OVERHEAD VERSUS LATERAL LOUDSPEAKER SYSTEM DESIGNS - CONSIDERATIONS FOR SPEECH INTELLIGIBILITY

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1 INTRODUCTION

Much competent sound system design relies heavily on calculations based on the %ALCONS equation. This equation considers the level of first arrival sound only (direct sound), and its relationships with the levels of the reverberant field and background noise. This can overlook the sometimes non-linear nature of sound arrivals at the listener's ears, and the uneven arrival of reverberant sound. Designs whose calculations would appear to provide adequate intelligibility can produce results that are poor.

This paper examines the effects of the interactions between widely spaced loudspeakers, the room environment and some basic principles of human sound perception. Simple systems are studied, allowing examination of the resulting direct sound, early reflection and long term energy distributions that result. Overhead and lateral sound system configurations are considered and defined, and advantages / disadvantages of these two basic system types are examined. Examples of successful and unsuccessful applications of each type of system are reviewed and key design parameters are affirmed.

2 THE %ALCONS EQUATION - USE AND MISUSE

The %ALCONS equation is commonly used in various forms to predict speech intelligibility in noisy and reverberant spaces. Like many acoustical equations, it is based on the statistical distribution of reverberant sound energy. In other words, it assumes an average and smoothly decaying room response over an audience area, providing a predictable result for most if not all listeners.

This equation, and later developments of it, provides much useful insight into expected listener perception. It is especially helpful to the sound system designer in evaluating the limits of what can be accomplished using particular loudspeaker characteristics within an acoustic environment. Minimum requirements for noise and/or reverberation control are made evident.

But beware, %ALCONS does not tell the whole story, and can lead to complacency over other important design issues. This equation assumes that all of the important characteristics of the sound transmission process are constant or decaying smoothly with time. In some sound system / room configurations this is essentially true, and in these cases calculating %ALCONS may be sufficient to provide confidence in the speech intelligibility of the system. This is usually the case where all of the sound from individual loudspeakers arrives within the early time period, and where later sound decays smoothly.

However, in many instances either the loudspeaker configuration, or strong room reflections deliver sound to the listener in packets which are relatively high in level. These can arrive at times that impair speech perception. Failure of the designer to account for this can ruin a sound system design.

In some applications, problems arise only over a limited part of the listener area. In the concourse of a railway station, this may be acceptable, since listeners can and do move around the space. However, unhappy audience members stuck in poor seats can result in complaints that displease the management, even if the designer has warned them in advance.

In summary, after the fundamental %ALCONS calculation, also examine the other interactions that produce strong packets of sound energy and therefore violate the suppositions made when using the equation. This paper examines some of the causes and effects that must be considered.

3 SOME SOUND ENERGY DEFINITIONS

To aid with the following discussion, it will be useful to define some terminology describing the time of arrival of sound energy. 35 ms is the accepted norm defining the end of the early sound period and will be used as the early sound interval within this paper. This relates to speech systems rather than systems primarily for music reinforcement. A shorter time interval of 25 ms is the author's preference, arising from listening tests using slightly damaged 50 year old hearing

- First Arrival — the first sound arriving from the nearest
- Early Sound — the sound arriving within 35 ms of the first arrival
- Late Sound — the sound arriving after the end of the 35 ms early sound period
- Reverberant Sound — the smoothly decaying sound due to multiple reflections

4 OVERHEAD OR LATERAL (HORIZONTAL) SOUND SYSTEM?

For the purposes of this paper an *overhead system* is defined as a sound system where the interactions between the loudspeaker sound and the room walls are minimised. The majority of loudspeaker sound energy is directed onto the listener from overhead. Any sound hitting the walls creates a first reflection that is mostly or entirely directed downward such that it arrives at the listener close in time to the first arrival. Most commonly, an overhead system uses loudspeakers mounted from or on the ceiling, or high on the wall above the listener's heads and directed strongly downward.

A lateral or horizontal sound system is therefore a sound system in which the substantial part of the sound energy arrives from a reduced angle such that wall reflections can travel some distance (and therefore time) before arriving at the listener. Horizontal will be used to describe this sound system type to avoid confusion with lateral sound terminology in auditorium acoustics.

Both overhead and horizontal sound systems are successfully used in conventional applications.

5 SOUND REINFORCEMENT OR PUBLIC ADDRESS

Again, some definitions will help. Sound reinforcement usually arises from the presence of a "live" sound source in the room with the listener that is visually the centre of attention. For this reason, it is desirable to position the loudspeakers so that sound arrivals provide directional clues that match the visual location. The loudspeakers are almost always positioned toward the stage end of the space to direct the sound sideways or horizontally toward the listeners. Parts of the sound system in larger or banqueting rooms may be located overhead and directed downward, but acoustic tricks such as the "Haas effect" are often used to keep the "sound image" and visual image aligned. The relative arrival times of the various loudspeakers have to be optimised to maintain the illusion, often forcing all of the loudspeakers into a horizontal configuration.

Public address usually arises where the sound source location is not located in the space with the listener, or for replay of pre-recorded sound. In speech applications, the loudspeakers should be positioned to optimise the intelligibility of communication. The designer uses his/her skill, experience and imagination to guide the selection of loudspeaker configuration. This paper concentrates primarily on public address applications, though the principals also apply to sound reinforcement systems.

6 SOUND ENERGY VERSUS TIME - LISTENER PERCEPTION

Fig. 1 shows a widely accepted curve relating to the perception of speech super-imposed over the energy-time response of a troublesome installation. The curve was derived from the perception of echoes between two discrete sources, but has been applied to the degradation of speech intelligibility. It is generally agreed that relative to the "first arrival", this represents the upper boundary of sound level over time. Sound arriving within 35 ms after the first arrival can totally merge with, and add to the apparent level of the first arrival and is termed the "early sound". Sound which arrives after this time period, and which exceeds the curve boundary, can be audible as echoes and/or disturbance of speech intelligibility.

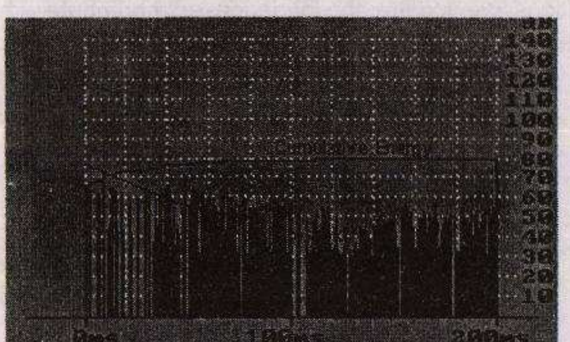

Fig 1 Approximate threshold curve for detection of disturbance

The vertical lines on the graph indicate the levels and arrival times of sound from a system implementation, measured at a listener position. Where these exceed the curve boundary, speech intelligibility is probably disturbed. Highlighting the need to design a system that prevents these trespasses, as well as meeting other key design criteria, is the key message of this paper.

7 OVERHEAD SOUND SYSTEMS - A STUDY OF ENERGY FLOW

7.1 A Ceiling Mounted Distributed Sound System

Fig. 2 shows a typical overhead sound system, using ceiling mounted loudspeakers. Three listeners are shown in positions directly beneath a loudspeaker, directly between four loudspeakers, and near a room boundary. Different elements of the sound field generated at the listeners are shown. Example designs using a conventional 200 mm diameter cone and alternatively a wide dispersion loudspeaker are compared.

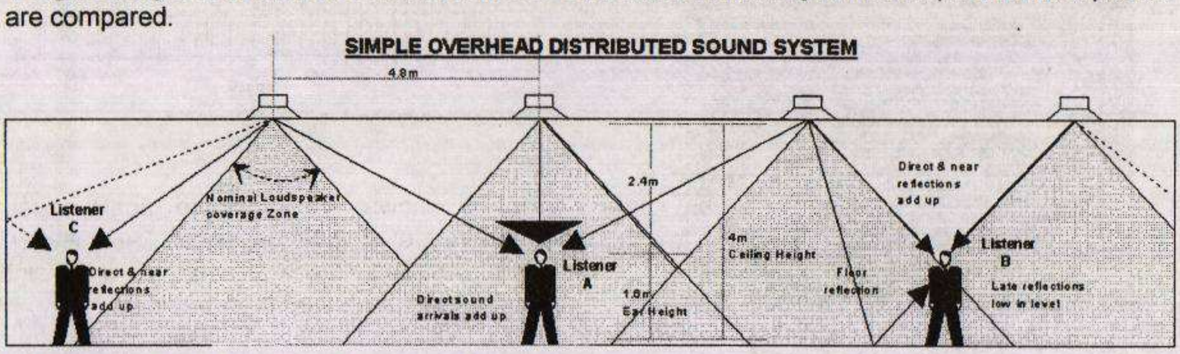

Fig. 2 Effects arising from an Overhead sound system design

Fig. 3 shows variation of coverage angle with frequency (-6 dB points) of an ideal 200 mm loudspeaker, unaffected by the grille and mounting arrangements. This loudspeaker is used for the first example. It can be seen that at 2 kHz, the -6 dB coverage angle is about 75°. 20 loudspeakers are required when are laid out to the "minimum overlap" spacing at this frequency. Fig. 4 displays the direct sound coverage at ear height of this loudspeaker layout. Each of the three listener position types is indicated.

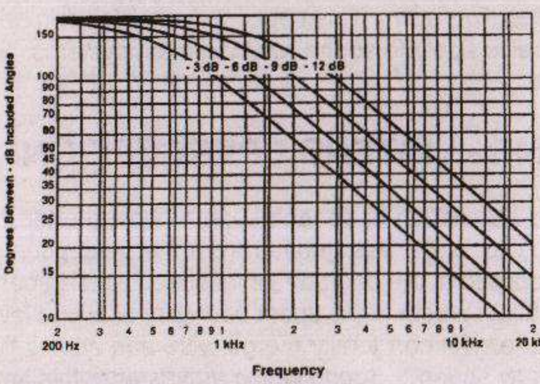

Fig 3 Coverage angle versus frequency of 200 mm cone driver

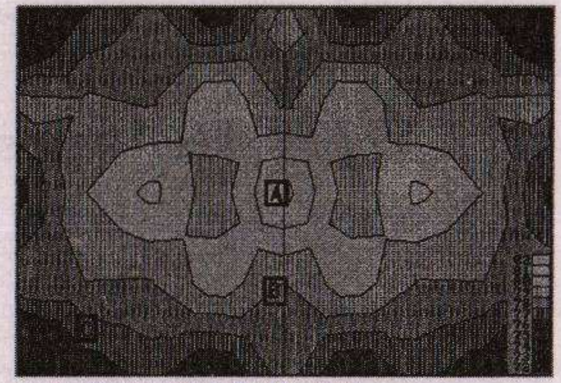

Fig 4 Direct sound coverage using 20 no. 200 mm loudspeakers

Fig. 5 shows the energy time curve from computer model of this layout for each of the three listeners. When the energy is grouped according to our definitions, we find that the loudspeakers contribute either to the direct, early (helpful) or reverberant sound energy, but do not produce any of the intelligibility-reducing high level, late sound arrivals. Thus, for this design, the %ALCONS equation can be used with impunity.

The room model includes an absorptive ceiling treatment. This absorbs most of the energy reflected from the floor, and allows the ceiling height to be adjusted with little effect on the intelligibility.

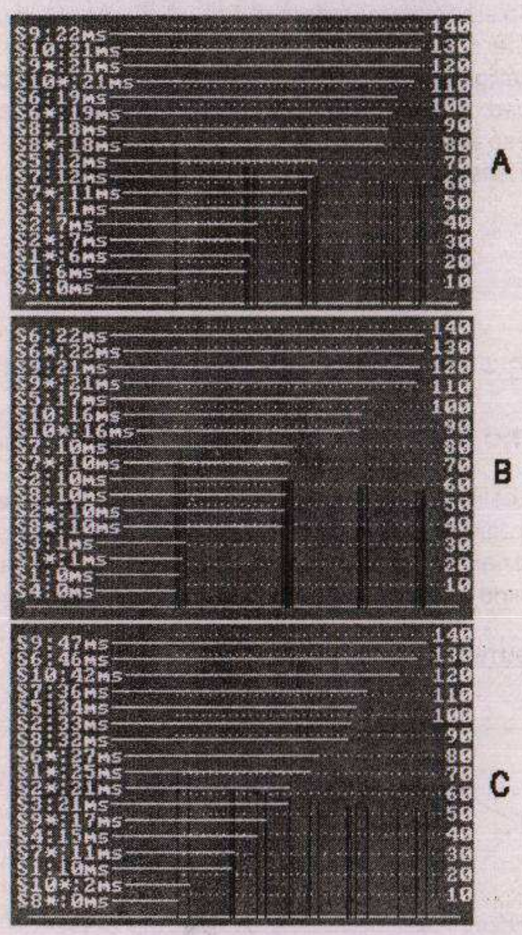

Fig 5 Energy-time curves for listeners A, B and C for 200 mm design

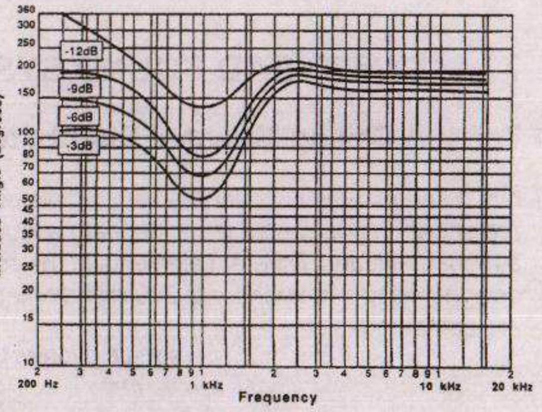

Fig 6 Coverage angle versus frequency of CT12E wide dispersion driver

Fig. 6 shows the coverage angle versus frequency of a wide dispersion loudspeaker. The resulting layout requires only eight loudspeakers, spaced more widely.

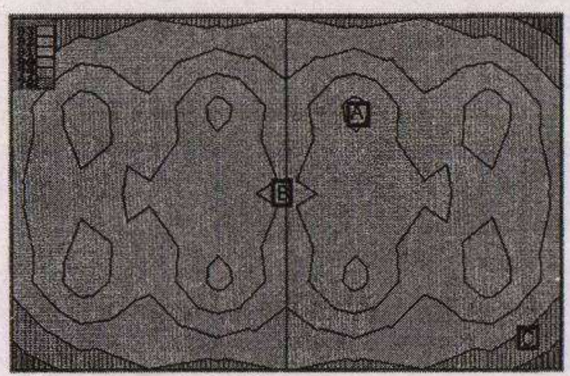

Fig 7 Direct sound coverage using 8 no. CT8 loudspeakers

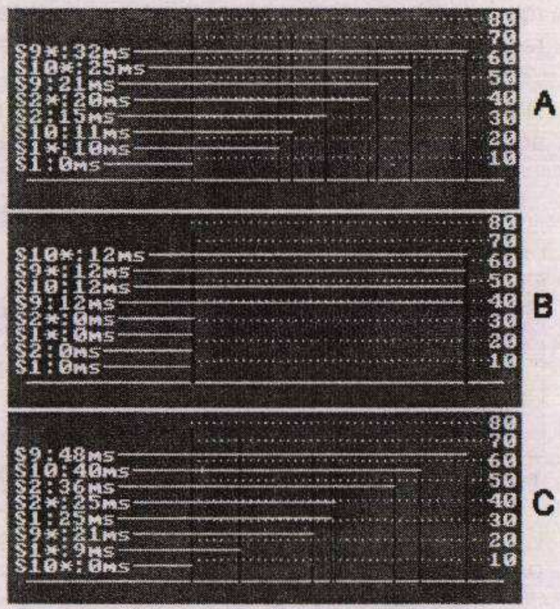

Fig 8 Energy-time curves for wide disperson design

Fig. 7 shows the sound coverage of the wide dispersion implementation, which is similar to Fig. 4 for a conventional loudspeaker. Energy arrivals for the wide dispersion loudspeakers, shown in Fig. 8, confirm that sound level versus time are safe.

It should also be noted that in Fig 2 that ALL of the sound output within the nominal coverage angle of the loudspeakers arrives at potential listener positions. This is not necessarily the case with a horizontal sound system design as will be shown later.

7.2 A Single Device Overhead Sound System

The other extreme of system design for an overhead system is the use of a single device or a cluster. If the loudspeaker is placed high in the room, then our criteria that first reflections are mainly downward and add to the early sound at the listener is fulfilled, though more of the loudspeaker's sound output may now reflect in a non-useful way. However, when a carefully selected loudspeaker is carefully positioned, excellent results are obtained.

7.3 Overhead Sound System Summary

Systems where the loudspeakers are overhead are generally more tolerant of room shape, the position of any sound absorption, and provide a uniformity of response that makes design relatively simple.

Overhead loudspeaker system designs do have disadvantages:

- for many implementations, many devices are needed. Though these are individually often inexpensive, cabling and installation costs form a substantial part of the total cost
- if the room has little or no sound absorption installed, and a relatively high ceiling, then distributed overhead systems can reach a limit determined by direct to reverberant ratio

8 HORIZONTAL SOUND SYSTEMS - A STUDY OF ENERGY FLOW

Horizontal sound systems are routinely used for sound reinforcement. Practicality means that temporary installations are simplified using such systems, since floor stands can be used toward the front of the venue. Another advantage is that the energy flow from the loudspeakers is in the same direction as the sound from the performers, helping to ensure that the two arrive at the listener within our 25 ms to 35 ms time limit, so that the sound image coincides with the visual image. Where the room has been designed for this type of system, placing diffusion or absorption on surfaces where reflections arise, then the results can be from acceptable to excellent.

However, horizontal sound systems are being used for speech applications also. Here, the originating source is not in the room, or is unimportant, therefore issues of audible image position are secondary.

SIMPLE LATERAL or HORIZONTAL DISTRIBUTED SOUND SYSTEM

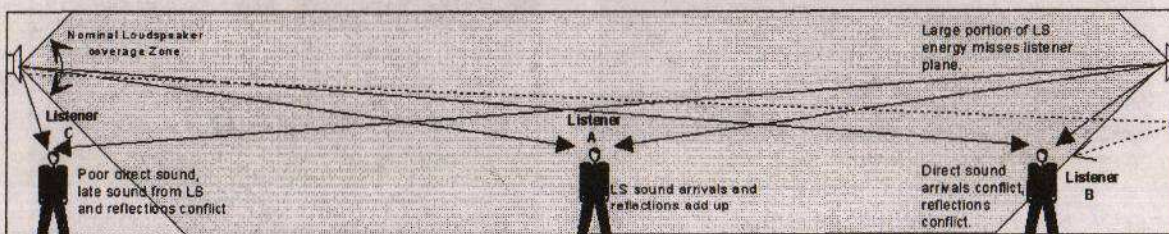

Fig. 9 Effects which can arise from a Lateral or Horizontal sound system design

Fig 9 shows one example of a lateral sound system design. In the design of lateral sound systems, great care must be taken to ensure that:

- energy within the loudspeaker coverage pattern is directed primarily on the listener plane. This is not always easy
- contributions from the sound output of each loudspeaker in the system contributes helpfully to the early sound at all listener positions - prevent "late direct" sound
- that reflections from room surfaces are considered carefully to ensure that they either assist, or at least do not conflict with the wanted sound at the listener - prevent "late reflected" sound

Horizontal sound systems *require* the designer to investigate the details of the time and level of sound arrivals from these sources for each listener location zone and for major room surfaces.

The study of the design constraints of lateral sound systems is given in several real-life examples.

9 SOME REAL LIFE EXAMPLES

9.1 Airport Departure Lounge

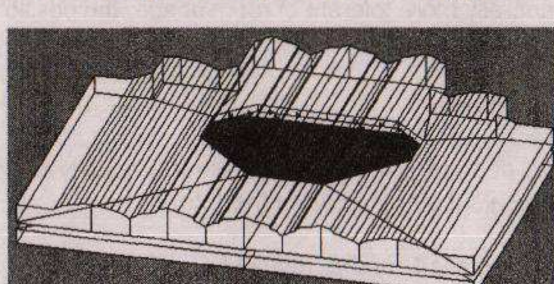

Fig 10 Room model for airport departure lounge showing central atrium area. Both old and proposed loudspeaker installations are shown.

An example of a horizontal loudspeaker installation was found at this project. As seen in Fig. 10, the architecture of the waiting area of the ground floor departure lounge is nearly circular in plan, with a glass roof light above. There was no sound absorption on the floor or ceiling.

The original installation comprised 200 mm loudspeakers mounted within the balcony balustrade upstand, pointing horizontally across and above the ground floor seating area at a height of about 4 m. Standing at the centre of the space, the speech intelligibility was good. However, when more than about 8 m off centre, none of the speech could be understood. RASTI ranged from 0.54 down to 0.34.

The solution was to fit loudspeakers overhead beneath the roof support beams on each side of the glass roof-light surround. This reduced the speech intelligibility at the centre of the space, but produced an even and usable 0.45 RASTI at all listener positions, now limited by reverberation and background noise levels. The addition of absorption at high level within the space or installation of a single high directivity device could provide further improvement. Neither of these options were permitted by the architect.

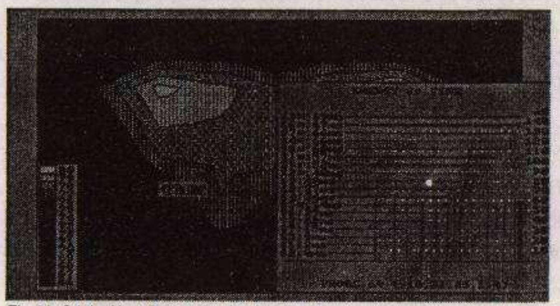
Fig 11 Original installation showing loudspeaker coverage and energy-time curve of loudspeaker direct sound at side listener positions

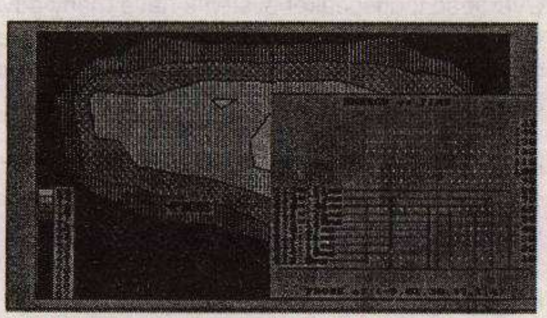
Fig 12 New proposal for overhead system, showing loudspeaker coverage and energy-time curve of loudspeaker direct sound at side listener positions

Fig. 11 and Fig. 12 compare the energy-time curves for loudspeaker direct arrivals for the two solutions, revealing the shortcomings of the original system primarily caused by the horizontal loudspeakers interfering with each other at many listener locations. Fig. 1 also shows the original system, but includes reflections. The overhead system eliminated this effect and also improved the distribution of direct sound energy. A reduction of reverberent energy in surrounding areas improved these as well.

The RASTI measurements included the effect of the transmission microphone as well as the PA amplifiers, processing and loudspeakers. After completion, speech intelligibility depended almost entirely on the quality of talker speech delivery. Further improvement would require some additional sound absorption within the space to reduce the level of the reverberant energy.

9.2 Lloyds TSB Lombard Street Banking Hall

This is an example of a recent refurbishment project. Formerly it was a conventional banking hall with cashier windows along each side. The loudspeakers were mounted overhead in coffers, pointing up toward the ceiling and reflecting downward from there. The author did not audition this system.

The banking hall is now a waiting area at the centre of a series of meeting rooms. It is an architecturally sensitive, large, highly reverberant space. The space is listed, making it impossible to consider a ceiling mounted loudspeaker system, though the carpeted floor area would have complemented this nicely. Possible solutions considered included short column loudspeakers located at the main structural column positions, directed toward the rear of the space and fitted with a series of delays. An alternative was the installation of a single phased array loudspeaker system positioned on the wall behind a structural pillar near the front of the space.

The architect preferred this last option, which was implemented using the Duran Audio Intellivox 2c phased array column loudspeaker. This permitted the loudspeaker to be mounted vertically against the wall, virtually out of sight behind a structural column. However, the sound beam directed downward at seated head height across the space. The use of a single loudspeaker prevented any interaction between multiple loudspeakers in this horizontal sound system design. However, the risk of a strong reflection from the rear wall of the space was introduced. Careful selection of mounting height and beam deflection angle makes this reflection virtually undetectable.

The result is highly satisfactory, delivering intelligible sound throughout occupied areas of the space. The loudspeaker itself is very visually discrete, contributing to the Civic Trust award given to this beautifully executed refurbishment project.

10 SUMMARY

Overhead loudspeaker systems have many advantages, not the least of which is that they are relatively tolerant of variations in the position of room acoustic treatment and wall finishes. Sound distribution can be designed to any level of evenness with no compromise in speech intelligibility. The sound output from multiple loudspeaker systems intrinsically adds up helpfully to the listener.

Horizontal loudspeaker system designs are suitable for many installations also. Careful consideration of the interaction between loudspeaker sound arrivals and reflections from room wall surfaces is required to obtain good results. The %ALCONS equation is necessary, but not sufficient to confirm good system design. New device types such as electronically controlled phased loudspeaker arrays provide new ways of overcoming design difficulties.