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A CONTROLLED-REFLECTION LISTENING ROOM FOR MULTICHANNEL SOUND.

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1. INTRODUCTION.

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

The auditioning of audio systems or processing algorithms also requires careful control of the listening conditions, if reliable and repeatable results are to be obtained. That is especially true for tests which are to be carried out by different organisations or where the tests will be spread over a significant period of time. Internationally-agreed test procedures may remain in use for many years, during which time the test arrangement may be dismantled and reconstructed. Especially in these days of international collaboration, tests are frequently carried out in more than one test location.

The three main components of the sound field in the vicinity of the listener are the direct sound, the early reflections and the later reflections which merge to form the reverberant field. All these components are functions of both time and frequency.

International Recommendations ITU-R BS.1116 [1] and EBU Rec. R22 [2] (Tech. Doc. 3276 [3]) include fairly closely-controlled acoustic parameters for listening rooms for critical listening. The room acoustic parameters included are the usual ones of room size, shape and reverberation time. In addition, the Recommendations specify the maximum permissible levels of early reflections. For multichannel listening, with four or more loudspeakers, the control of early reflections is complicated by the large number of combinations of potential sources and reflecting surfaces.

This paper describes the acoustic design of a new listening room intended to meet those ITU and EBU requirements. It does not include any discussion of the non-room related aspects of the Recommendations, such as the objective performance of the loudspeakers. It should also be noted that the two Recommendations are essentially identical, with only a very few differences. In all the following, any reference to the Recommendations should be assumed to refer to either one.

The new listening room was constructed at the BBC's Research and Development Department, in an existing double-skin 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 is believed to satisfy all of the acoustic requirements of BS.1116 and Rec. 3276 for a high-quality sound control room/reference listening room. It has already been used for a number of subjective test programmes involving multichannel sound systems.

The paper includes a brief discussion of the measurement of early reflections and gives the results of measurements made during the commissioning and adjustment of the room. It also illustrates some of the effects on early reflections of different means of reflection control.

2. ROOM SIZE AND SHAPE.

The limits given in the Recommendations for room size cover a reasonably broad range. In practice, for multichannel listening, the minimum floor area is set by the loudspeaker arrangement and the minimum permissible distances from the loudspeakers to the wall surfaces. The recommended layout for the five monitor loudspeakers for multichannel reproduction is given in Fig. 1 [4]. The admissible limits of the base width, b are from 2.0 to 4.0 m. If the monitor loudspeakers are not built into the wall, the distance of their acoustical centres from the surrounding walls should be at least 1 m.

Room proportions have a pronounced effect on the uniformity of low-frequency responses, especially in relatively small rooms. Historically, ratios of dimensions satisfying some 'golden' rule have been used. For the purposes of international standardisation, the use of a restricted selection of possible room shapes is not practicable. Few organisations would be able to justify the construction of special rooms and, in the case where the space available was larger, there would not necessarily be a benefit in reducing the size of the space simply to fit one or other special ratio (there is, in any case, little agreement about what the actual optimum shape is). Accordingly, as part of the work of drafting those Recommendations, a new approach was produced giving a much wider choice of reasonably-proportioned room shapes [5,6]. The specification does not necessarily lead to the optimum room shape for a given volume; it should, however, lead to room responses which are, in practice, not much worse than the optimum. Every room, of whatever shape, is ultimately subject to some degree of low-frequency response irregularity.

In the Recommendations, the limits for the room proportions are given by:-

$$1.1w/h \leq l/h \leq 4.5w/h - 4$$

where: l = larger dimension of floor plan
w = shorter dimension of floor plan and
h = height.

In addition, both l and w must be less than $3h$ and ratios of l, w and h which are within ± 5% of integer values should be avoided.

For the new listening room, the available space in the new room was only just adequate to meet the layout requirements for the recommended five-channel loudspeaker arrangement and to meet the requirements for the room shape. The room floor plan was 6.76 m × 4.94 m, giving a floor area of 33.4 m^2. The free height to the structural ceiling was 3.2 m. The room dimensions resulted in the following proportions :-

$$1.69\,(1.1w/h) \le 2.11\,(l/h) \le 2.93\,(4.5w/h - 4).$$

3. EARLY REFLECTIONS.

3.1 Measurement and specification.

The measurement of early reflections is a complex issue [7,8]. The unavoidable, combined time/frequency resolution limits mean that the simultaneous, complete identification of time delay, bandwidth 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 which 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 which 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 FT 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 filtered by a one-third octave filter in the frequency domain.

The Recommendations specify that levels of reflections earlier than 15 ms relative to the direct sound should be at least 10 dB below the level of the direct sound for all frequencies in the range 1 kHz to 8 kHz.

3.2 Control.

For multichannel listening, with five loudspeakers and six main room surfaces, there would be 30 first order reflections and 150 second-order reflections. Clearly, to achieve any significant degree of control it is necessary to reduce that large set of potential reflections down to something manageable. As a start, most of the second-order reflections can be ignored on the basis of the total time delay and natural attenuation with distance. With a loudspeaker/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 effects of normal spreading loss. In any reasonable room, that will eliminate all of the potential second-order reflections from the wall 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 5.5m, but those surfaces must be treated sufficiently to attenuate the first-order reflections anyway. All of this assumes that there is no acoustic focusing, no excessive off-axis source directivity and no other effects which could increase the relative reflection strength. In practice, some margin of additional attenuation would be desirable to accommodate those types of imperfections.

In all of the design of the reflection control for the new room, no allowance was made for any causes of additional attenuation. The loudspeakers were assumed to be omnidirectional. In practice, virtually all loudspeakers become significantly directional by 1 kHz. That would reduce the amplitudes of potential reflections from surfaces behind the loudspeakers. There are also some 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. 2 shows the loudspeaker layout in the room. It also shows the three potential reflections from the front loudspeakers via the right-hand side wall. It shows that the potential reflection points on the walls are clustered in comparatively small regions.

Fig. 3 shows the complete first-order reflection pattern for all loudspeakers (including the cross-reflections which may already be attenuated adequately by their path length). The clusters 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 [9,10,11,12]. 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 the panels would have projected much too far into the room. Initially, that 2 m wide area was treated with acoustic diffusers (2-D primitive root diffusers). However,

* Of course, real sound propagation does not follow the simple geometric pattern implied by this. It is subject to the rules of diffraction. This simple geometric approach is reasonably valid for obects of more than 0.5 m in extent and for those frequencies most important in the localisation of sound direction (1 kHz and above). In practice, it has been shown to be a realistic design procedure [9,11]. The use of a relatively large 'exclusion zone' allows for some degree of diffraction.

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 [13] and was actually observed in this case. Whether the result would have been subjectively significant is unclear, but they certainly caused the specification to be exceeded. The rear centre section was then replaced by a set of angled flat panels, which reflected the sound vertically, either down to the floor or up to the ceiling.

Fig. 4 shows the completed wall design (for half of the room), including angled panels, areas of both deep and shallow acoustic absorption (see Section 3 below) 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. The floor is also the surface which provides the earliest and strongest reflection. In this case, the only practicable solution was to provide large, portable floor units made of thick acoustic absorption with angled surfaces, to stand on the floor between the listeners and each of the sources. In fact, at the time of writing, those units had not been constructed and temporary provisions could be made when necessary. In practice, such units would be obstructive and cumbersome and would only be used for the most critical tests, where the exact letter of the recommendation had to be observed*.

The acoustic design for the ceiling (see Section 3 below) and its distance from the source / listener meant that reflections from the ceiling would be attenuated sufficiently without additional control.

3.3 Results.

Fig. 5 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 is not part of the specification - it is included here for completeness and to illustrate that lower-frequency 'reflections' cannot be controlled in this way (and probably not in any other way either). Also, in all of these MLSSA plots, the direct sound amplitude was equalised 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 Fig. 5, at about 1600 Hz / 3.4 ms (highlighted by the cursor), there is a peak reaching up to -9.5 dB due to the floor reflection. There is also a scatter of irregular peaks over the whole frequency range, at about 10 ms. The amplitudes are all well below -10 dB, but they were caused by the diffraction from the diffusers on the rear wall. At that off-axis angle, a flat surface would have produced no reflections. Fig. 6 shows the effect of replacing the diffusers by flat reflecting panels directing the sound to either floor or ceiling. Almost all of those peaks were removed (at least to below -16 dB). Fig. 7 shows the effect of

* It is the author's view that, because a floor reflection is so much part of everday experience, it may well be less disturbing than lateral reflections. There is, however, very little objective evidence for that.

placing a floor reflector/absorber between the source and the listening position. The peak in Fig. 5 was reduced to below -16 dB for frequencies above 1 kHz. The remaining low-frequency peak in the floor reflection response just meets the -10 dB / 1 kHz specification.

The effect of the diffusers is illustrated better by Figs. 8 and 9. Those are the responses for the Centre-Front loudspeaker, at an angle which would have given a strong reflection from a flat surface. Fig. 8 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. 9 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 Front-Centre loudspeaker.

4. REVERBERANT FIELD

After the positions of reflecting panels had been fixed, the remaining internal acoustic treatment was designed to meet the requirement for the overall (average) reverberation time, using conventional absorbing materials fixed to the floor, walls and ceilings. The wall design led naturally to an alternating sequence of deep and shallow treatment, as shown in Fig. 4. Fortunately, the requirements for low-frequency, mid-band and high-frequency acoustic treatment fitted almost perfectly with the available space. All of the deep treatment was in the same form as had been recently developed for the treatment of large TV studios [14]. It consisted of standard industrial metal studs (as used in metal-framed partition walls) 180 mm deep. The space was filled entirely with medium-density glass-wool. The front surface was covered approximately in equal proportions with metal mesh (for protection against accidental damage) and 1.0 mm steel sheet to provide low-frequency absorption. The shallow treatment was 3 mm perforated hardboard over 25 mm glass-wool. It was intended to provide selective mid-band absorption to control frequencies around 400 Hz (where there was a lack of overlap in the low and high frequency absorption responses of the deep treatment). The whole wall surface was then covered with stretched fabric, spaced 6 mm from the main treatment to avoid excessive high-frequency absorption.

The ceiling was treated with modular acoustic boxes. That was partly to give a degree of flexibility to adjust the final reverberation time. The boxes were also much easier to fix to the ceiling than the type of treatment used for the walls. The visible ceiling surface finish was formed from stretched fabric on thin frames, supported by a standard 1200 × 600 mm suspended ceiling grid, 500 mm below the structural roof. The combination of fabric, 600 mm airspace and acoustic boxes gave more than adequate attenuation of the first-order ceiling reflection.

The floor treatment consisted of standard carpet tiles laid on a heavy, access floor. The first-order floor reflection was significant and required additional, moveable absorbers / reflectors, as described in Section 2 above.

According to the Recommendation, the nominal reverberation time, T_m, for the 1/3-octave bands from 200 Hz to 4 kHz should be in the range 0.2 - 0.4 s.

Ideally, $T_m = 0.25(\textit{Room Volume / Ref. volume}\ (100))^{1/3}$ s

For this room of 106 m^3, that gives a nominal target value of 0.255 s.

Fig. 10 shows the final reverberation time characteristic, together with the tolerances. The final average value was 0.236 - 0.238, depending slightly on the measurement technique.

5. BACKGROUND NOISE.

The Recommendations require that sound pressure level of the continuous background noise should not exceed NR 15 and should preferably not exceed NR10. It should not be perceptibly impulsive, cyclical or tonal in nature. In the existing room there was no possibility for improvement of the sound insulation. The room had, in any case, been in use for many years as an experimental listening environment, with only very occasional disturbance from nearby vehicle movements (onsite, and therefore subject to control) and overflying aircraft.

The main contributions to the room background noise came from the heating and ventilation system and from the fluorescent light fittings installed as working lights. When the room is in use as a listening environment, an alternative incandescent lighting system, incorporating dimmers and producing much less noise, are used.

Fig. 11 shows the background noise level with ventilation and technical power on. It just manages to meet NR15. Fig. 12 shows the background noise level with all power off. It easily meets NR10. The ventilation system is fully variable, and can be set to produce somewhat lower noise levels, or switched off altogether if no heating is required. The noise levels at all frequencies above 630 Hz were, by a large margin, entirely due to the inherent electrical noise level of the loudspeaker amplifiers radiated by the loudspeakers. (The loudspeaker gains at the time were set to produce the standard output levels of 85 - 10log(n) dB for reference input level. [1,3]).

6. REFERENCES

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7. ACKNOWLEDGEMENTS

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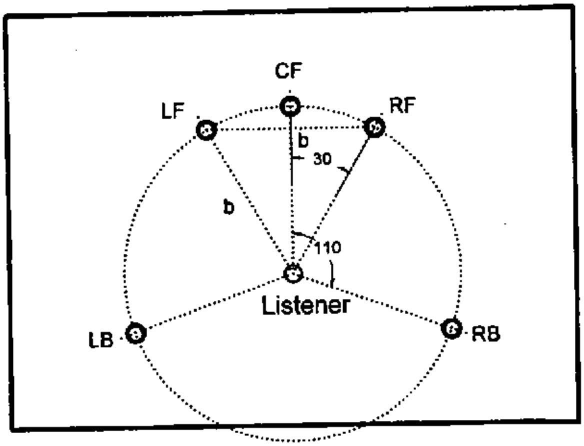

Fig. 1. Loudspeaker layout for five-channel multichannel sound.

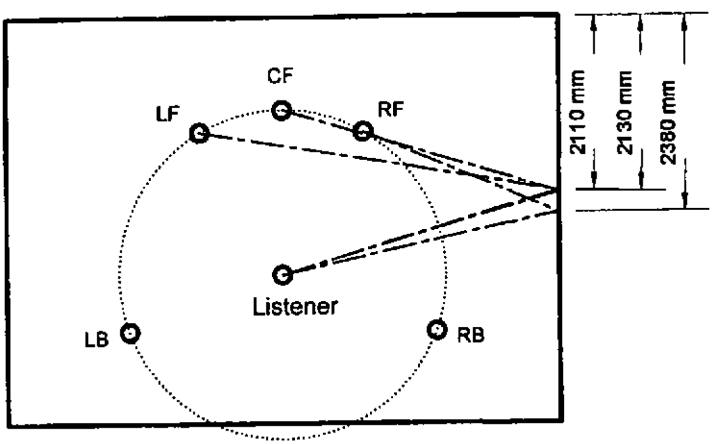

Fig. 2. Potential reflections from front loudspeakers via right-hand wall.

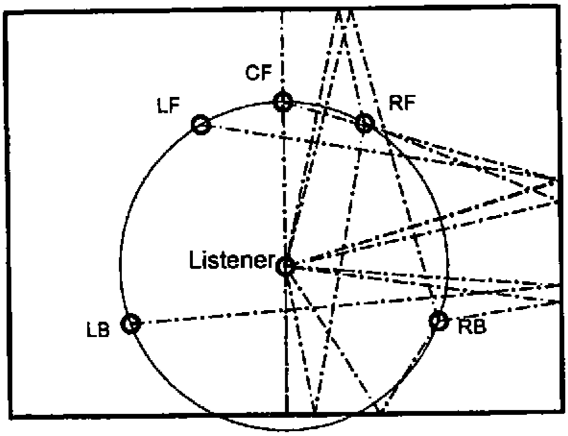

Fig. 3. Complete set of first-order wall reflections (for half-room).

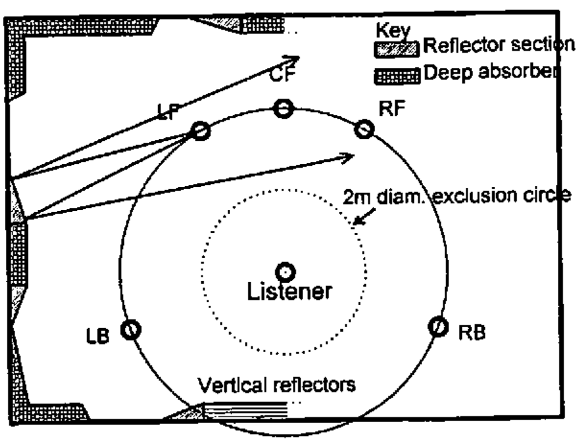

Fig. 4 Layout of reflecting panels and acoustic treatment, showing control of reflection from Left-Front loudspeaker.

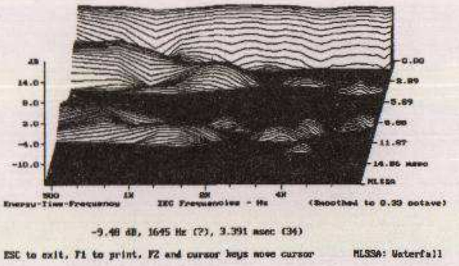

Fig. 5. Time-frequency response, Left-Front loudspeaker, initial construction.

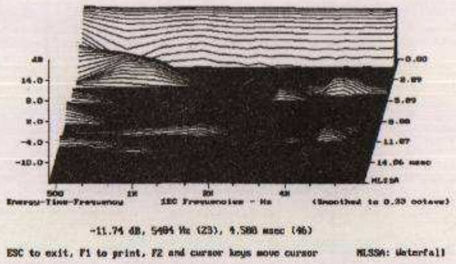

Fig. 7. Time-frequency response, Left-Front loudspeaker, with floor reflector.

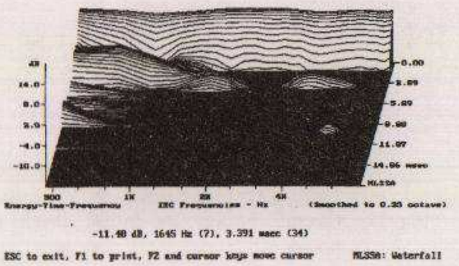

Fig. 6. Time-frequency response, Left-Front loudspeaker, after replacement of rear wall diffusers.

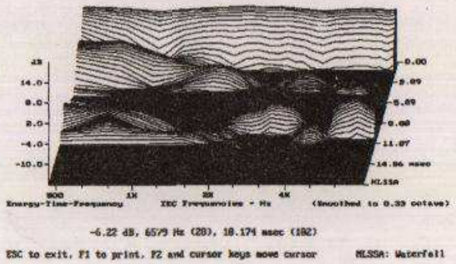

Fig. 8. Time-frequency response, Centre-Front loudspeaker, initial construction.

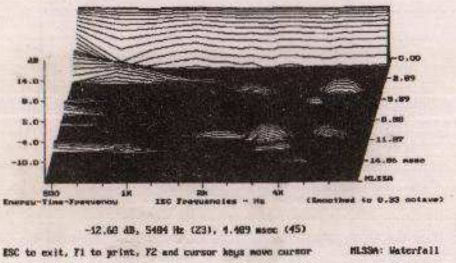

Fig. 9. Time-frequency response, Centre-Front loudspeaker, after replacement of rear wall diffusers and with floor reflector

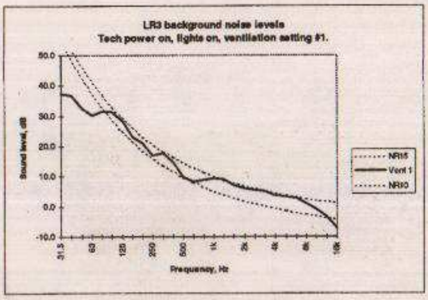

Fig. 11 Overall background noise level, ventilation and technical power on.

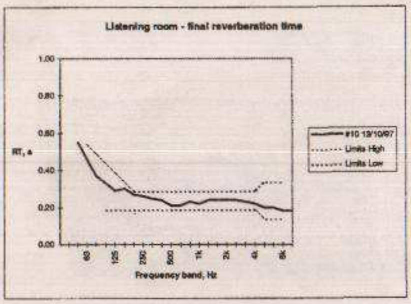

Fig. 10. Overall reverberation time, with tolerances.

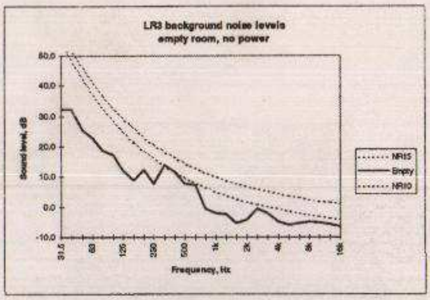

Fig. 12 Overall background noise level, all power off.