

ROOM OPTIMIZER™: A Computer Program to Optimize the Placement of Listener, Loudspeakers, Acoustical Surface Treatment and Room Dimensions in Critical Listening Rooms

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ABSTRACT

An automated Windows 95™ program has been developed to optimize the placement of listener, loudspeakers, and acoustical surface treatment, as well as the room dimensions in critical listening rooms. The quality of the low-frequency room response is monitored in terms of the spectra received by the listener over just the early reflections (65 ms) and also over multiple (15-30) reflection orders. This amounts to monitoring the effects of comb filter coloration due to early arriving reflections and the quality of the modal response, respectively. The program uses optimization routines to achieve the flattest response over these two spectra, while satisfying displacement, symmetry and stereo angular constraints. This has required the development of a cost parameter to monitor the quality of the spectra produced. The cost parameter is equal to the combined, weighted standard deviation of the two spectra. To provide good imaging as well as bass response and account for physical limitations on listener and loudspeaker placement, limits can be placed on listener and loudspeaker search ranges. The first order specular reflection points are determined for the optimum listener and loudspeaker locations to aid in the placement of absorbing and diffusing acoustical surface treatment. The room dimensions can also be included in the optimization, although this feature is not included in the initial version. Wizards are provided for stereo, stereo with multiple woofers per loudspeaker, stereo plus center channel, 5.1 THX home theater surround and multichannel music (using 5 matching loudspeakers), and sub-woofers. Additional configurations can be created, saved and reloaded for evaluation. The program's output can be printed and also saved in a comma delimited form for more detailed evaluation in a spreadsheet. The wizards help the user by automatically setting up the constraint relationships among the independently varying drivers and the constrained dependent drivers, in addition to setting limits on the search ranges for the listener and loudspeakers. Examples of some of these wizard configurations are also presented.

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[1] INTRODUCTION

The sound that we hear in a critical listening room is determined by the complex interaction among the quality of the electronics, the quality and placement of the loudspeakers, the hearing ability and placement of the listener, the room dimensions (or geometry if non-cuboid) and the acoustical condition of the room's boundary surfaces and contents. All too often these factors are ignored and emphasis is placed solely on the quality of the loudspeakers. However, the tonal balance and timbre of a given loudspeaker can vary significantly, depending on the placement of the listener and loudspeaker and the room acoustic conditions. The acoustic distortion introduced by the room can be so influential that it dominates the overall sonic impression [1,2]. The two causes of this acoustic distortion are the acoustical coupling between the loudspeakers and listener with the room's modal pressure variations or room modes and the coherent interaction between the direct sound and the early reflections from the room's boundaries.

Critical listeners have invested considerable time in trial and error attempts to minimize these effects, however, no automated method to search for the optimum locations has been proposed. With the advent of 5.1 home theater and multichannel music, physical trial and error approaches become even less feasible. The task of optimally locating 5 loudspeakers and multiple subwoofers presents a significant challenge. In addition to optimizing the low frequency response via optimum listener/loudspeaker placement, one must also address imaging [3,4] and the influence of acoustical surface treatment on the size and location of sonic images, as well as the sense of envelopment or spaciousness experienced in the listening room..

Therefore, to address these acoustical issues we describe an automatic computerized simulation program that suggests optimum locations for loudspeakers, listener and acoustical surface treatment. In addition, the program can also help with new room design, by optimizing the room dimensions. For this discussion, we will focus on the optimum placement of loudspeakers and listener in a room.

[1.1] Modal Response

All mechanical systems have natural resonances. In rooms, sound waves coherently interfere as they reflect back and forth between hard walls. This interference results in resonances at frequencies determined by the geometry of the room. In loss-less

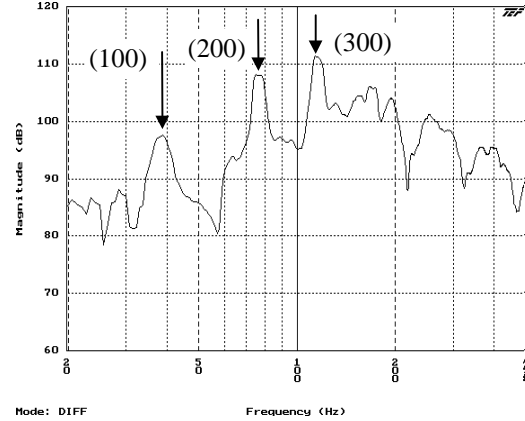


Figure 1. Measured modal frequency response in a room 2.29 m (W) x 4.57 m (L) x 2.74 m (H). The (100), (200), and (300) modes are identified.

cuboid rooms, where the normal component of the particle velocity is zero at the surface, the modal frequencies, associated with the eigenvalues of the wave equation, $f_{n_x n_y n_z}$, are determined by Eq. 1.

$$f_{n_x n_y n_z} = \frac{c}{2} \sqrt{\left(\frac{n_x}{L_x}\right)^2 + \left(\frac{n_y}{L_y}\right)^2 + \left(\frac{n_z}{L_z}\right)^2} \quad (1)$$

n_x , n_y and n_z are non-negative integers, L_x , L_y and L_z are the length, width and height of the room and c is the speed of sound. These modal frequencies are distributed among axial modes involving two opposing surfaces (e.g. $n_x=1, n_y=0, n_z=0$), tangential modes involving 4 surfaces ($n_x=1, n_y=1, n_z=0$), and oblique modes involving all surfaces ($n_x=1, n_y=1, n_z=1$). For an axial mode between two opposite boundaries, this frequency is equal to the speed of sound, c , divided by twice the room dimension in that direction. For example, for $c = 344$ m/sec, a 4.57 m wall to wall dimension results in a first-order fundamental room mode of 37.6 Hz. As an example, in Figure 1 we present the measured modal frequency response of a room with a 4.57 m dimension. The loudspeaker was located in a corner and the microphone was placed against a wall perpendicular to the 4.57 m dimension, in order to record all axial modes. The first-order (100), second-order (200) and third-order (300) modes are identified in Figure 1 at 37.6 Hz, 75.3 Hz and 113 Hz, respectively.

The pressure [5,6] of the eigenfunctions or normal modes in a rectangular parallelepiped at $\vec{P} = (x, y, z)$ is given by Eq. (2). Q_s is the velocity

$$P(\rho|\rho_0) = \frac{Q_s}{L_x L_y L_z \epsilon_x \epsilon_y \epsilon_z} i \rho \sum_{n_x=-\infty}^{\infty} \sum_{n_y=-\infty}^{\infty} \sum_{n_z=-\infty}^{\infty} \frac{1}{k_h^2 - k^2} \left[\cos\left(\frac{n_x x \pi}{L_x}\right) \cos\left(\frac{n_y y \pi}{L_y}\right) \cos\left(\frac{n_z z \pi}{L_z}\right) \cos\left(\frac{n_x x_0 \pi}{L_x}\right) \cos\left(\frac{n_y y_0 \pi}{L_y}\right) \cos\left(\frac{n_z z_0 \pi}{L_z}\right) \right] \quad (2)$$

of a point source at $\vec{r}_0 = (x_0, y_0, z_0)$, $k^2 = \frac{\omega^2}{c^2}$,

$$k_h^2 = \left(\frac{n_x \pi}{L_x}\right)^2 + \left(\frac{n_y \pi}{L_y}\right)^2 + \left(\frac{n_z \pi}{L_z}\right)^2, \quad \text{the}$$

Neumann symbol ϵ_i is 1 if n_i equals 0 and 2 otherwise, for $i \in \{x, y, z\}$, and ρ is the air density.

The integers n_x , n_y , and n_z represent the numbers of nodal planes perpendicular to the x, y and z axes. On either side of these nodal planes, the sound pressures have opposite signs.

Thus, in addition to the modal frequency distribution, the coupling between the loudspeakers and listener with the modal pressure is also important. The

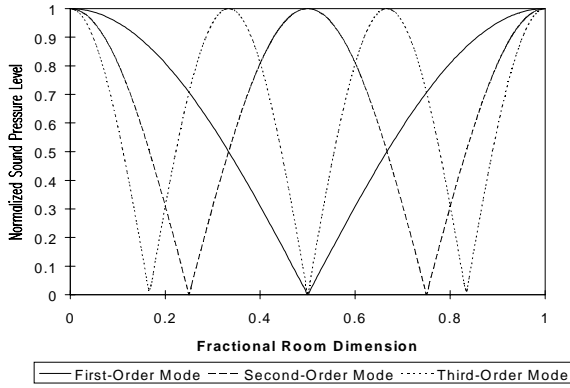


Figure 2. Normalized energy distribution of the first three modes in a room.

loudspeaker placement will accentuate or diminish coupling with the room modes. Similarly, a listener will hear different bass response depending on where he or she is seated. Figure 2 illustrates how the sound pressure is distributed along a room dimension. The room dimension is shown as a fraction ranging from 0 to 1. 0.5 would be in the center of the room and 1 would be against a wall. Examining Figure 2 reveals that the fundamental first-order mode has no energy in the center of the room. Physically this means that a listener seated in center of the room would not hear this frequency. The second-order mode, however, is at a maximum. It can be inferred from this plot that, in the center of the room all odd-order modal frequencies are absent and all even harmonics are at a maximum. Therefore, when we listen to music in a room, the music will be modified by the room's

modal response and this acoustic distortion will depend on where the speakers and the listener are located and how they couple with the room. Ideal room dimensions represent the acoustical search for the “Holy Grail”. There are various suggested approaches [7,8]. While the distribution of the modal frequencies is important, it is equally important to consider the placement of the loudspeakers and the listeners with respect to the boundary surfaces to minimize the acoustic distortion introduced by the room. Thus to minimize the modal coloration, we must optimize both the room dimensions and the locations for loudspeakers and listeners.

[1.2] Speaker-Boundary Interference Response

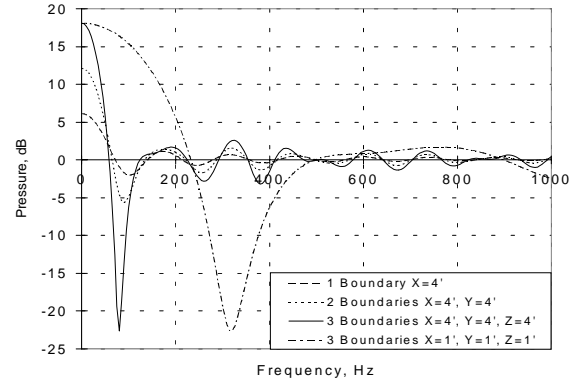


Figure 3. Averaged speaker-boundary interference response for several boundary conditions.

In addition to modal pressure variations, the interaction of the direct sound from the loudspeakers with reflections from the walls can result in dips and peaks in the spectra due to interference effects. We refer to this as the speaker-boundary interference response. This issue has been examined by Allison [9,10], Waterhouse [11,12] and Waterhouse and Cook [13]. The interference occurs over the entire frequency range, with predominant effects at low frequency. The typical effect is a low frequency emphasis followed by a notch. To illustrate the effect in Figure 3, the speaker-boundary interference is averaged over listening positions [14] with the speaker located 1.22 m from one, two and three walls surrounding the loudspeaker. It can be seen that as each wall is added, the low frequency response increases by 6 dB and the notch at roughly 100 Hz deepens. This demonstrates the fact that each time the

solid angle into which a speaker can radiate is reduced by a factor of 2 (by adding a boundary surface, for example), we increase the sound pressure at low frequency by a factor of 2 (6 dB). Thus by placing a loudspeaker on the floor near a corner (three boundaries) we reduce the full solid angle of 4π steradians to $\pi/2$ and increase the total low frequency gain by roughly 18 dB! Figure 3 also illustrates how the notch increases in frequency as the speaker spacing is decreased to 0.31 m from each wall. By moving the loudspeakers and listeners to optimum positions in the room, the coloration produced by the room transfer function can be greatly reduced.

[1.3] Optimization

Sections [1.1] and [1.2] describe the complex interaction among the listening room, and the locations of the listener and loudspeakers. There are already guidelines and procedures available that address these issues [15,16,17]. Modal frequencies for cuboid rooms and their pressure distribution are well known [18]. These can be used to aid listener and loudspeaker placement and room design. Positioning loudspeakers different distances from the nearest floor and walls can reduce the speaker-boundary interference. Simple computer programs that simulate the effect of loudspeaker and listener placement are also available. While these procedures are useful, they can never properly account for the complex sound field, which occurs in real listening rooms. Optimum placement of the loudspeakers and listener must be made taking all of these factors into consideration simultaneously, since the speaker-boundary interference and modal excitation are independent effects. That is, listener/loudspeaker locations that minimize the speaker-boundary interference do not necessarily lead to minimum modal excitation, and vice versa. To the author's knowledge, such an algorithm has not been published. For this reason, an iterative image method was developed to optimize the placement of listener and loudspeakers by monitoring the combined standard deviation of the speaker-boundary interference and modal response spectra.

In recent years, there has been a great increase in knowledge concerning computer models to predict the acoustics of enclosed spaces [19]. In addition, there has been a great increase in the computing power available on personal computers. This enables algorithms, which determine the best listener and loudspeaker position within a space, to use complex calculation procedures based on more accurate predictions of the sound field received by the listener.

These have many advantages over the simpler placement theories. For example, they take into account many more reflections from all surfaces in the room. This enables the examination of the subtle effects of many surfaces working in unison. Furthermore, by combining the room prediction models with optimization routines, the computer can determine the best positions for the loudspeakers and listener by processing the laborious trial and error optimization rather than the user.

In this paper, a program is described which combines an image source model to calculate the room transfer function with a simplex routine to carry out the optimization process. An appropriate cost function to characterize the quality of the spectra received by the listener has been developed. This parameter is based on the extensive subjective evaluations and listening tests of Toole and his colleagues [20,21,22,23]. They have confirmed that speakers which have flat on-axis frequency responses are preferred in standardized listening tests. In addition, similarly good off-axis response is also required, since the listener is hearing the combination of direct and reflected sound from the room's boundary surfaces. At low frequencies speakers are essentially omnidirectional. Since most rooms are not anechoic at low frequencies, we have chosen the flatness of the perceived spectra as a way to evaluate listener and loudspeaker placement and room dimensions. The cost parameter penalizes positions with uneven spectral responses. The optimization program we describe concentrates on lower frequencies (<300 Hz), where the individual room modes and the primary speaker/boundary interference are most influential and problematic. The goal of the program is to enable relative non-experts to determine the best positions for listener, loudspeakers, and acoustical surface treatment in a cuboid room.

[2] THEORY

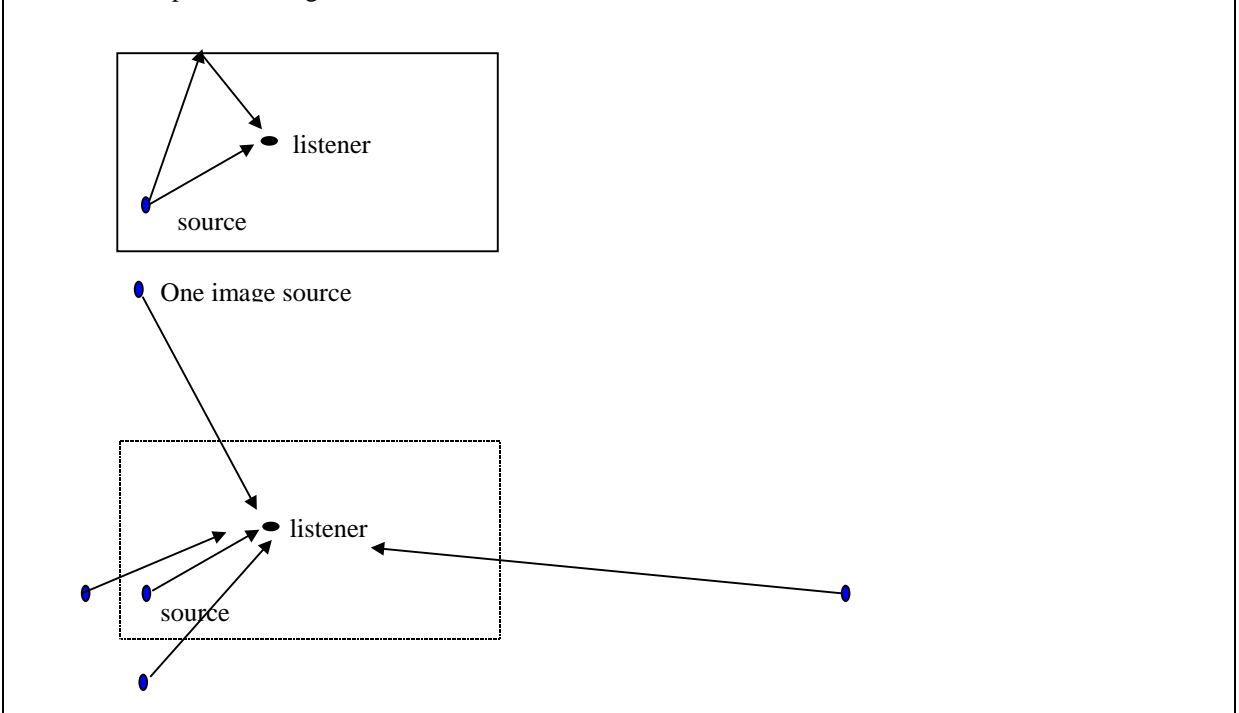
[2.1] Prediction of room responses

There has been considerable research carried out in recent decades concerning the prediction of room acoustic responses using geometric models. Reference [19] details some of the model types available. The fastest, and probably simplest prediction model for a cuboid room is based on the image source method. The image solution of a rectangular enclosure rapidly approaches an exact solution of the wave equation as the walls of the room become rigid. The image model provides a good time domain transient description of the room response and is appropriate for listener/loudspeaker predictions because of its speed. While the small rooms considered here do not require extensive time to determine their impulse response, the program described will use an iterative optimization process which will necessitate *many hundreds* of impulse response calculations. The image method includes only those images contributing to the impulse response and provides appropriate weighting of the modal frequencies. On the other hand, the alternate normal-mode solution of the enclosure [6,24] would require calculation of all modes within the frequency range of interest, plus corrections for those outside this range. Allen has derived the exact relationship between the normal-mode and the image solutions for

a loss-less room [25]. Since the impulse response can be equivalently viewed as a sum of normal modes, there must be repetitive patterns in the impulse response that form early in the response after a transient period. This has been demonstrated by Kovitz [5], using the algorithm of Burrus and Parks. Kovitz [5] has shown that the full impulse response can be described by an IIR filter that is derived from the early time FIR impulse response. The equivalence between the impulse response and modal frequency summation method will be demonstrated later in the paper using the program.

The image source model algorithm constructs all possible image sources for the listener and loudspeaker pairs. Figure 4 shows a two dimensional example, with only the first order reflections shown. At the top the direct sound and a side wall reflection are shown. In the lower illustration, each first order reflection can be modeled by replacing the surface with an image source at the appropriate position. This is further illustrated in Figure 5 showing a real source at coordinates (3,3,3) and its virtual image sources, which occur at an equivalent perpendicular distance on the opposite side of each boundary. The room is 10 units in height.

Figure 4. The effects of the direct sound and reflections can be modeled by the equivalent system of the original source, and all possible image sources.



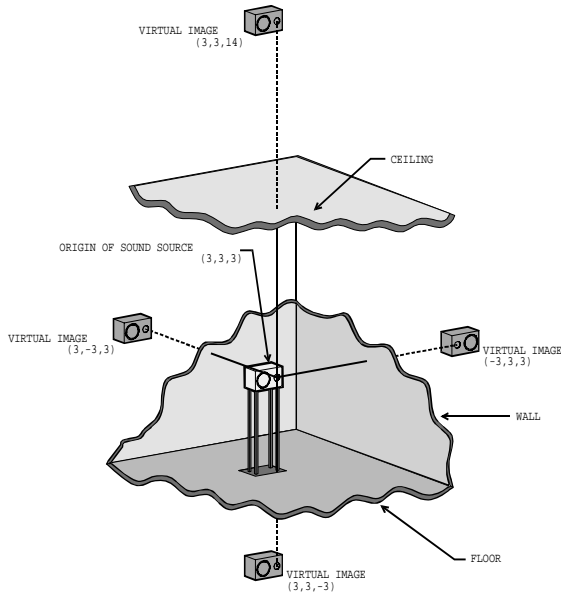


Figure 5. Real and virtual images construct

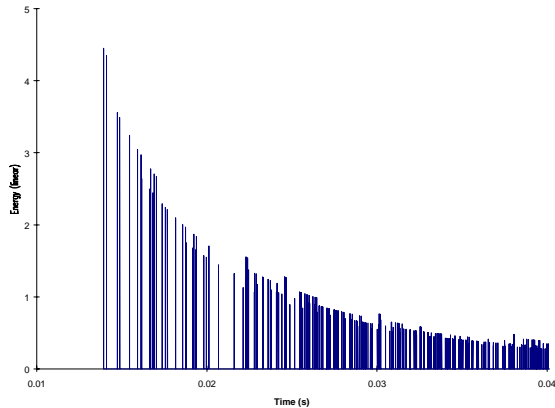


Figure 6. Typical energy impulse response generated by image source model

The sound at the listener is calculated by propagating the image source wave to the receiver, using the standard equation of a point source, and attenuating the wave according to the absorption coefficient of the boundary it 'reflects' from. Obviously, the power of computing enables many orders of reflections to be accounted for, not just the first order indicated in Figure 4 and Figure 5. The prediction of the pressure received by the listener then reduces to a set of infinite series [19] which can be encoded and evaluated relatively easily. The image source model as described is restricted to cuboid rooms. The model is also limited in that it does not account for any phase change on reflection. This is a common trait among geometric computer models and is also an

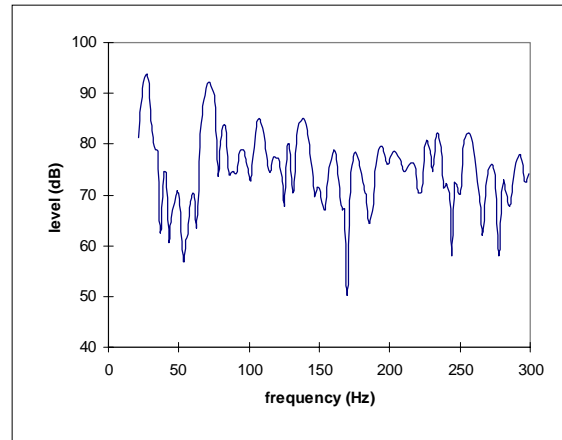


Figure 7 Example long-term spectrum

implicit assumption in other procedures for calculating the position of loudspeaker and listeners. The lack of modeling of the phase change has arisen because it is not a simple process to treat the wall as an extended absorber. This then means that the model is most accurate for rooms with relatively hard surfaces, where the phase change effects are at their smallest. No account of diffusion caused by surface scattering is made. Fortunately, this is less crucial at the low frequencies being considered here.

Table 1. Modal Frequencies for a 3m x 3m x 3m room

n_x	n_y	n_z	f, Hz
0	0	0	0
0	0	1	56.67
0	1	1	80.14
1	1	1	98.15
2	0	0	113.33
2	1	0	126.71
2	1	1	138.8
0	2	2	160.28
2	1	2	170
3	0	1	179.2
3	1	0	179.2
3	1	1	187.94
2	2	2	196.3
3	2	0	204.32
3	2	1	212.03
4	0	0	226.67
4	1	0	233.64
4	1	1	240.42
3	3	1	247
4	2	0	253.42
4	2	1	259.68
3	3	2	265.79
4	2	2	277.61
5	0	0	283.33
5	1	0	288.94
5	1	1	294.45

The image source model produces an impulse response for the room, where the direct and reflected sounds are clearly distinguishable. An example is shown in Figure 6. A Fourier transform of this gives the spectrum received by a listener if the sound source was producing a continuous tone. This long-term spectrum is shown in Figure 7. The long-term spectrum is similar to the modal response of the room (the modal response calculates

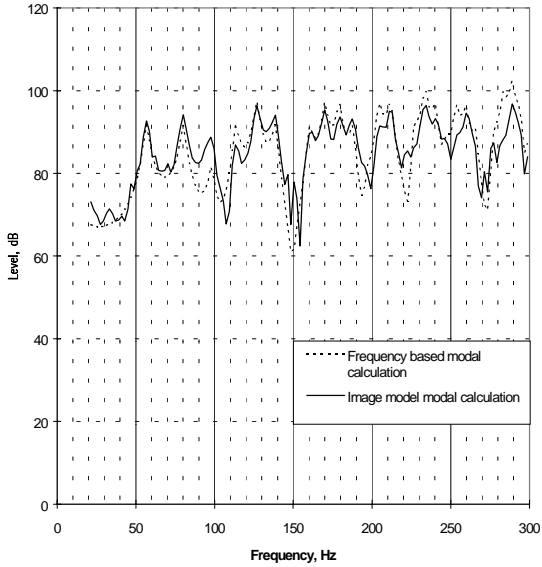


Figure 8. Comparison of image source calculation (solid line) and modal response (dotted line).

the sound field at the listener by adding together the effects of individual modes in the frequency domain). In fact, the responses are equivalent, provided that the image source model takes into account an infinite number of sources and the modal calculation includes an infinite number of possible modes.

As an example we examine a 3 m x 3 m x 3 m room. The modes below 300 Hz calculated with an exact frequency overlap algorithm, are shown in Table 1. Figure 8 compares this frequency based calculation with the image model using 30 orders and a wall absorption coefficient of 0.12. The time and frequency based calculations give very similar answers. The discrepancies that do occur could be due to taking insufficient reflection orders, the fact that the impulse response is windowed with a cosine squared term for transforming and that the frequency based calculation doesn't consider any modes above 300 Hz.

Music is naturally, however, a transient signal, and the ear can distinguish the effects of early arriving reflections. Furthermore, with many audio signals such as music, only the first few reflections are heard before the next musical note arrives and masks the later reflections. Consequently, it is also necessary to investigate the response received by the listener for just the first few reflections - this will be referred to as the short-term spectrum. The short-term spectrum is a Fourier transform of the first 64ms of the impulse response after the direct sound has arrived. The impulse response is windowed using a quarter period

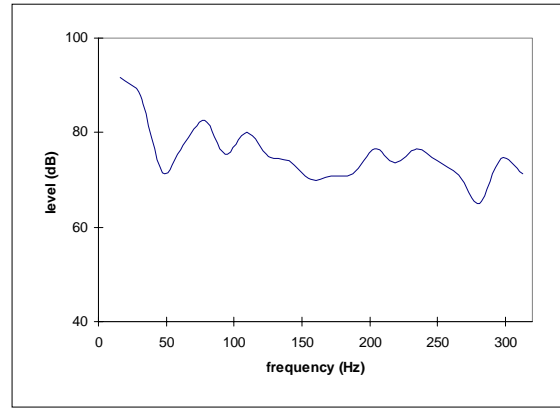


Figure 9. Example short-term spectrum

cosine squared window. The window starts at 32 ms after the direct sound and gradually weights the impulse response to zero at 64 ms. These times are motivated by the integration time of the ear, which is typically taken to be between 35 and 50ms. The windowing is necessary to prevent the sudden cut-off of the impulse response producing spurious effects in the spectrum. An example of the short-term spectrum is shown in Figure 9. The two spectra shown in Figure 7 and Figure 9 are taken to represent the

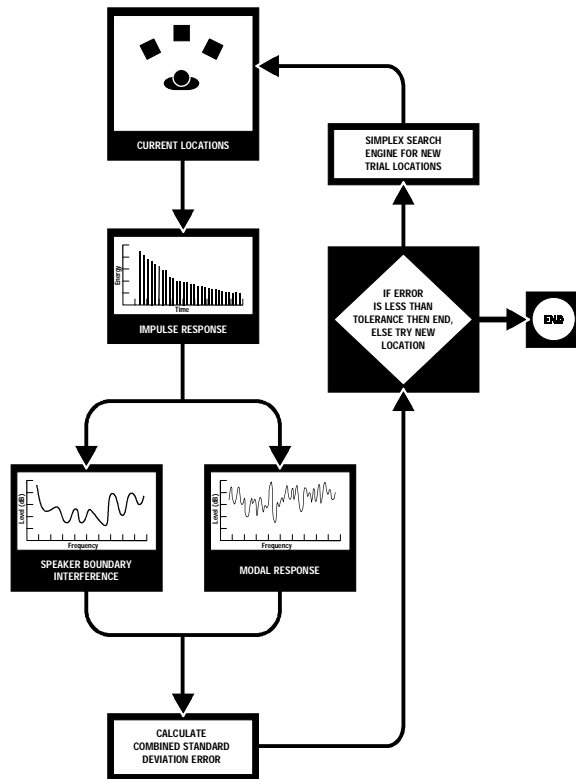


Figure 10. Iterative cycle to determine optimum listener/loudspeaker locations

audible characteristics of the propagation from source to receiver, and it is the characteristics of the low-frequency spectra that are optimized to find the best locations for listener and loudspeakers within the room.

[3] OPTIMIZING PROCEDURE

The computer optimizing process finds the best position for the listener and loudspeakers by an iterative process illustrated in Figure 10. The short and long-term spectra are predicted by the image source method. From these spectra, a cost parameter (described below) is derived which characterizes the quality of the sound produced. Then new listener and loudspeaker positions are repeatedly tried until a minimum in the cost parameter is found indicating that the best positions are found. The movement of the listener and loudspeaker positions is carried out using a search engine following a standard minimization procedure [26].

[3.1] Cost parameter

$$\sigma_i = \sqrt{\frac{\sum_{nf=1}^N (L_{p,nf} - \bar{L}_p)^2}{N-1}} \quad (2)$$

It is assumed that the best position within the room is represented by the position where the short-term and long-term spectra have the flattest frequency response. This then motivates the production of a cost parameter that measures how much the true frequency spectrum deviates from a flat response. Previous work by the authors [27,28] has shown that a standard deviation function is a good measure for characterizing how even the pressure scattered from diffusers are. Consequently, a standard deviation was used here also. The cost parameter, σ_i , for one of the spectra is given in Eq. (2). The sum is carried out over N discrete frequencies - typically ranging from 20 to 300 Hz; $L_{p,nf}$ is the sound pressure level at that particular frequency bin, nf; and \bar{L}_p represents the average sound pressure level over the frequency range of interest. In reality some smoothing over a few adjacent frequency bins is carried out, typically over 1-3 bins. This is done to simulate the effect of spatial averaging which would naturally happen in actual listening rooms. Otherwise, there is a risk that the optimization routine will find a solution which is overly sensitive to the exact solution position.

To form the single cost parameter required, the cost parameters for each of the two spectra are added. More or less importance can be given to the short-term (or long-term) spectrum by the use of a weighting parameter. The total cost parameter, σ , is:

$$\sigma = w\sigma_s + (1-w)\sigma_l \quad (3)$$

Where σ_s and σ_l are the cost parameters for the short-term and long-term spectra respectively, and w is a weighting parameter set between 0 and 1. For the examples given here, w is given a value of 0.5. Figure 11 and Figure 12 show an example short-term speaker-boundary interference response and long-term modal response for an intermediate (non-

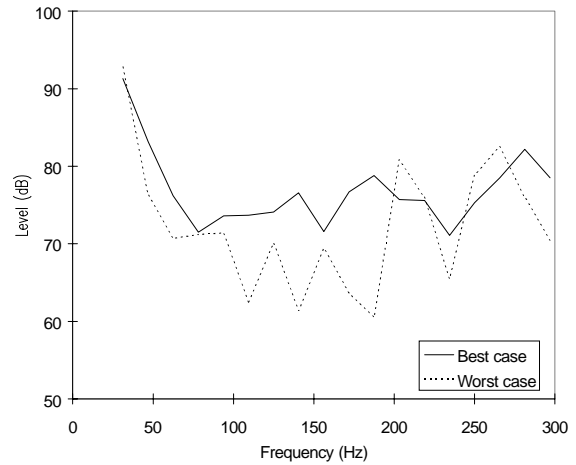


Figure 11 Short-term spectrum. The standard deviations are 4.67 and 8.13 dB for the best solution and worst case respectively.

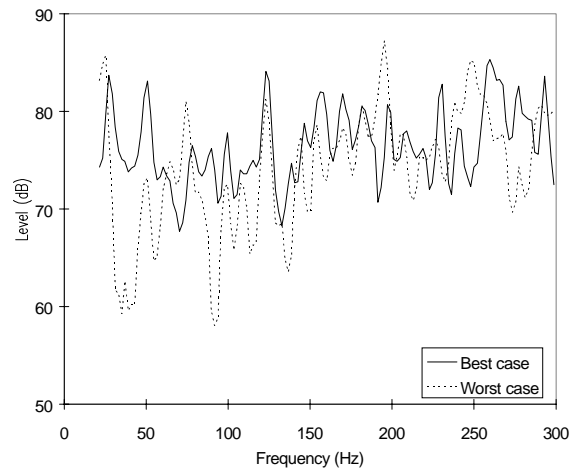


Figure 12 Long-term spectrum. The standard deviations are 3.81 and 6.28 dB for the best solution and worst case, respectively.

optimized) arrangement of listener and loudspeakers of a stereo pair configuration. The error parameters given in the captions indicate the ability of the standard deviation to measure the quality of the spectra.

[3.2] The optimization procedure

The optimization procedure used is a standard simplex routine. The simplex has a series of nodes which are different points in the error space (representing different listener and loudspeaker positions). These nodes move around the space until either (i) the difference in the error parameter between the worst and best nodes is less than some tolerance variable (e.g. 10^{-6}) or (ii) a maximum number of iterations is exceeded (set at 500). Most of the time the program stops because of (i). The simplex routine has the advantage of being a robust system, which does not require first derivatives for calculations. Unfortunately, derivatives of the spectra with respect to the listener and loudspeaker positions are not immediately available from a numerical method such as the image source model. The penalty for using a function-only optimization routine is that the number of iterations used to find a solution is longer and so the procedure takes longer.

The user of the program inputs various parameters to define the optimization procedure. Table 2 lists the parameters which are under the users control. These can be input via standard Windows 95 dialog boxes

Table 2. Parameters presently under user control
Room dimensions (width, length, height)
Rectangular volume defining the x, y and z limits for the listener position
Rectangular volumes defining x, y and z limits for the independent loudspeaker(s) position(s)
Number of independent and dependent loudspeakers
Displacement and symmetry constraints relating the dependent loudspeakers to the independent loudspeakers e.g. simple mirror image symmetry or x, y, z displacement.
Stereo constraints
Minimum stereo pair separation
The weighting parameter, w, that determine the balance between the errors of the short and long-term spectra
Frequency range of interest (default setting 20 - 300 Hz)
Number of solutions required

making the program user friendly. The optimization

routines cannot be used completely without some interpretation of the results from the user. For example, there is a tendency for the routines to want to place the source and receivers on the room boundaries as this will minimize the interference effects. Obviously, it is not always possible to build the loudspeakers into the walls and so this may not be a useful solution. Furthermore, there is a risk that the optimization routines will place the loudspeakers close enough to the surfaces to reduce the interference within the frequency band selected (say 20-300 Hz), ignoring the fact that there may be audible interference effects just outside this frequency range. Also the best solution found for the bass response will not always be optimized for stereo imaging, physical listener and loudspeaker placement and other factors.

Therefore, the user is given the opportunity to limit the search range for the listener and loudspeakers. The limits of the listener and independent loudspeakers are defined in terms of rectangular volumes, determined by the minimum and maximum coordinates. The program allows the user to find the most appropriate solution within these imposed limits. The listener and loudspeakers can vary within the rectangular volume limits for an optimum practical solution. These limit constraints are applied to the simplex routine by brute force. For example, if the simplex routine asks for a prediction for a point outside the listener's rectangle, the program forces the co-ordinates of the point onto the nearest edge of the listener's constraint boundaries.

The loudspeakers can all be treated as independently varying. However, in most listening situations certain loudspeaker positions are determined by others. For example, in a simple stereo pair, both loudspeakers are related by mirror symmetry about the plane passing through the center of the room. As the number of loudspeakers increase in the 5.1 home theater and multichannel music surround formats, we can make the program more efficient by taking advantage of positional relationships between the speakers. It is usual to search the room and find several minima. The use of geometric constraints increases the chance of finding the global minimum.

To accomplish this, a system of independent and dependent loudspeakers is adopted with each dependent loudspeaker position being determined by an independent loudspeaker. For the stereo pair example, the left front loudspeaker can be considered the independent loudspeaker and the right front loudspeaker can be defined as the dependent

loudspeaker with its position determined by a simple mirror image of the independent loudspeaker's position about the center line of the room. The program allows mirror symmetry operations with respect to the x, y, z planes passing through the center of the room or with respect to the x, y, z planes passing through the listener's position. Mirror symmetry about planes passing through the variable listener position allows constraints to be imposed on the rear surround speakers. For example, in a 5.1 multichannel music format with 5 matching speakers equi-spaced from the listener, we can set up constraint relationships with 1 independent speaker (left front) and 4 dependent speakers (center, right front, left surround and right surround).

To include the lessons we have learned about good stereo imaging, the program make use of a stereo constraint. The stereo constraint refers to the normal angular constraints between a stereo pair and the listener, which are applied to give a good stereo image. In the program this constraint is applied by

Table 3. Parameters presently not under user control
Minimum stereo pair separation (0.6m)
Absorption coefficient of the surfaces (0.12)
Maximum order of reflections traced in image source model (15)
Number of frequency bins to smooth short-term and long-term spectra over (1 and 3 respectively)

ensuring that the ratio of the distances between the listener to the center point of the speaker plane, and the distance between the stereo pair is within a

specified range. The default is between 0.88 (equilateral triangle) and 1.33. Applying such a non-linear constraint to the simplex routine can only be achieved by brute force. If a position, which violates the constraint, is required, the simplex routine moves both the listener and loudspeaker positions to the nearest points in the room, which comply with the constraint. The simplex routine can accommodate such abuses, but there is a risk that this will slow the procedures finding of the optimum position. When optimizing independent loudspeakers, like subwoofers for example, this constraint need not be applied. Table 3 lists the parameters that at the moment are not controllable by the user.

[4] RESULTS

[4.1] Stereo pair

The program was required to find the best solution for a stereo pair. The geometry and solution for the optimization are shown in Table 4. Figure 11 and Figure 12 showed example intermediate spectra for this configuration. It is apparent how poor the spectral responses can be, and also how they can be improved by the use a positioning procedure as outlined here. It is often found that the improvement for the short-term spectrum is more dramatic than for the long-term spectrum. The complexity and number reflections in the long-term spectrum means that there is less of a chance that there are positions in the room where large improvements in the standard deviation can be found. Even with this complexity, however, useful improvements are found by the optimization routines for the long-term spectrum. The short-term spectrum is much more sensitive to the positions of

Table 4. Geometry and solution for a stereo pair configuration

	X (m)	Y (m)	Z (m)
Room dimensions	7	4.5	2.8
Listener limits	2.0 - 6.0	2.25 (fixed)	1.14 (fixed)
Independent loudspeaker 1 (front left)	0.5 - 3	0.5 - 1.34	0.35 - 0.8
Dependent loudspeaker 1 (front right)	Mirror of left front at room center Y = 2.25		
Stereo constraint	0.88 - 1.33		
Best error parameter	2.24		
Worst error parameter	3.84		
Positions of listener and loudspeakers for best solution			
Listener position	3.05	2.25	1.14
Independent (left front)	1.28	1.34	0.69
Dependent (right front)	1.28	3.16	0.69

Table 5. Geometry and solution for a stereo pair configuration with two woofers per loudspeaker

	X (m)	Y (m)	Z (m)
Room dimensions	5.791	4.267	3.048
Listener limits	2.591 - 3.962	2.134 (fixed)	1.14 (fixed)
Independent loudspeaker 1 limits (Lower left front)	0.61 - 1.829	0.457 - 1.067	0.381 (fixed)
Dependent loudspeaker 1 (Upper left front)	Constrained to lower left front	Constrained to lower left front	Displaced 0.343
Dependent loudspeaker 2 (Lower right front)	Mirror of lower left front at room center Y = 2.134		
Dependent loudspeaker 3 (Upper right front)	Mirror of lower left front at room center and displaced in Z by 0.343		
Stereo Constraint	0.88 - 1.33		
Best error parameter	2.1774		
Worst error parameter	4.0839		
Positions of listener and loudspeakers for the best solution			
Listener position	3.149	2.134	1.14
Independent lower left front	0.947	0.912	0.381
Dependent upper left front	0.947	0.912	0.724
Dependent lower right front	0.947	3.355	0.381
Dependent upper right front	0.947	3.355	0.724

listener and loudspeaker.

4.2] Stereo pair with two woofers per loudspeaker

We next determine the optimum arrangement of a stereo pair with two woofers vertically displaced by 0.343 m in each loudspeaker. The geometry and best solution are shown in Table 5. The optimization assumed constant Z loudspeaker floor mounting. The speaker-boundary interference response is shown in Figure 13 and the modal response is shown in Figure

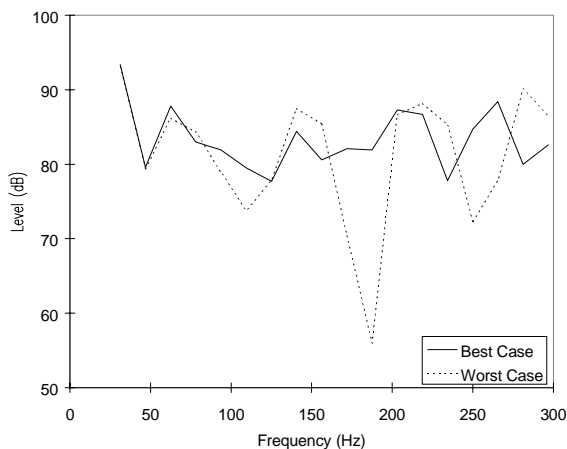


Figure 13. Comparison of the speaker-boundary interference response for two listener/loudspeaker arrangements of a stereo pair with two woofers per loudspeaker

14. The program makes use of mirror symmetry and displacement relationships to reduce the number of independent speakers that have to be optimized. In this case even though there are four woofers, we actually only need to optimize one, which we will call the lower left front. The upper left front is constrained to follow the lower left front coordinates, while being displaced vertically in z by 0.343 m. The lower and upper front right woofers are also dependent on the position of the lower left, because of the mirror symmetry of the stereo pair about the center plane of

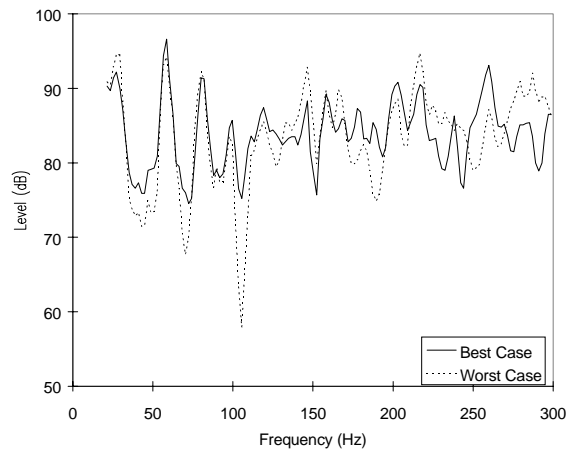


Figure 14. Comparison of the modal response for two listener/loudspeaker arrangements of a stereo pair with two woofers per loudspeaker

Table 6. Geometry and solution for a THX surround sound configuration of L/C/R with dipole surrounds.

	X (m)	Y (m)	Z (m)
Room dimensions	5.791	4.267	3.048
Listener limits	2.286 - 3.962	2.134 (fixed)	1.14 (fixed)
Independent loudspeaker 1 limits (left front)	0.61 - 1.829	0.457 - 1.067	0.305 - 0.914
Independent loudspeaker 2 limits (left surround)	Constrained to listener	0.076 - 0.152	2.134 - 2.743
Dependent loudspeaker 1 (right front)	Mirror of left front at room center Y = 2.134		
Dependent loudspeaker 2 (center)	Constrained to left front/listener distance		
Dependent loudspeaker 3 (right surround)	Mirror of left surround at room center Y = 2.134		
Stereo Constraint	0.88 - 1.33		
Best error parameter	1.9476		
Worst error parameter	3.7991		
Positions of listener and loudspeakers for best solution			
Listener position	3.961	2.134	1.14
Independent left front	1.438	0.723	0.461
Dependent center	1.071	2.134	0.461
Dependent right front	1.438	3.544	0.461
Dependent left dipole surround	3.961	0.123	2.301
Dependent right dipole surround	3.961	4.144	2.301

the room located at Y = 2.134 m. Thus, in this optimization there is one independent loudspeaker, the lower left front, and three dependent loudspeakers, the upper left front, the lower right front and the upper right front. Of particular note is the avoidance of the roughly 25 dB notch at about 180 Hz in the speaker-boundary interference of Figure 13. The standard deviations for the best and worst solutions were 2.17 and 4.08 dB.

[4.3] THX Home Theater

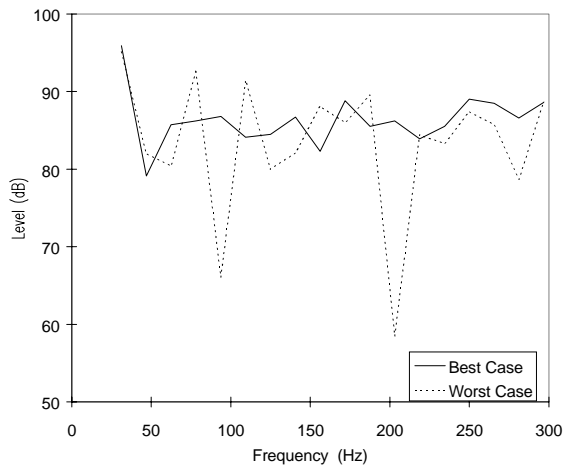


Figure 15. Comparison between two listener/loudspeaker arrangements of a THX dipole surround configuration

The emerging 5 channel digital format, with low frequency effects channel, commonly called 5.1, offers an exciting new aural experience. The program can be used to optimize the placement of any number of loudspeakers, so this surround configuration will provide a good example. We can illustrate this by examining the THX home theater surround configuration of a left/center/right (L/C/R) group of front speakers and a pair of dipoles used for the surround channels. We introduce a new type of constraint in this optimization. The center channel

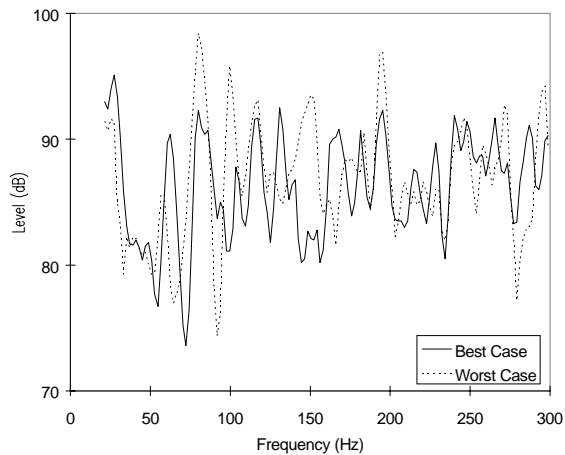


Figure 16. Comparison between the modal response for two listener/loudspeaker arrangements of a THX dipole configuration

Table 7. Geometry and solution for a 5.1 multichannel configuration

	X (m)	Y (m)	Z (m)
Room dimensions	5.791	4.267	3.048
Listener limits	2.591 - 3.2	2.134 (fixed)	1.14 (fixed)
Independent loudspeaker 1 (left front)	0.914 - 1.829	0.457 - 1.067	0.305 - 0.914
Dependent loudspeaker 1 (right front)	Mirrors left front at room center Y = 2.134		
Dependent loudspeaker 2 (center)	Distance to listener constrained to equal left front-listener distance and constrained to lie on the Y = 2.134 line.		
Dependent loudspeaker 3 (left rear)	Mirrors left front across X about the listener		
Dependent loudspeaker 4 (right rear)	Mirrors left front across X and Y about the listener		
Best error parameter	2.0399		
Worst error parameter	4.0633		
Positions of listener and loudspeakers for best solution			
Listener position	3.099	2.134	1.14
Independent loudspeaker 1 (left front)	1.05	0.625	0.361
Dependent loudspeaker 1 (right front)	1.05	3.642	0.361
Dependent loudspeaker 2 (center)	0.554	2.134	0.361
Dependent loudspeaker 3 (left rear)	5.148	0.625	0.361
Dependent loudspeaker 4 (right rear)	5.148	3.642	0.361

constraint assures that the center loudspeaker remains on the centerline of the room at a loudspeaker-listener distance equal to that of the left front-listener distance. In this way, all of the arrival times from the front speakers are maintained equal. Of course, if this is not desired, the constraint can simply not be applied. In this optimization the front loudspeakers are allowed to range in X, Y and also Z. The Z search can be used to determine an appropriate elevation above the floor. In some instances this will be useful, while in others the location of the midrange and tweeter may take precedence for good imaging. The dipoles are omnidirectional below 300 Hz, so we will consider them as a point source, for the optimization. The geometry and solution for this configuration are listed in Table 6.

Another new constraint relation is added to this optimization to maintain that the dipole surrounds follow the listener's X coordinate, so that the listener will remain in the null. Thus, as the listener moves forward and backward during the optimization the X coordinate of the dipoles follows this value. The Y coordinate, or spacing from the side walls is optimized over a limited range, and the Z coordinate can assume any value within it range limits. A comparison of the speaker-boundary interference response and modal response of the best and worst solutions found for the THX configuration in a 5.791 m x 4.267 m x 3.048 m room are shown in Figure 15

and Figure 16. The standard deviations for the best and worst solutions were 1.95 and 3.80 dB.

[4.4] Multichannel music

In addition to the use of 5.1 in home theater, it is also being proposed as a music-only or multichannel music format. In addition to the previous dipole surround format, another configuration using 5 matching loudspeakers is also being used. If the physical constraints of the room permit, all 5 loudspeakers would be equidistant from the listener.

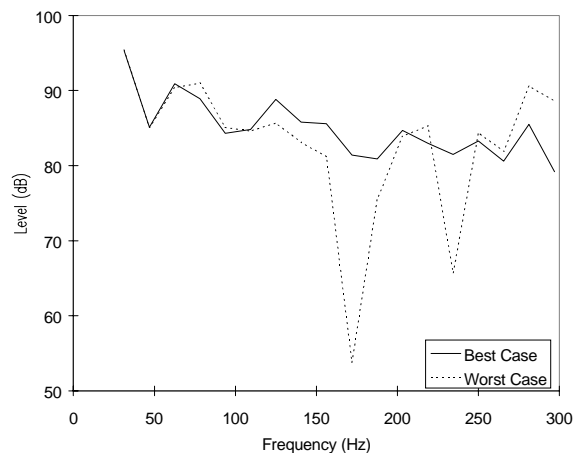


Figure 17. Comparison of the speaker boundary interference response for two listener/loudspeaker arrangements of 5 equidistant matching speakers

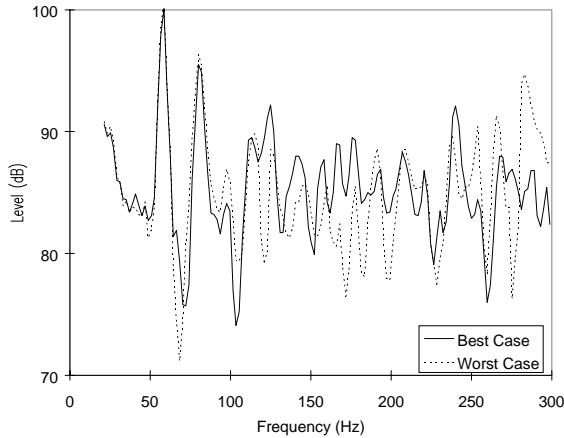


Figure 18. Comparison of the modal response for two listener/loudspeaker arrangements of 5 equidistant matching speakers

To develop the constraints needed for this optimization, we would make use of the previous center channel constraint as well as a new rear channel constraint. The rear loudspeakers can be constrained to the front by the use of mirror planes about the listener. This is a dynamic constraint that follows the listener. The geometry and solution for this configuration is given in Table 7.

A comparison of the speaker-boundary interference response and modal response of the best and worst solutions found for the multichannel music configuration in a 5.791 m x 4.267 m x 3.048 m room are shown in Figure 17 and Figure 18. The standard deviations for the best and worst solutions were 2.04 and 4.06 dB.

[4.5] Subwoofer

The use of sub-woofers is growing in popularity, especially with the surround sound formats. The program can provide optimization of sub-woofers via a separate optimization over the 20-80 Hz frequency range. Once the listening position is determined, you can optimize any number of sub-woofers. As an example, the geometry and solution for a single subwoofer in a 10 m x 6 m x 3 m room are listed in Table 8.

Figure 19 and Figure 20 show the results of an optimization using a single sub-woofer working in the range 20-80 Hz. The geometry for the optimization and solution are shown in Table 8. For the short-term spectrum the variation in the frequency response reduces from a range of about 30dB in the worst case to around 10 dB for the solution found. The optimized solution provides a somewhat less dramatic

Table 8. Geometry and solution example for a subwoofer

	X (m)	Y (m)	Z (m)
Room dimensions	10	6	3
Listener limits	5.5 (fixed)	3 (fixed)	1.2 (fixed)
Independent loudspeaker 1	5.6 - 9.9	0.1 - 2.9	0.1 - 2.9
Best error parameter	2.7051		
Worst error parameter	5.5535		
Positions of listener and loudspeakers for best solution			
Listener position	5.5	3	1.2
Loudspeaker 1 (Subwoofer)	7.398	0.231	1.227

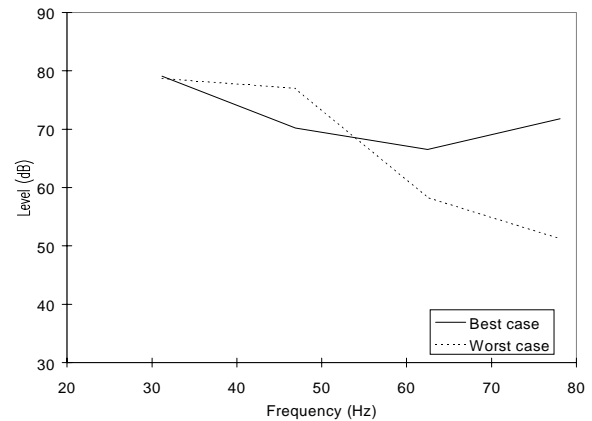


Figure 19. Comparison between the speaker-boundary interference response for two listener/loudspeaker positions of a sub-woofer

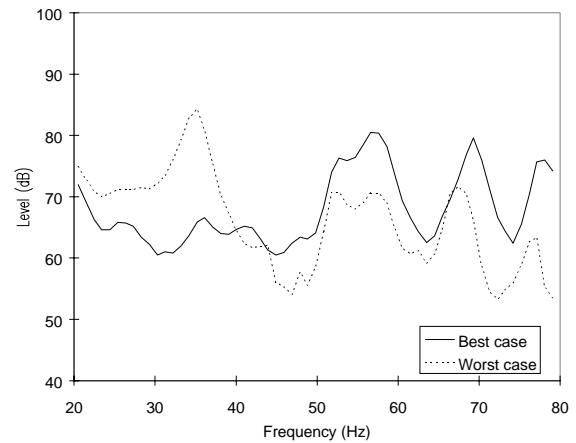


Figure 20. Comparison between the modal response for two listener/loudspeaker positions of a sub-woofer

improvement in the long term spectrum. The standard deviations for the best and worst solutions were 2.7 and 5.6 dB, respectively.

[5] CONCLUSIONS

A computer program has been developed that allows automated selection of positions for listeners and loudspeakers within listening rooms. The criterion for optimum listener and loudspeaker positions within the room is the minimum standard deviation of the combined short and long-term spectra. A cost parameter based on the standard deviation function was developed and used to monitor the quality of the short and long-term spectra. Predictions of the spectra are carried out using an image source model. The optimization is carried out using a standard simplex routine. Some examples have been presented. All cases demonstrate the ability of the program to find the best positions for listeners and loudspeakers within the room.

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[7] REFERENCES

- 1 P.L. Schuck, S. Olive, J. Ryan, F.E. Toole, S. Sally, M. Bonneville, E. Verreault, K. Momtahan, "Perception of Reproduced Sound in Rooms: Some Results from the Athena Project", pp. 49-73, Proceedings of the 12th International Conference, Audio Eng. Soc. (June 1993).
- 2 S.E. Olive, P. Schuck, S. Sally, M. Bonneville, "The Effects of Loudspeaker Placement on Listener Preference Ratings", J. Audio Eng. Soc., **42**, pp. 651-669 (September 1994)
- 3 K. O. Ballagh, "Optimum Loudspeaker Placement Near Reflecting Planes", J. Audio Eng. Soc., **31**, pp. 931-935 (December 1983); Letters to the Editor, J. Audio Eng. Soc., **31**, p. 677 (September 1984).
- 4 A.R. Groh, "High-Fidelity Sound System Equalization by Analysis of Standing Waves", J. Audio Eng. Soc., **22**, pp. 795-799 (December 1974).
- 5 P. Kovitz, "Extensions to the Image Method Model of Sound Propagation in a Room", Pennsylvania State University Thesis (December 1994).
- 6 Morse, P.M. and Ingard, K.U., **Theoretical Acoustics**, McGraw-Hill, 555-572 (1968).
- 7 M.M. Louden, "Dimension-Ratios of Rectangular Rooms with Good Distribution of Eigentones", *Acoustica*, **24**, pp. 101-104 (1971).
- 8 O.J. Bonello, "A New Criterion for the Distribution of Normal Room Modes", J. Audio Eng. Soc., **19**, pp. 597-606 (September 1981).
- 9 R.F. Allison, "The Influence of Room Boundaries on Loudspeaker Power Output", J. Audio Eng. Soc., **22**, pp. 314-319 (June 1974).
- 10 R. F. Allison, "The Sound Field in Home Listening Rooms, II", J. Audio Eng. Soc., **24**, pp. 14-19 (January/February 1976).
- 11 R. V. Waterhouse, "Output of a Sound Source in a Reverberant Sound Field", J. Acoust. Soc. Am., **27**, pp. 247-258, (March 1958).
- 12 R.V. Waterhouse, "Output of a Sound Source in a Reverberation Chamber and other Reflecting Environments", J. Acoust. Soc. Am., **30** (March 1965).
- 13 R.V. Waterhouse and R.K. Cook, "Interference Patterns in Reverberant Sound Fields II", J. Acoust. Soc. Am., **37**, pp. 424-428 (March 1965).
- 14 P. D'Antonio and J.H. Konnert, "The RFZ/RPG Approach to Control Room Monitoring", 76th AES Convention, Preprint No. 2157, New York (October 1984).
- 15 F.E. Toole, "Subjective Evaluation", in **Loudspeaker and Headphone Handbook**, 2nd Edition, Chapter 11, Borwick, J. (Ed), Focal Press (Oxford 1994).
- 16 AES Recommended Practice for Professional Audio- J. Audio Eng. Soc., 44, No. 5, pp. 383-401 (May 1996).
- 17 P. D'Antonio, C. Bilello and D. Davis, "Optimizing Home Listening Rooms", 85th AES Los Angeles Convention, Preprint 2735 (November 1988).
- 18 Everest, F.A., **The Master Handbook of Acoustics**, 3rd Edition, Tab Books.
- 19 Stephenson, U., "Comparison of the mirror image source method and the sound particle simulation method", *Applied Acoustics*, **29**, 35-72 (1990).
- 20 F.E. Toole, "Loudspeaker Measurements and Their Relationship to Listener Preferences", J. Audio Eng. Soc. **34**, Pt. 1. PP 227-235 (April 1986); Pt. 2, pp. 323-348 (May 1986).
- 21 F.E. Toole and S.E. Olive, "Hearing is Believing vs. Believing is Hearing: Blind vs Sighted Listening Tests and Other Interesting Things", 97th Convention, Audio Eng. Soc. Preprint No. 3894 (November 1994).
- 22 S.E. Olive, "A Method for Training of Listeners and Selecting Program Material for Listening Tests", 97th Convention, Audio Eng. Soc., Preprint No. 3893 (November 1994).
- 23 F.E. Toole and S.E. Olive, "The Modification of Timbre by Resonances: Perception and Measurement", J. Audio Eng. Soc., **36**, pp. 122-142 (March 1988).
- 24 Y.W. Lam and D.C. Hodgson, "The Prediction of the Sound Field Due to an Arbitrary Vibrating Body in a Rectangular Enclosure", J. Acoust. Soc. Am., **88** (4) , pp. 1993-2000 (October 1990).
- 25 J.B. Allen and D.A. Berkley, "Image Method for efficiently Simulating Small-room Acoustics", J. Acoust. Soc. Am., **65**(4), 943-950 (April 1979).
- 26 W.H.Press, B.P.Flannery, S.A. Teukolsky and W.T.Vetterling, **Numerical Recipes, The Art of Scientific Computing**, Second Edition, Cambridge University Press (1992).
- 27 Cox, T.J., "Optimization of Profiled Diffusers", J. Acoust. Soc. Am., **97**, 2928-2936 (1995).
- 28 Cox, T.J., "Designing Curved Diffusers for Performance Spaces", J. Audio. Eng. Soc., **44**, 354-364 (1996).