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Subwoofer positioning, orientation and calibration for large-scale sound reinforcement

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ABSTRACT

It is often difficult to achieve even coverage at low-frequencies across a large audience area. To complicate matters, it is desirable to have tight control of the low-frequency levels on the stage. This is generally dealt with by using cardioid subwoofers. While this helps control the stage area, the audience area receives no clear benefit. This paper investigates how careful positioning, orientation and calibration of a multiple subwoofer system can provide enhanced low-frequency coverage, both in the audience area and on the stage. The effects of placement underneath, on top of and in front of the stage are investigated as well as the performance of systems consisting of both flown and ground-based subwoofers.

1. INTRODUCTION

Achieving desirable low-frequency coverage in large scale sound reinforcement applications is a complex task that is often simplified for convenience. Often this simplification is necessary when keeping truck space, sight lines and system efficiency in mind. Manually calibrating the subwoofers of a PA system for each individual venue would require time that isn't always available.

Desirable coverage is most often defined as an even sound pressure level across the core of the audience area with low-frequency energy on stage kept to a minimum to ease the requirements on the stage monitor system and to provide musicians with a reasonable working environment. Often (but not always), it is required to avoid an overly strong sound pressure level down the center of the audience area, commonly referred to as "power alley."

It is possible to give consistently good coverage, regardless of the differences between venues, by keeping certain aspects in mind when setting up the system. These aspects include proper spacing, orientation and delay of the subwoofers. This paper will highlight each of these areas, giving suggested placement/calibration techniques that have been validated with a three-dimensional acoustics simulation toolbox and also with field measurements. As such we support the philosophy that when designing a complex sound system it is now prudent to employ accurate simulation of the environment to enable initial alignment of the principal system parameters that include polar response, delay function and loudspeaker location. Without such assistance it is impossible to achieve a system alignment that performs accurately over a substantial fraction of the listening space. The methods and results presented in this paper demonstrate how this may be realized and also highlight the substantial performance advantages that become attainable.

The paper will begin with an overview of the history of subwoofer use in sound reinforcement, showing how subwoofers have progressed in terms of technology and also importance in the industry. This will be followed by a theoretical exploration into low-frequency directivity through gradient loudspeakers. After the theoretical aspects of low-frequency control are presented, optimal subwoofer setups will be explored giving the positives and negatives for various techniques highlighting the many benefits of proper subwoofer calibration, both for the audience and the musicians on stage. Key suggestions will be compared with field measurements to validate the simulation software. A discussion will follow, focusing on the practicality of the suggested methods as well as discussing how acoustics simulation software can be of great help to engineers when tuning systems on site.

2. HISTORY OF SUBWOOFER USE IN SOUND REINFORCEMENT

Prior to the late 1970's disco fever, a loudspeaker known as a "woofer" reproduced the lower portion of the audio spectrum. This was generally crossed over below 500 Hz into a 15" loudspeaker in an infinite baffle cabinet or in professional applications, such as the hybrid horn loaded bass reflex Altec cabinet known as an A-7 (a.k.a the famed "Voice of the Theater").

Altec introduced bi-amplification in the early 1970's to improve distortion specifications and to get the vocal range isolated from the low-frequency components of the sound (such as the bass drum), which required the majority of the power from modest wattage amplifiers of the day. Early bi-amplification would commonly have 30 W for the high frequency channel and 100 W for the low frequency channel. These early active methods of bi-amplification paved the way for multiple band separation of frequencies using active crossovers, which can be considered one of the most important innovations in audio since the invention of the horn and prior to the popularization of the line array.

By the late 1970's disco music had become hugely popular. What separated disco music from rock and pop music of the day was powerful bass drum. The audio reproduction of the bass drum frequency range required a new approach for woofer usage. It was discovered that this fundamental tone operated in the range centering around 80 Hz. Allowing for an octave below to 40 Hz, and half an octave above to 120 Hz, a third crossover frequency was added. This range being below the previous woofer range of 500 Hz became known as the "subwoofer."

At first, additional 15" loudspeakers in bass reflex cabinets were added to sound systems, along with much larger power amplifiers in the 300 to 500 watt range, usually with no regard to phase or cabinet design. As demand for more powerful bass drum SPL increased, subwoofer design and size improved rapidly. Loudspeaker cone size increased from 15" to 18" and even to as large as 30".

Designers soon returned to studying Harry F. Olsen's speaker theory [1] and utilized the early RCA W bin design. This was known in the industry as the "folded horn" where a long bass horn was cut in half and folded back onto itself to allow it to fit in truck and be delivered to a club or concert hall where it would hopefully fit though the door.

Community Light and Sound of Philadelphia, Pennsylvania produced a large bass horn out of fiberglass that separated into light weight sections to allow for maximum horn length in an easily transportable unit. This circumvented the problems of weight and portability of the large RCA W bins that could weigh as much as 250 kg. It also allowed the upper most crossover frequency to be raised back to 500 Hz, which led some people to believe that it was not a true subwoofer. The RCA W bin was limited to 125 Hz

and below as the folding of the horn prevented higher frequencies from being reproduced efficiently as they would not make it around the corners of the labyrinth inside the cabinet.

The quest for more bass was becoming so popular that in 1974 an early disaster movie called *Earthquake* played in many theaters utilizing a portable subwoofer touring system provided by manufacturer Cerwin Vega, called Sensurround. Later these same cabinet designs found their way into disco clubs of the era. Utilizing a folded horn cabinet with detachable horn walls to increase horn length and mouth area, this was a hybrid of two design styles. Later Cerwin Vega developed subwoofers with multiple folds to provide up to four meters of horn length in a box that would fit in a small delivery van.

Neville Thiele proposed cabinet designs based on electrical filter theory in an Australian journal which became known in the audio industry only after it was re-published in the Journal of the Audio Engineering Society in 1971 [2][3]. In 1972, Richard H. Small published a series of highly influential papers in the Journal of the Audio Engineering Society expanding Thiele's ideas [4 – 6]. The Thiele/Small parameters allowed an alternate line of thinking and hence manufacturing to be established that put compact size and efficiency above the "bigger is better" mentality of many manufactures' marketing departments of the day.

In the mid 1980s, Tom Danley developed a device using a metal speaker cone driven by a servo motor and belt drive which converted audio to mechanical movement without the use of a voice coil in a magnetic gap. His Intersonics Servo Drive subwoofer was the first breakthrough in subwoofer speaker design in a decade. Unfortunately as distortion and voice coil compression was almost totally absent from the audio output, the sound of the speaker lacked "musicality" and did not become very popular.

Later subwoofer developments included higher power voice coils using higher temperature glues, ferrofluid injected into the gap, and JBL's vented gap cooling scheme which allowed larger amounts of power to be used. As a result, larger power amplifiers were developed, such as today's light weight digital switching amplifiers that can provide many thousands of watts driving loudspeakers capable of handling these huge amounts of power (relative to a mere quarter century earlier).

As subwoofer SPLs were pushed to new extremes by the recycling of disco music into today's hip hop, the omnidirectional nature low frequency reproduction became an issue as energy leaked onto the stage and back into the turntables used by vinyl spinning DJs and microphones of performers creating a new frequency of feedback. The use of phasing to create cardioid speaker cabinets (Nexo CD-18 and Meyer Sound PSW-6), time alignment and sophisticated processors as well as computer modeling and even the simple JBL Vertec owner's solution of turning half of the subwoofers around facing backwards, have become an accepted everyday solution.

3. GRADIENT LOUDSPEAKERS

The most common technique for controlling low-frequency directionality is the use of what are known as gradient loudspeakers. This idea was proposed by Olson in 1973 [7]. Olson based this technique on what was known about the control of microphone directionality, treating the loudspeakers as microphones working in reverse.

In Olson's words, a gradient loudspeaker is: "A loudspeaker consisting of two or more loudspeakers separated in space and operating with a difference in phase or powers of the difference in phase between the loudspeakers" [7]. These are also referred to as differential loudspeakers.

Gradient sources can be thought of as loudspeakers that can achieve different polar responses based on contributions from spherical harmonics. This paper will focus on the basic polar patterns that can be achieved through this method: omnidirectional, dipole and cardioid. A more advanced investigation into this technique for small room low-frequency correction is presented in [8].

A number of gradient loudspeaker varieties are possible. The simplest is the zero-order gradient sound source (Figure 1). This source consists of a single drive unit which produces an omnidirectional polar pattern, as shown in Figure 2.

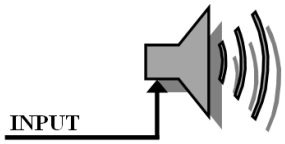


Figure 1: Zero-order gradient sound source

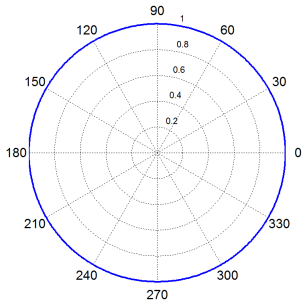


Figure 2: Zero-order gradient sound source polar pattern

Building upon the zero-order gradient sound source is the first-order gradient source (dipole). This consists of two zero-order gradient sources with opposite polarity, separated by a small distance (Figure 3). The resulting polar pattern is shown in Figure 4.

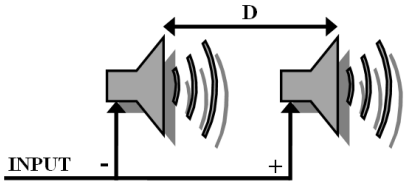


Figure 3: First-order gradient sound source (dipole)

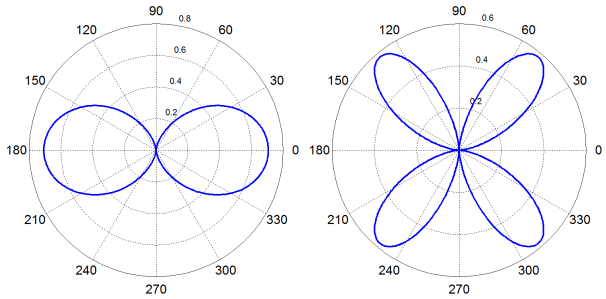


Figure 4: First-order gradient sound source (dipole) polar pattern with D = quarter wavelength (left) and D = full wavelength (right)

The polar patterns shown in Figure 4 highlight the importance of proper driver spacing. A separation of a quarter-wavelength of the target frequency will give a tight dipole response while separating the drivers by a full wavelength will result in a four-lobed response.

A variant of the first-order dipole source is achieved by adding a small amount of time delay to one of the drivers in the system (Figure 5). This will result in a cardioid radiation pattern when proper spacing and time delay are applied. The polar pattern for this system is shown in Figure 6. A true cardioid radiation pattern can be achieved when the time delay corresponds exactly to the driver separation distance [7].

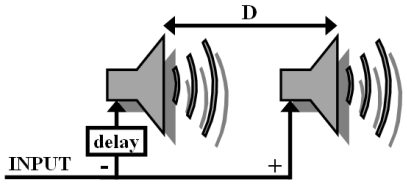


Figure 5: First-order gradient sound source (cardioid)

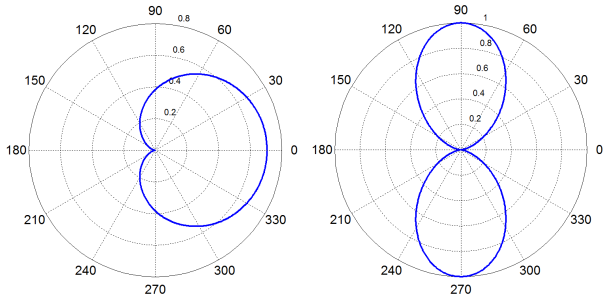


Figure 6: First-order gradient sound source (cardioid) polar pattern with D = quarter wavelength (left) and D = full wavelength (right)

Again, proper separation distance and delay are critical to achieve the desired polar pattern. For the cardioid variety of first-order gradient sources, full wavelength separation with the corresponding delay results in a sideways radiating dipole pattern, while reducing the spacing/delay to a quarter wavelength gives the desired cardioid pattern.

A final type of gradient loudspeaker that Olson presents is a second-order gradient source. This consists of two first-order sources of the dipole variety that are separated by a small distance, have reverse polarity and one of the first-order units is given a small time delay (Figure 7). This system provides even greater polar pattern control than the first-order systems. Here the polar pattern can be significantly tightened to nearly avoid any rear or extreme side radiation. The polar pattern is shown in Figure 8.

When the first-order sources are spaced and delayed at a quarter wavelength of the target frequency the polar pattern is approximately that of a shotgun microphone. Carrying on with this trend, it would be expected that

the polar pattern will become tighter for higher-order gradient sources.

Gradient components can be of great use when low-frequency directivity control is necessary. These gradient systems must be implemented with careful choice of physical spacing and delay based on the target frequencies. The remainder of this paper will use quarter-wavelength based spacing/delay unless otherwise specified.

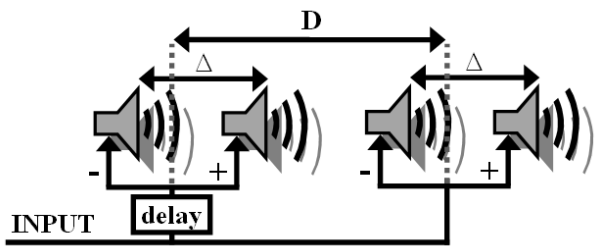


Figure 7: Second-order gradient sound source

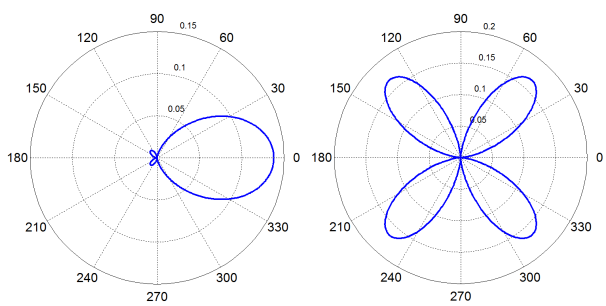


Figure 8: Second-order gradient sound source polar pattern with D = quarter wavelength (left) and D = full wavelength (right)

Gradient loudspeakers can be easily modeled within acoustic simulation software to help show their benefits regarding low-frequency reproduction in large-scale sound reinforcement applications.

4. FINITE-DIFFERENCE TIME-DOMAIN SIMULATION

The simulation method adopted in this research is Finite-Difference Time-Domain (FDTD). When dealing with small rooms especially where wavelength size can exceed the maximum room dimension, FDTD can give extremely accurate calculations at low frequencies where image source or ray tracing methods exhibit inaccuracies [9]. This, however, is not an issue when simulating larger spaces. There are a number of reasons, though, why FDTD simulation was chosen over other methods for this work.

The FDTD method operates with a collection of offset grids, both spatially and temporally. In a two-dimensional simulation the grid structure consists of three grids: one for sound pressure and two for the x- and y-particle velocities (Figure 9) [10].

The sound pressure and particle velocity grids are updated in an alternating fashion through simple matrix algebra (Equations 1 & 2) [10][11]. Generally FDTD simulations contain boundary condition equations that assume perfect rigidity and frequency-independence of the boundary absorption levels (Equation 3) [10][11].

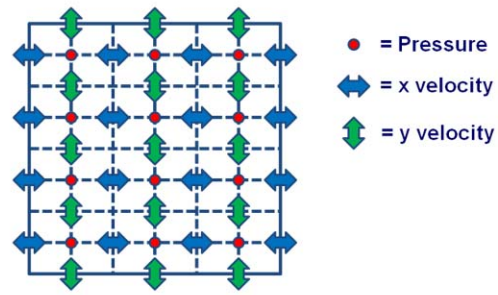


Figure 9: 2D FDTD simulation grid structure [10]

$$u^x_{x+\frac{dx}{2},y,z}\left(t+\frac{dt}{2}\right)=u^x_{x+\frac{dx}{2},y,z}\left(t-\frac{dt}{2}\right)-\frac{dt}{\rho dx}\left[p_{x+dx,y,z}(t)-p_{x,y,z}(t)\right] \quad (1)$$

$$\begin{aligned}p_{x,y,z}(t+dt)=p_{x,y,z}(t)&-\frac{c^2\rho dt}{dx}\left[u^x_{x+\frac{dx}{2},y,z}\left(t+\frac{dt}{2}\right)-u^x_{x-\frac{dx}{2},y,z}\left(t+\frac{dt}{2}\right)\right]\\&-\frac{c^2\rho dt}{dy}\left[u^y_{x,y+\frac{dy}{2},z}\left(t+\frac{dt}{2}\right)-u^y_{x,y-\frac{dy}{2},z}\left(t+\frac{dt}{2}\right)\right]\\&-\frac{c^2\rho dt}{dz}\left[u^z_{x,y,z+\frac{dz}{2}}\left(t+\frac{dt}{2}\right)-u^z_{x,y,z-\frac{dz}{2}}\left(t+\frac{dt}{2}\right)\right]\end{aligned} \quad (2)$$

$$u^x_{x,y,z}\left(t+\frac{dt}{2}\right)=\frac{R_x-Z}{R_x+Z}u^x_{x,y,z}\left(t-\frac{dt}{2}\right)+\frac{2}{R_x+Z}p_{x,y,z}(t) \quad (3)$$

where $u^x_{x,y,z}(t)$, $u^y_{x,y,z}(t)$ and $u^z_{x,y,z}(t)$ are the particle velocity components and $p_{x,y,z}(t)$ is the sound pressure at a point specified by x, y, z and time step, t. Points are spaced according to dx, dy, dz and the simulation is updated based on the time step, dt. The speed of sound and air density are represented with c and ρ, respectively. The characteristic wall impedance, Z, is defined by $Z = \rho c \frac{1+\sqrt{1-\alpha}}{1-\sqrt{1-\alpha}}$, where α is the boundary absorption coefficient and $R_x = \frac{\rho dx}{dt}$.

These straightforward update equations allow for efficient simulations, with all data points within a grid being updated in one step. An advantage to this procedure is that it allows all points within the grids to be monitored and then analyzed at the conclusion of the simulation. Also, the grid structure allows for simple placement of sound sources at any grid point in the simulated space.

It has been shown that reactive surfaces and frequency-dependent absorption can be modeled with FDTD, if necessary [12]. As this paper deals with either large concert venues or outdoor situations, the boundary conditions remain as frequency-independent with the overall absorption level independently controllable for all surfaces.

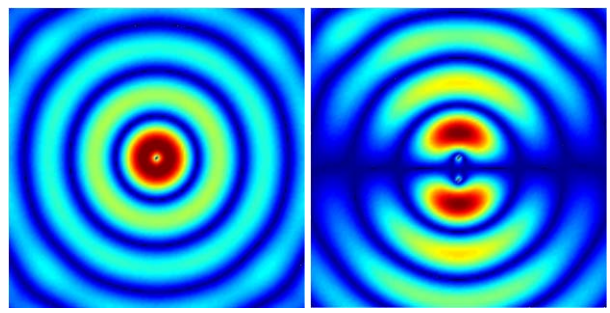
Along with the advantages of efficiency, data analysis and source placement capabilities, the FDTD method forms the basis of a proprietary acoustic simulation toolbox within the Audio Research Laboratory at The University of Essex [10][11]. The toolbox, although developed for small room low-frequency acoustical analysis, is fully capable of simulating spaces of any shape or size with any number of listening locations, obstacles or sources which are excited by any user-defined source signal. Each source can have a polar pattern of omnidirectional, dipole or cardioid and can be rotated 360°, as needed. All polar patterns are achieved automatically with the gradient loudspeaker methods described in the previous section.

The FDTD toolbox allows for full control over all simulation parameters, permitting straightforward implantations of complex simulation requirements. All simulation results in this paper come directly from the analysis output of the toolbox.

5. LOW-FREQUENCY STEERING

It is desirable in large-scale live sound situations to distribute low-frequency energy equally across the entire audience area while minimizing it on stage. A first step in achieving these goals involves controlling the polar pattern of the subwoofer system.

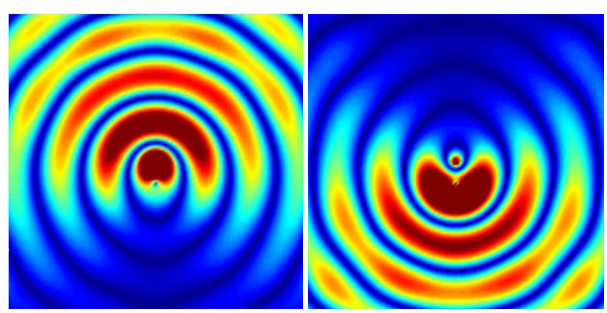
Most subwoofers regularly used in live sound exhibit an omnidirectional polar pattern (Figure 10a). Placing a secondary subwoofer (or drive unit) with reverse polarity in close proximity to the primary source will result in a dipole pattern (Figure 10b). Generally, this will not achieve the stated goals and also is known to be an inefficient source configuration [13].



(a) (b)

Figure 10: Simulated omnidirectional (a) and dipole (b) polar response at 80 Hz in anechoic 14 m x 14 m space with quarter wavelength spacing (1.07 m)

A cardioid pattern can be achieved by adding a small delay to the secondary drive unit without adjusting the physical layout of the dipole configuration (Figure 11a). This pattern can easily be reversed by removing the reverse polarity on the secondary unit (Figure 11b).

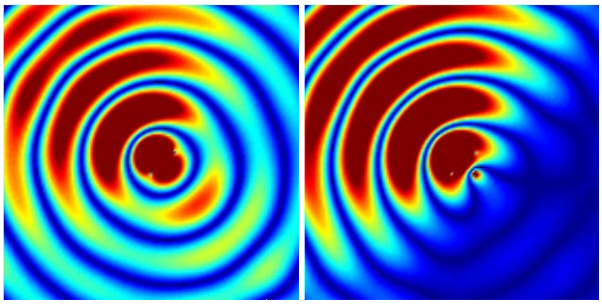


(a) (b)

Figure 11: Simulated cardioid polar response at 80 Hz in anechoic 14 m x 14 m space with quarter wavelength spacing (1.07 m) and 3.125 ms delay (a = 2nd unit reverse polarity, b = 2nd unit normal polarity)

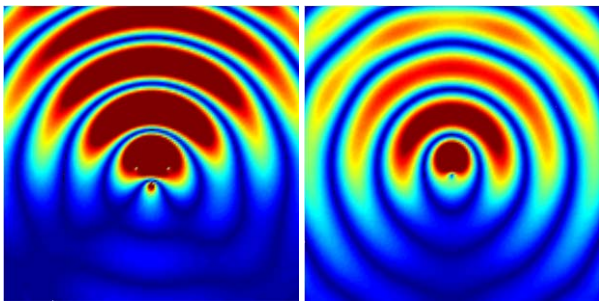
The above plots, which have a linear pressure scale, can be thought of as overhead views of a standard concert situation where the primary source is roughly parallel with the front of the stage while the stage is off to the right side of the plot (Figure 14). Even with a cardioid coverage pattern there is energy wrapping around onto the stage. Also, if the audience area is configured in an arena type layout the areas to the sides of the stage are not receiving ample energy from the subwoofers.

One solution to this coverage problem is to add a third drive unit to the configuration. This unit will receive the exact same signal as the second unit, but will be placed directly to the right of the primary source maintaining consistent spacing (Figure 12a). While this will steer the low-frequency energy more to the sides and less onto the stage, a clear buildup of energy can be seen to the rear of the subwoofer cluster. This can be dealt with by adding a fourth drive unit spaced equally from the second and third unit, with reverse polarity but no added delay (Figure 12b, configuration shown in Figure 14, disregarding source orientation).



(a) (b)

Figure 12: Simulated polar response for a three drive unit cluster (a) and a four drive unit cluster (b) at 80 Hz in anechoic 14 m x 14 m space with quarter wavelength spacing (1.07 m) and 3.125 ms delay



(a) (b)

Figure 13: Simulated polar response of the four drive unit cluster rotated 45° (a) compared to the two drive unit cardioid configuration (b)

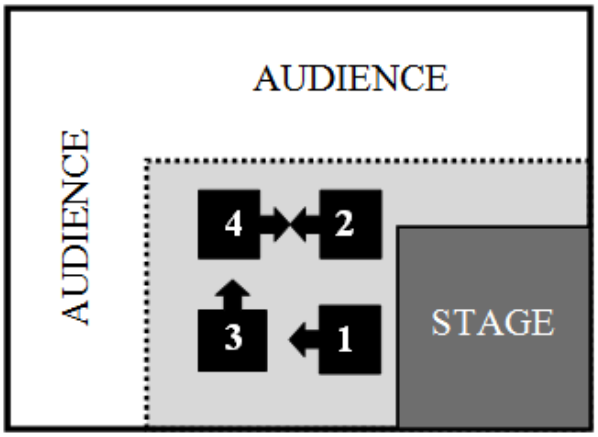


Figure 14: Four cardioid unit cluster setup (arrows indicate cardioid orientation, with the right direction corresponding to 0°)

The four drive unit configuration gives good low-frequency energy directly in front of and to the sides of the cluster. Either the cluster can be rotated 45° to direct energy in the forward direction (Figure 13a) to cover the center audience area or additional subwoofers can be placed under or in front of the stage. A similar four source configuration has been alluded to in the work of Dave Rat of Rat Sound.

While these configurations consist of four separate omnidirectional sources, they do not require their own dedicated channel of processing and amplification. This is because the first and fourth sources are identical except for reverse polarity and can therefore share a channel of processing/amplification with correct reverse wiring to the fourth source. Similarly, the second and third source output identical signals allowing for them to share a processing/amplification channel. This amounts to two channels of processing/amplification needed to implement this system correctly.

As discussed in [14], the individual omnidirectional sources in the four-unit clusters can be expanded to each be standalone cardioid sources by either stacking a second omnidirectional source on top of the initial source and adding delay or by placing an additional drive unit within the subwoofer enclosure. The remainder of this paper will refer to cardioid sources as subwoofer enclosures containing two closely spaced drive units with corresponding delay added to the secondary drive unit.

The expansion to individual cardioid sources will allow for each individual source to be rotated as needed to achieve the desired coverage. It must be noted at this point that with the addition of supplementary drive units the overall subwoofer system efficiency will decrease due to destructive interference between the sources.

A variation on the four cardioid unit cluster discussed in [14] is presented in Figure 14. All units are spaced at one quarter wavelength of the center of the subwoofer operating range (usually around 45 – 60 Hz). Each source can have delay applied as needed.

For the situation in Figure 14, if unit four is delayed by half the propagation delay between units, then simulations show that there will be approximately 270° of coverage directly to the front and left side of the audience area (Figure 15).

The low-frequency energy can be directed and focused in nearly any direction with this simple setup. Figure 16 contains a number of examples of this with the setup parameters detailed in Table 1.

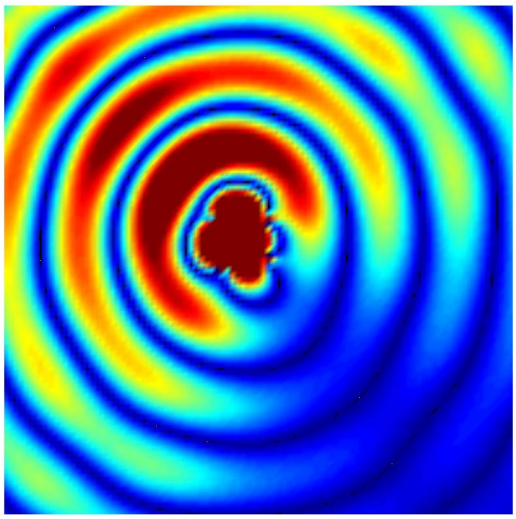


Figure 15: Simulation results for four-unit cluster setup as shown in Figure 14 (linear pressure scale)

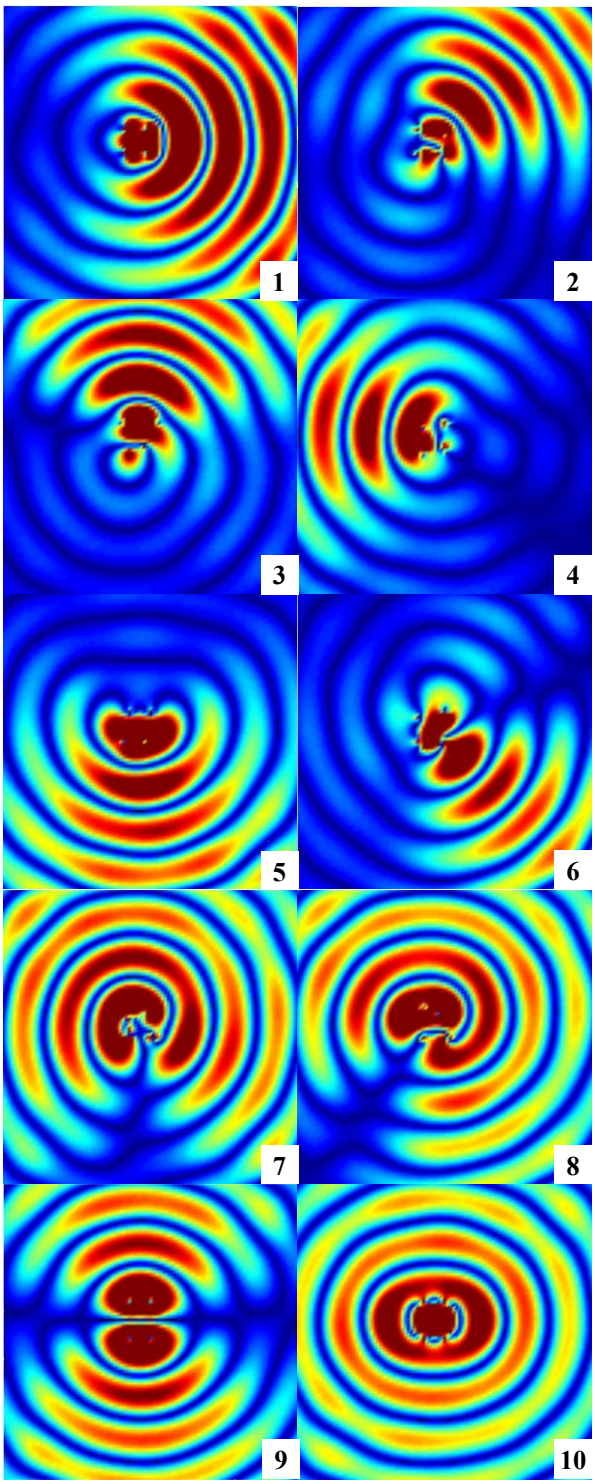


Figure 16: Four cardioid unit cluster configuration examples as detailed in Table 1(linear pressure scale)

#	O_1	O_2	O_3	O_4	d_1	d_2	d_3	d_4
1	0°	0°	0°	0°	0	0	0	0
2	0°	90°	0°	0°	0	0.5	2	0
3	0°	180°	90°	0°	0	1	0	1
4	90°	180°	90°	90°	0	0	1.5	0.5
5	0°	270°	0°	270°	0	0	1	0
6	0°	270°	0°	0°	0	2	2	1
7	180°	0°	270°	90°	0	2	1.5	1.5
8	180°	0°	90°	270°	0	2	0.5	1.5
9	90°	270°	90°	270°	0	2	0	2
10	90°	270°	90°	270°	0	0	0	0

Table 1: Four cardioid unit cluster configuration example details (O_N = orientation angle for unit N, d_N = multiplication factor of quarter wavelength propagation delay for unit N time delay)

6. SUBWOOFER SPACING

The ability to direct and focus the low-frequency energy into the audience and away from the stage will not solve all problems in large scale situations. In most cases the subwoofer system will consist of more than one source (or cluster). The sources are often located at opposite sides of the stage or under/in front of the stage. Interference between the sources will play a major role in altering the low-frequency response in the audience area. This interference is largely dependent on the spacing of the sources.

The sensitivity of subwoofer spacing can be demonstrated by running two simulations consisting of two omnidirectional sources placed within a two-dimensional (50 m x 40 m) "outdoor" environment. The first test places the sources with four meters separation (Figure 17) while the second increases the separation to twenty meters (Figure 18). Simulation results for cardioid sources are also included to demonstrate that only the stage area is affected by the difference in polar pattern. The test signal used was a 60 Hz sinusoid.

Another common subwoofer placement strategy calls for equal spacing of subwoofers in front of the stage. This technique was simulated with four subwoofers separated by two meters each for both omnidirectional and cardioid polar patterns (Figure 19). By examining the low-frequency response in the audience area there are clear issues for each of these cases. The two subwoofers with four meter spacing simply will not manage enough output when operating in a three-dimensional real world space.

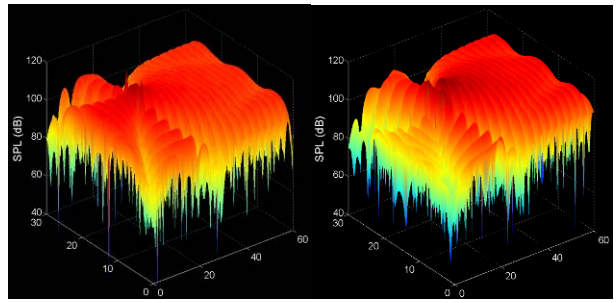


Figure 17: Simulation results – two subwoofers with 4 meter spacing (left = omnidirectional, right = cardioid)

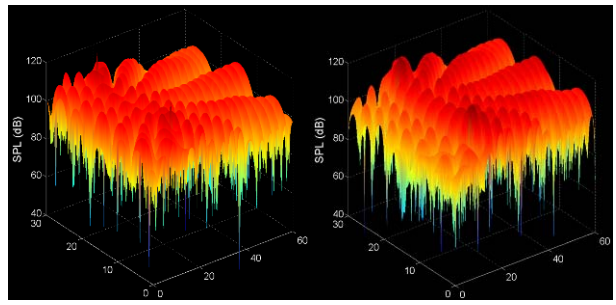


Figure 18: Simulation results – two subwoofers with 20 meter spacing (left = omnidirectional, right = cardioid)

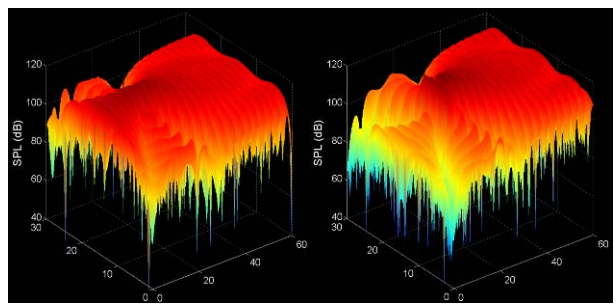


Figure 19: Simulation results – four subwoofers with 2 meter spacing (left = omnidirectional, right = cardioid)

The same configuration with twenty meter spacing gives significant nodes within the audience area. This is highly undesirable since one of the goals is to give even low-frequency coverage across the entire audience area. The four subwoofers spaced across the front of the stage avoid the creation of nodes in addition to providing more acoustical output, although the audience area closest to the stage receives a significantly higher SPL which could become unsafe since the low-frequency levels are generally adjusted to suit the front-of-house position which is usually located only fifteen to twenty meters away from the stage.

7. STAGE PROXIMITY EFFECTS

An often overlooked aspect involved in the configuration of subwoofer systems is the effect the stage can have on the overall response of the system. This can cause great variations, especially to the low-frequency levels on stage, depending on where the subwoofers are placed in relation to the stage.

In each of the following cases, the response of the system was simulated in a 40 m x 16 m x 3 m "outdoor" space (full absorption on all surfaces except the ground) both with and without a small stage included in the model. When included, the stage (dimensions: 10 m x 5 m, height: 1.6 m) was set to have 10% absorption on all sides. Again, a 60 Hz sinusoid was used as the test signal.

Simulated tests were carried out with the subwoofers located underneath, but just in front of the stage (Figure 20), directly underneath the stage (Figure 21) and on the stage corners (Figure 22). When underneath the stage two cardioid subwoofers had four meter spacing while when on the stage corners eight meter spacing was used.

The simulation comparisons presented in Figures 20 – 22 provide clear evidence that it is essential to include the stage in simulation models concerning subwoofer system performance. The left hand (no stage) plots of Figures 20 and 21 are nearly identical, despite the fact that the subwoofers are two meters closer to the stage in Figure 21. When the stage is added, though, a clear difference can be seen.

Based on these results, it is evident that subwoofer placement directly underneath the stage can almost eliminate any advantages gained with cardioid polar patterns; the low-frequency SPL on the stage is virtually identical to that in the audience (Figure 22). Moving the subwoofers two meters forward so that they are not underneath the stage results in much lower SPL on stage while preserving the audience area response (Figure 21).

Placement on the stage corners shows less dependency on the stage in the simulation, but again emphasizes the importance of placement at this increased spacing, as compared to the spacing in the cases below the stage, results in a narrow area down the center of the audience area where SPL is significantly greater than in other areas. This occurrence is commonly referred to as "power alley."

Two clear points emerge from the results of the simulation concerning the stage. Firstly, it is essential to include the stage in simulation models to ensure accuracy. Secondly, subwoofer placement in front of the stage gives far lower stage SPL than when the subwoofers are placed directly below the stage.

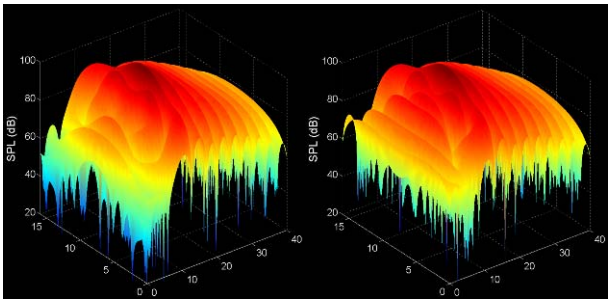


Figure 20: Two subwoofers below and just in front of the stage (left = stage not included in simulation, right = stage included in simulation)

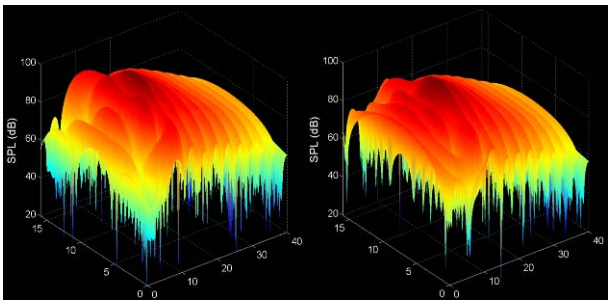


Figure 21: Two subwoofers directly below the stage (left = stage not included in simulation, right = stage included in simulation)

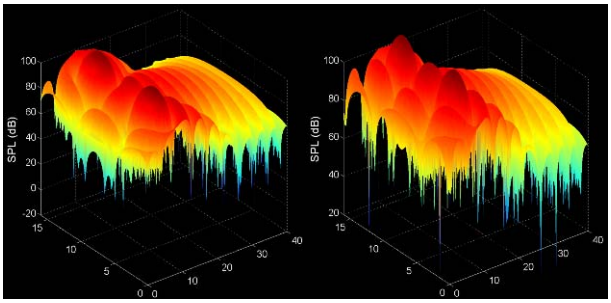


Figure 22: Two subwoofers on the stage corners (left = stage not included in simulation, right = stage included in simulation)

8. EFFECTS OF FLOWN VERTICAL ARRAYS

An increasingly common subwoofer configuration for large venues is the flown vertical array. Generally, these arrays are positioned directly next to the left and right main PA arrays. These vertical arrays have the advantage of a greater distance from the audience, where ground based subwoofers are usually only a few meters from the first row of the audience. This would be expected to give much more even coverage from the front to the back of the audience area than with a ground-based system.

This concept can be simulated where a ground based system is directly compared to a flown vertical array system. The ground-based system consists of two three-high vertical stacks of subwoofers directly to each side of the stage, separated by two meters. There are also four additional subwoofers spaced evenly across the ground just in front of the stage. The vertical arrays are positioned above the corners of the stage with the bottom box of the array being eight meters off the ground. The arrays consist of seven boxes each, spaced at one meter intervals.

The chosen test space is a three-dimensional 40 m x 30 m x 15 m anechoic space (with the exception of the ground). A 16 m x 8 m stage is included in the simulation with 10% absorption on all surfaces. All subwoofers used in these simulations are of the cardioid variety and fed a 60 Hz sinusoid test signal.

The ground based system first was tested on its own, as described above (Figure 23). Next, the ground system was turned off and the vertical arrays were tested with twelve meter horizontal spacing (Figure 24). To give further depth to this exploration, the vertical arrays were then configured as a center cluster, now with four meters horizontally between them (Figure 25).

The result from the combined subwoofer system gives added rejection on stage while providing even front to back coverage. The nodes created by the ground based system are still present, causing problems across the horizontal axis of the audience area (Figure 26).

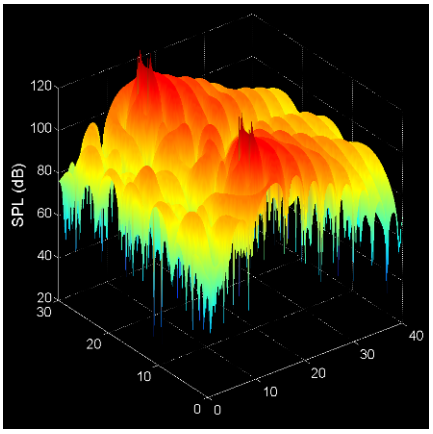


Figure 23: Ground-based subwoofer system results

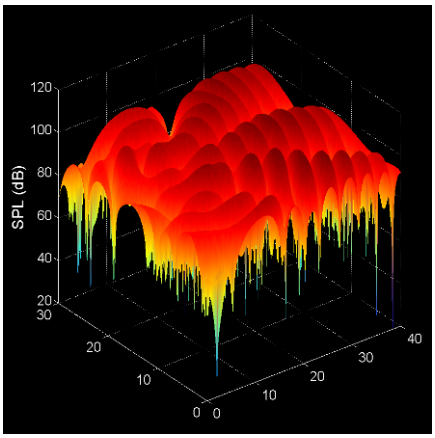


Figure 24: Flown vertical subwoofer array results (12 meter horizontal spacing)

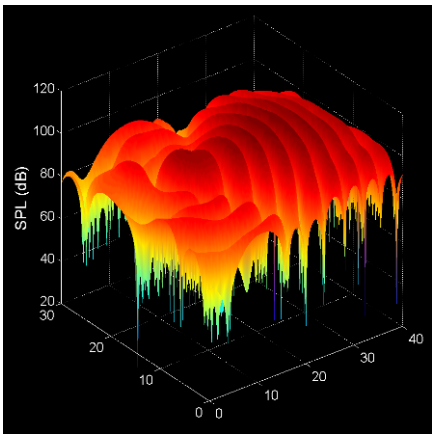


Figure 25: Flown vertical subwoofer array results (4 meter horizontal spacing)

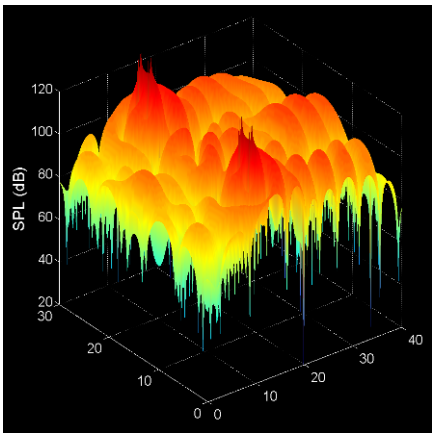


Figure 26: Results for flown vertical subwoofer array (4 meter horizontal spacing) w/ a ground-based system

One possible conclusion from this section is that vertical arrays may be preferable over ground-based systems since they can provide more even front to back coverage of the audience area. Not all venues, though, are capable of accommodating these arrays and in some cases when it is possible, a center cluster may not be practical. The next section will keep these problems in mind in an attempt to derive a generalized ground-based subwoofer setup for large indoor or outdoor venues.

9. OPTIMAL SUBWOOFER SETUP

As demonstrated in the subwoofer spacing section, an even coverage in the audience area is best achieved when subwoofer spacing is minimized. This will avoid the occurrence of nodes within the audience area that arise when subwoofers are only placed near the outside corners of the stage. A 50 m x 30 m x 5 m space was setup in the FDTD simulation toolbox similar to previously discussed simulations in this paper. Again, a 16 m x 8 m stage was included in the simulation. As a starting point, four single cardioid subwoofers were placed across the front of the stage on the ground with four meter spacing (Figure 27).

This initial setup gives very limited coverage across the audience area, although there are no noticeable nodes anywhere in the coverage area. The bottom plot of Figure 27 shows a clear ten meter wide "power alley," which would be expected from the centrally-located subwoofer system.

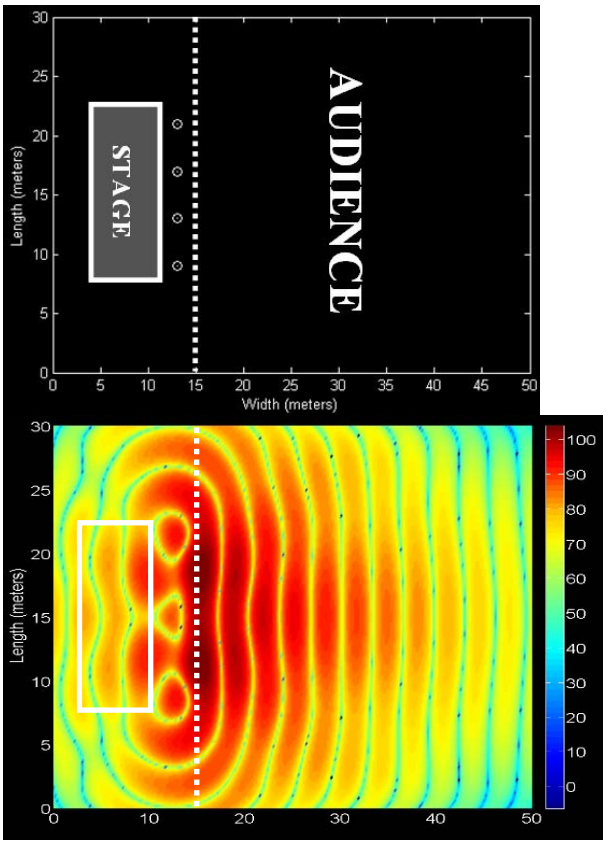


Figure 27: Simulation results (bottom) for the initial setup (top) for subwoofer system optimization

This system can be expanded both to the left and right of the stage while maintaining four meter spacing. Since the additional subwoofers of the system will be off to the sides of the stage, they can each be stacks of three subwoofers. The setup and results of this configuration are shown in Figure 28.

To expedite the fine tuning process in this system, the subwoofer configuration was run through an optimization routine within the FDTD toolbox which aims to find the configuration that gives the most even coverage in the audience area. The optimization routine shows that simply rotating the outside subwoofer stacks away from the stage by 45° gives very even results across the audience area while keeping SPL on the stage under control (Figure 29).

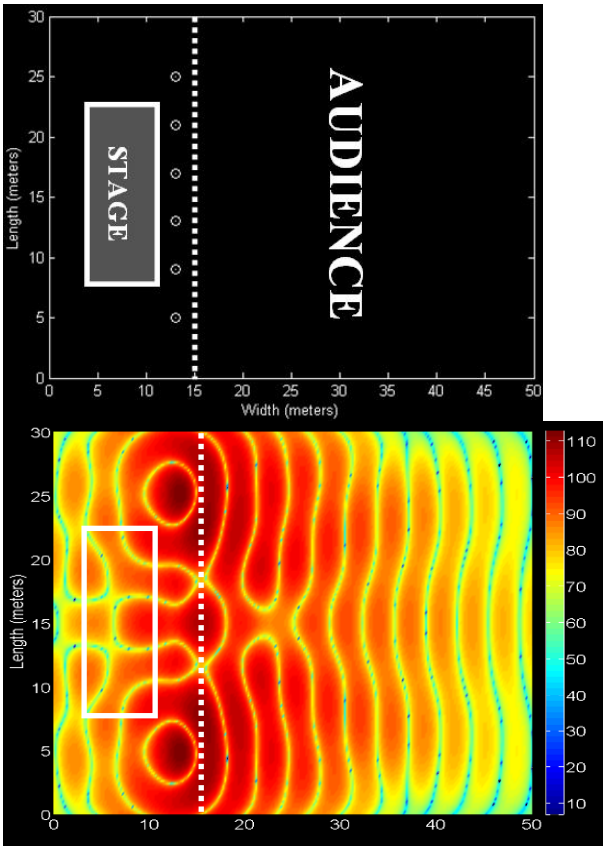


Figure 28: Simulation results (bottom) for the second setup (top) for subwoofer system optimization

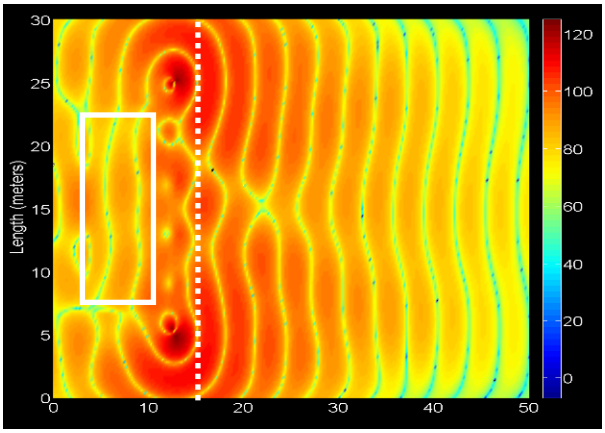


Figure 29: Optimized subwoofer setup results

The optimized system results show a much more even SPL across the rows of the audience area with no major peaks or dips in the response. Also, the SPL on the stage has been lowered to around 85 dB when it was around 90-95 dB in the initial setups (Figures 27 & 28). It is also important to note that with this optimized setup the front rows of the audience are not receiving an unreasonable level of low-frequency energy (around 105 dB) as with the initial setup (over 110 dB). The SPL roll-off as distance from the stage increases appears to be much more linear than in the previous cases.

Even with a basic setup as shown above, very even results can be achieved with only simple rotations of a few subwoofers. Often in large arenas, though, it is required to cover 270° of audience area. This will require a slightly more complex system that has greater ability to steer the low-frequency energy to the targeted areas while keeping the stage levels reasonable. One way to address this problem is to utilize the four subwoofer clusters as described in the low-frequency steering section of this paper. These clusters will replace the three-high subwoofer stacks used in the previous example.

When 270° of coverage is needed, the configuration highlighted in Figure 14 in the low-frequency steering section is a good starting point. A 40 m x 30 m x 5 m space was setup in the FDTD simulation toolbox similar to previously discussed simulations in this paper. Again, a 16 m x 8 m stage was included in the simulation

The first task is to determine how the two mirrored four-unit clusters will interact with one another (Figure 30). Each was positioned just beyond the corners of the stage on the ground. To provide higher output SPL, the clusters were expanded vertically so that each unit is a vertical stack of three subwoofers. The resulting pressure response over the venue is displayed in Figure 30. The SPL distribution shows a good first step towards the goals of keeping stage SPL low and audience SPL even. In this example, the audience within about ten meters of the stage will be expected to receive around 110 dB at 60 Hz while the stage level is about 80 dB.

Node problems towards the audience center exist with this configuration as well as a generally lower SPL down the center of the audience. A logical solution to this is to place some additional single cardioid subwoofers across the front of the stage. In this case four additional subwoofers were placed on the ground just in front of the stage with four meter spacing and are each delayed to the closest of the clusters (Figure 31). The results are shown in Figure 31.

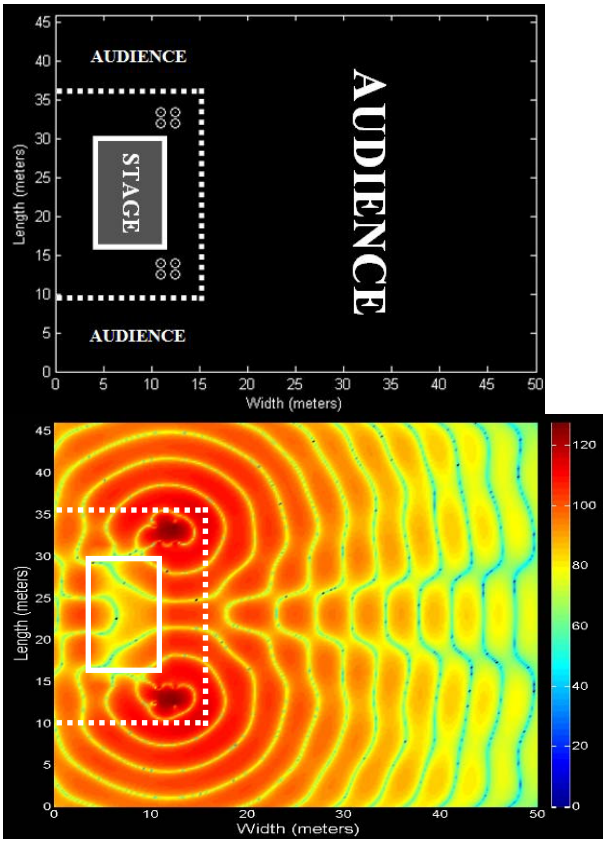


Figure 30: Simulation results (bottom) for the initial setup (top) for subwoofer system optimization

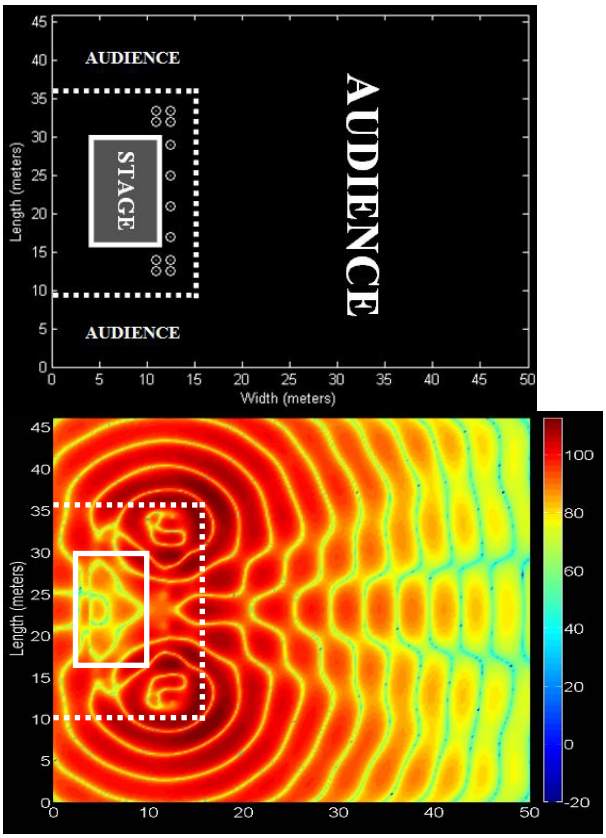


Figure 31: Improved subwoofer system setup results

While the node problems are not fully corrected with the addition of the center subwoofers, the SPL down the center of the audience has increased to match the SPL off to the side areas of the audience. The addition of the center subwoofers only slightly raise the stage SPL, which still remains in the 80 dB range while the audience within twenty meters of the stage receives around 100 dB of low-frequency.

Further fine tuning is always possible, but the purpose of this demonstration was to make the point that achieving even low-frequency coverage can be accomplished with clever subwoofer orientation and a minimal amount of signal processing.

In the above case for 270° of coverage only four signals are needed for the entire system. One is the unprocessed signal for units one to three in the clusters while the second is the initial signal with a delay applied equivalent to one-eighth a wavelength of the target frequency which is fed to the fourth unit in the clusters. The third and fourth signals are the delayed signals for the center subwoofers. Most modern day PA controllers are fully-capable of delivering these requirements with the push of a button.

10. FIELD MEASUREMENT COMPARISONS

In order to give further validation to the FDTD simulation toolbox, field measurements were taken at Niles West High School's auditorium (Skokie, IL USA). Four Nexo CD-18 cardioid subwoofers (in stacks of two) were used for the measurements, driven by Camco Vortex V200 power amplifiers. Measurements were taken at ten listening locations (seven in the audience and three on stage) with both an SPL meter (dBA, slow average) and with the RTA function of Smaart Live 6.0 [15]. The test signal used was a 60 Hz sinusoid with the measurement setup shown in Figure 32.

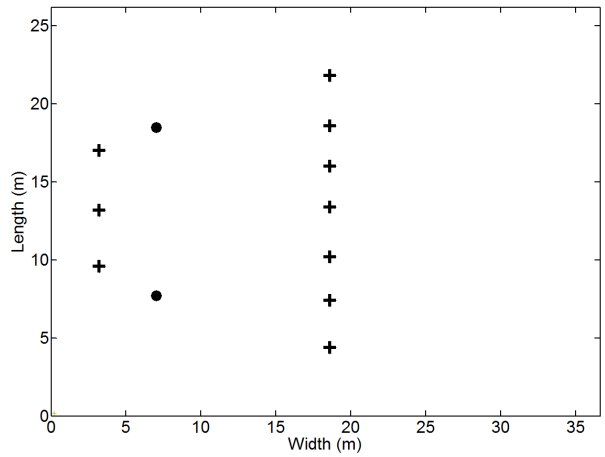


Figure 32: Measurement setup (circles = sources, crosses = listening locations)

Three subwoofer spacings (10.8 m, 6.4 m and 1.6 m) were tested. Simulation results were not expected to match the measured values perfectly since the simulation was set up to model all surfaces except the ground, stage and band shell as anechoic with no surface reactance. The measurements, due to extreme weather conditions, were taken indoors in a medium sized auditorium. The results, though, should show similar trends that should give confidence in the simulation.

The first subwoofer spacing of 10.8 meters (symmetrically around the stage center) audience simulation and measurement results are presented in Figure 33. While the simulation results are not precise, they do follow the same trends as the two sets of measured data. The stage simulation and measurement results for the 10.8 meter spacing test are presented in Figure 34. Similarly, the 6.4 meter (Figures 35 & 36) and 1.6 meter (Figures 37 & 38) spacing results do not agree perfectly with the simulation, but they do once again follow similar trends. The discrepancies can again mostly be attributed to the presence of the band shell (approximated within the simulation) and the previously mentioned simplification of the simulated model.

These measurements do confirm the trends highlighted in the simulation results in the subwoofer spacing section of this paper. Larger spacing does indeed seem to cause nodes within the audience area, giving a "power alley." Closer spacing still can give a less pronounced "power alley," but the overall response across the audience is very smooth without any large nodes.

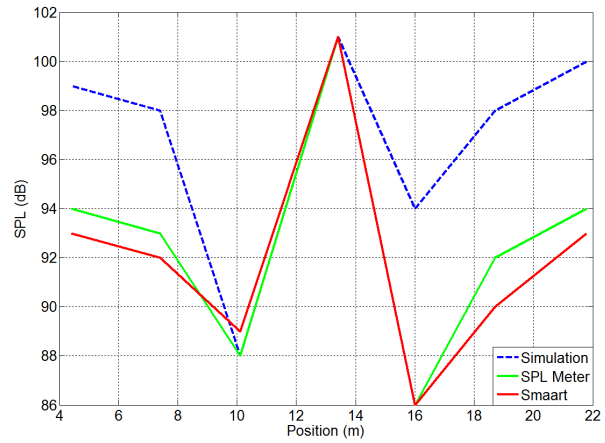


Figure 33: 10.8 meter spacing simulation and measurement results (audience listening locations)

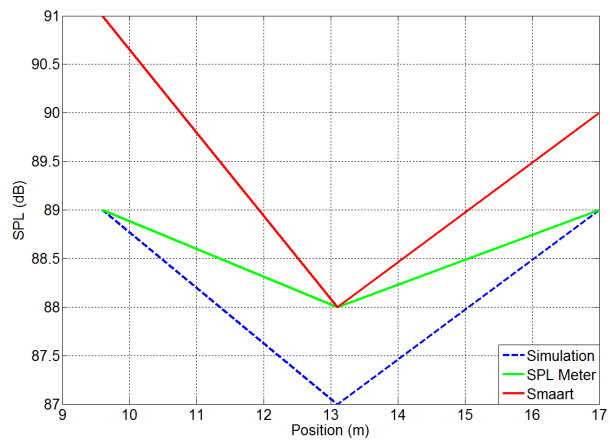


Figure 34: 10.8 meter spacing simulation and measurement results (stage listening locations)

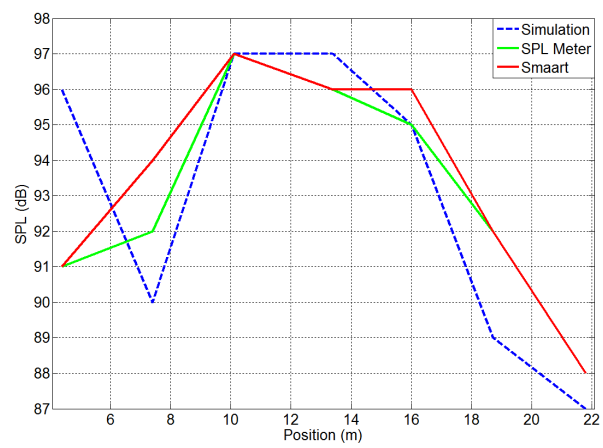


Figure 35: 6.4 meter spacing simulation and measurement results (audience listening locations)

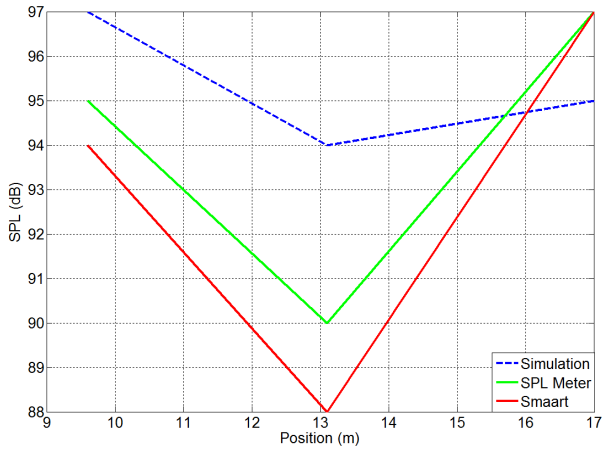


Figure 36: 6.4 meter spacing simulation and measurement results (stage listening locations)

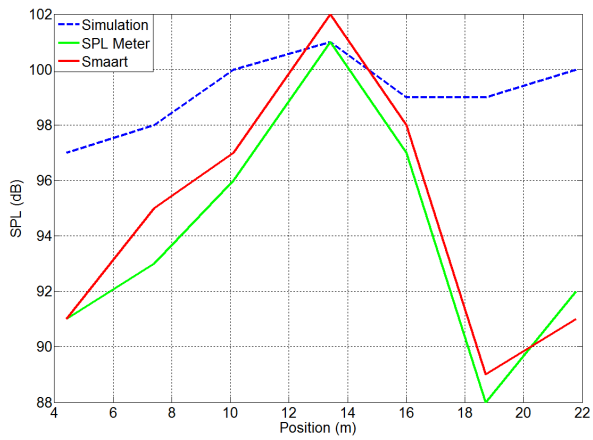


Figure 37: 1.6 meter spacing simulation and measurement results (audience listening locations)

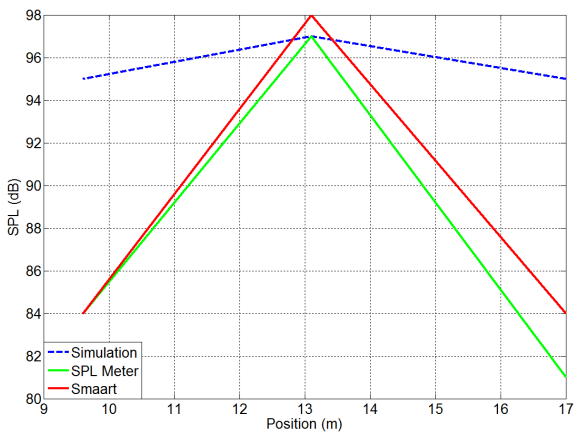


Figure 38: 1.6 meter spacing simulation and measurement results (stage listening locations)

11. DISCUSSION

When deploying subwoofers for an event the goal is to create even coverage across the audience area. In most modern music, subwoofers reproduce the foundation and energy of the music. There are many advantages that come with the use of cardioid subwoofers but without proper placement these advantages will quickly decrease.

Without readily available digital signal processing (DSP), many configurations of steerable subwoofers would not be possible. Most DSP units have the ability to take in two inputs and put out four to six independently controlled outputs, while some are expandable for even more inputs and outputs. By adjusting the delay between subwoofers on the output of the DSP units many coverage patterns can be made as demonstrated in Figure 16. DSP provides a valuable set of tools that can greatly enhance system performance and flexibility.

Keeping low frequency in the audience area and off the stage can significantly increase the audio quality. Omnidirectional subwoofers cause a buildup of low frequency energy on the stage due to lack of directionality. This can cause low frequency energy to be picked up by the microphones in varying phase, further reducing the audio quality and sometimes resulting in feedback. This is one reason it is necessary to use high pass filters on input channels or on the microphones themselves, often filtering low frequencies that would be present on studio recordings. Cardioid subwoofers do not eliminate the unwanted low frequency energy on stage, but can significantly reduce it, achieving higher gain before feedback with less reliance on high pass filtering.

Figures 21 and 22 demonstrate how placing subwoofers under the stage can prohibit the cardioid pattern control, causing additional problems. Most temporary stages are made up of many smaller sections of deck. These pieces of deck are in many cases just sitting on (or clamped to) the stage legs. These pieces commonly vibrate when subwoofers underneath the stage are operating at show level. This can make it very challenging to achieve the desired gain before feedback with even a few microphones placed on the vibrating stage before it is necessary to compromise the equalization. Shock mounts and rubber feet can only provide a small amount of decoupling between the stage deck and microphones, but do not solve the problem completely. The worst possible situation is having subwoofers underneath a

temporary stage with a large number of acoustic instruments on stage (Image 1).

Image 1: Example of a symphony orchestra performing on a temporary staging unit with three ground stacks of subwoofers just in front of each corner of the stage (photo courtesy of Adam Rosenthal)

Image 2: Example of a flown array of Nexo CD-18 cardioid subwoofers alongside a 30-box Nexo Geo-T array (photo courtesy of Adam Rosenthal)

In addition to polar pattern loss and stage vibration problems, placing cardioid subwoofers underneath a stage will waste channels on amplifiers and DSP units since the cardioid pattern achieved through use of the DSP is lost due to subwoofer placement underneath the stage.

Subwoofers that are flown in arrays (Image 2) have the advantage of providing better coverage of the audience from front to back (Figures 23 – 25) while the front rows of the audience are not exposed to extreme levels that sometimes result from the use of ground stacks. Flown subwoofers can also provide better phase coherency by having all subwoofers in close proximity to one another, although this may increase power alley. Flying subwoofers close to the main sound system will minimize the time differential from mains to subwoofers, thus simplifying the time alignment procedure.

The difficulty in flying subwoofers is that additional rigging will be required which is an added expense. Flown subwoofers require additional units to compensate for the reduced output due to the absence of ground coupling. Supplementary ground stacked subwoofers are sometimes required at reduced output levels to compensate for this output reduction (Image 3). Using flown subwoofers with ground based subwoofers can provide very good coverage, but more setup time is usually needed for rigging and time aligning the system (which is not always readily available). Without the proper setup of a system consisting of flown subwoofers with ground stacks, diminished results are highly likely.

The greatest problem with flown subwoofers is that the venue must be capable of supporting the additional weight while having sufficient ceiling height. Due to this, flown subwoofers are often not an opinion.

Even with the capability to achieve optimal subwoofer system performance, this often takes a backseat to the sight lines of the performance. This can be especially difficult when there is seating on all sides of the stage (after all, people are not paying to see a pile of subwoofers!). In addition to audience sight lines of the stage, compromises in subwoofer placement must also be made to accommodate the production needs. Many production elements such as video walls, cameras, lighting, special effects and staging all compete for space around the stage. This is why it is crucial to understand how different subwoofer configurations will affect the overall audio performance. Simulation tools can help formulate a broad understanding (as demonstrated in earlier sections) that can be used to meet the audience and production needs for an event.

Image 3: Example of ground stacked subwoofers used in conjunction with the flown array shown in Image 2 (photo courtesy of Gary Gand)

In addition to the aspects of the performance itself (low-frequency coverage, audience sight lines, production needs and venue capabilities), truck space is a cost that cannot be overlooked with touring sound. Efficient use of subwoofers can minimize the required truck space. Poor time alignment and placement of subwoofers will create more destructive interference and less overall output from a given sound system.

Even though many manufacturers of speakers are mindful of truck dimensions making sure their speakers can be packed into neat rows on trucks, needing to pack more subwoofers than necessary for a production wastes truck space and fuel. With a long tour the cost of additional trucking can add up quickly. A smaller number of well placed subwoofers can outperform a larger number of poorly placed subwoofers; therefore careful subwoofer system planning can not only enhance the audio quality of an event, but also minimize the event's budget.

Well planed subwoofer placement and optimization will not only benefit the audience but the performers as well. With the use of high performance simulations and careful subwoofer placement, predictable results can be achieved and low-frequency beam steering becomes easy to implement. Examining all the options of placement and beam steering, a good solution can often be determined. Even if not optimal, careful subwoofer placement can still be very effective.

12. CONCLUSIONS

Achieving desirable subwoofer system behavior in large-scale live events can be a daunting task considering all the involved variables: audience versus stage SPL, available amplification/processing channels, sight lines, production requirements, venue capabilities, truck space and event budget.

While it is unlikely that the ideal subwoofer configuration could be implemented in reality, a high performance compromise can often be made to meet all the requirements. This is easily accomplished with the use of acoustical simulation software along with a strong understanding of subwoofer behavior trends. As highlighted in this paper, it is absolutely essential to include the stage in the simulation process, otherwise it can have immensely negative effects of system performance depending on subwoofer positioning.

While flown vertical subwoofer arrays have been shown to give very low front to back SPL variation over the audience area (and low horizontal variation in a center cluster configuration), they do place more low-frequency energy onto the stage. This problem, though, can be addressed with supplemental ground based subwoofers. While this variety of configuration may be ideal in theory, it is often impractical due to venue and sight line limitations.

Even without the help of flown vertical arrays, it has been shown that acceptable coverage can be given to 270° of audience, with appropriate rejection on stage, with the use of a four unit cluster of cardioid subwoofers. These clusters require a minimal amount of DSP to operate correctly in addition to occupying a minimal amount of space, both at the event and in the trucks. Based on the results discussed in this paper it is concluded that this solution may come closest to meeting all the requirements of an event and can be quickly fine-tuned for each venue with the DSP units.

While the authors are not presenting the ultimate solution to low-frequency coverage in this paper, it is their hope to highlight key aspects of low-frequency control giving sound engineers in the field a well-defined set of tools in dealing with this very important issue that is far too often overlooked.

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