ROOM ACOUSTICS FOR MULTICHANNEL LISTENING: EARLY REFLECTION CONTROL

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This paper briefly outlines the development of control room acoustics from the earliest inception, through phases of monophonic, two-channel stereophonic and, most recently, multichannel sound. It concentrates especially on the control of early reflections from the boundary surfaces of the room and the detrimental effects of those reflections on sound stage imaging. Design methodologies are described that allow the shapes of the room boundaries to be so arranged that the early reflected sound energy does not return to the principal listener's position until after an initial time gap. Results are presented from measurements on a conventional control room, a stereophonic room designed with minimum early reflections and from a multichannel room. Though the discussion is presented in terms of control room design, the simplified principles for multichannel design are also applicable directly to domestic listening spaces.

INTRODUCTION - AND A LITTLE HISTORY.

"Listening" is an integral part of all sound production operations. Despite the very significant advances in measurement technology, objective methods remain unable to tell us what a programme or recording will sound like to the listener at home. The human ear alone is able to judge the aesthetic or artistic quality of audio material and, indeed, many aspects of the technical quality. However, it is self-evident that both the acoustics of the listening environment and the electro-acoustic properties of the loudspeakers will influence the perceived sound. Both must be controlled in order to allow consistent subjective assessments to be made.

In the earliest days of both sound broadcasting and commercial record production the 'control room' did not exist at all. Signals went more or less directly to the transmitter or recorder. The combined skills of studio and microphone designers and the production engineers created a sound quality that was considered acceptable at the time. The acoustic design of the studio was an important part of the signal chain and there was no scope for modifying the signal characteristics in the ways that are commonplace today.

In broadcasting, that situation continued only for a very short time. It was quickly realised that some means had to be provided at the studio end of the transmission chain for ensuring that the outgoing signal was reasonable – at first, simply that it was present. The first control rooms consisted of a small cubicle (cupboard)[1], inside the studio but separated acoustically by thin panels of wood and glass. It contained a person monitoring the studio output, usually with headphones, but with no means for modifying the signal, except perhaps to adjust the gain. The shortcomings of such an arrangement were evident from the beginning, but that situation continued until specially designed studio facilities with separate monitoring areas became available, in about 1928. Even then, no arrangements were provided for altering the quality of the signal, except perhaps in level and selecting the microphone. Indeed, in the BBC at least, it was considered unacceptable *in principle* to modify the characteristic quality of the signal[2]. In those circumstances, there was no need for any significant acoustic design of the control room. Its sole purpose was to 'mix' microphone signals and other sources, without altering their basic

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[1] To this day and for this historical reason in the BBC a radio studio control room is still called a "cubicle" and not a "control room".

[2] Even in the late 1940's, in the main London BBC radio studio centre there was just one "equaliser", the use of which had to be authorised for each special occasion. It was a very large and heavy piece of equipment, fixed on a trolley which could be moved from studio to studio as required.

audio characteristics. The rooms were generally moderately acoustically treated, mostly for the comfort of the operators, in a manner similar to contemporary domestic living rooms.

Eventually the flexibility provided by modern electronics, the improving quality of receiving equipment and the normal progress of technological expectations led to more widespread implementation of some sorts of equalisation. That brought with it the concept of the control room being some sort of model for the listener's home environment. By accurately modelling a 'typical' listener's room, the expectation was that the sound quality could be adjusted until it would sound at its best in the listener's home. Studies were carried out into typical home listening environments in order to guide the acoustic design of the control room [1,2].

In practice, it was soon found that actually modelling the acoustics of the listener's home was not the optimum approach. Instead, a control room environment had to be provided in which the operator was able to make accurate assessments of the quality so that it would sound acceptable in a range of home listening conditions. These are not the same thing, but it still led to reverberation times of 0.3 – 0.4s in the control rooms. Little attention was given to the distribution of the acoustic treatment, other than the avoidance of gross defects, such as 'flutter echoes'. The internal acoustic design was essentially limited to control of the reverberation time (RT). The other acoustic requirements of low background noise levels and good sound insulation were essentially self-evident and were for the convenience of the production process rather than as a model for the home environment. That design philosophy continued until the advent of stereophony in the early 1960's.

STEREOPHONY AND THE INCREASE IN THE IMPORTANCE OF THE 'EARLY' REFLECTION.

The sound field in the vicinity of the listener can be divided into three main components – the direct sound, the early reflections and the later reflections that merge to form the reverberant field. All these components are functions of both time and frequency. The division is not absolute – there is much discussion about the locations of the boundaries – in time, amplitude and frequency.

With the advent of two-channel stereophony and the emphasis (at the time) on exact and objectively accurate image localisation, the disturbing effects of early reflections soon became apparent. Strong, discrete reflections arriving at the listener's position in the period up to about 20ms after the direct sound cause distortion of the perceived sound stage and significant image shifts. Beginning in the early 1960's, acoustic treatment was applied selectively to control those reflections. That led to an acoustic design in which patches of absorption, particularly for high frequencies, were strategically placed around the room and especially around the loudspeakers, which were almost always free standing. To maintain (as much as possible) the uniform sound field that was felt to be essential, the remainder of the room was usually treated to about the same extent.

For reasons that have never become entirely clear, the extent of this 'acoustic control' increased progressively, leading eventually to very large total quantities of acoustic treatment and almost anechoic rooms. Measured mid-band decay times of 500 dB/s, equivalent to an 'RT' of 0.12 s, were encountered frequently. That large quantity of acoustic treatment was expensive in capital and installation costs and as well as in space within the room. It also led to rooms that were extremely oppressive to work in.

The production emphasis gradually changed to one with a less objectively accurate image localisation (many sources were, and still are, 'panned' into artificial locations) but retaining a high degree of apparent image definition. It became perhaps even more important that the stereophonic illusion was clear and consistent. Commercial control-room design came to be dominated by several fashions that have been more or less time-sequential. These were all based on less uniform distributions of acoustic treatment [3].

One of the more recent ones was the concept of placing the listener in a so-called 'reflection-free zone' [4, 5] – in reality, a region of the room where some of the early reflection amplitudes were rather less than they would have been otherwise. The underlying concepts were the use of redirection and/or diffusion to reduce the amplitudes of the early reflections in the vicinity of the listener. The intentions, in principle, were to improve the image sharpness and to make the stereophonic effect less dependent on the room. Because the key factors in achieving that were the use of less absorbing surfaces, a 'dead' acoustic was not an inevitable consequence. Indeed, the designer had considerable freedom in the choice of reverberation time. Thus the oppressive feeling could be avoided and normal activities within the room made easier and more comfortable, as well as more closely approaching the audience's room conditions (in one respect at least).

DESIGN TARGETS FOR EARLY REFLECTION CONTROL.

Much has been written on the audibility of relatively early 'echoes', essentially beginning with Haas in 1951

[6, 7]. The majority of this work has been on isolated (or small numbers of) discrete echoes. The relevance of these types of results to the listing experience in a room full of myriad reflections is, at best, doubtful. Some more recent work has dealt with larger numbers [8], but the difficulties arising from the vastly increased number of degrees of freedom of such tests make general interpretations difficult. More recent results from the Archimedes Project [9] do have more relevance, though even in that case, the numbers of simultaneous reflections simulated was quite small. There is also the problem of where to draw the boundary between an effect detectable under stringent test conditions and one that materially alters the listening experience.

A recent, and very thorough, analysis of all of the factors involved in listening to reproduced sound in small spaces [10] has essentially concluded that none of the hitherto assumed objective acoustic requirements for control rooms have much experimental justification. In the transition from large rooms (concert halls) in which they were originally derived to the entirely different conditions in small control rooms so much has changed that their relevance has been lost. The author also makes valid comments about the differences between listening for pleasure and objective programme production. That aspect is discussed in more detail later in this paper.

Nevertheless, this author considers that the avoidance of gross acoustic defects in production control rooms is still important, even if there is disagreement about the exact parameters. It is certainly accepted that the original targets for early reflection control (see below) have been found to be both excessively stringent and barely achievable (if at all).

The first experiment with new designs for reflection control in the BBC was with a research room to test the principles. As a target for that prototype design, a very stringent criterion was proposed, namely 20ms and –20dB. That is, at the listener's position there should be no sound energy components higher than –20dB relative to the direct sound in the period up to 20ms after the arrival of the direct sound. This was not intended to be a wholly justifiable and objectively supportable criterion. Rather, it represented a goal which was thought to be achievable in reasonable sizes of room and which encompassed much of the objective information then available about the disturbance of stereophonic images. It was a convenient, simple rectangle in time and amplitude, intended to allow the principle to be evaluated. The intention had been to relax the specification progressively until the benefits, if any, were lost.

THE FIRST CONTROLLED IMAGE DESIGNS.

Beginning with an empty shell and the traditional triangular loudspeaker/listener layout, it is necessary to locate internal surfaces that will reflect the sound, but not in the direction of the listening position. In particular, it is necessary to make the transition from one boundary surface to an adjacent one (which is generally at something close to a right angle). Although this can sometimes be done by inspection, it becomes difficult to manage when the presence of two sources and the three-dimensional nature of the problem are taken into account. An important simplification is to deal with the reflecting surfaces in only two projections – plan and elevation. That constrains the reflecting surfaces to be parallel to one or other of the principal axes of the room shell. It also means that the design is carried out effectively for sections through the listening position. In consequence, many parts of the resulting reflecting surfaces are acoustically redundant - the three-dimensional reflection angle being greater than that required to meet the design criterion.

The first step in the design process is to specify the listening position. Geometrically, that is trivial. Acoustically, the effects of diffraction will result in some energy being reflected in non-specular directions. Thus, it is necessary to consider a zone around the nominal listening position large enough to make those effects meet the criterion at all frequencies important to the stereophonic illusion. Accordingly, in each projection, a circle is drawn around the nominal listening position into which no (geometric) first-reflection sound ray should pass.

To help to achieve this, a computer program was developed to create a series of boundary paths of reflector critical angles, such that any reflection was just tangential to the circle (geometrically). Fig. 1 shows the plan for a typical room at that stage. Also shown are hypothetical reflections from the curved boundaries always just tangential to the circle around the listening position.

Such curved surfaces are not practical. They would be difficult to specify, expensive to build and aesthetically undesirable. Also, they would not work acoustically at low frequencies because they would tend to focus the low-frequency sound. However, planar reflecting surfaces can be constructed, using the curved boundaries as guides, in such a way that the final flat surface is, at worst, just tangential to the boundary. In general, it is not possible to complete the transition from, say, front wall to side wall on this basis without 'stepping' from one boundary path to another. These transition steps must be filled with acoustically absorbing material. Fig. 2 shows an implementation for a typical room. It also shows two limiting reflections that are just tangential to the circle around the listening position, other non-limiting reflections and absorption at one of the transition steps.

In control rooms, one uncontrolled reflection remains in such a design. It is from the rear wall and usually occurs at about 20ms (depending on the size of the room and the listener's position). The acoustic treatment of that wall ought to attenuate and diffuse the reflection. However, the path length difference alone will produce about 10dB attenuation and it is therefore not necessary to install large quantities of absorption. Nor is it necessary to use elaborate means for diffusion – scattered patches of normal acoustic treatment generally provide adequate diffusion (and in three dimensions). All of the remaining room surfaces not directly part of the reflection control system can be used for acoustic absorption to control the longer-term sound field (from about 20ms into the reverberation period). For a mean reverberation time of about 0.35s, the total quantity of acoustic treatment used in the experimental room was about one quarter of that which would have been used in a conventional BBC design.

The design was based on the normal BBC practice using freestanding loudspeakers. The method can just as easily accommodate loudspeakers built into the front wall, in the fashion favoured in many other organisations.

Based on the results from the research room, four production sound control rooms (cubicles) were built by the BBC in London. Because of the user's reactions to the prototype room they used the same uncompromising design principles, without any modifications. Three of those were in Broadcasting House (B11, B12 and B13) and one was in Bush House (Transcription Unit).

APPROXIMATIONS AND ASSUMPTIONS.

In most of the above it has been implied that sound energy travels like light waves, in straight lines with specular reflections from solid surfaces. However, the wavelength range of normal audio signals extends from about 15mm to 10m. At the longer end of the range, even the room itself is not large relative to the wavelength. This leads to well-known, low frequency problems involving room modes, which are not relevant to image formation in stereophonic listening. At the shorter end of the range, most objects are large relative to the wavelength and sound will propagate and be reflected approximately geometrically.

The mid and high frequency region includes the frequencies that are involved in stereophonic image formation. The question is how much can and should they be controlled? It is fairly widely accepted that there is no stereophonic information below about 300Hz. It could easily be argued that 500Hz represents a limit below which the discrete image forming content is at least less critical.

A frequency of 500Hz corresponds to a wavelength of 650mm. Reflections from an object of about that size, for example an element of a complex reflecting structure (or a small quadratic diffuser) would be seriously limited by diffraction and would produce a considerably wider spread of reflected energy than is suggested by simple geometric considerations. The 'ray-tracing' approach should be regarded as no more than a guide to the actual acoustic behaviour. The combined effect of this diffracted energy sets the lower limit to the degree of reflection control possible.

Because of these diffraction effects, the size and location of the circle of control around the listening position is somewhat arbitrary. It should be as large as possible but, in a given room, the design solution becomes more difficult for larger circles. This is especially true for the elevation – in most rooms the height is more restricted than either length or width. In reasonable sizes of room geometric solutions are usually feasible for circles 3m in diameter in plan and 2.5m diameter in elevation.

The design relies on the presence of a mixing desk to control the floor reflections. It is impractical to shape the floor surface in the same way as the ceiling. The back of the mixing desk also provides an absorbing 'sink' for some of the reflections from the front wall/ceiling area. If it is not already absorbing, some acoustic treatment should be located in that zone. However, the shape of the space behind the desk will usually ensure that any sound energy that eventually emerges is diffuse.

The angled, reflecting surfaces also have other benefits. In the past, glazed surfaces such as observation windows have been tolerated out of necessity, despite their generally detrimental acoustic properties. With this design, any of these surfaces may be windows, cupboards or doors. Much of the paraphernalia associated with a modern control room, for example clock patresses, indicator lights, computer monitors, etc., may be hidden behind glass panels, thereby tidying up both the acoustic and the aesthetic aspects of the room. The surfaces must of necessity be hard and may therefore be more serviceable, robust and easier to keep clean.

EARLY MEASURED RESULTS[1].

In the following presentations of results, the direct frequency response of the loudspeakers themselves has been removed by computation. That was done because the measurements extended over a significant period of time, in different localities and with different loudspeaker types, giving rise to other differences besides those from the room reflections. The correction has resulted in minor artefacts in the responses presented here, mainly an apparent resonance at the upper end of the frequency range. The slight emphasis of frequencies between about 9/10kHz should be ignored. It is not important to the main argument. The 'floor' level of the results presented has been set at -20dB relative to the direct sound.

Fig. 3 shows a sample measurement for a conventional BBC-design control room, considered to be typical of that type of design. Reflections are clearly visible, despite the use of nearly 100% coverage of very effective acoustic treatment. These were from equipment trolleys (≈ 2 ms), ceiling (3/4 ms), side walls (4/6 ms), rear wall (≈ 12 ms), etc.

Fig. 4 shows a result for the prototype Controlled Image Design room. A small group of 'defects' was evident between about 9 and 12 ms. Their amplitudes were about -14 dB relative to the direct sound. Investigation revealed that they were due to corner reflections from the sides of the first set of modular acoustic treatment on the ceiling and side walls respectively. It was a simple matter to fill those small corners with acoustically absorbing material. There were also some effects at lower frequencies. Those indicated the failure of the reflecting structure to act geometrically at frequencies of the order of 1 kHz and show the residual diffraction limit of those surfaces. The final result showed no measurable reflections above -16 dB in the first 19 to 20 ms.

Overall, the work in the experimental room showed that the initial targets of -20dB and 20ms were not quite achievable, even under research conditions. Even so, the room was considered to be live yet accurate and revealing, with a more comfortable working environment for the occupants. Some reactions did include comments that it was "too analytical".

Despite reservations, the decision was taken by the Head of Radio Engineering to use the design for three new production studios, based on the experimental room. Those rooms were constructed in the early 1990's and have recently been demolished for re-development (2006). Another was built at Bush House for the Transcription Unit of the World Service. One of the significant findings was that the sound quality was sensitive to the position of the listener's head – much more so than in conventional rooms. This is now a well-known feature of rooms with very low levels of early reflections. It probably arises because of the absence of the masking by the large number of uncontrolled early reflections inherent in other designs. It also occurs very dramatically when listening to stereo in anechoic chambers [11]. Whether or not that is considered to be an advantage or a defect is a matter for individual judgement – whether it is better to have a very precise sound image in one fixed position or rather less precise images everywhere depends to some extent on the intended use of the room. Three of the production rooms (and one of those especially) were used mainly for 'current affairs' speech programmes. With up to seven or even eight people in the room, it is clear that not everyone could be in the optimum location. The sound quality in places significantly away from the centre position was significantly worse than it would have been in a conventional design. It was obviously an unsuitable design for the purpose. However, where the rooms have been used for music production, with one or two principal listeners, the reactions were favourable. It was also recognised that the design principles were going to be more difficult to achieve in multichannel rooms.

It is still not clear whether the sound quality, and especially the stereophonic image quality, in such rooms at slightly off-axis positions is actually worse than in a conventional room or just seems poor in comparison with the clarity of the central position.

A CONTROLLED-REFLECTION ROOM FOR MULTICHANNEL SOUND.

The original designs for stereophonic listening attempted to deal with all possible first-order reflections from each source and all surfaces. Extension of the design method to multichannel listening required some simplifications. With four or more loudspeakers, the large number of potential combinations of source and reflecting surface significantly complicates the control of early reflections. It essentially means that total control by re-direction is not feasible. However, the earlier experience with the stereophonic rooms showed that the original design targets had been significantly more stringent than necessary. The original design method also did not take into account any attenuation from either distance or surface absorption.

The opportunity arose to design a reference listening room to satisfy the requirements of International Recommendations ITU BS.1116 [12], EBU Rec. R22 – 1997[13] and EBU document Tech. 3276 [14]. Those

1 See Appendix.

three Recommendations had basically the same acoustic requirements. The requirement set for the early reflections levels was –10 dB and 15 ms. That was significantly less stringent than had originally been specified for the BBC stereophonic control rooms. It represented a compromise, based on subsequent experience, between idealised requirements and what was reasonably achievable in practice.

The new listening room was constructed at the BBC's Research and Development Department, in an existing shell, which was already in use as a listening room and which had reasonable insulation from exterior noises. The room was essentially completed by the end of August 1997. It satisfied the acoustic requirements of BS.1116 and Rec. 3276 for a high-quality sound control room/reference listening room. It was subsequently used for many subjective test programmes and evaluations involving multichannel sound or sound systems.

The recommended arrangement for the monitor loudspeakers for five-channel (5.0 or 5.1) multichannel listening in ITU BS.775-1 [15] is shown in Fig. 5.

Early reflection control.

The advent of multichannel operation made the task of controlling early reflections even more difficult. With five loudspeakers and six primary room surfaces, the number of potential first-order reflections increased to 30 and second-order reflections to 150. Clearly, to achieve any significant degree of control it was necessary to reduce that large set of potential reflections to something manageable.

As a beginning, in most rooms, all of the second-order reflections can be ignored on the basis of the total time delay and natural attenuation with distance. Fig. 6 shows the attenuation function in terms of relative distance. For example, for a typical loudspeaker to listener distance of 2 m, any reflection with a total path longer than 6.34 m will already be attenuated by at least 10 dB relative to the direct sound by the normal spreading loss. In any reasonable room, that will adequately control (to –10 dB) potential second-order reflections from the room boundary surfaces, even without assuming any additional attenuation by the absorption of the wall treatment. It will also eliminate many of the cross-reflections, that is, those from a source on the opposite side of the room from the reflecting wall. The earliest second-order reflections involving the ceiling or floor might have a path length around 5.5 m, but those surfaces must be treated sufficiently to attenuate the first-order reflections anyway. This does assume that there is no acoustic focusing, no excessive off-axis source directivity and no other effects that could increase the relative reflection strength. In practice, some margin of additional attenuation might be desirable to accommodate those types of imperfections.

In the design of the reflection control system for the new room, no allowance was made for any additional attenuation other than that entirely predictable effect due to distance. The loudspeakers were assumed to be omnidirectional. In practice, virtually all loudspeakers become significantly directional above 1 kHz. Any additional directionality would further reduce the amplitudes of potential discrete reflections from surfaces around the loudspeakers. There are also some additional occurrences of obstruction, for example, the reflection from the centre-front loudspeaker in the rear wall is obstructed by the listener's body (though not by a measurement microphone).

The early reflection problem is thus reduced to that of dealing with a few first-order reflections from each source. Some parts of the room surfaces had to be considered in detail and had to be specially treated. Those were the parts of the wall surfaces, which could potentially generate a first-order image, 'visible' in the listening area, of any of the five loudspeakers. Fig. 7 shows the loudspeaker layout in the room and the three potential reflections from the front loudspeakers via the right-hand side wall. It shows that the potential reflection points on the side walls are clustered in comparatively small regions.

Fig. 8 shows the complete first-order reflection pattern for all loudspeakers (including the cross-reflections that may already be attenuated adequately by their path length). The clustering of potential wall reflection points can be clearly seen. The additional attenuation required to reduce the reflected sound to below –10 dB relative to the direct sound was more than could be achieved by either absorption or diffusion. It was therefore necessary to angle portions of the wall surfaces in order to redirect the first-order reflections away from the main listening area [16,17,18,19]. Studies of the potential reflection patterns showed that the angled portions could be confined to only nine segments of the total wall surface and that the angles required could easily be achieved within the normal thickness of acoustic treatment. The angles were chosen on the geometric basis of a 2 m diameter exclusion circle around the reference listening position.

The centre section of the rear wall presented a more difficult problem. The angles required to redirect the sound horizontally were extreme and laterally reflecting panels would have projected too far into the room. Initially, that 2 m wide area was treated with acoustic diffusers. However, subsequent measurements showed that although the overall attenuation of the reflections was adequate, some diffraction peaks exceeding the specification did occur. It is a well-known feature of number-theoretic diffusers that such peaks will occur [20] and these were actually observed in this case. Whether the result would have been subjectively significant is not clear, but they certainly caused the specification to be exceeded. The rear centre section was subsequently replaced by a set of angled flat panels that reflected the sound vertically, either down to the floor or up to the ceiling.

Fig. 9 shows the completed wall design (for half of the room), including angled panels, areas of both deep and shallow acoustic absorption and the 2 m circle of ‘exclusion’. The redirection of one potential reflection from the left-hand wall is illustrated.

The control of reflections via ceiling and floor is much more difficult. Floors usually have to be flat, strong and relatively hard. In a listening room with no mixing desk, the floor is also the surface that potentially creates the earliest and strongest reflection. The only practicable solution was to provide portable units made of thick acoustic absorption with angled surfaces, to stand on the floor between the listeners and each of the sources. In fact, those units were never constructed and temporary provisions were made whenever it was thought to be necessary. In practice, such units would be obstructive and cumbersome and would only be used for the most critical tests, where every detail of the recommendation had to be observed.

The acoustic design for the ceiling and its distance from the source and listener meant that reflections from the ceiling would be attenuated sufficiently without additional control.

Results.

Fig. 10 shows the time-frequency response for the left-front loudspeaker, as measured at the reference listening position for the room as first built. The frequency range below 1000 Hz was not part of the specification - it was included for completeness and to illustrate that lower-frequency ‘reflections’ cannot be controlled in this way. Also, the whole response was equalised to the direct sound amplitude to remove most of the loudspeaker irregularities. The nominal direct sound reference level was therefore 0.0 dB. For instrumental reasons, the actual displayed direct sound level usually lay between 0.0 dB and -0.5 dB. In the following discussion, all amplitudes are given relative to 0.0 dB. The ‘floor’ of the displayed amplitude range was set to -16 dB, well below the specified limit, otherwise very little of the reflection responses would have been visible in the results.

In Fig. 10, at about 1600 Hz / 3.4 ms (highlighted by the cursor), there was a reflection peak up to -9.5 dB via the floor. There was also a scatter of irregular peaks over the whole frequency range, at a time delay of about 10 ms, though their amplitudes were all well below -10 dB. They were caused by diffraction from the diffusers on the rear wall. At that off-axis angle, a flat surface there would have produced no reflections. Fig. 11 shows the effect of replacing the diffusers by flat panels directing the reflected sound to either floor or ceiling. Almost all of those peaks were removed (at least to below -16 dB). Fig. 12 shows the effect of placing a reflector/absorber on the floor between the source and the listening position. The peak visible in Fig. 10 was reduced to below -16 dB for frequencies above 1 kHz. The remaining low-frequency peak in the floor reflection response just met the -10 dB / 1 kHz specification.

The effect of the diffusers is illustrated better by Figs. 13 and 14. They show the responses for the centre-front loudspeaker, at an angle that would have given a strong reflection from a flat surface. Fig. 13 shows the response with the diffusers. The response shows a moderately regular structure, with peaks at about 6.5 kHz and 3.0 kHz, and for all frequencies below about 800 Hz (the design lower limit of the diffuser panels). The highest of those peaks measured about -6.2 dB – well above the specified limit. Fig. 14 shows the response after the diffusers had been replaced by vertically angled reflectors (and with the floor reflectors/absorbers). The residual reflections from the final rear-wall structure were well below the -10 dB limit, even for the centre-front loudspeaker.

Evaluation.

Since its construction, the room has been used ever since for many tests and evaluations, mostly to international standards, and is widely recognised (and remembered) as being a good multichannel listening environment. Subsequently, a second listening room was converted using the same simplified reflection control principles, though being rather less equal in length/width, the emphasis was on two-channel stereophonic listening. It also presents clear stereophonic images and is usable for 5.0/5.1 multichannel listening, though the clearances around the loudspeakers are somewhat smaller.

An additional practical benefit of the design principle is the integration of the reflection control and the remaining acoustic treatment. To control the overall reverberation, additional acoustic absorption has to be added to a room. Without it, most rooms would have mid-band reverberation times 0.8 – 1.0 s. Whatever the arguments about the rights and wrongs of numerical specifications [10], it is certain that most mixing engineers would not be content to work in such a room.

The absorption is usually in the form of either relatively thick (deep) material for low frequencies and shallower material for the higher frequencies. The design principle, using sections of angled wall reflectors provides a neat and convenient way of accommodating the differences. In most room designs, the fractions of shallow and deep areas provided by the layout of the reflecting panels would be quite close to satisfying the requirements for areas of deep and shallow treatment as well.

Control rooms v. listening rooms.

Reference 10 includes a substantial discussion about the merits of early reflection control. It is argued that the efforts put into reducing early reflection amplitudes might be misplaced and that early reflections might actually be beneficial to the overall listening experience. Many references quote some sort of "improved spatial impression" or "pleasant image broadening", etc. as a result of added early reflections. Certainly, the potential deleterious effects of sparse isolated early reflections are acknowledged.

In the present author's view, this represents a marked divergence between the requirements of control rooms and recreational listening spaces. The prime purpose of a studio control room is not to provide a comfortable and entertaining space but to provide a tool by which the production process is facilitated. The mixing engineer needs to have clear information about what is being recorded. It may be that a high density of reflections, as in a concert hall, can also create an acoustic environment in which accurate judgements can be made about perceived image sizes and positions. In most control rooms, that is not the situation. The early reflection pattern is dominated by a few, perhaps four or five, early reflections with amplitudes above about -10dB. Sometimes, because of asymmetry and the closeness of a loudspeaker to a wall, one or two of those might be at a much higher level than that. In those circumstances, control of all early reflections is likely to be beneficial.

CONCLUSIONS.

This paper has discussed briefly some aspects of listening room and control room design, with particular emphasis on the effects and control of early reflections. In the early designs for two-channel stereophony, the requirements in control rooms for accurate image localisation were leading to the installation of large quantities of acoustic treatment. That was expensive, both financially and in space utilisation. It also led to rooms that were acoustically very oppressive and uncomfortable to work in. Beginning in the middle 1980's, considerations were given to alternative approaches. Eventually, that led in turn to experiments in early reflection control that did not rely on high degrees of acoustic absorption. The resulting rooms were much more comfortable for the occupants and gave accurate and well-defined stereophony listening conditions. The main penalty was that the area of the room over which the best listening conditions could be obtained was reduced to a relatively narrow region down the centre of the room. For music production with small numbers of occupants, or for listening rooms with few listeners, that was no disadvantage.

The results and experience from that stereophonic work led to a simplified design principle for multichannel listening rooms and control rooms. The original principles were much simplified by taking into account the inherent attenuation of the indirect sound with distance. That allowed the reflection control to be restricted to relatively small sections of the room boundary surfaces. The resulting arrangements also allowed for neat and convenient installations of the remaining acoustic treatment, necessary to control the overall reverberation.

The resulting designs for mutichannel listening are sufficiently unobtrusive to be considered practicable for the highest quality domestic listening environments. If appropriate, the method is reasonably easily adapted to domestic listening environments, where the panels may be made reasonably inconspicuous.

REFERENCES.

1. 1959, Gilford, C.L.S. *The acoustic design of talks studios and control rooms*. Proc. Inst. Electrical Engineers, **106**, pp 245/258.
2. 1985, Burgess, M.A. and Utley, W.A. *Reverberation times in British living rooms*. Applied Acoustics, **18**, pp. 369/380.
3. 1980, Davies, D. and Davies, C. *The LEDE concept for the control of acoustic and psychoacoustic parameters in recording control rooms*. J. Audio Eng. Soc., **28**, 9, pp. 585/595.
4. 1984, D'Antonio, P. and Konnert, J.H. *The RFZ/RPG approach to control room monitoring*. 76th Audio Engr. Soc. Convention, New York, October 1984, preprint #2157.
5. 1986, Muncy, N.A. *Applying the reflection-free zone RFZ concept in control room design.*, dB The Sound Engineering Magazine, **20**, 4, pp. 35/39.
6. 1951, Haas, H. *The influence of a single echo on the audibility of speech*. Acustica, 1, 2, p. 49.
7. 1954, Nickson, A.F.B., MUNCY, R.W. and Dubout, P. *The acceptability of artificial echoes with reverberant speech and music.* Acustica, **4**, pp. 447/450.

8. 1990, Fincham, L.R., Jones, A., Wilson, R.J. and Small, R.H. *Free-field simulation of loudspeaker/ room acoustics*. Proc. I.O.A., **12**, 8, Reproduced Sound 6, pp. 135/142.

9. 1995, Bech, S. *Perception of Reproduced Sound: Audibility of Individual Reflections in a Complete Sound Field*, II, 99th AES Convention, October 1995, Preprint Number 4093.

10 2006, Toole, F.E. *Loudspeakers and rooms for sound reproduction – a scientific review*. JAES, **54**, 6, June 2006.

11. 1974, Ratliff, P.A. *Properties of hearing related to quadraphonic reproduction*. BBC Research Department Report No. 1974/38.

12. 1998, ITU BS.1116. *Methods for the subject assessment of small impairments in audio systems, including multichannel sound systems*. International Telecommunication Union, Geneva, 1998.

13. 1997, EBU Rec. R22 - 1997. *Listening conditions for the assessment of sound programme material*. European Broadcasting Union, Geneva, 1997.

14. 1997, EBU document Tech. 3276 (2nd edition - 1997). *Listening conditions for the assessment of sound programme material*. European Broadcasting Union, Geneva, 1997.

15. 1996, ITU BS.775-1. *Multichannel stereophonic sound system with and without accompanying picture*. International Telecommunication Union, Geneva, 1996.

16. 1994, Walker, R., *Controlled image design: the management of stereophonic image quality*. BBC Research and Development Department Report RD1995/4.

17. 1995, Walker, R., *Controlled image design: results from the first installations*. BBC Research and Development Department Report RD1995/5.

18. 1993, Walker, R., *A new approach to the design of control room acoustics for stereophony*. 94th AES Convention, Berlin, 1993, Preprint #3543.

19. 1994, Walker, R., *Early reflections in studio control rooms: the results from the first installations*. 96th AES Convention, Amsterdam, 1994, Preprint #3853.

20. 1984, D'Antonio, P. and Konnert, J.H., *The reflection phase grating diffuser: design theory and application*. JAES, **32**, 4, April 1984, pp 228-236

21. 1995, Walker, R., *Controlled image design : the measurement of time-frequency responses*. BBC Research Department Report RD1995/3.

APPENDIX – MEASUREMENT OF EARLY REFLECTIONS.

The measurement of early reflections is a complex issue [21]. The unavoidable, combined resolution limits in time and frequency mean that the simultaneous, complete identification of time delay, frequency response and amplitude for an acoustic event is not possible.

The conventional way of describing the characteristics of acoustic or audio systems is as functions of frequency. However, all real signals, whether acoustic or otherwise, are inherently functions of time – in the sense that the signal only exists at all as some measure of a physical attribute, which may or may not vary with time. The concept of the frequency domain is a mathematical abstraction, with no physical existence. It is well known that the impulse response of a linear, time-invariant system theoretically contains all of the information necessary to specify the system response fully. However, the impulse response is a time domain function. In practice, it may or may not effectively be limited in the frequency domain, depending on the equipment used to measure it.

For all of these reasons, it is important to understand the transformations from time domain to frequency domain, and, in particular, the inherent resolution limits of the joint frequency-time space. Many commercial measurement systems are, at best, unclear about the limitations of the transformations that are being carried out between the time and frequency domains and the weighting functions being applied. They can give seriously misleading results under some circumstances. For the purposes of this paper (and in the EBU Tech. Doc. 3276), it is assumed that a measurement system with well-defined Fourier-Transform windows with a time resolution of about 1-2 ms and a (commensurate) frequency resolution of about 500 Hz will be adequate to describe the acoustic room responses from about 1 kHz upwards. Those are the main frequencies giving rise to the directional information that might be disturbed by early reflections.

For the results presented in this paper, a MLSSA measurement system was used. The bandwidth was set to 10 kHz (30 kHz sampling), the FFT window to 'half-Hann' of length 128 samples, giving a half-amplitude time resolution of about 2 ms and a frequency domain sample spacing of 234 Hz. The results were further convolved with a one-third octave filter in the frequency domain.

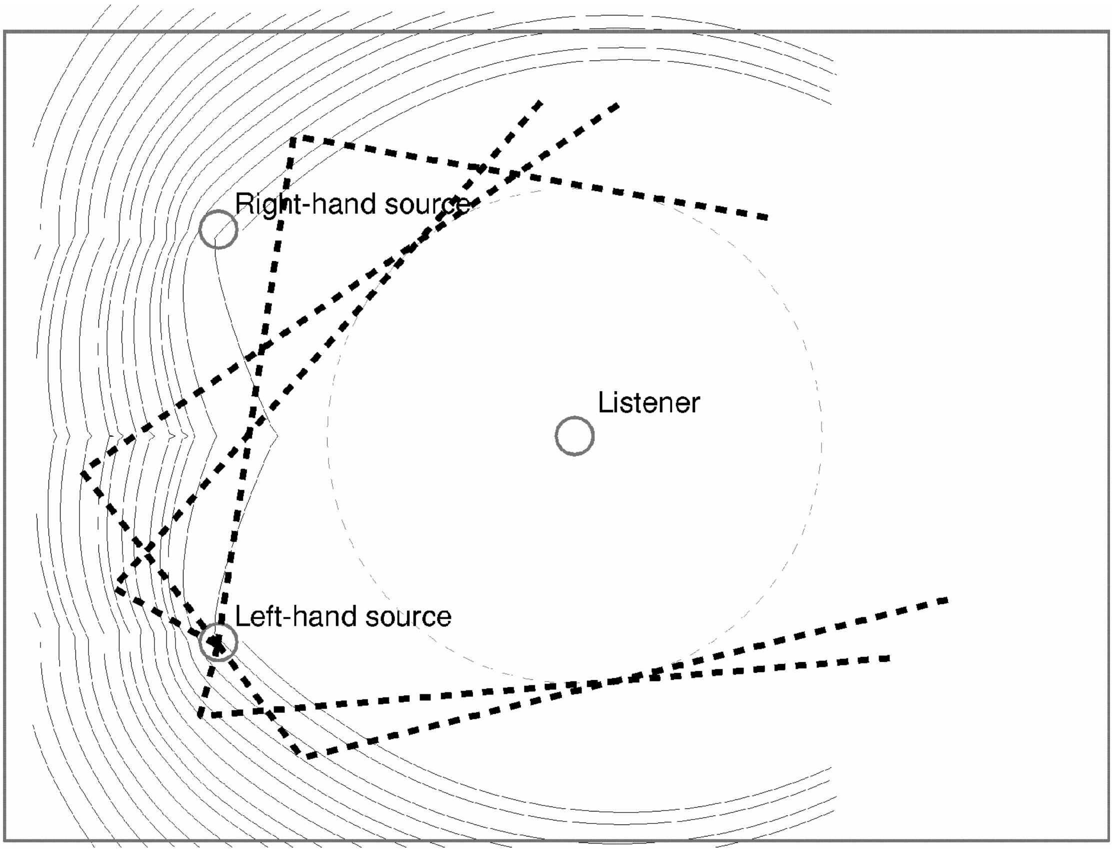

Figure 1. Room layout for reflection control.

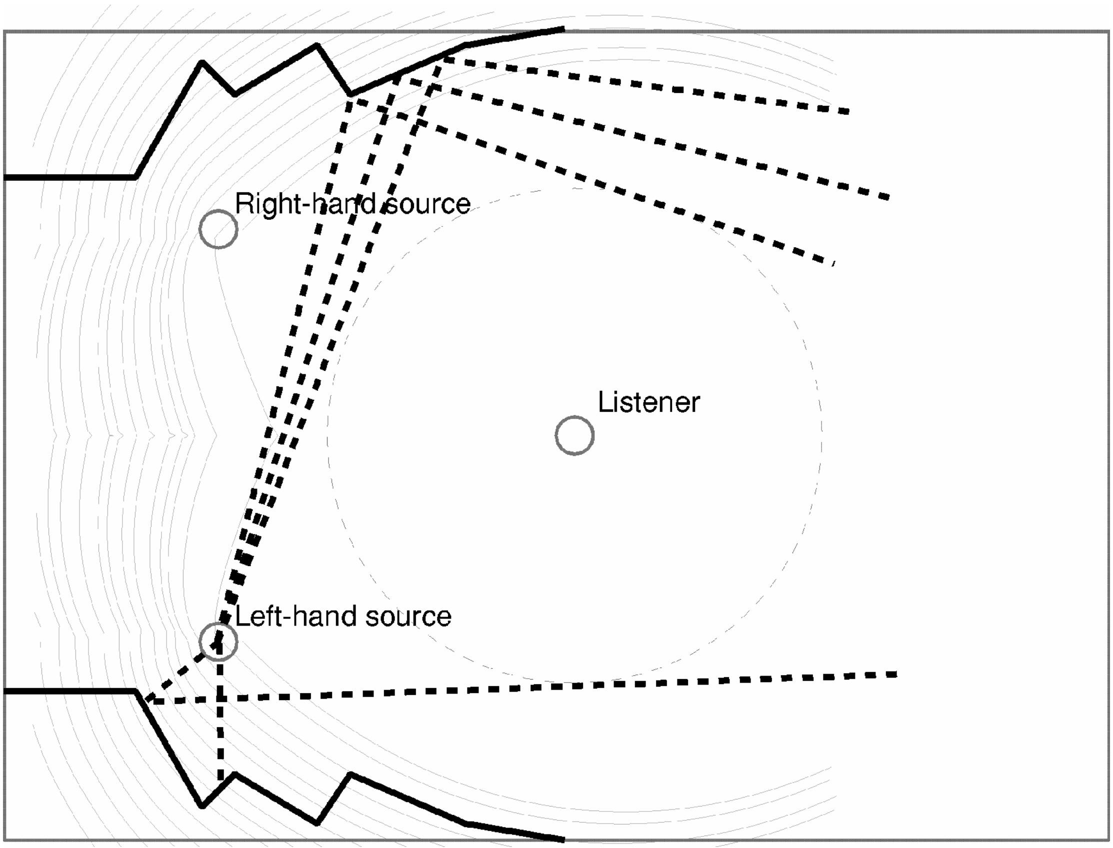

Figure 2. Room layout for reflection control with flats and reflections.

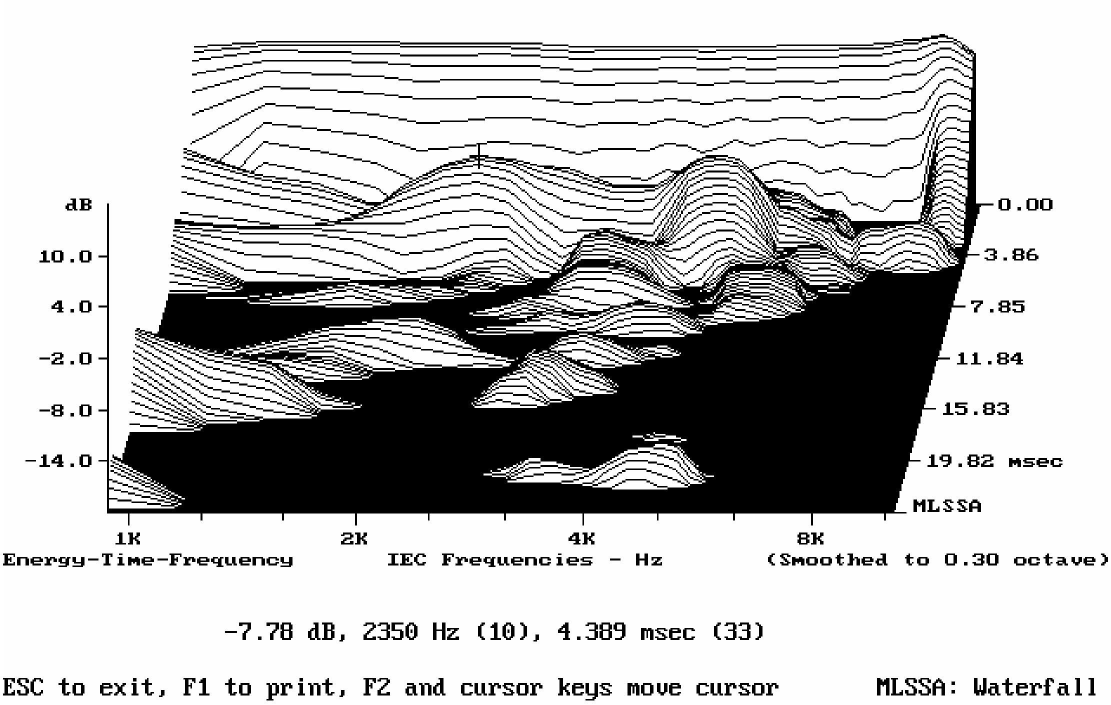

Figure 3. Measured results from EH1 - left speaker

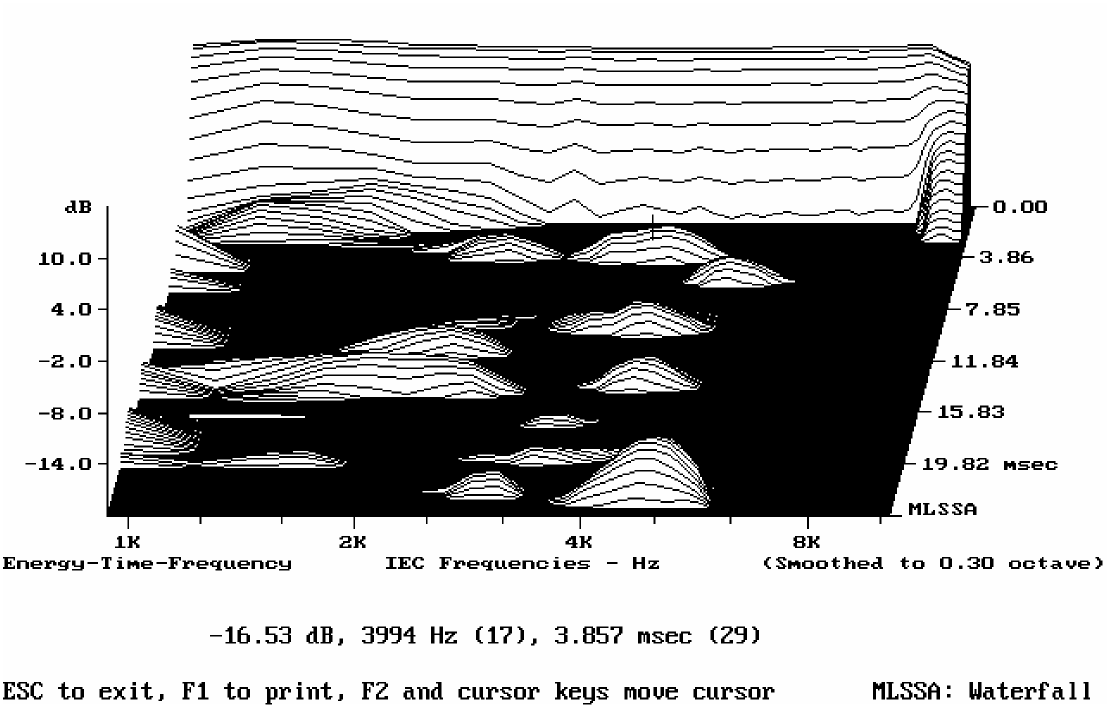

Figure 4. Measured results from prototype Controlled Image Design room.

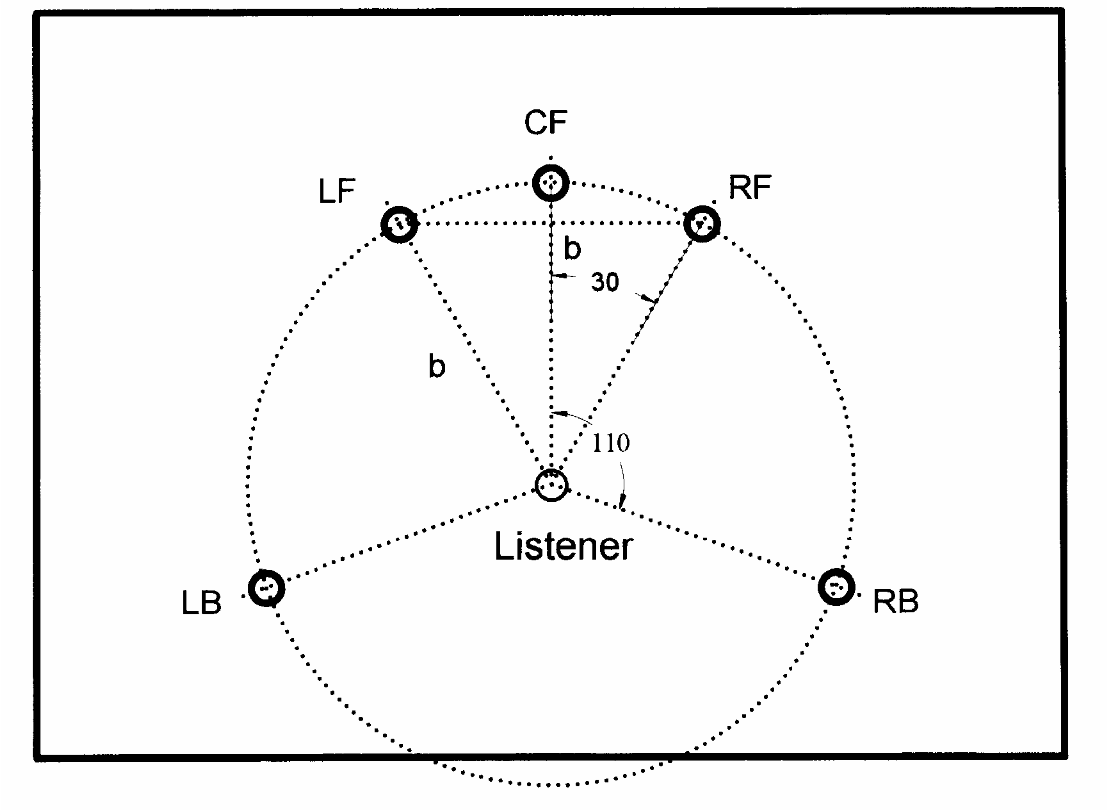

Fig. 5. Loudspeaker layout for five-channel multichannel sound from Ref. 2.

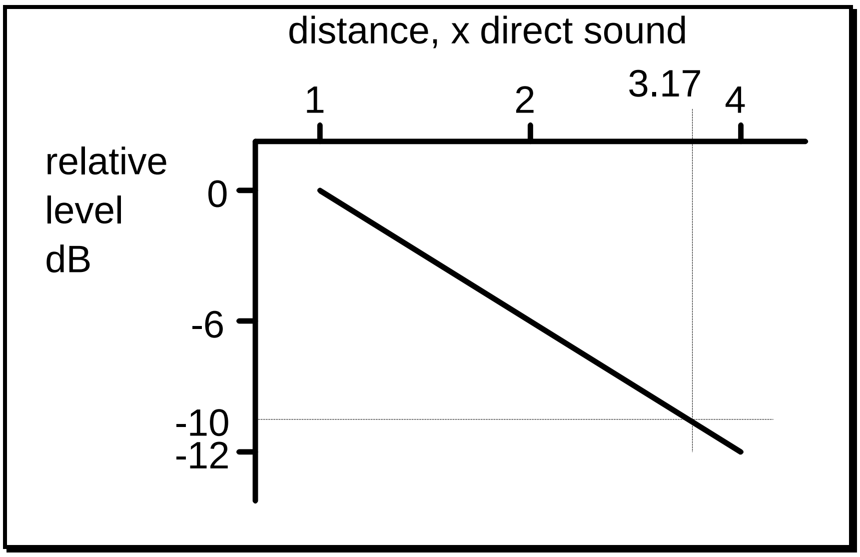

Fig. 6. Attenuation *v*. relative distance.

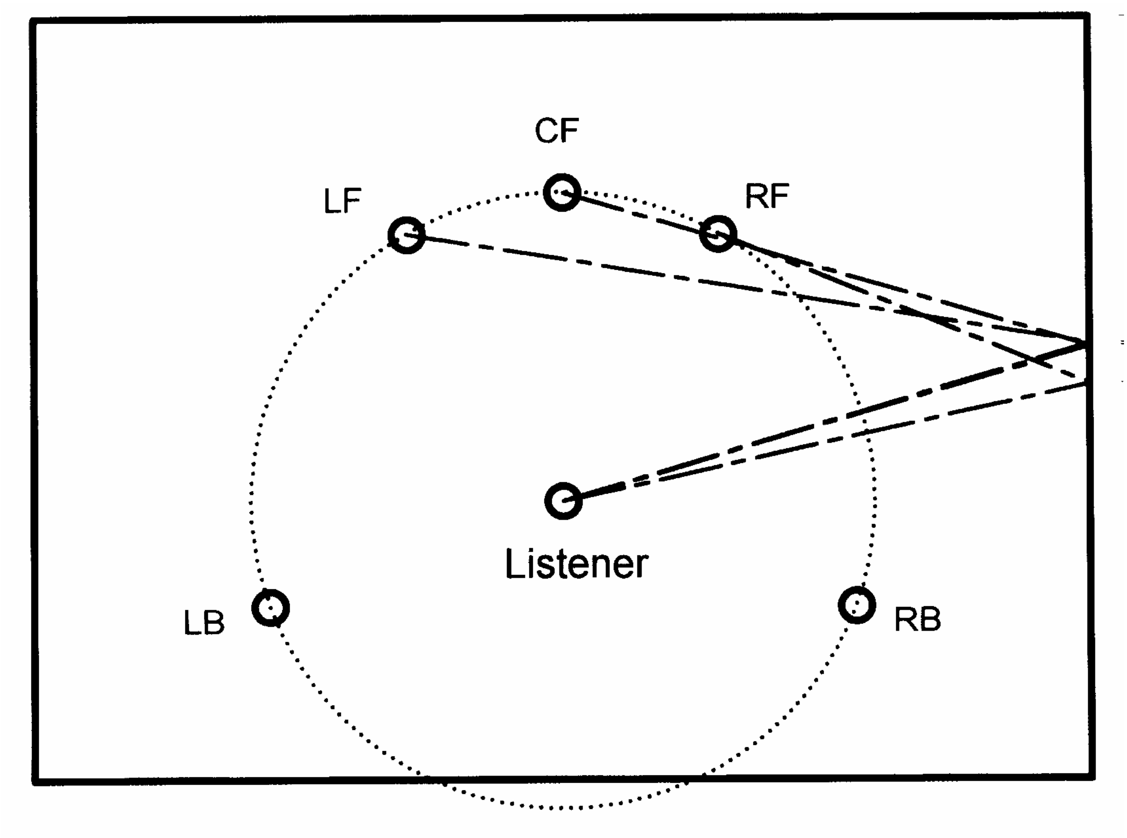

Fig. 7. Potential reflections from front loudspeakers via right-hand wall.

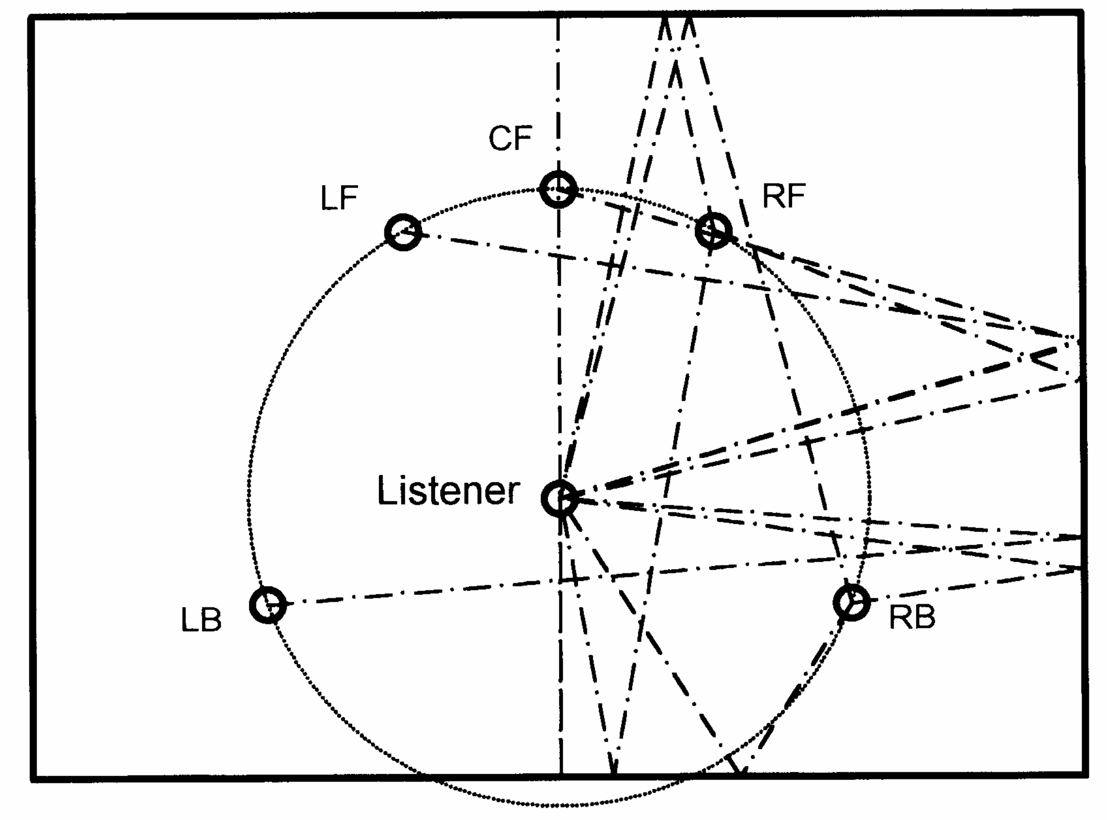

Fig. 8. Complete set of first-order wall reflections (for half-room).

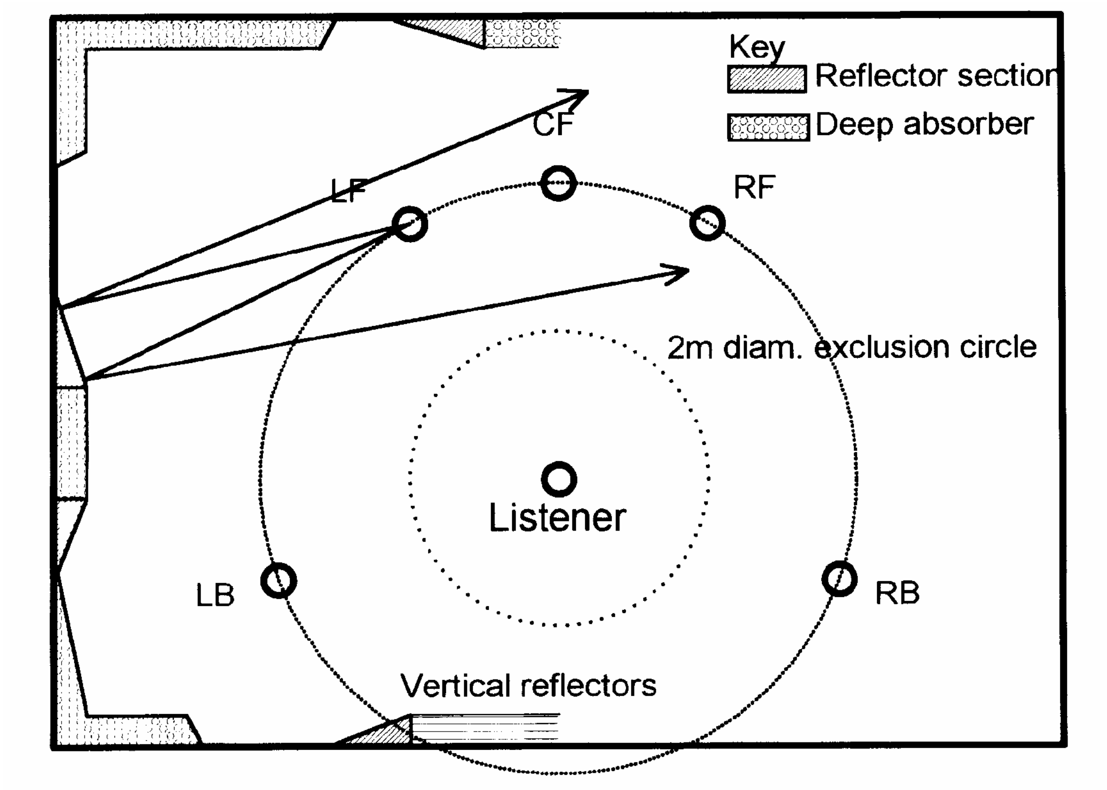

Fig. 9 Layout of reflecting panels and acoustic treatment, showing control of reflection from Left-Front loudspeaker.

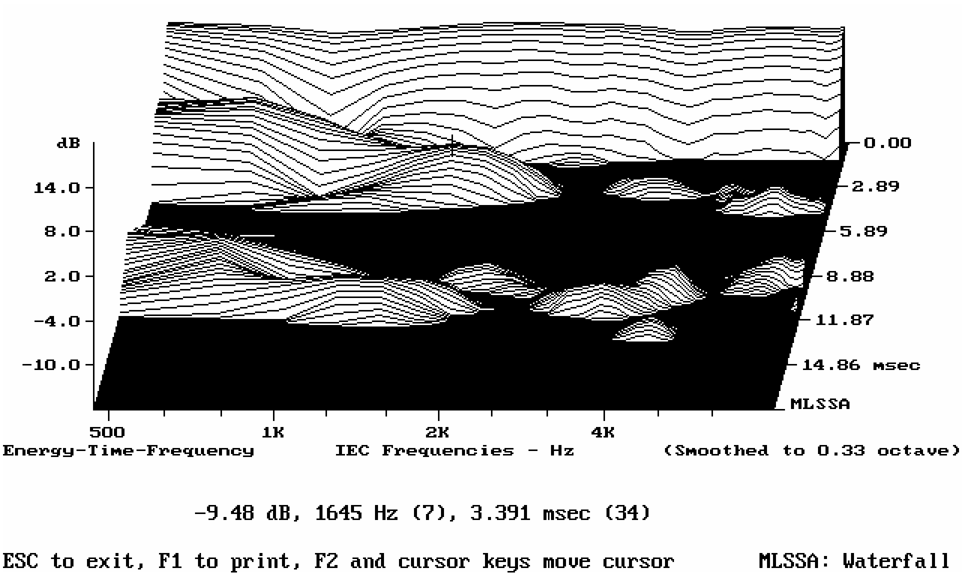

Fig. 10. Time-frequency response, Left-Front loudspeaker, initial construction.

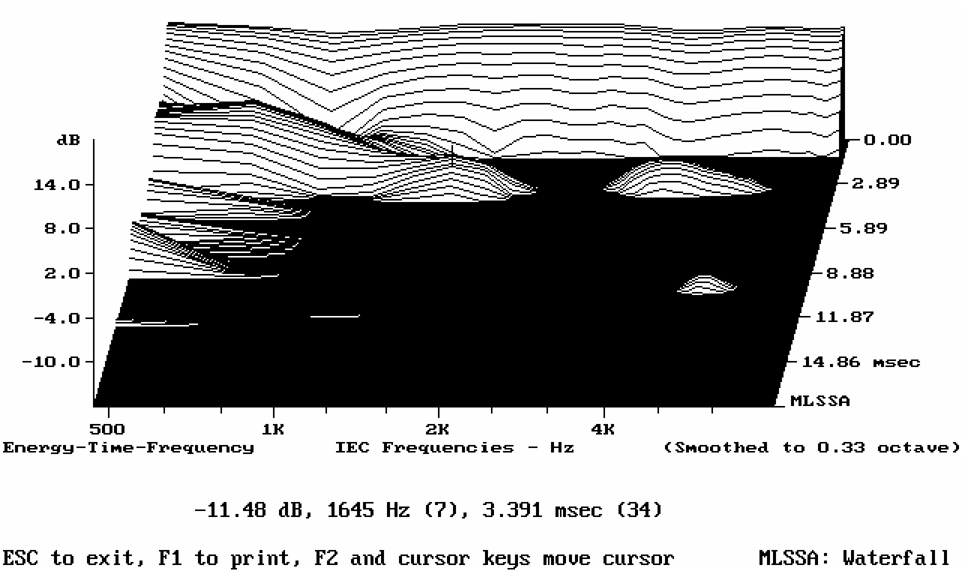

Fig. 11. Time-frequency response, Left-Front loudspeaker, after replacement of rear wall diffusers.

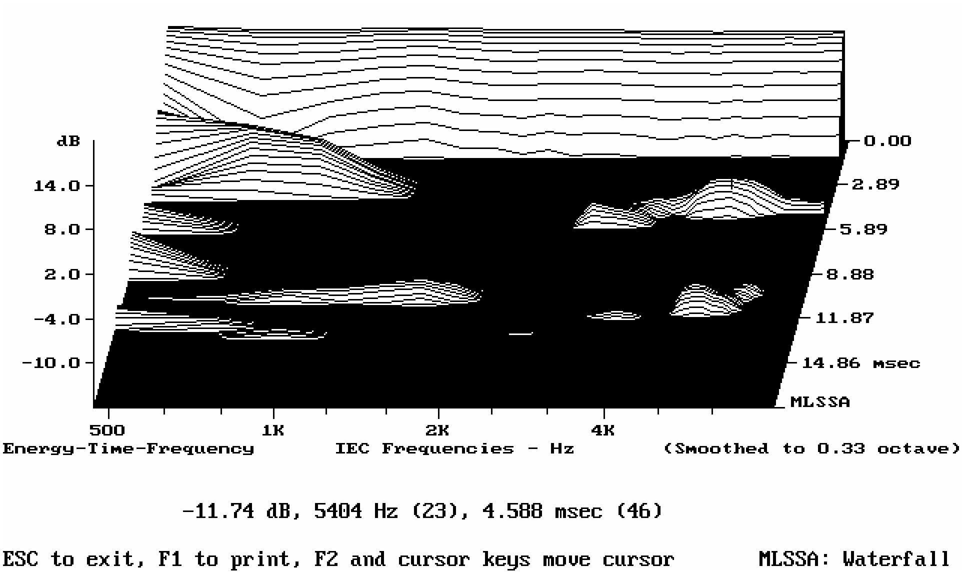

Fig. 12. Time-frequency response, Left-Front loudspeaker, with floor reflector.

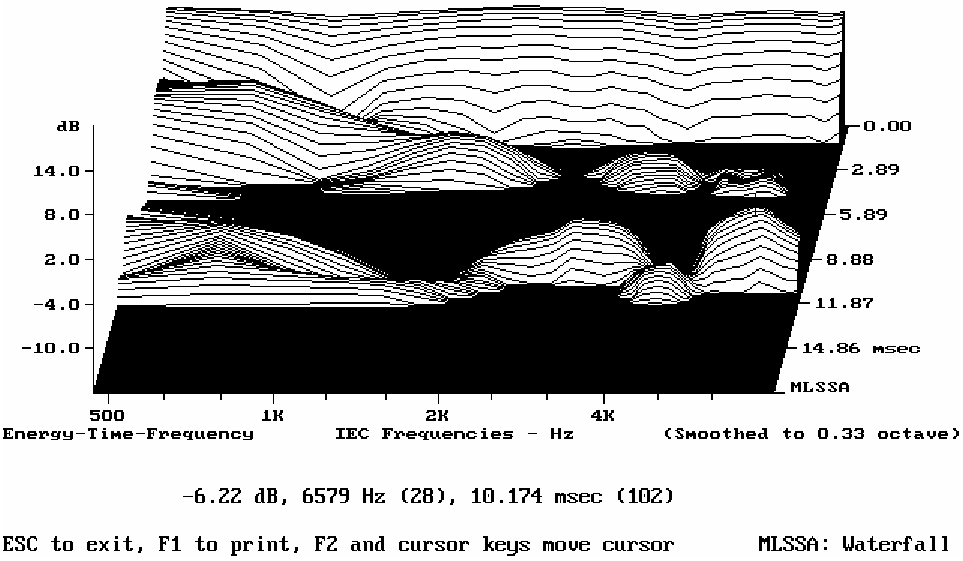

Fig. 13. Time-frequency response, Centre-Front loudspeaker, initial construction.

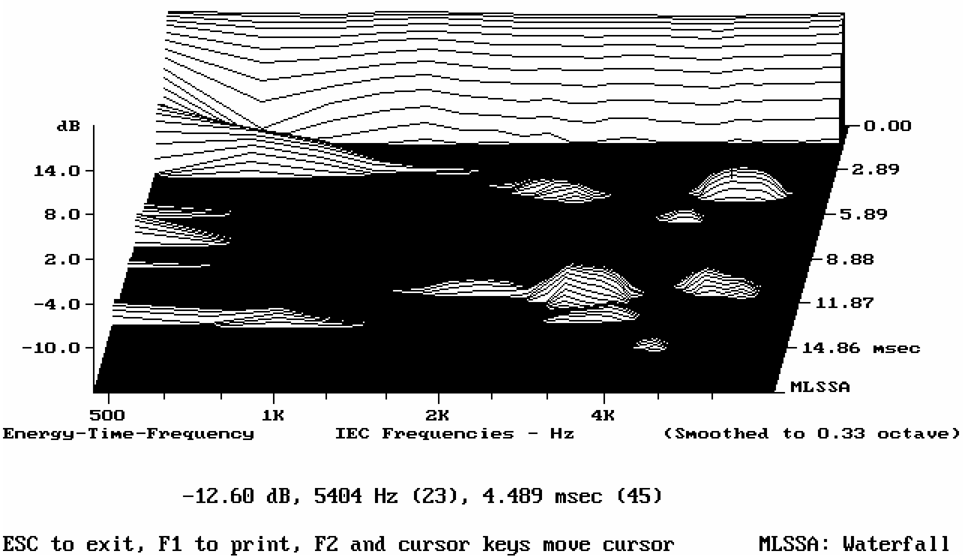

Fig. 14. Time-frequency response, Centre-Front loudspeaker, after replacement of rear wall diffusers and with floor reflector