TRINNOV AUDIO WAVEFORMING

An ideal sound system for home theater must ensure a flat and uniform acoustic response over the entire listening area. A main challenge in achieving this goal is to control the acoustic field at very low frequencies (below about 100 Hz). The acoustic field at these frequencies is strongly dominated by the modal behavior of the room, resulting in large differences in acoustic pressure throughout the listening area due to modal maxima and minima. In addition, the many reflections and long reverberation times of these room modes obscure much of the dynamics and details that could otherwise be perceived and enjoyed.

I. INTRODUCTION.
Traditional passive solutions require large amounts of absorption to be effective at low frequencies, resulting in a disproportionately large footprint that is expensive not only in terms of materials but also in terms of real estate. Other approaches, such as bass traps, are generally only effective at certain frequencies and are impractical as a broadband solution. As such, traditional passive acoustic treatments for low frequencies alone are inadequate for home theater.

In response to this reality, many home theater specialists have adopted multiple subwoofer arrangements in addition to passive treatments. There are several arrangements that aim to disrupt room modes. Our research has shown that some approaches can actually mitigate the effects of room modes, but do not address the root cause (wave interference) and therefore produce undesirable side effects without solving the entire problem.

The exception is the "Double Bass Array" (DBA) method. The traditional DBA approach, as the name implies, uses two arrays of subwoofers: one on the front wall (the radiating array) and another on the rear wall (the absorbing array). The radiating arrangement creates a plane wave to reduce interference in the room from side wall, ceiling and floor reflections. Then the absorbing arrangement attempts to cancel the back wall reflection with the same signal, but inverted and delayed by the time it takes the sound to travel the length of the room.

WAVEFORMING

However, this approach only gives good results under ideal conditions, which are difficult to achieve in practice. Too often, the walls are not sufficiently reflective to produce a good planar wave. In addition, the wave that reaches the back wall has changed during its journey through space because the walls are insufficiently stiff or parallel to properly guide the wave.... Finally, the nature of the wave changes as it encounters furniture, elevations, tiered seating, etc. The result is that the wave that reaches the back wall is no longer the same as the wave that left the front wall, and cannot be effectively eliminated. To the extent that there is a discrepancy, unwanted energy is introduced into the room.

Trinnov's WaveForming™ overcomes the limitations of existing solutions and provides a more effective and versatile tool for controlling very low frequency acoustic fields. The key aspects of WaveForming and some guidelines and recommendations on how to best use this technology are outlined below. Waveforming is a powerful and flexible tool. However, the laws of physics still apply, regardless of the sophistication of the signal processing. There are two factors in particular that determine the recommended number of subwoofers for a given room:

The size of the front and rear walls. Understandably, larger rooms require more subwoofers than smaller rooms.
The highest frequency you want to control. Higher frequencies mean shorter wavelengths, which in turn require closer spacing of the subwoofers to maintain planar wave control.

Please note that this document addresses the number of subwoofers and their recommended placement to maximize waveforming performance. It does not provide recommendations for the type of subwoofer to use or technical specifications for each subwoofer. This document also does not provide a means for calculating the acoustic pressure level of the WaveForming™ system based on the performance of each subwoofer. These recommendations will be available in a separate implementation document at a later date.

The best recommendation at this stage is:

Use the same subwoofers within each group.

Specify subwoofers with the same frequency range for both front and rear wheel arrays.

The rear wheel array may consist of subwoofers with lower power capability than the front subwoofers.

II. ADVANCED CONTROL OF LOW FREQUENCY ACOUSTIC WAVES WITH WAVEFORMING™

Figure 1 below shows the working principle of WaveForming, which consists of two main steps:

In the first step, the acoustic field within a volume around and within the listening area is evaluated. The goal of this step is to retrieve the necessary information about the model behavior of the room (as well as any changes introduced by objects in the room) so that the algorithm can eliminate these unwanted contributions. This is done by sampling the acoustic field in a three-dimensional grid of microphone positions throughout the listening area (blue dashed rectangle in Figure 1).

From the acoustic field measured in the previous step, the WaveForming processor calculates the filters to be applied to each subwoofer in the system and applies these filters to eliminate the model signature of the room.

The filters applied to the speakers ensure the generation of the narrowest and most uniform wavefront possible within the listening area, while the filters applied to all subwoofers (including the front and rear subwoofer arrays) absorb most room reflections and resonances (modes) together.

WaveForming's processing delivers unprecedented performance, thanks to its sophistication and ability to adapt to various constraints (such as irregular subwoofer arrangements):

Refined:

WaveForming combines several advanced and unique technologies such as "acoustic reshaping," "wavefront synthesis," and "multi-source, multi-controller optimization" to synthesize a specific filter for each subwoofer in such a way that the entire system functions as an idealized subwoofer.

WaveForming maximizes the homogeneity of the field in time, space and frequency across the entire listening area. These complex filters overcome the limitations of simple gain and delay filters.

Adaptive: These filters are calculated from the measured field and adapt to the physical characteristics of each individual room, including the precise shape and acoustic property of each wall and everything in the room.

Once again, it delivers more effective filters than simple gain and delay filters by adapting to the specific factors that affect performance in the listening area. This powerful analysis enables more robust and efficient control of the acoustic field, even under challenging conditions such as less than ideal room geometry.

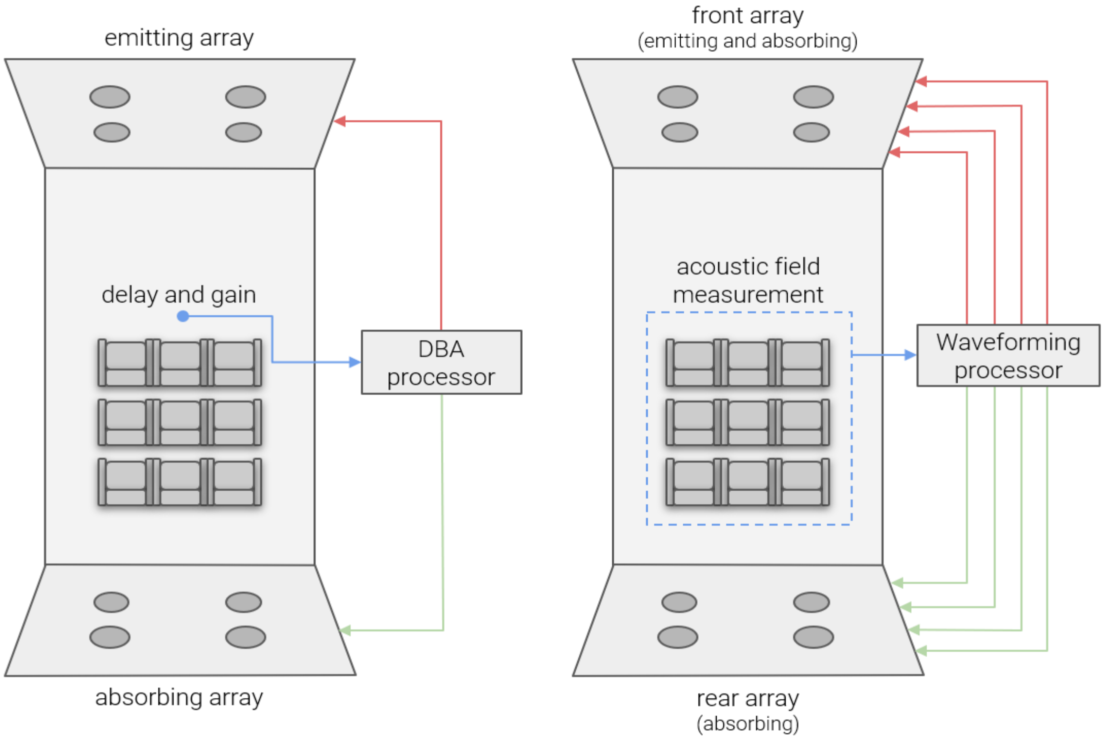

Figure 1. Working principle of the DBA (left) versus WaveForming (right).

III. SPATIAL REFERENCE SCALING GUIDELINES

When sampling the acoustic field with microphones, the following guidelines are critical to achieve good performance.

The distance between the front array and the measurement zone should be at least 2 meters.

The distance between the measurement zone and the rest of the walls and ceiling should be at least 1 meter.

The measurement grid should have at least 2 horizontal levels, with the first level 1 meter above the floor (typical ear height for a seated person).

The maximum distance between two adjacent microphone positions should be 1 meter, so that the acoustic field is clearly characterized up to frequencies of about 100 Hz.
A certain precision in the placement of these microphones during the measurement process is important, since the WaveForming algorithm requires a clear
"understanding" of the three-dimensional field throughout the listening area. Objects in the room and even the room itself cause changes in the wave as it travels the length of the room. These changes must be documented.

IV. DETERMINING THE NUMBER AND PLACEMENT OF SUBWOOFERS

The first questions that come to everyone's mind when they think about incorporating WaveForming into their room design are 1) "How many subwoofers do I need?" and 2) "How do I position them in the room?" The answer depends largely on two parameters:
The size of your room (more specifically, the dimensions of your front and rear walls).

The highest frequency you want (or need) to control.
It's pretty intuitive that larger rooms may require more subwoofers. But the density of those subwoofers on the wall will determine the highest frequency at which a clean, flat wavefront can be produced. Both of these parameters must be established before an informed decision can be made.

We will approach these two considerations in reverse order. We believe that once you have a better understanding of the different possible layouts and the flexibility we have in placing the subwoofers, it will be easier for you to understand the required number of subwoofers.

V. GUIDELINES FOR THE ARRANGEMENT OF SUBWOOFERS

This section provides recommendations for the optimal positioning of subwoofers. These recommendations are based on extensive research including numerical simulations, experiments and theoretical analysis. All experimental data were developed using a dedicated microphone array that respected the previously described guidelines for spatial coverage of the acoustic field. The following subwoofer positioning recommendations are derived from these data and the spatial coverage guidelines.
The designations in the layouts follow the format N_f- N_r, indicating the number of subwoofers in the front emitter array and the number of loudspeakers in the rear absorber array.

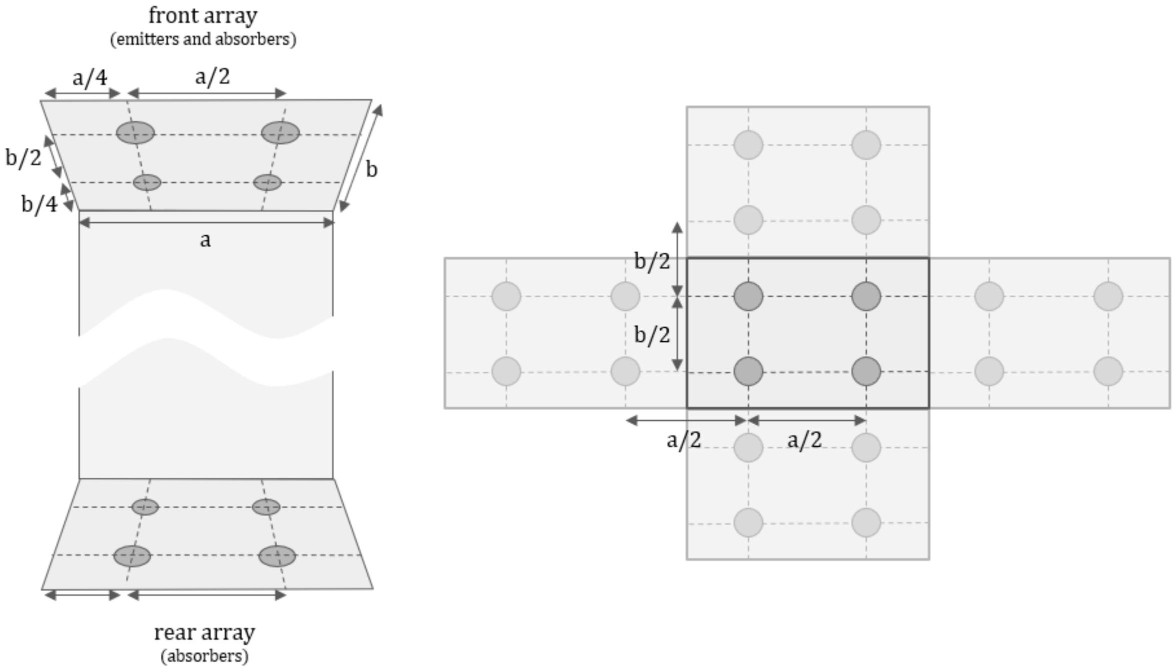

Figure 2. A 4-4 regular layout (left, top view) and the wall of emitters with their image sources (right, front view).

A. REGULAR LAYOUTS: REGULAR POSITIONS

As can be seen from the figure above (Figure 2), the ideal spacing of subwoofers is divided so that the space between a subwoofer and the adjacent room surface (wall, ceiling or floor) is half the distance between it and its neighboring subwoofer. This distance ensures that the reflected energy caused by these room surfaces acts as "virtual subwoofers" with the same distance to the adjacent actual subwoofers. Ideally, this distance should be consistent both horizontally and vertically. The width of the wall ("a") is divided by the number of subwoofers along the width of the room, and the height of the wall ("b") is divided by the number of subwoofers along the height of the room. (In another room, there might be a 3 x 2 arrangement horizontally and vertically, requiring "a/3" and "b/2" for spacing). We call this a "regular arrangement", where "regular" refers to the consistency of the arrangement.

In a regular array, the subwoofers are arranged so that they are evenly spaced (including reflections that act as "virtual" subwoofers), both horizontally and vertically. Therefore, the distance between a subwoofer at the edge of the array and the adjacent wall must be half the distance between two adjacent subwoofer columns. Similarly, the distance between an "edge" subwoofer and the adjacent ceiling or floor must be half the distance between two adjacent rows of subwoofers.

Therefore, if A is the room width and we have C subwoofer columns, the distance between two adjacent columns is a/C, and the distance from a side subwoofer to the adjacent wall is a/2C. Likewise, if we have height b and R rows, the distance between two adjacent rows is b/R, and the distance from the bottom/top row to the floor/ceiling is b/2R.

Note that with WaveForming, the number of subwoofers radiating to the front does not have to be equal to the number of subwoofers absorbing to the rear. The particular arrangement where the two arrays have the same dimensions and the same number of subwoofers is called a Double Bass Array (DBA). Figure 2 shows a 4-4 regular arrangement with 2×2 arrays in a room with a width a and a height b.

B. IDEAL LAYOUTS: IDEAL NUMBER OF SUBWOOFERS

The distance between the subwoofers determines the upper frequency limit that can be effectively controlled as a plane wave. This results from the fact that higher frequencies have shorter wavelengths and the radiating subwoofers must be within a certain portion of that wavelength of each other for plane wave generation to work well. (There is no way around the laws of physics).

The ideal arrangement is a regular arrangement where the arrays have the same dimensions. In such an arrangement, the positions of the rows and columns of subwoofers are dictated by the height and width of the room, respectively. In addition, the distance between two subwoofers determines the bandwidth of optimization. Therefore, for a room of a certain size, the number of rows and columns determine the upper limit of the controlled bandwidth.

Figure 3 and the following calculator give the number of rows and columns of the ideal array for a given width and height for a typical bandwidth up to 100 Hz. Note that since we are proposing a discrete output (the number of subwoofers) for a continuous input (the dimensions of a wall), the bandwidth would not be the same for all combinations of room dimensions. Therefore, the calculator will issue a warning if at least one of the dimensions is within 15 cm of the boundary, as shown in the gray areas in Figure 3.

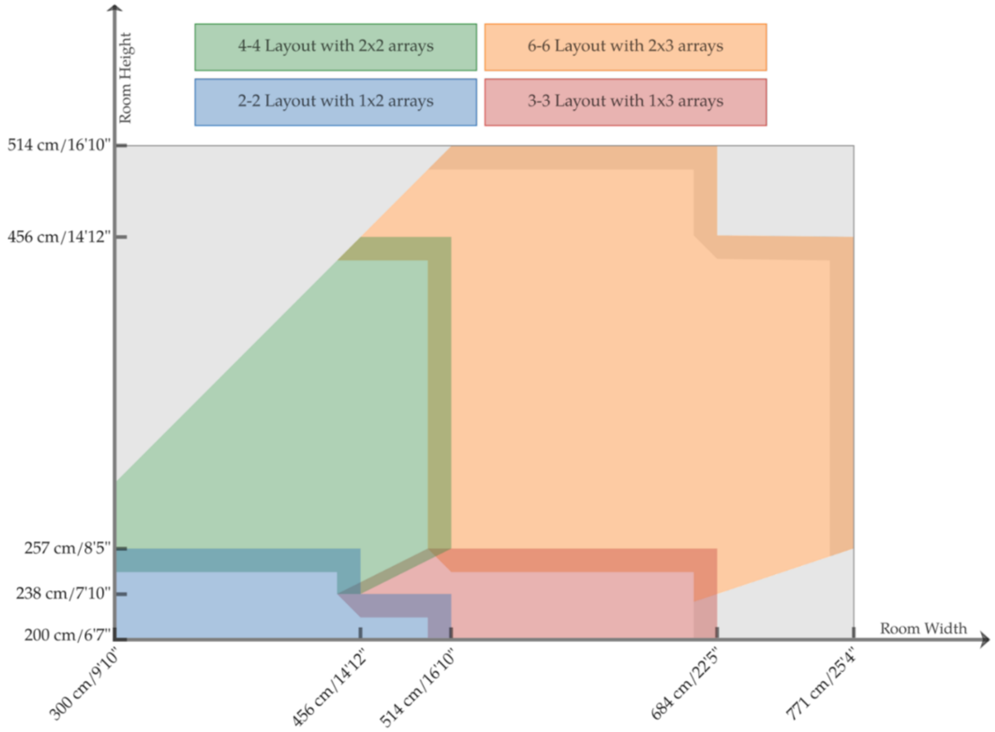

Figure 3. Recommended layouts in terms of room width and height.

The "ideal" arrangement provides the best performance of WaveForming. This means having the recommended number of subwoofers (see Section IV. C) with an equal number of front and rear subwoofers, all in the regular positions (see Section IV. B). However, the sophistication and adaptability of WaveForming allows it to support a wide variety of arrangements while maintaining a high level of performance. In short, it tolerates deviations from the "ideal" arrangement:

Reducing the number of subwoofers: the number of subwoofers in the ideal arrangement, especially the rear subwoofers (absorbers only), can be reduced if necessary. This may affect the results, but in all cases good performance is expected. It is preferable to reduce the number of rear subwoofers rather than reduce the number of subwoofers in the front array, as the loss of power is minimal.

Support for asymmetric arrays: With waveforming, the front and rear arrays do not have to match as long as they each remain regular. In this case, the preferred scenario is when the rear array has fewer subwoofers than the front array. Using fewer rear subwoofers does not significantly affect the overall performance, while using fewer front speakers does. This is a simple consequence of the fact that front subwoofers are more important: They are the radiators and at the same time absorbers.

Asymmetrical arrays with fewer rear subwoofers can be useful in two ways. First, it is an effective way to reduce the number of subwoofers while maintaining high performance. Second, it is a good way to get the best performance for a given number of subwoofers. For example, an array of 4-2 often delivers higher overall power than an array of 3-3 with 6 subwoofers. And with 8 subwoofers, an arrangement of 6-2 often delivers higher performance than an arrangement of 4-4.

This is a general tendency and not an absolute rule, as each situation depends on the specific room conditions.

Support for irregular arrangements: Some shifting of subwoofers within an array can be tolerated and sometimes even recommended, such as placing 3 subwoofers in an irregular triangular arrangement. This "leeway" is valuable in cases where subwoofer placement is limited by physical constraints, such as working around on-screen speakers. (See Section D for displacement recommendations.)

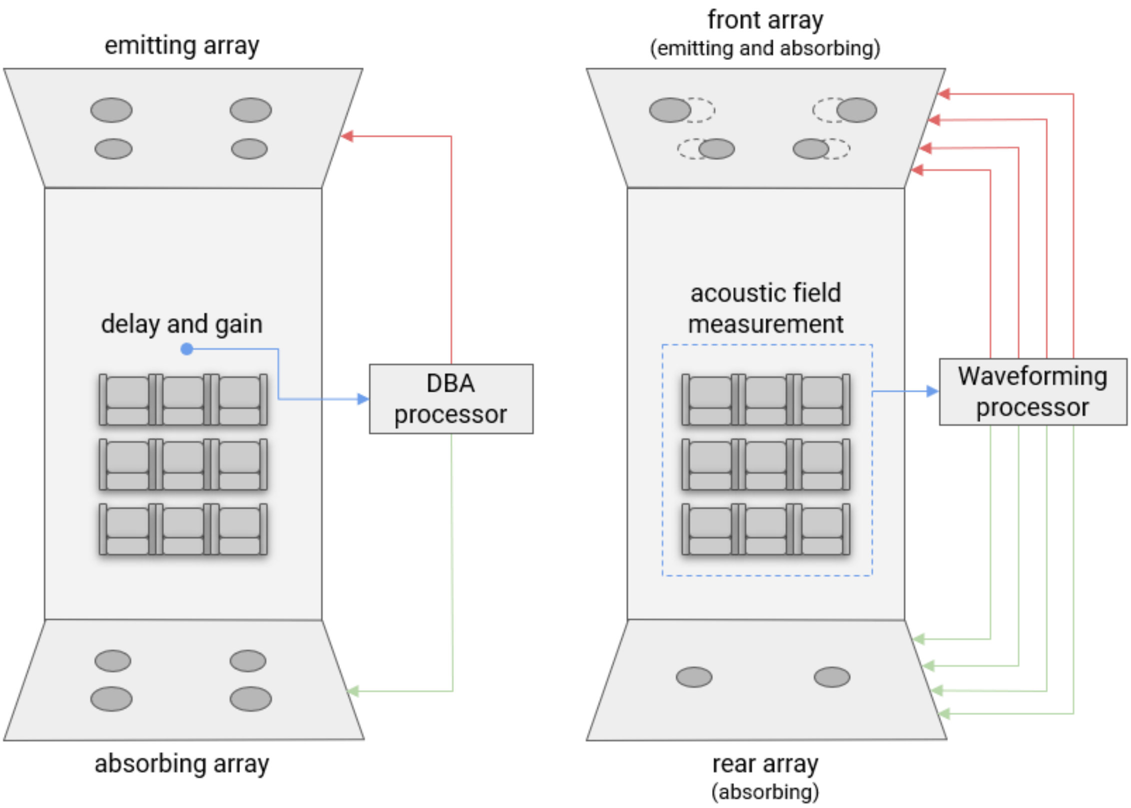

Figure 1b. Working principle of the DBA (left) versus WaveForming (right) with asymetric and irregular layout.

C. REDUCTION OF THE NUMBER OF SUBWOOFERS AND POWER

Remember that the optimum number of subwoofers for a given room is determined by two factors: the size of the room and the upper frequency you want to control. Understandably, larger rooms require more subwoofers for both control and output. But for a given room size, the distance between subwoofers determines the upper limit of waveforming's ability to produce a planar wave.
The following section provides general guidelines for reducing and/or moving the subwoofers and the corresponding power levels.
Dark green corresponds to maximum power.
Lighter green indicates that power may be reduced somewhat.
The lightest green is the minimum recommended WaveForming implementation.

Dennoch garantieren alle aufgeführten Layouts eine minimale zufriedenstellende Schwelle.

THE IDEAL 2-2 LAYOUT

This is the regular layout with two 1×2 arrangements (for example, a row of two subwoofers on each wall). Since it already has a small number of subwoofers, it cannot be reduced.

Layout 2-2	Ideal Layout (tolerates minimal displacement)	Ideal Layout with Displacement (tolerates maximal recommended displacement)

THE 3-3 IDEAL LAYOUT

This is the normal layout with two 1x3 arrangements (for example, a row of three subwoofers on each wall). It allows reducing the number of subwoofers by one.

Layout 3-3	Ideal Layout (tolerates minimal displacement)	Ideal Layout with Displacement (tolerates maximal recommended displacement)
Layout 3-2	Reduced Layout (tolerates minimal displacement)	Reduced Layout with Displacement (tolerates maximal recommended displacement)

For the reduced layout, the subwoofers are placed in the regular positions (see IV. a).

THE IDEAL 4-4 LAYOUT

This is the regular layout with two 2×2 arrays (e.g., two rows and two columns of two subs each, on each wall). It tolerates reducing the number of subs by

4-4 Layout	Ideal Layout (tolerates minimal displacement)	Ideal Layout with Displacement (tolerates maximal recommended displacement)
4-2 and 3-3 Layouts	Reduced Layout (tolerates minimal displacement)	Reduced Layout with Displacement (tolerates maximal recommended displacement)

For the reduced layout, the subwoofers should be placed in the regular positions (see IV. a). Reducing to 4-2 is preferred over reducing to 3-3 when the ceiling is too high to have only one row of subwoofers and the room is too narrow to require three columns.

DAS IDEAL 6-6 LAYOUT

This is the regular layout with two 2x3 arrays (for example, two rows of three and two columns of two subwoofers on each wall). It allows reducing the number of subwoofers from 12 to 8.

6-6 Layout	Ideal Layout (tolerates minimal displacement)	Ideal Layout with Displacement (tolerates maximal recommended displacement)
6-5, 6-4, 5-5, & 5-4 Layouts	Reduced Layout (tolerates minimal displacement) Ideal Layout (tolerates minimal displacement)	Reduced Layout with Displacement (tolerates maximal recommended displacement)
5-3 & 6-2 Layouts	Reduced Layout (Regular) (tolerates minimal displacement)	

In cases 6-4 and 5-4, the four absorbers should be placed in the usual positions (see IV. a). However, it is unusual to have a room wide enough to require three rows of subwoofers while its ceiling is low enough for the processing to work well. Therefore, if 3 or 5 subwoofers are to be placed against a wall, we recommend positioning them in this case as follows (see Figure 4):

• 3 subwoofers (irregular triangular arrangement): one subwoofer at half the width and a quarter of the height (from the floor), and the others both on one-sixth and five-sixths of the width and three-quarters of the height (from the ground).

• 5 subwoofers (irregular trapezoidal arrangement): two subwoofers on one-fourth and three-fourths of the width and one-fourth of the height (from the floor) and three subwoofers on one-sixth, one-half and five-sixths of the width and three-fourths of the height (from the floor).

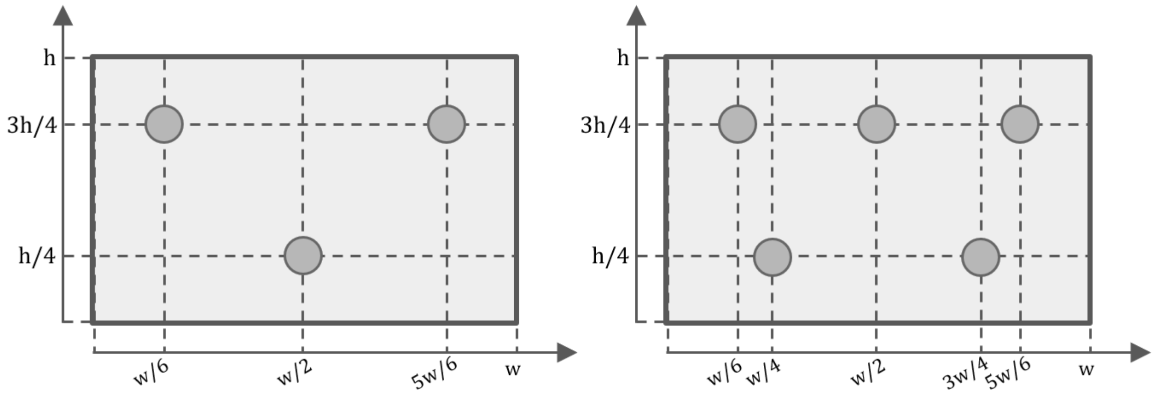

Figure 4. Irregular layouts with 3 subwoofers and 5 subwoofers

D. GUIDELINES FOR MOVING SUBWOOFERS

COMMON GUIDELINES FOR ALL LAYOUTS

1. In general, it is preferred to move the subwoofers away from each othe instead of moving them closer to each other. The most unfavorable situation occurs when all subwoofers are next to each other (which corresponds to a single acoustic source).

2. We recommend to use at least one of the regular position coordinates to be observed. In other words, displacements from the regular positions should be either horizontal or vertical, but preferably not in both directions at the same time.

In the rest of this section, the horizontal displacement is given as a percentage of the width of the room and the vertical displacement as a percentage of its height.

SPECIAL CASES FOR THE 2-2 ARRANGEMENT:

Simultaneously moving radiators and absorbers in horizontal direction should be avoided. The best performance is achieved when either the radiators or the absorbers remain in their regular horizontal position.
Radiators and absorbers can be moved simultaneously in the vertical direction, but not more than 10%.

SPECIAL CASES FOR THE 3-3 LAYOUT:

When only the center emitter is moved:

horizontal: 15% (Figure 5)

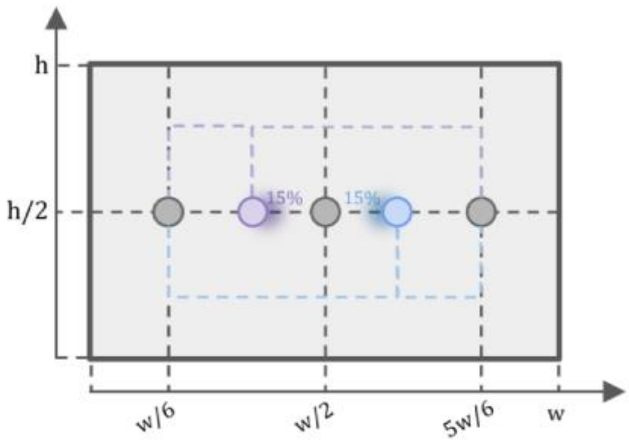

Figure 5. Displacing center emitter horizontally

- vertical: 30% (Figure 6)

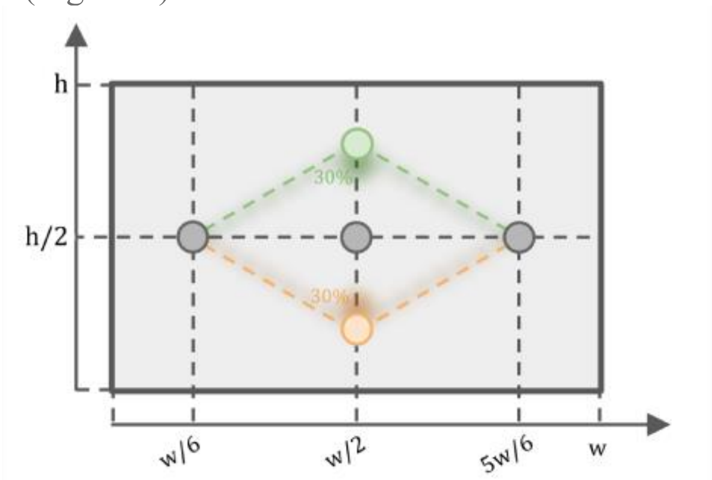

Figure 6. Displacing center emitter vertically

It is better to form triangles or diagonals instead of moving all subsections vertically by the same amount:If all emitters are moved vertically:

- +/- 5 % if all subwoofers are moved up or down (Figure 7)

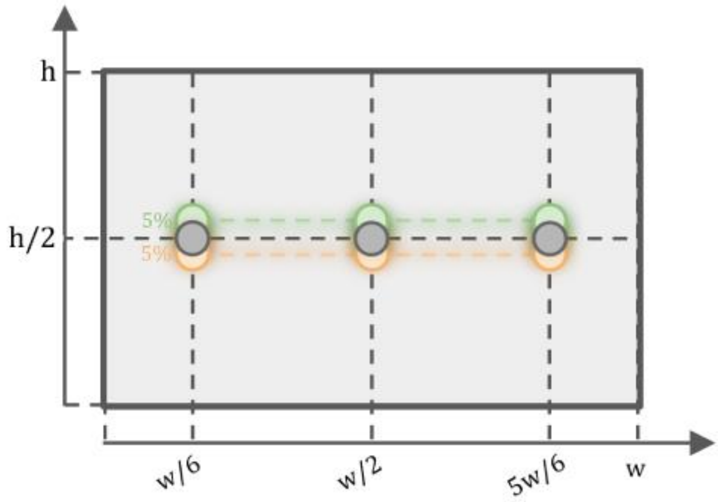

Figure 7. Displacing all 3 emitters vertically

+/- 15 % if they form a triangle (Figure 8)

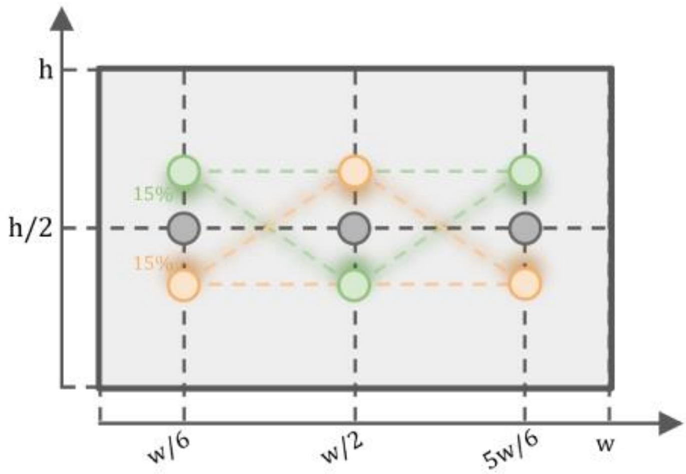

Figure 8. Displacing all 3 emitter vertically (triangular layout)

+/- 20% if they form a diagonal (Figure 9)

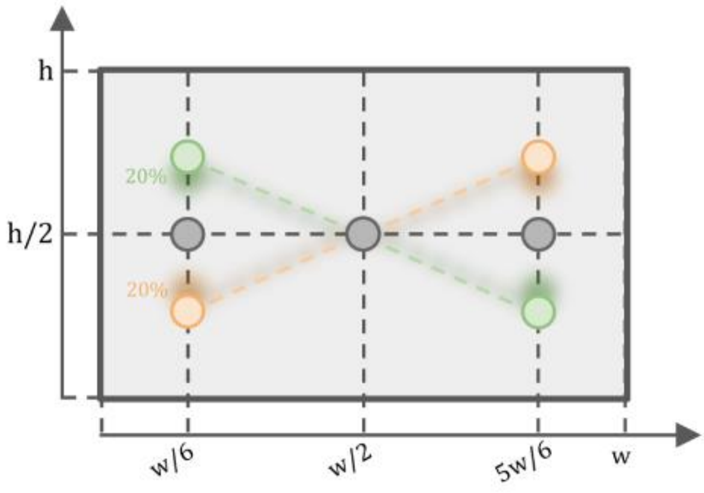

Figure 9. Displacing the side emitters vertically (diagonal layout)

When all absorbers are moved vertically, the boundaries are more flexible:

- +/- 10% when all subwoofers are moved up or down.
- +/- 30% if they form a triangle
- +/- 30% when they form a diagonal

SPECIAL CASES FOR THE 3-2 ARRANGEMENT:

When only the center emitter is moved:

- horizontal: +/- 15%
- vertical: +/- 30%

When all emitters are moved vertically:

- +/- 15% when all subwoofers are moved up or down.
- +/- 20% if they form a triangle
- +/- 20% when they form a diagonal

When the two absorbers are moved vertically:

- +/- 10% when all subwoofers are moved up or down.
- +/- 20% if they form a diagonal line

SPECIAL CASES FOR THE 4-4 LAYOUT:

- When the radiators are moved (horizontally or vertically): +/- 10% (Figures 10 and 11)

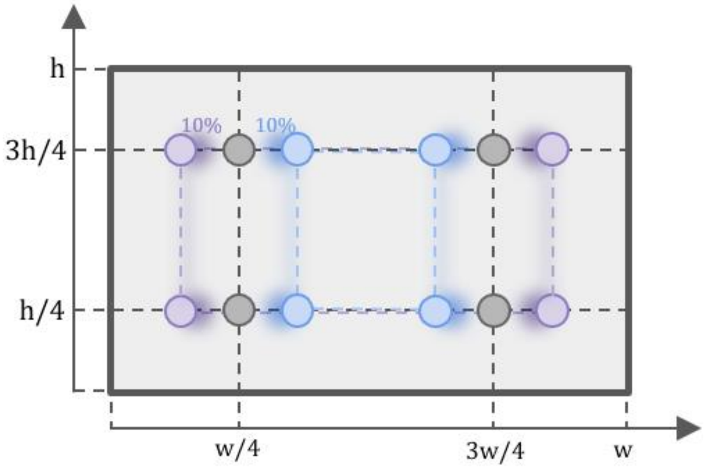

Figure 10. Displacing all 4 emitters horizontally

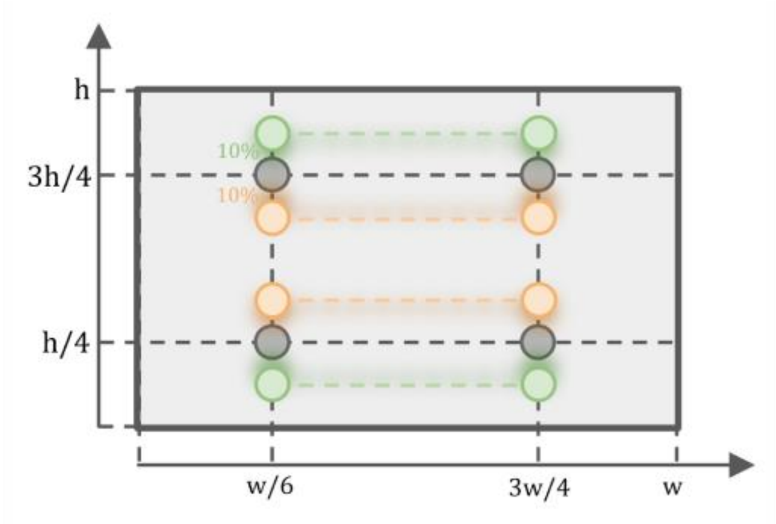

Figure 11. Displacing all 4 emitters vertically

• When the absorbers are moved (horizontally or vertically): +/- 15%
• It is better to move the subwoofers away from each other than to move them closer together or to move them all in one direction.Wenn der Hörbereich weit genug von der Decke entfernt ist (mit anderen Worten, wenn die Abtastzone näher am Boden als an der Decke liegt), ist es zu empfehlen,

place the subwoofers in a trapezoidal layout.* (Figure 12)

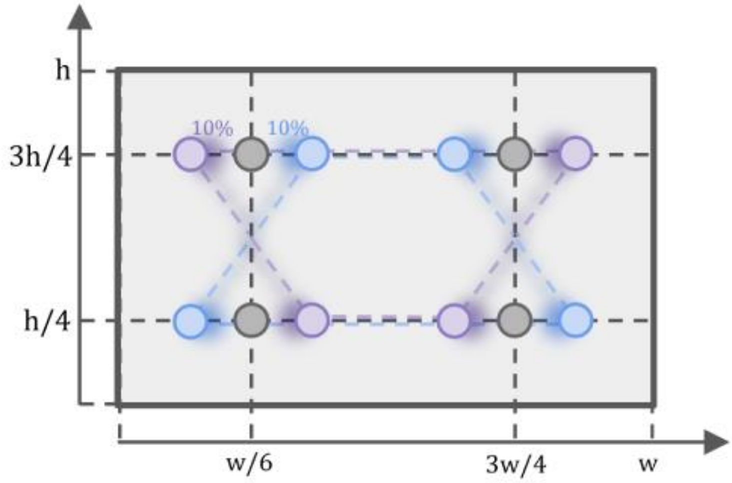

Figure 12. Displacing all 4 emitters horizontally (trapezoidal layout)

This means moving the upper subsections away from each other and moving the lower subsections closer to each other or vice versa.

VI. CONCLUSIONS

Trinnov was founded twenty years ago to conduct fundamental research into how we humans perceive complex, three-dimensional sound fields. Much of the early research focused on the possibility of capturing such a sound field in, say, a concert hall, with the goal of reproducing the same sound field in a much smaller space (your home). In fact, our Optimizer technology was developed as a direct result of this early research.

However, there was much more to learn about low frequencies and their interactions with these small spaces (i.e., apartment-sized rooms, not concert halls or sports stadiums). Although many scientists and engineers have looked at this problem, most of this work has led to ways to mitigate the problems at these frequencies.

We wanted to find out if there was a way to eliminate these problems.

During our research, we have learned a lot about the complex processes at low frequencies in small spaces. We expect that it may take five or even ten years to implement the technologies that have emerged from this research. In short, there is still a long way to go.

However, we expect that the best and brightest implementations of our findings will always bear some resemblance to the traditional Double Bass Array (DBA). WaveForming makes such designs much more flexible and effective by incorporating a high degree of "intelligence" into its sophisticated algorithms. For this reason, we decided to first present the best implementation of WaveForming: We want to demonstrate what is now possible thanks to this year-long research project.

This is just the beginning of the technological release of WaveForming. We plan to expand the capabilities that result from the lessons learned, including new features that apply to these front and rear bass arrays as well as other, less sophisticated system designs. The powerful PC-based signal processing enabled by our unique hardware platform allows us to develop these features and make them available to our customers via simple software updates. This confirms our decision many years ago to follow a less beaten path.

We hope you have found this short white paper interesting and educational. We look forward to helping people discover the world of low-frequency dynamics and detail that are revealed when you eliminate the cacophony of bass reflections and resulting modal problems that normally dominate low-frequency reproduction in the home.