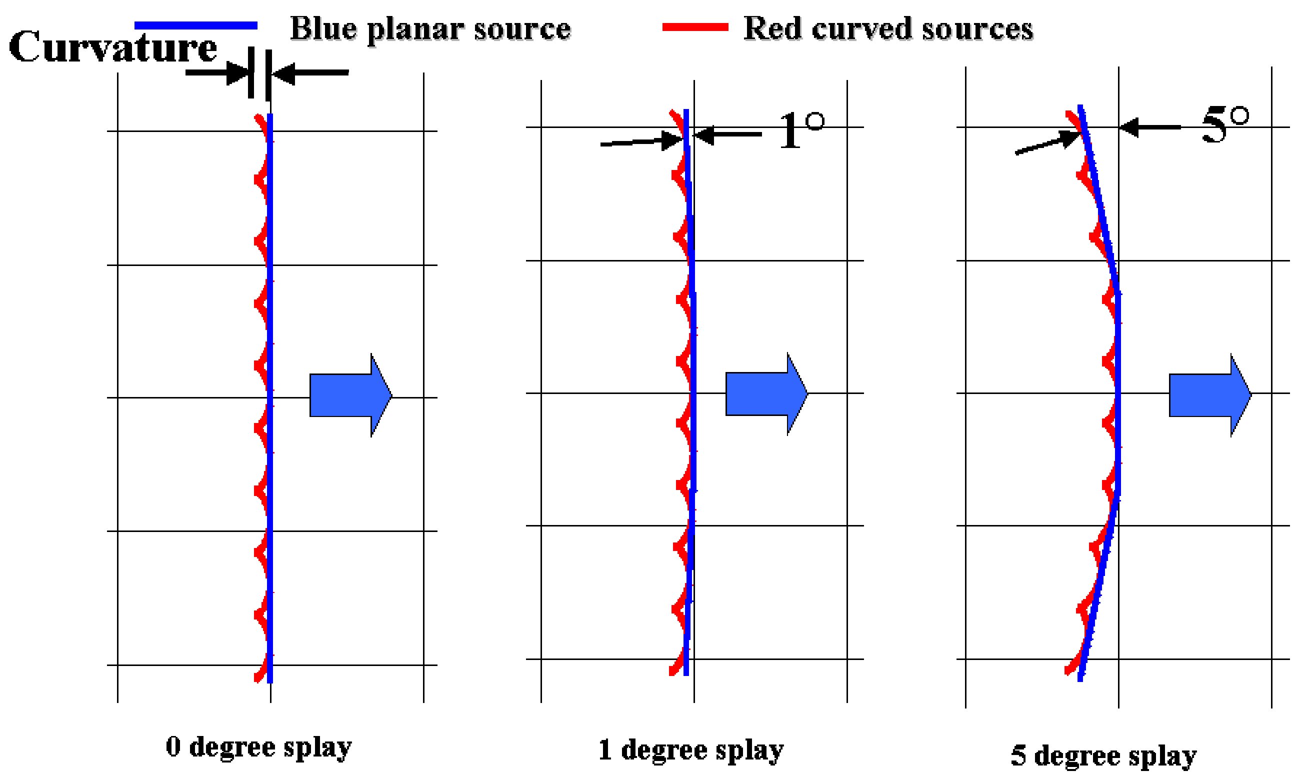


Figure 12. Graphic representation of slightly curved sources used in multiples to represent a pseudo planer source. Curvature must be ¼ of a wavelength or less of highest expected usable frequency.

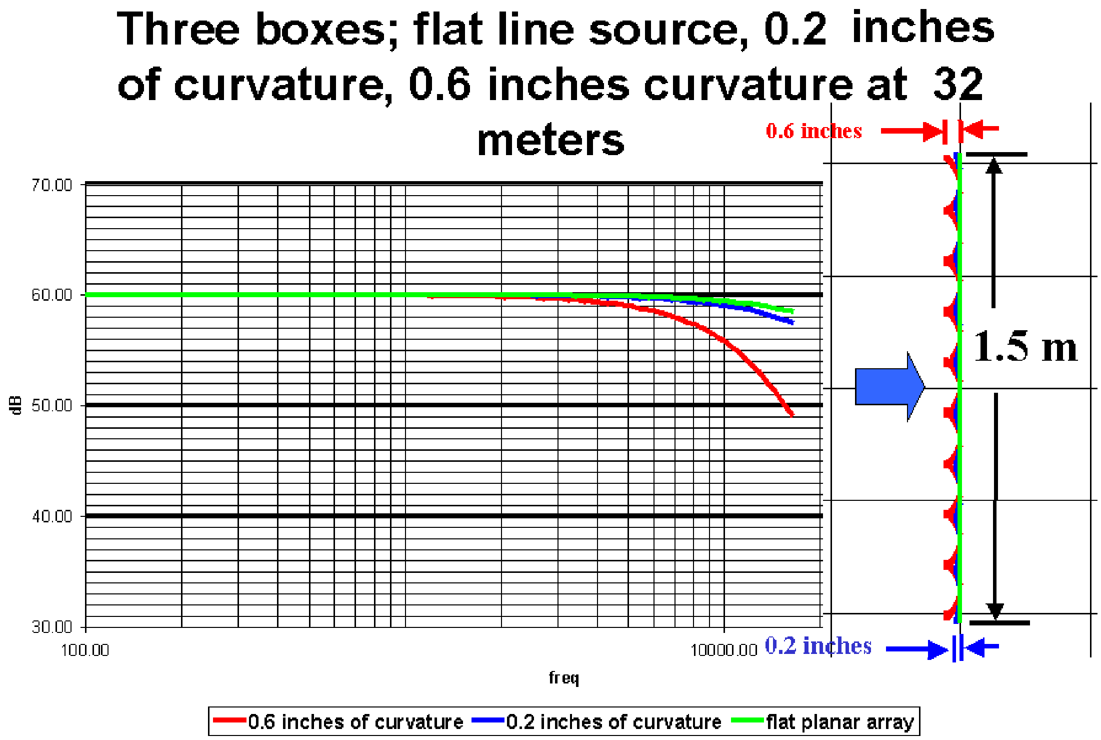


Figure 13. Modeled response of the effects of increased curvature in the far field. 0.2 inches represents ¼ wavelength of 15 kHz.

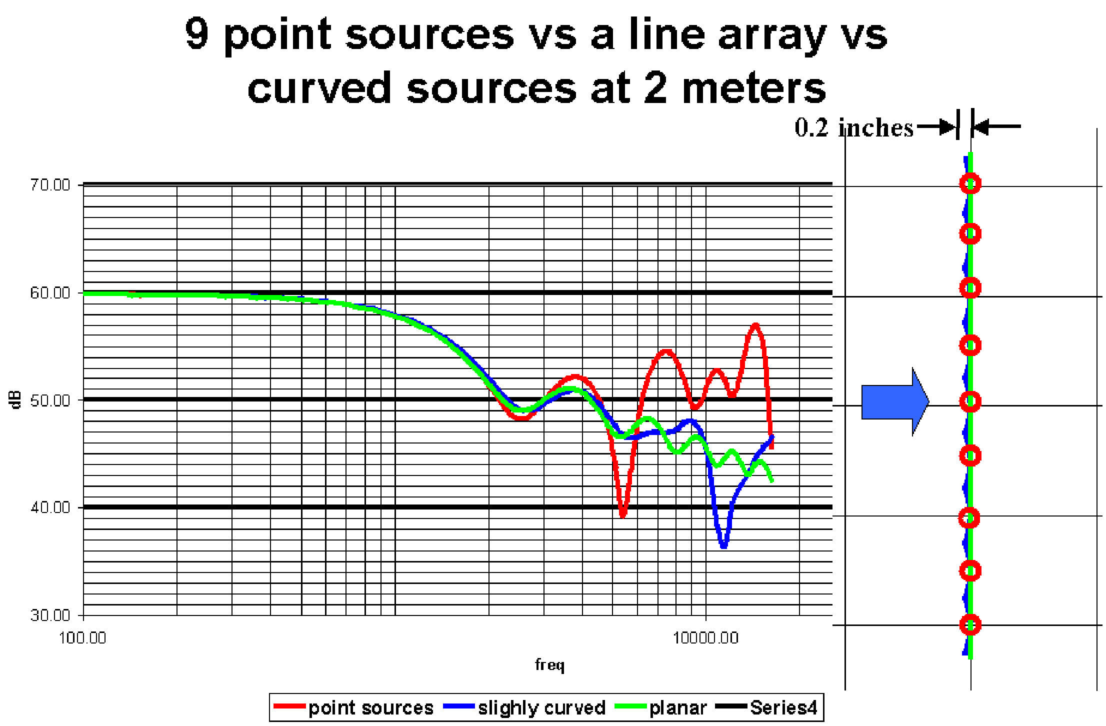


Figure 14. Modeled response comparison of 9 points sources with planer and pseudo planer sources. 1.5 m tall.

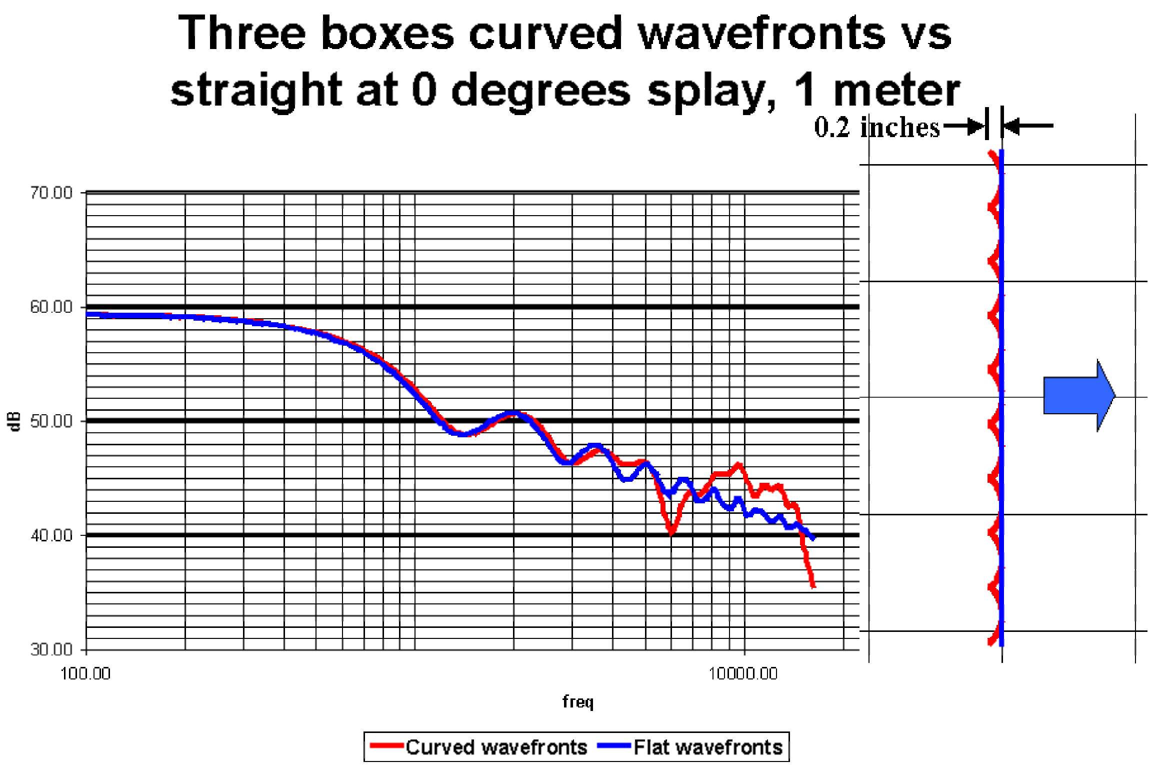


Figure 15. Modeled response of slightly curved wavefronts vs true planer wavefronts in the very near field. 1.5 m tall.

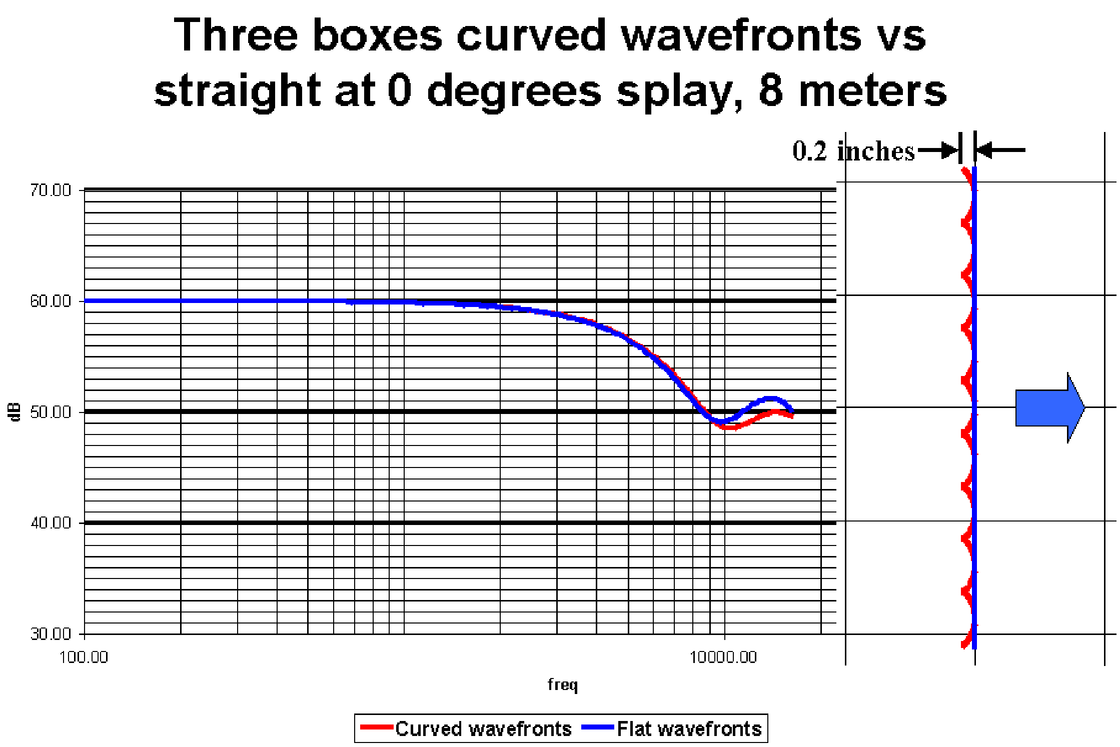


Figure 16. Modeled response of slightly curved wavefronts vs true planer wavefronts in the intermediate near field. 1.5 m tall.

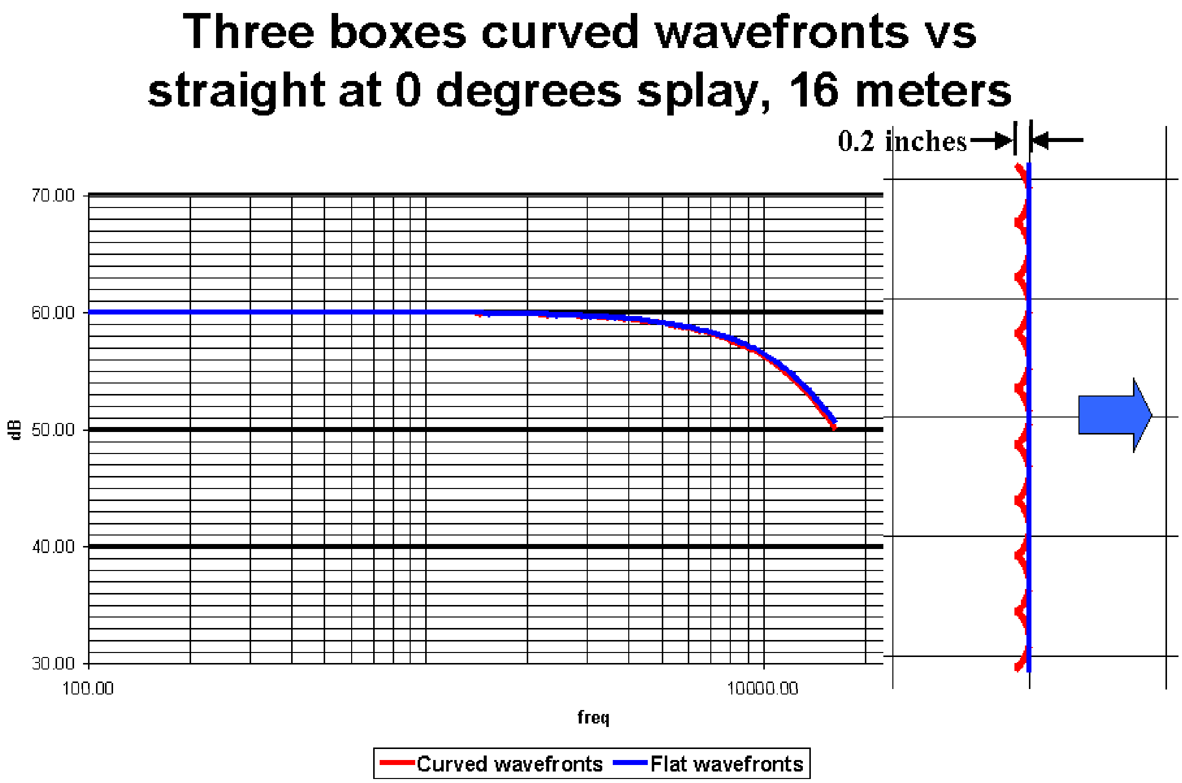


Figure 17. Modeled response of slightly curved wavefronts vs true planer wavefronts in the intermediate field. 1.5 m tall.

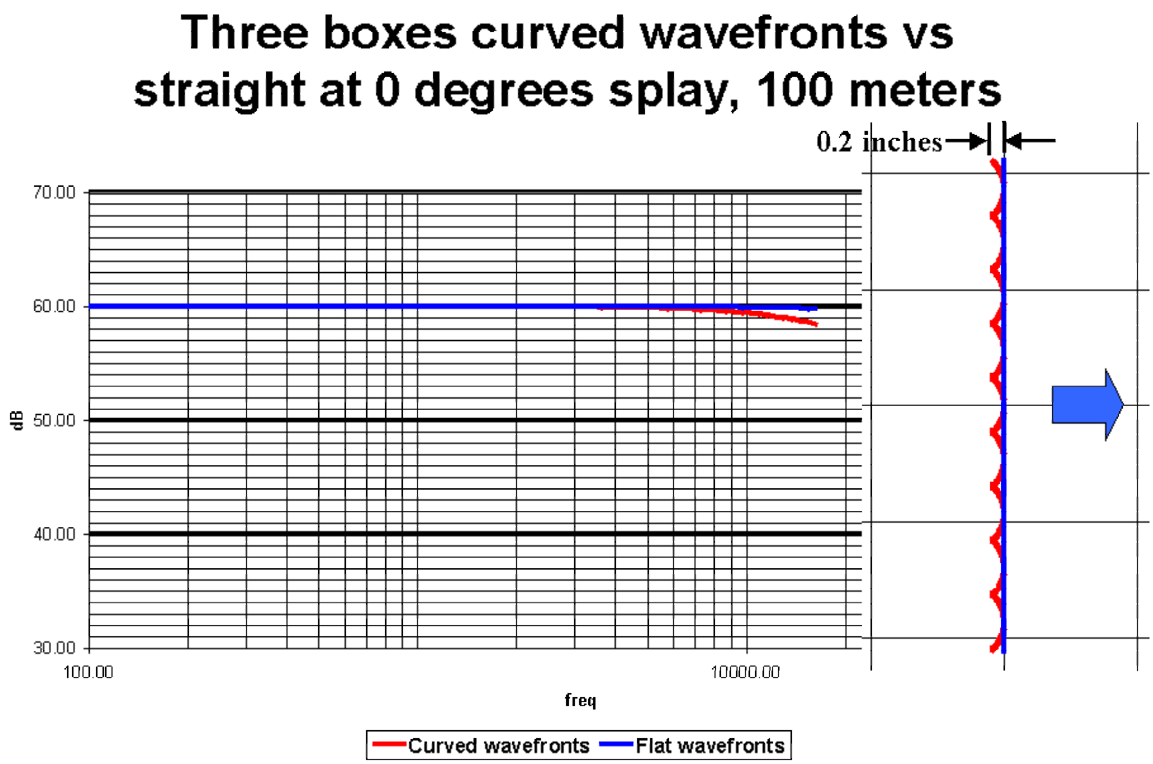


Figure 18. Modeled response of slightly curved wavefronts vs true planer wavefronts in the far field. 1.5 m tall.

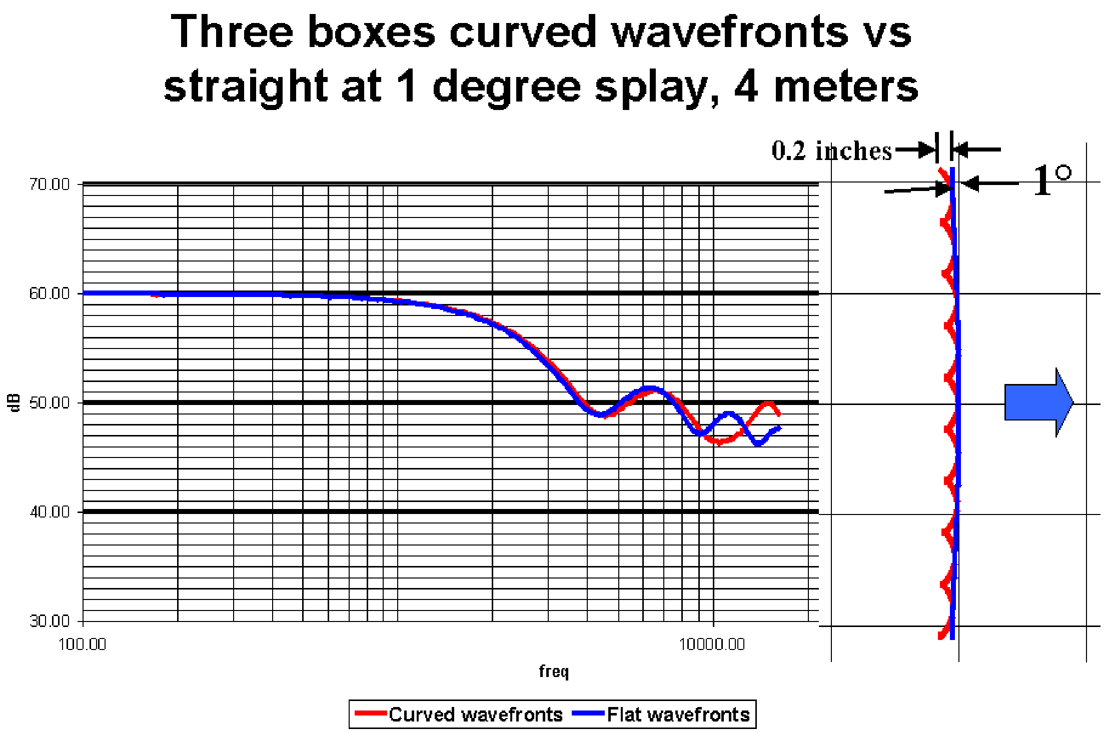


Figure 19. Modeled response of slightly curved wavefronts vs true planer wavefronts with 1 degree of splay on top and bottom 1/3. 1.5 m tall.

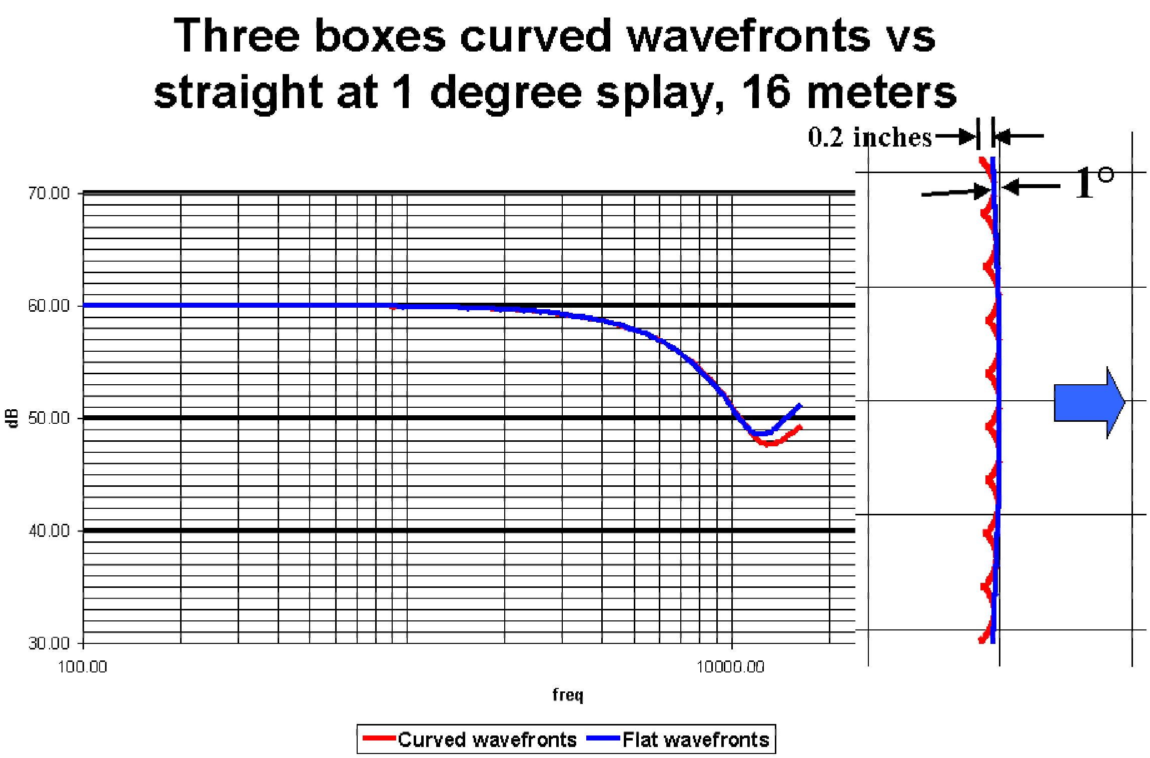


Figure 20. Modeled response of slightly curved wavefronts vs true planer wavefronts with 1 degree of splay on top and bottom 1/3. 1.5 m tall.

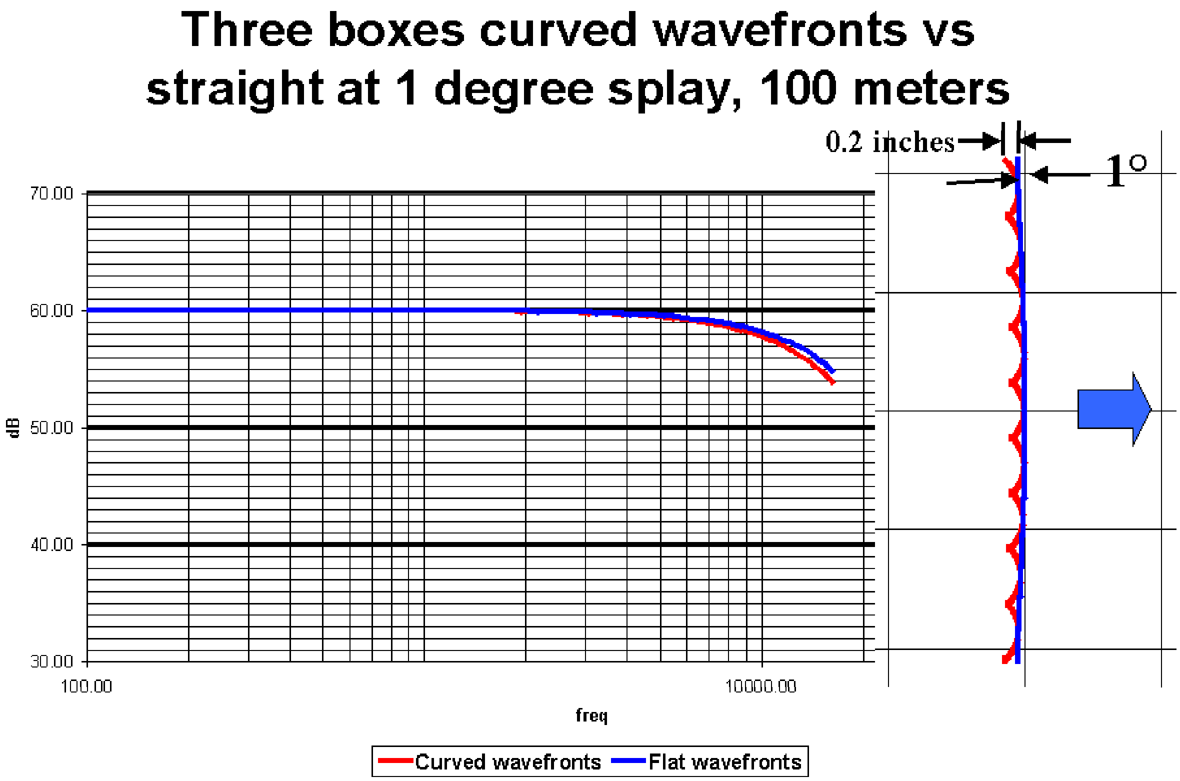


Figure 21. Modeled response of slightly curved wavefronts vs true planer wavefronts with 1 degree of splay on top and bottom 1/3. 1.5 m tall.

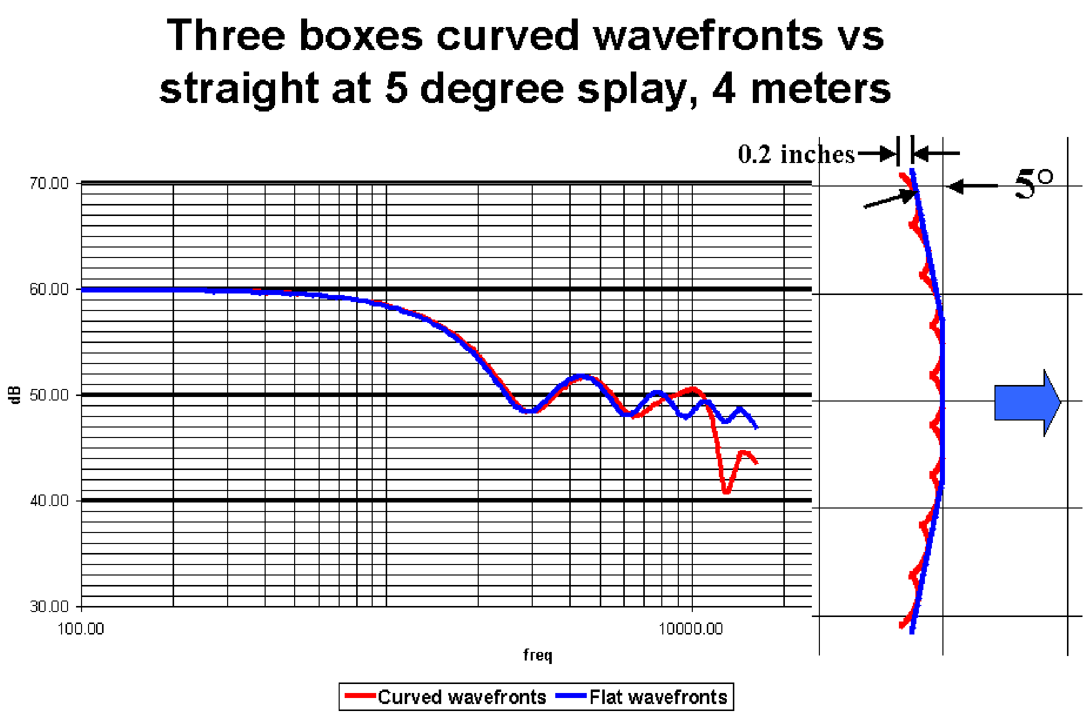


Figure 22. Modeled response of slightly curved wavefronts vs true planer wavefronts with 5 degrees of splay on top and bottom 1/3. 1.5 m tall.

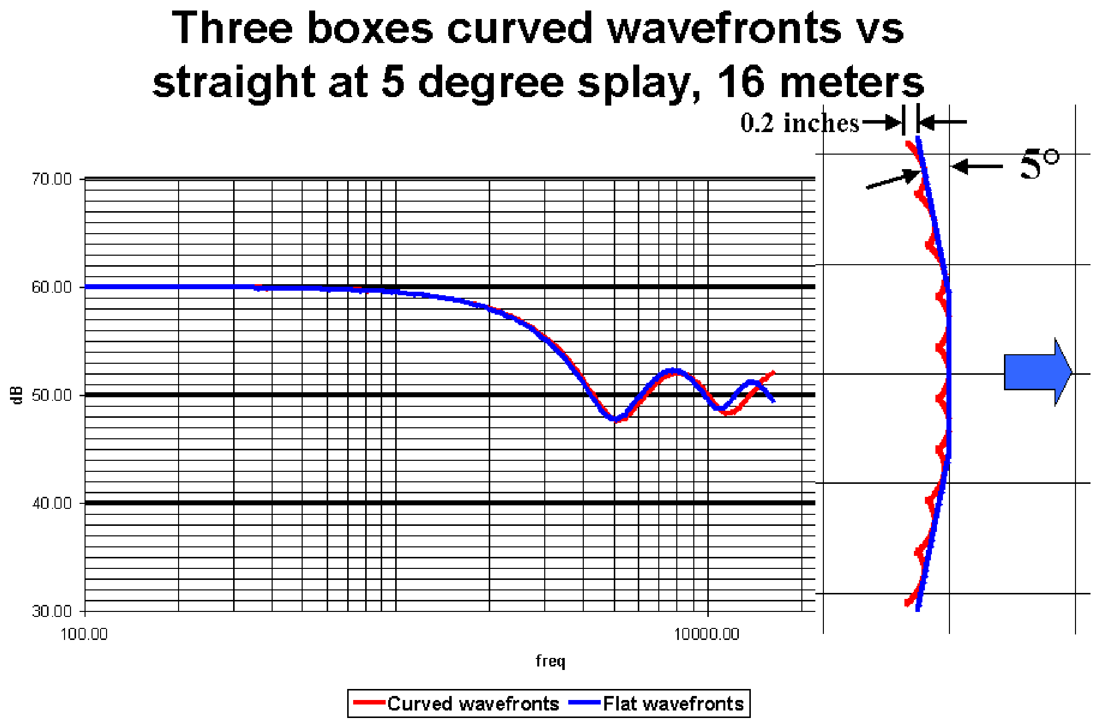


Figure 23. Modeled response of slightly curved wavefronts vs true planer wavefronts with 5 degrees of splay on top and bottom 1/3. 1.5 m tall.

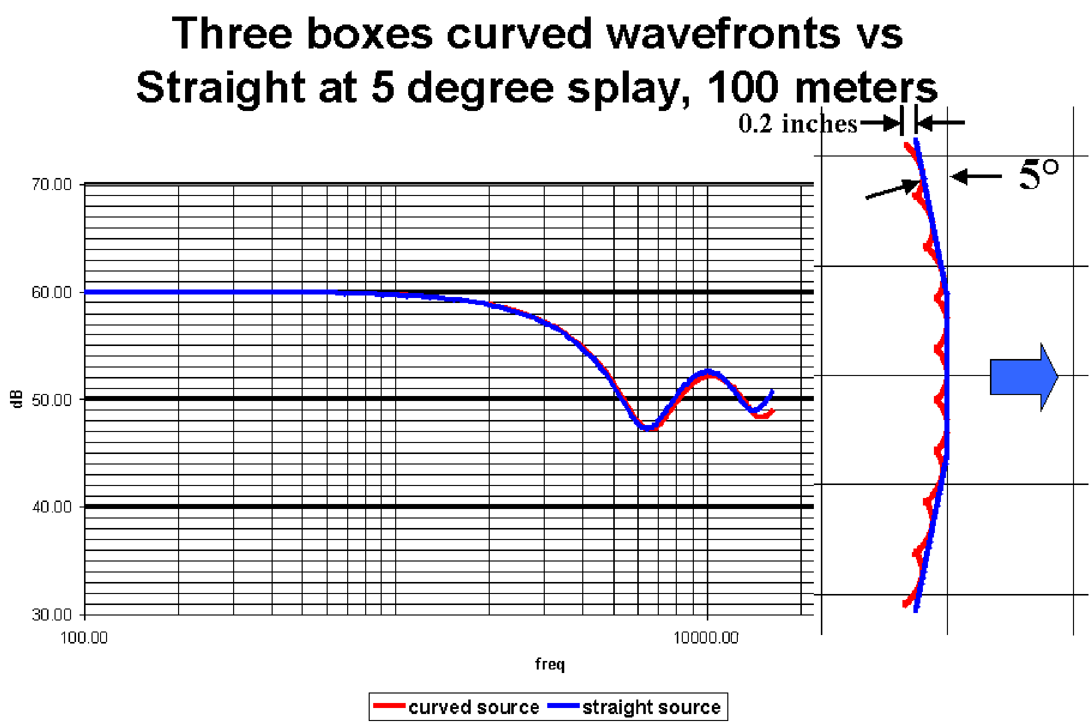


Figure 24. Modeled response of slightly curved wavefronts vs true planer wavefronts with 5 degrees of splay on top and bottom 1/3. 1.5 m tall.

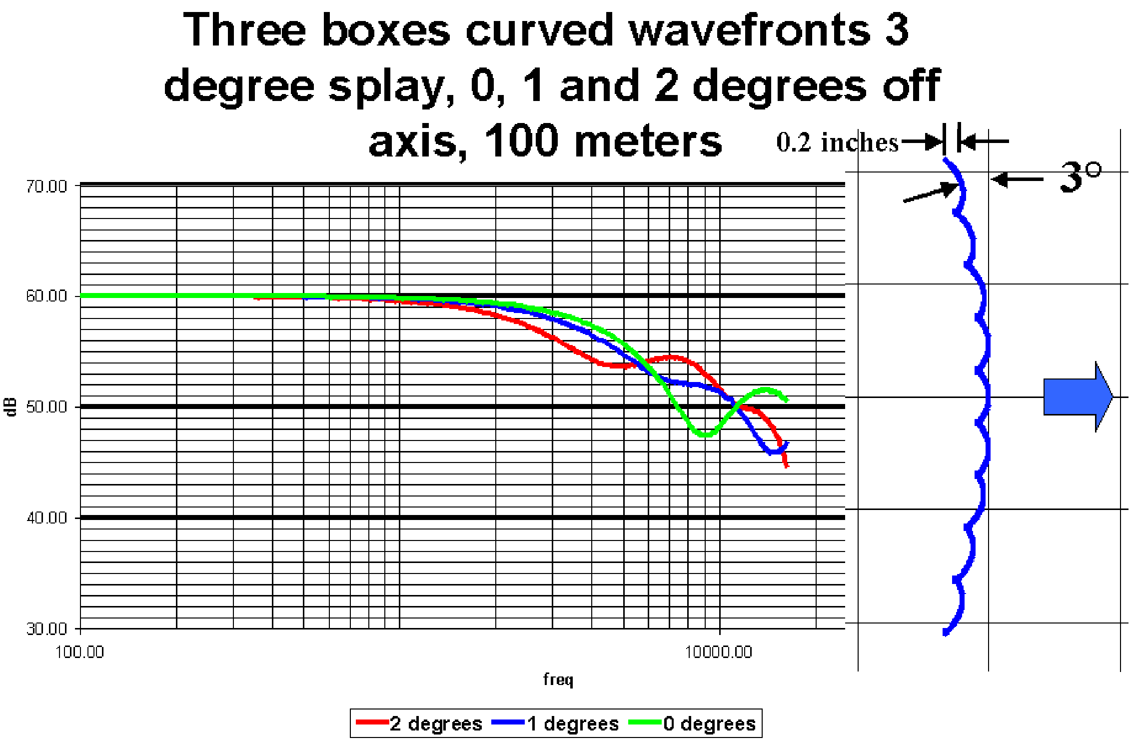


Figure 25. Modeled response of slightly curved wavefronts with 3 degrees of splay taken at 0,1 and 2 degrees off axis on top and bottom 1/3. 1.5 m tall.

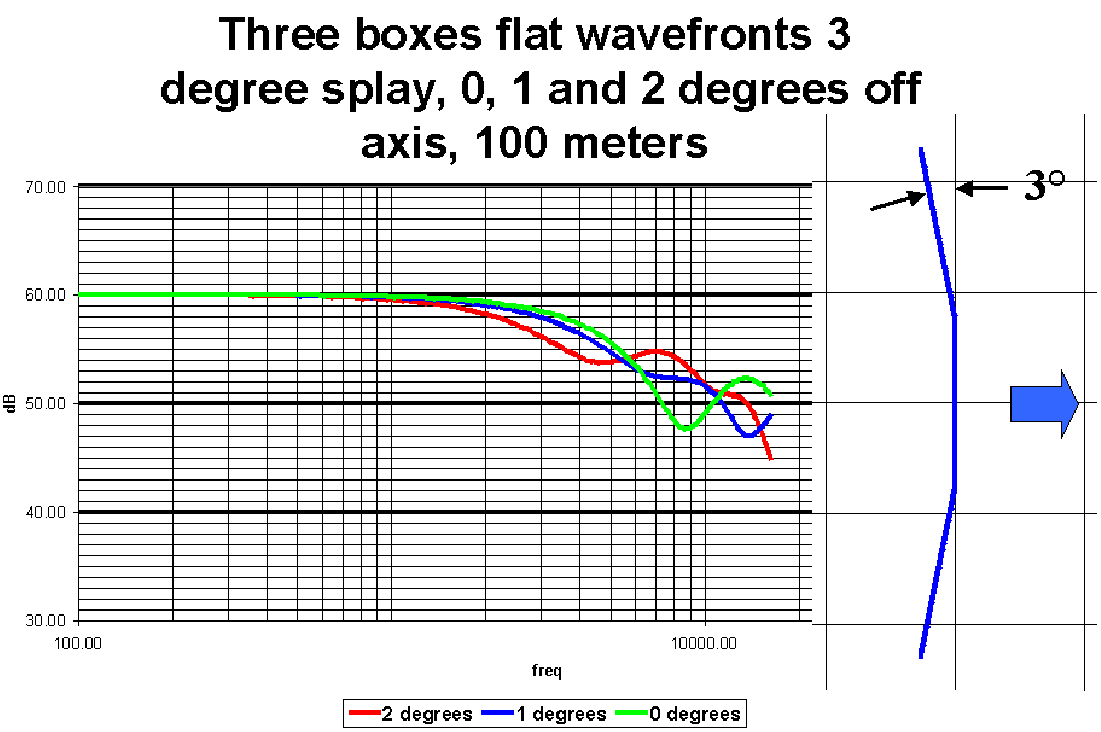


Figure 26. Modeled response of planer wavefronts with 3 degrees of splay taken at 0,1 and 2 degrees off axis on top and bottom 1/3. 1.5 m tall.

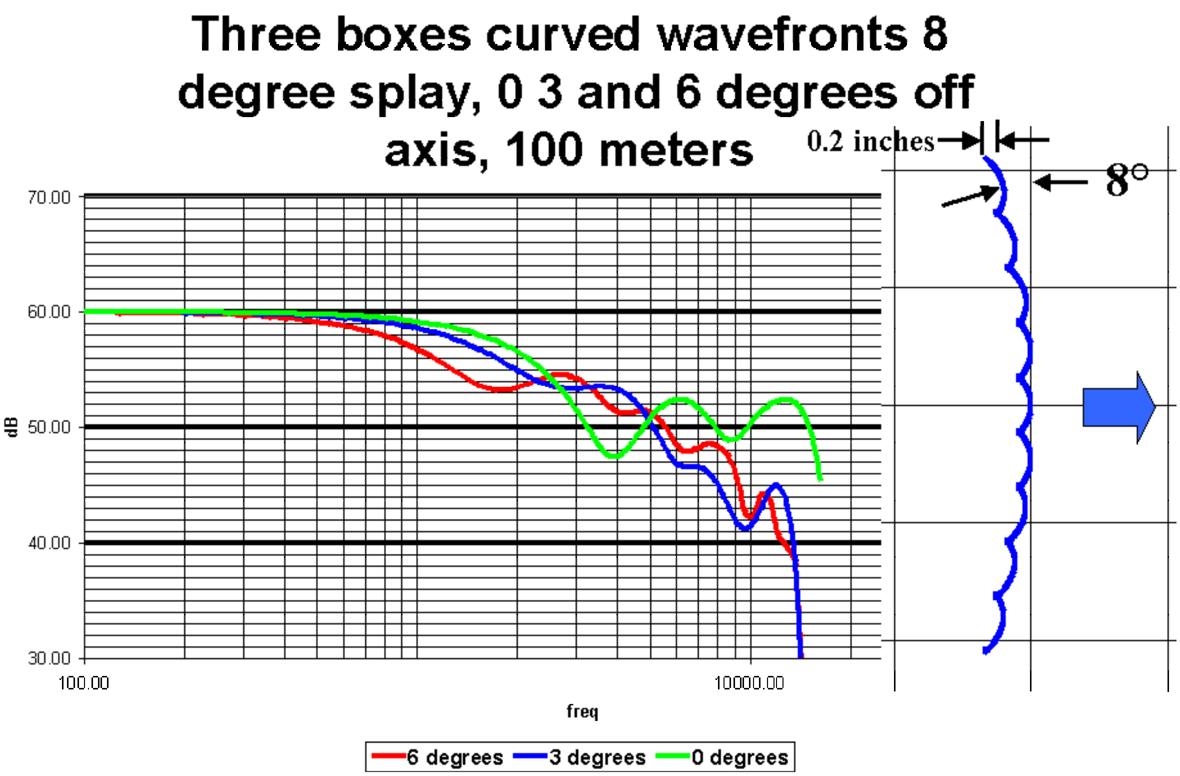


Figure 27. Modeled response of slightly curved wavefronts with 8 degrees of splay taken at 0,3 and 6 degrees off axis on top and bottom 1/3. 1.5 m tall.

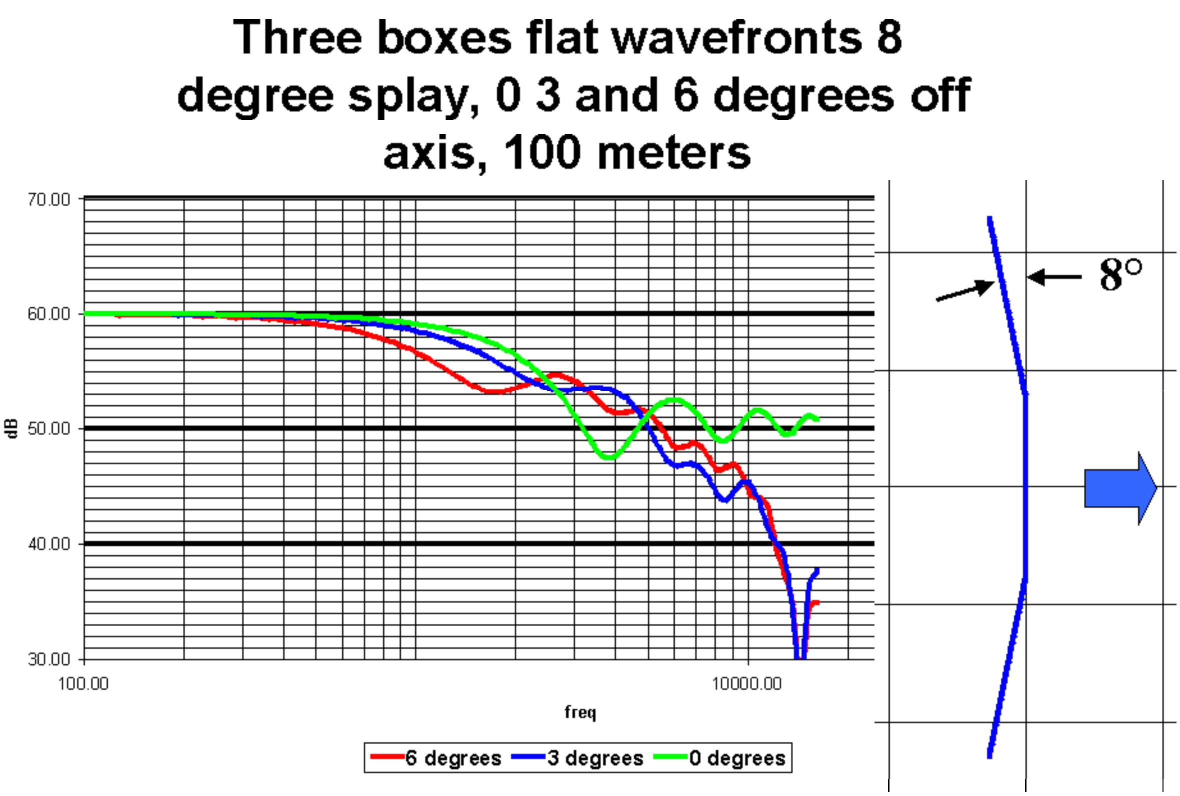


Figure 28. Modeled response of planer wavefronts with 8 degrees of splay taken at 0,3 and 6 degrees off axis on top and bottom 1/3. 1.5 m tall.

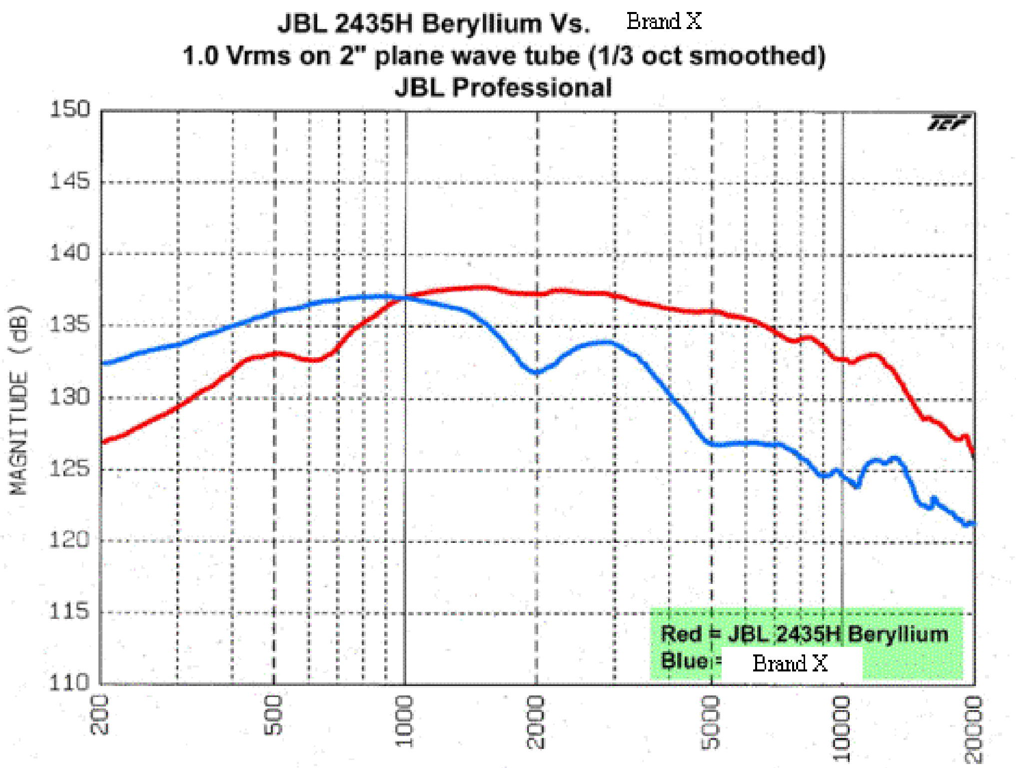


Figure 29. Plane wave tube response of 2435 3" dome vs popular 3" titanium driver.

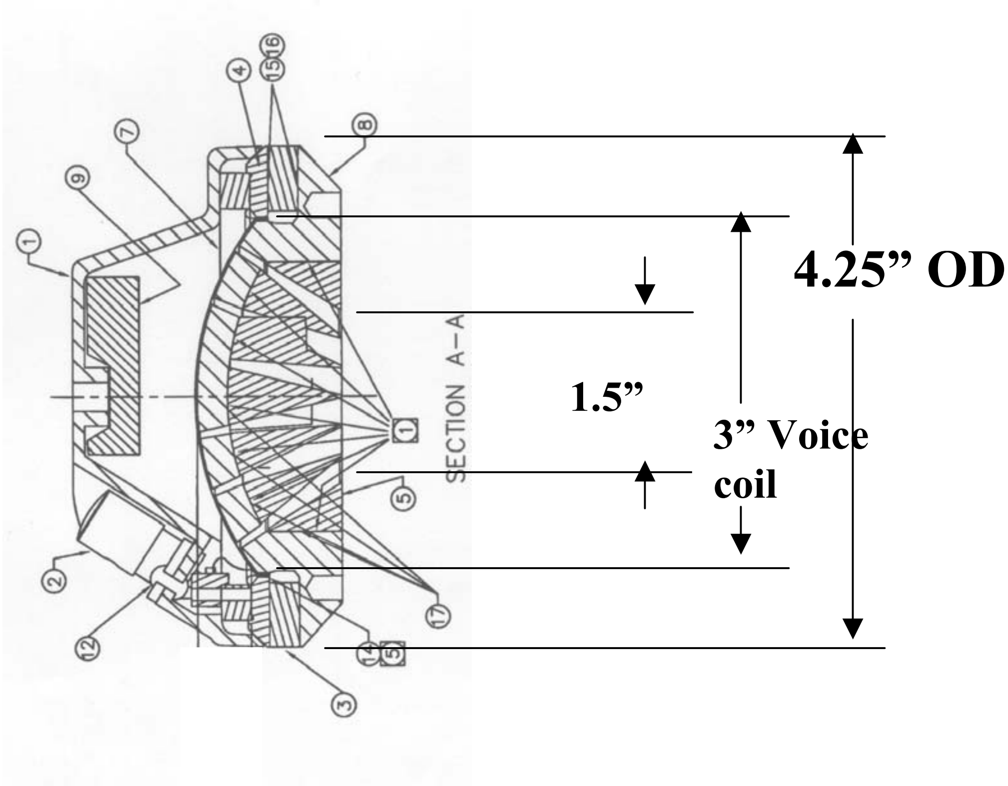
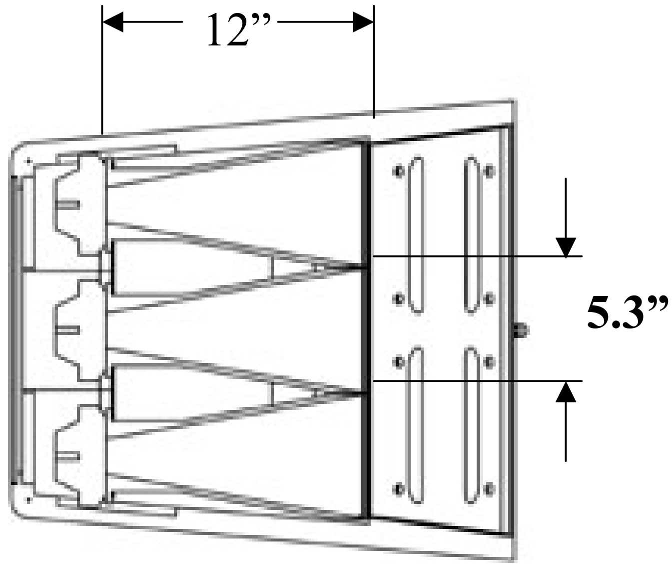
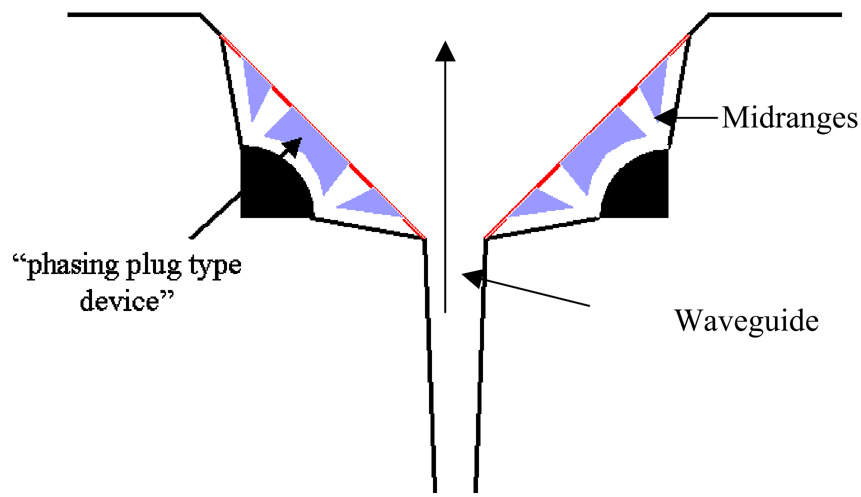


Figure 30. Cross-section of 2435 driver



31a. 3 waveguides in a box

31b. 2435 on aluminum waveguide



31c.Plan view

Figure 31. different views of the wave guide and compression driver configuration yielding a curvature of 0.2”

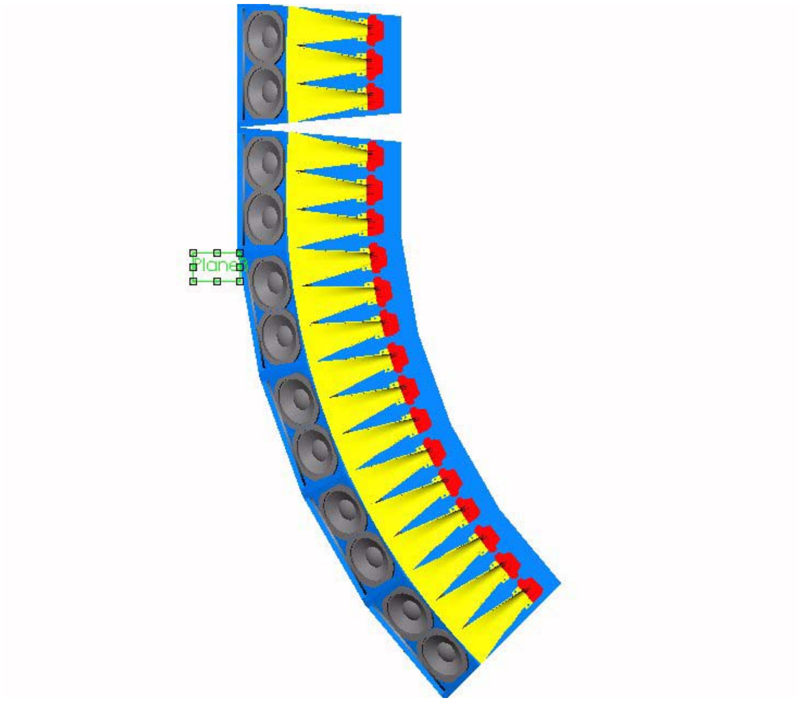


Figure 32. Boxes with 3.3 degrees between waveguide. Well suited for 10 degrees of splay but wrong for the 0 degree of splay at the top.

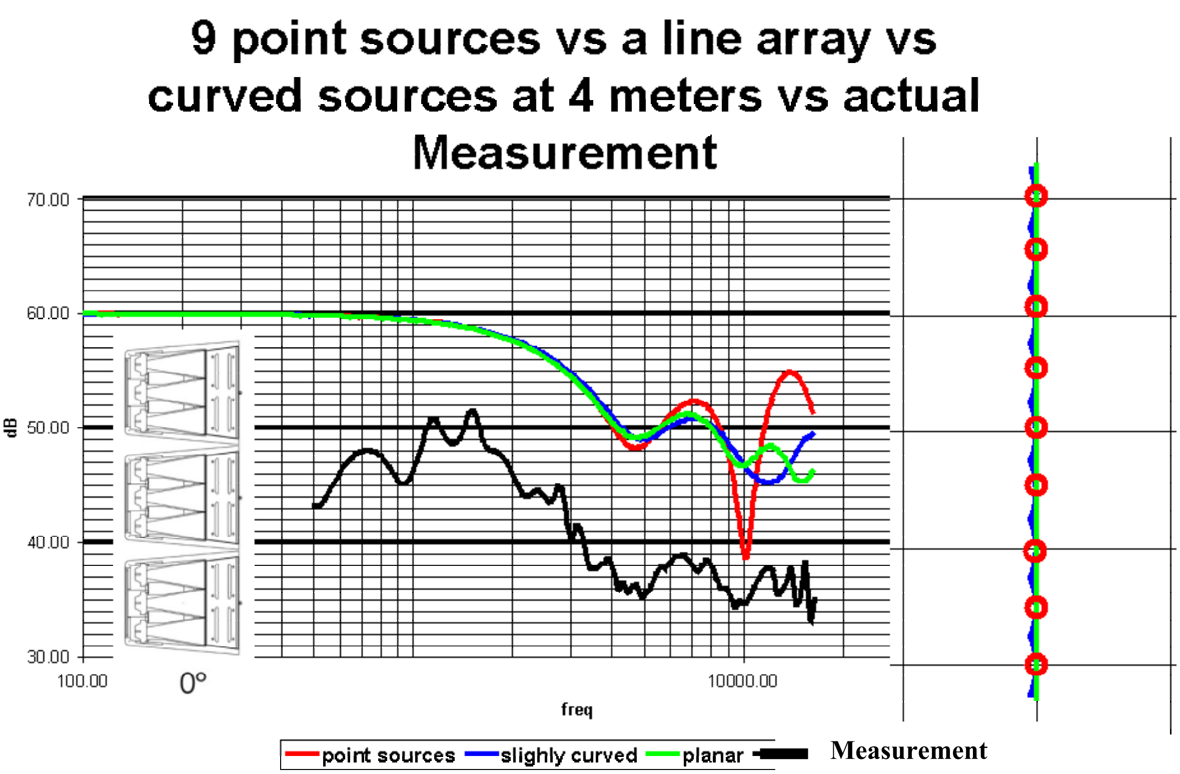


Figure 33. Models vs actual measurement **(offset for comparison).** The actual measurement much more resembles the continuous sources.

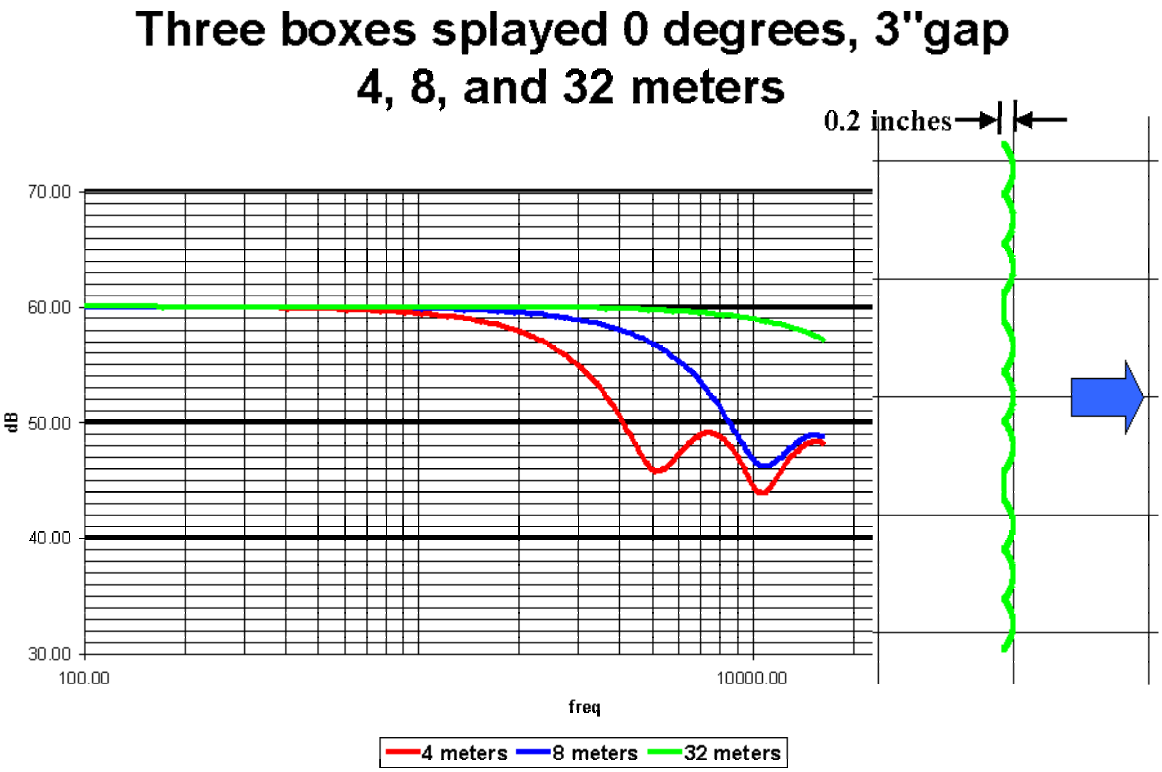


Figure 34. Modeled response of the three boxes at 0 degrees of splay.

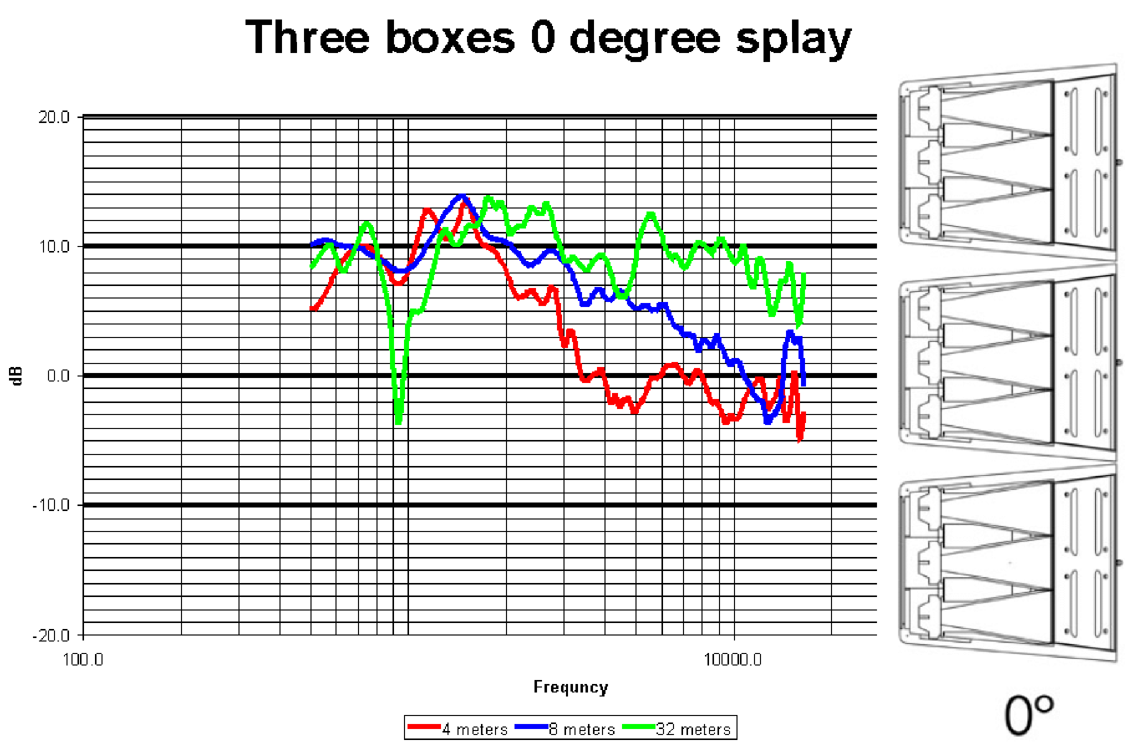


Figure 35. Measured response of three boxes at 0 degrees of splay.

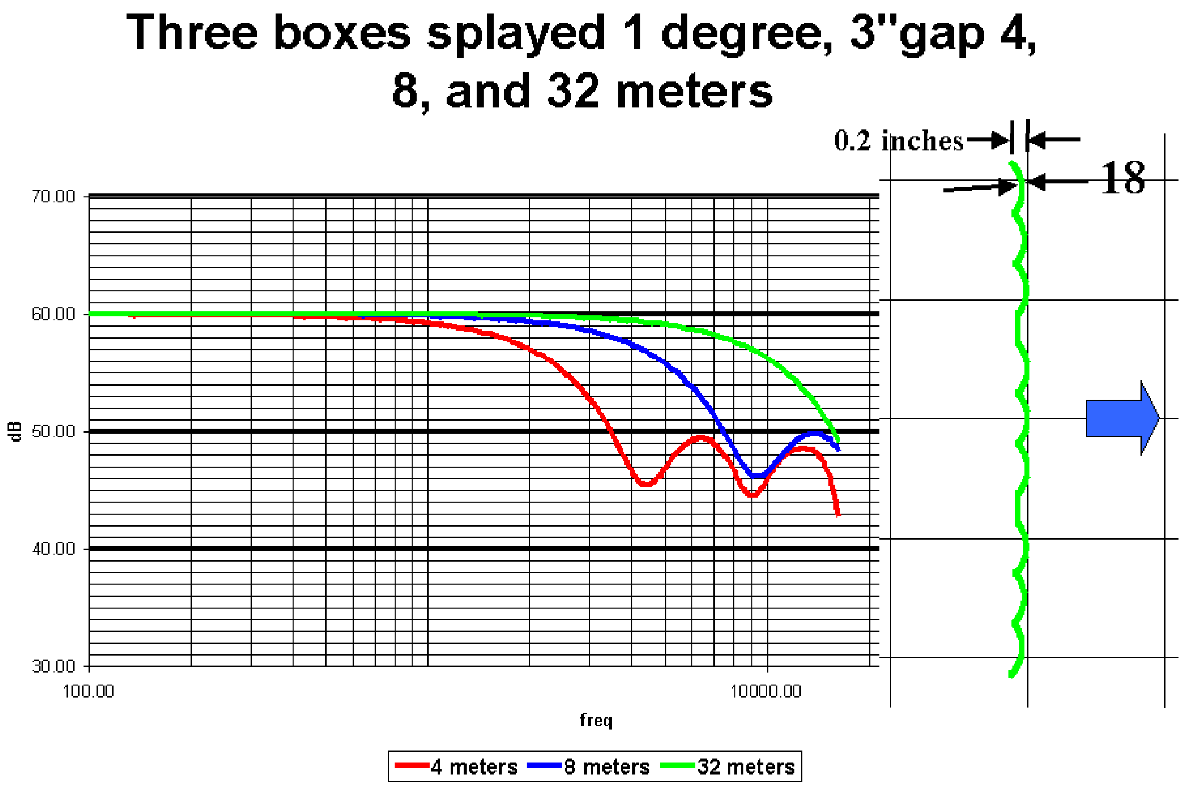


Figure 36. Modeled response of the three boxes at 1 degrees of splay.

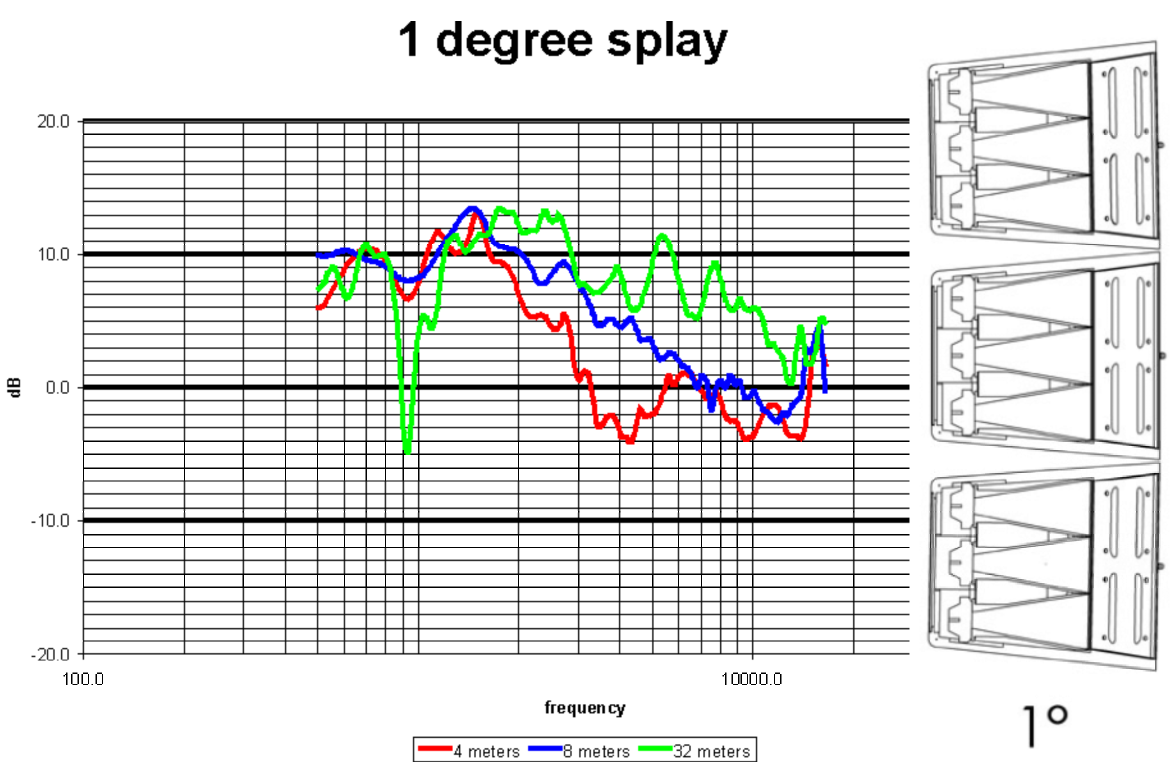


Figure 37. Measured response of three boxes at 1degree of splay.

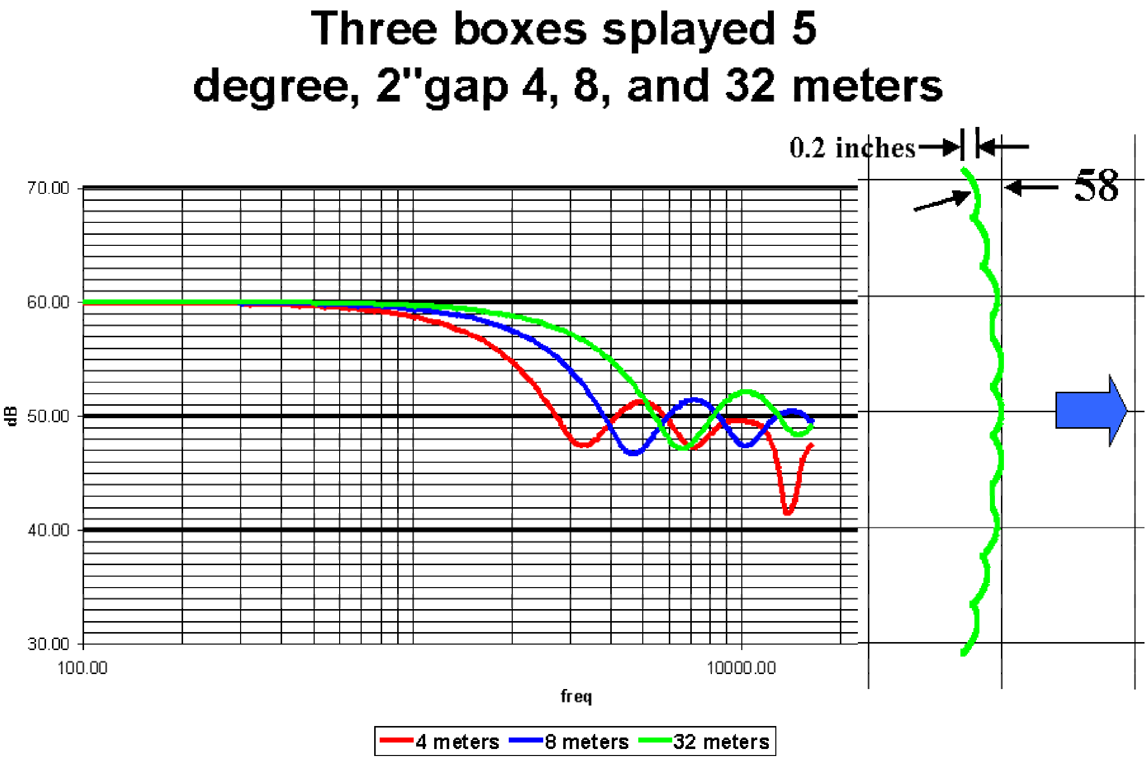


Figure 38. Modeled reponse of three boxes at 5 degrees of splay.

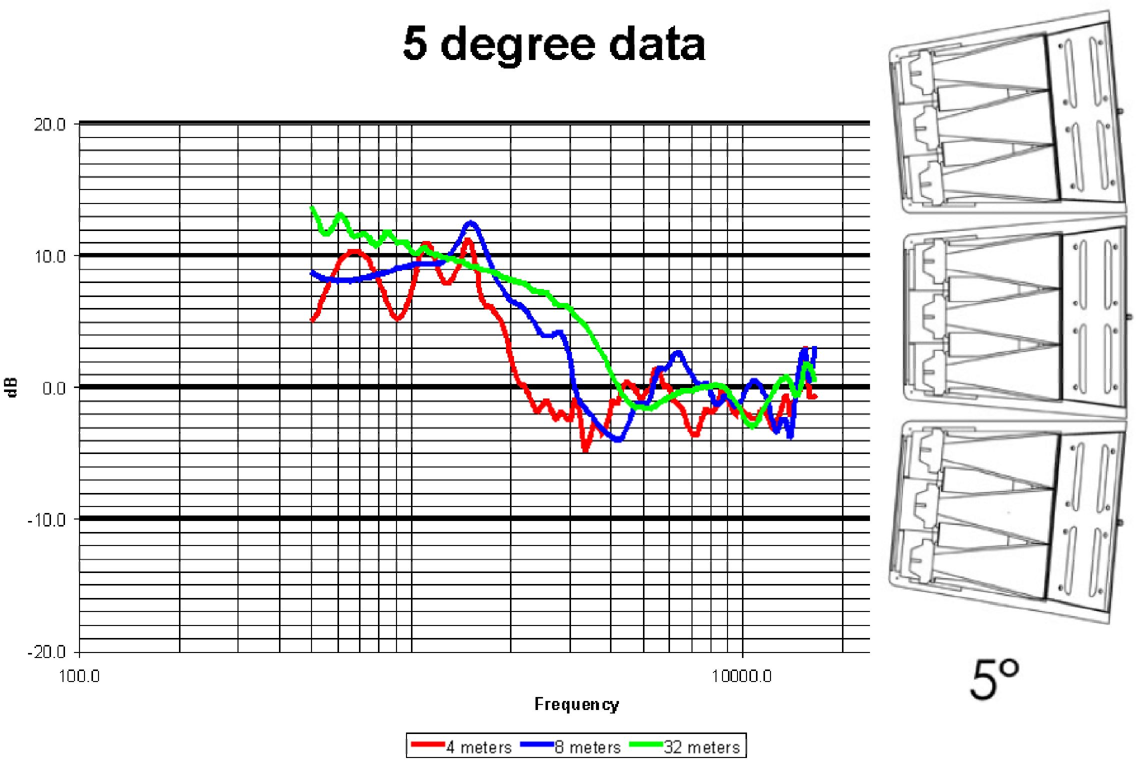


Figure 39. Measured response of three boxes at 5 degrees of splay.

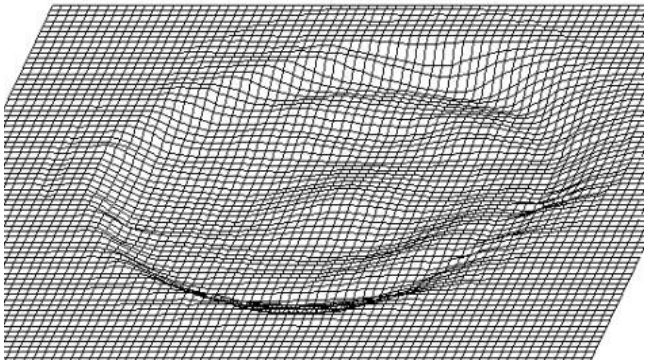


Figure 40a. Displacement of 3” beryllium dome at 14.5 kHz

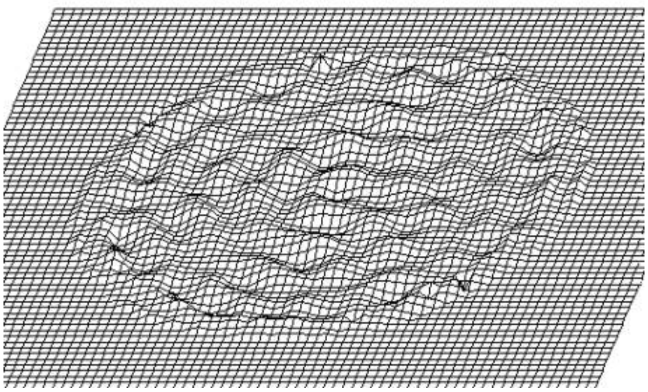


Figure 40b. Displacement of 3 “ titanium dome at 14.5 kHz

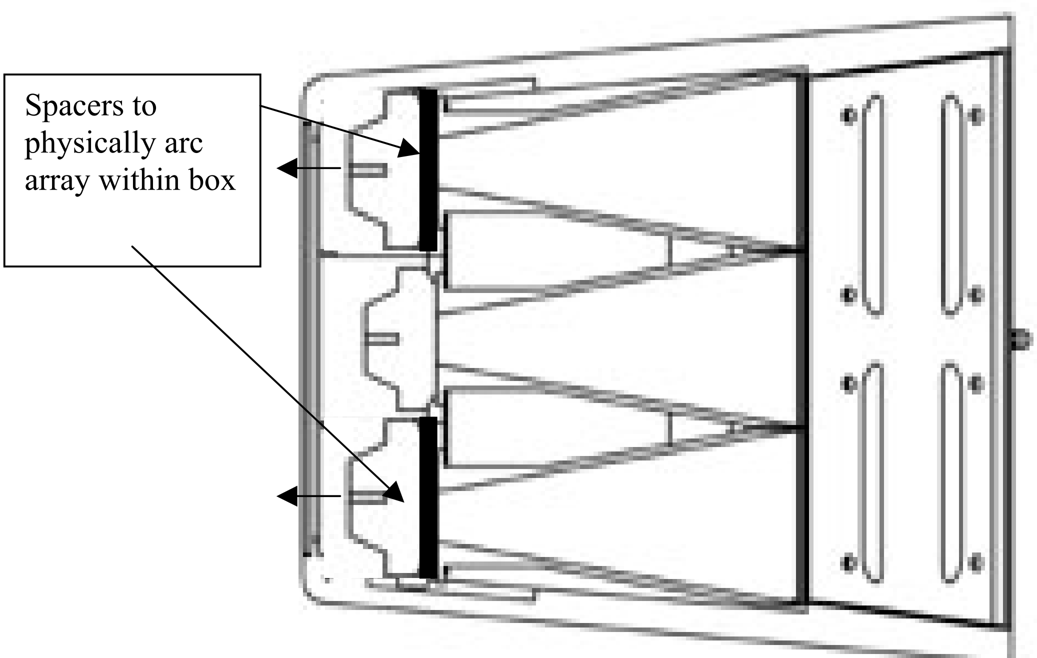


Figure 41. Spacers added to outside drivers to increase path length and effective arc the array within the box.

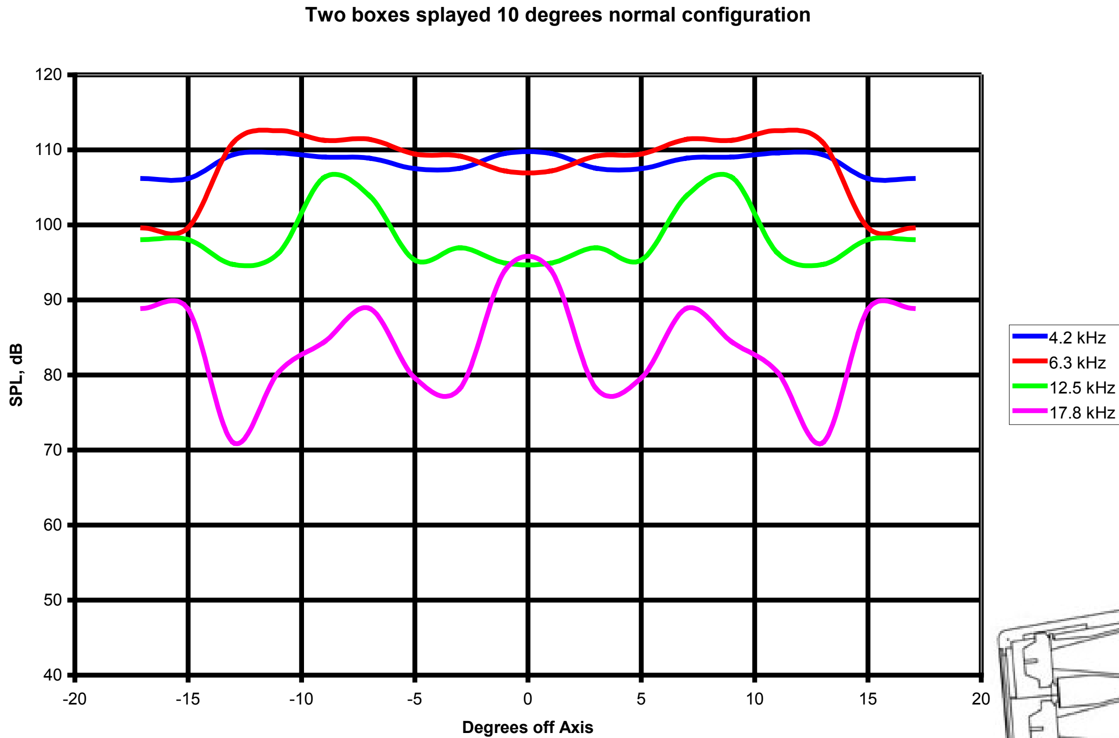


Figure 42. Off axis response of two boxes splayed 10 degrees. Note irregularity at high frequencies in +/- 10 degrees. Curves not normalized (absolute levels).

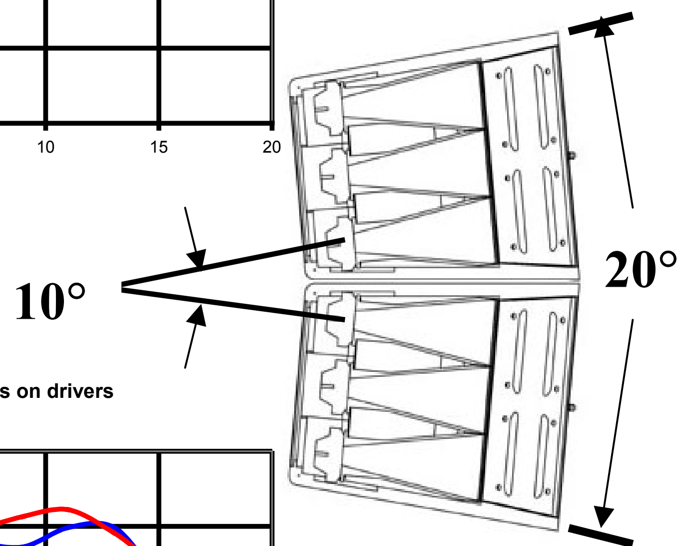


Figure 43. Off axis response of two boxes splayed 10 degrees. Note no irregularity at high frequencies in +/- 10 degrees. Curves not normalized.