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THE CONTROL OF EARLY REFLECTIONS IN STUDIO CONTROL ROOMS

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1. INTRODUCTION.

In the earliest days of studio control rooms, the main design aim was to achieve some representation of the final listening environment — indeed, studies were carried out into typical living room conditions[1,2]. Considerations of increased accuracy of listening and more analytic conditions ensured that the control room design reverberation time was somewhat lower. This led to a criterion for control rooms of all kinds of about 0.3s reverberation time.

With the coming of stereophony, the disturbing effects of early reflections became particularly apparent. In the time-interval up to about 10–20ms after the arrival at the listener of the direct sound, such reflections may cause distortion of the perceived sound and significant image shifts. The basis of much control room design for stereophony has been the reduction of these discrete early reflections by means of sound absorbing materials.

The extent of this 'control' has increased progressively up to the present time, leading to to excessively short reverberation times and to rooms which are subjectively 'dead' and oppressive to work in. Measured mid-band 'reverberation times' of less than 0.15s have frequently been encountered.

One of the more recent developments is the concept of placing the listener in a so-called 'reflection-free zone' — actually, a region of the room where the early reflection amplitudes are rather less than they would have been otherwise[3,4,5]. The underlying concept is the use of redirection and diffusion to reduce the early reflection amplitudes in the vicinity of the listener. By this means it is possible, in principle, both to improve the image sharpness and make the stereophonic effect less dependent on the room. Because the key factor in achieving this is the use of non-absorbing surfaces, a 'dead' acoustic is not an inevitable consequence and, indeed, the designer has considerable freedom in the choice of reverberation time. Thus the oppressive feeling can be avoided and conversation within the room made easier and more comfortable, as well as more closely approaching the domestic room conditions (in one respect at least).

The design of the reflecting surfaces is non-trivial, especially in rather small rooms. A computer-based method, Controlled Image Design, was developed and a prototype room constructed to demonstrate the principles. As a result of that experimental work, the redevelopment of three main studio areas in Broadcasting House, London and a new post-production area in Bush House were based on these principles.

These rooms have now been completed and extensive measurements have been carried out in them. The first measurements revealed some minor errors in the implementation of the design, relating to reflections from the top surfaces of the mixing consoles, an effect which, as well as being of the utmost significance, is a potential problem in any monitoring area, whatever the basis of the design. After the necessary (minor) remedial work, further measurements showed that the acoustic objectives had been largely achieved in all three rooms. Listening tests indicated that the stereophonic image quality was excellent. The design reverberation times had been achieved and, as a consequence, the rooms were subjectively less oppressive.

This paper presents examples of measurements from both before and after the remedial work. Some aspects of reflections from the top surfaces of the mixing console and the problem of diffraction over the top edge of the mixing desk upstand are also discussed briefly.

2. DESIGN TARGETS.

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 listening experience in a room full of myriad reflections is, at best, doubtful. Some more recent work has dealt with larger numbers[8,9], but the difficulties arising from the vastly increased number of degrees of freedom of such tests make general interpretations difficult.

For this design method a very simple criterion was proposed as a target objective — namely 15ms and −15dB. That is, at the listening position, there should be no sound energy components higher than −15dB relative to the direct sound in the period up to 15ms after the arrival of the direct sound. This was not supposed to be a precisely justifiable and objectively supportable criterion. Rather, it represented a goal which was realistically achievable in reasonable sizes of room and which encompassed much of the objective information available about the disturbance of stereophonic images. It is a convenient simple rectangle in time and sound level. The setting of these design targets pre-dates, but is compatible with, recently-released work on the audibility of multiple reflections[9]. What is meant acoustically by "the listening position" is discussed below.

3. THE DESIGN METHODOLOGY.

Beginning with an empty shell and traditional triangular loudspeaker/listener layout, it is necessary to position surfaces which will reflect the sound, but not in the direction of the listening position. An important simplification is to deal with the reflecting surfaces in only two projections — plan and elevation. This constrains the reflecting surfaces to be parallel to one or other of the principal axes of the room shell.

The first step in the design process is to specify the principle listening position and the listening area. Geometrically, this is trivial. However, the propagation of sound does not obey the rules of Euclidian geometry and is, in practice, dominated by diffraction effects at most audio frequencies. Nevertheless, the optical analogy is useful and reasonably valid for those frequencies important for the creation of the stereophonic illusion. The effects of diffraction will ensure that some sound energy is reflected in non-specular directions. Thus, it is necessary to consider a zone around the nominal listening position, large enough to make these effects meet the chosen criterion at all frequencies important for stereophony.

To help to achieve this, a computer program was developed to assist in the positioning of reflecting surfaces. Fig. 1 shows an outline design for the plan of the prototype room. Beginning with the locations of the loudspeakers and the main listening position, the CAD system generates curved lines showing the critical angle for a surface at any point. That angle is the limiting angle which will cause any reflected sound path from either loudspeaker to be just tangential to the circle around the main listening position. Based on those curved lines, flat reflecting surfaces can be positioned so that they are, at worst, just tangential to the critical angle. In most small rooms, this requires steps to be made between the flat surfaces. The steps are filled with highly effective acoustic absorption.

The angled, reflecting surfaces also have other benefits. In the past, large hard surfaces such as observation windows, have been tolerated out of necessity, despite their generally detrimental acoustic properties. With the Controlled Image Design, any of the reflecting surfaces may be windows or cupboards or doors. Much of the paraphernalia associated with a modern control room 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 and easier to keep clean.

4. 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 10m to 15mm. At the longer end of this range, even the room itself is not large relative to the wavelength. This leads to well-known, low-frequency problems with room modes[10,11,12,13] which are not directly relevant to stereophonic listening and not the subject of this work. At the shorter end of the range, many objects are large relative to the wavelength and sound will propagate and be reflected in a geometric manner.

The interesting region is in the middle – what frequencies are involved in the stereophonic aspects of listening and how much need 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 stereophonic content is less critical.

A frequency of 500Hz is equivalent to 650mm wavelength. Reflections from an object of about that size, for example an element of a complex reflecting structure, would be seriously diffraction limited and would produce a considerably wider spread of reflected energy than simple geometric considerations would suggest. The 'ray-tracing' approach should be regarded as no more than a rough guide to the actual acoustic conditions. The combined effect of this diffracted energy is what limits the degree of exclusion of early reflected energy from the region around the listening position.

Because of the diffraction effects, the size and location of the circle of control 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 of the elevation, because in most rooms the height is more restricted than either length or width. In reasonable sizes of room (that is, more than about 5m wide and 3m high) solutions for circles 3m in diameter in the plan and 2.5m diameter in the elevation are feasible.

The design relies entirely on the presence of the 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 inherently absorbing, some acoustic treatment must be located in that zone. The shape of the space behind the desk will usually ensure that any sound energy which eventually emerges is reasonably diffused.

5. PRACTICAL IMPLEMENTATION

Initially, a prototype room was constructed to investigate whether this controlled reflection approach had any real acoustic or other benefits. The first results from this room were very promising and the room was demonstrated to and assessed by broadcasters, architects and managers. The reactions were generally favourable. Based on the characteristics of the prototype room, decisions were made to redevelop three studio control rooms in Broadcasting House and one post-production control room in Bush House on the basis of the Controlled Image Design methodology. Three of designs were based on the normal BBC practice using free-standing loudspeakers. The fourth was based on built-in loudspeakers. There is no fundamental difference in the design procedure for the two types.

6. MEASUREMENTS.

Using Fourier Transforms of the measured impulse response, some estimates of the 3-dimensional time/frequency/level response of rooms can be made. The resolutions are inevitably limited by the fundamental restrictions on time-frequency measurements but, accepting these and making some simple assumptions (mainly that the frequency responses of reflections are fairly uniform), it is possible to obtain meaningful estimates for the higher frequencies. This enables isolated individual reflections to be identified.

Fig. 2 shows the results of such a measurement for a conventional BBC-design control room, considered to be typical of that type of design. Reflections are clearly visible from equipment trolleys (≈2ms), ceiling (3–4ms), side walls (4–6ms), rear wall (≈12ms), etc., despite the use of nearly 100% coverage of very effective acoustic treatment. It is true that the angles of incidence in all of these cases are close to glancing angles but calculations based on level differences (including corrections for additional path length) suggest an effective absorption coefficient of around 0.6–0.7.

Fig. 3 shows the results of the same kind of measurement for the prototype Controlled Image Design room. A small group of 'defects' are evident between about 9 and 12 ms. Their amplitudes are about -14dB relative to the direct sound. Investigation revealed that they were due to corner reflections from minor untreated elements on the side walls and occurred because of the prototype nature of the room and because the internal finishes were incomplete.

In both of these figures, the direct frequency response of the loudspeakers themselves has been removed (by computation). This was mainly because the measurements extended over a significant period of time, in different localities and, in some cases, with different loudspeaker types. This has led to slight artifacts in the responses presented here — namely, an apparent resonance at the upper end of the frequency range. This slight emphasis of frequencies between about 9–10kHz should be ignored. It is not important to the main argument.

7. RESULTS FROM THE FIRST INSTALLATIONS.

Fig 4 shows a photograph of part of the first installations. Extensive measurements were carried out in all rooms on completion. In the case of the Broadcasting House rooms, these showed that the loudspeakers had been positioned about 240mm too high, causing direct, geometric reflections from the desktops in two rooms.

Fig. 5 shows the ET response for one loudspeaker in one of the rooms. Three main features are evident. The first is a reflection at about 1.2ms/-13dB. This was the near-direct desktop reflection, the amplitude being limited by diffraction over the top of the desk upstand. The second main feature, at 7ms/-15dB, was second-order reflection via the top of the desk upstand and a room ceiling panel. This was quite surprising because the upstand top surface was only about 120mm wide and angled so as not to cause a first-order reflection at the listening position. The third main feature is the group of reflections beginning at about 12ms. This was caused by furniture and equipment in the room.

Fig. 6 shows the ETF response for the same measurement. The second-order reflection feature at 7ms is clearly visible and, as would be expected from the mechanism involved, strongly frequency dependent. It has a maximum value of about -8dB relative to the mean value of the direct sound. The later reflections are also clearly evident and also are strongly frequency dependent.

The most striking feature of Fig. 6 is the unevenness of the 'direct' sound. This results from the interference between the direct sound and the desktop reflection. The path length difference of 1.2ms corresponds to cancellation at 420Hz and all odd multiples. This is clearly consistent with the measured direct sound. The shape of the early response also shows severe irregularities on the 'shoulder', that is, at about 2ms. All of these early features are related to the reflection from the main working surface of the desk.

8. RESULTS FROM THE SECOND SERIES OF MEASUREMENTS.

After the measurements described in Section 7 had been carried out, the loudspeakers were lowered, by 240mm, to the correct design height.

Figs. 7 and 8 show the responses for the same room and loudspeaker as for Figs. 5 and 6. In Fig. 7, the ET response shows that both the desktop reflection and the anomalous reflection at 7ms have been essentially eliminated. All of the other reflections, in the range from 12ms upwards have been significantly reduced, to the point where they are all (with one exception) at or below -20dB. The one exception is at a time delay of 28ms — well outside the intended control range. The ETF response, Fig. 8, also shows significant improvement. The large reduction in the desktop reflection resulted in a more uniform direct sound response. Some reflections at 4-6ms just rise above the -16dB floor of the plotted response. Another group of relatively narrowband reflections occurs at 12-16ms, at maximum levels about -12dB relative to the direct sound. These are unlikely to be audible[9]. The severe irregularity on the 'shoulder' of the direct sound has also been virtually eliminated.

9. CONCLUSIONS.

The development of a method for controlling early reflection amplitudes in studio control rooms has been described. The computer-aided design program, developed as part of this work, greatly simplifies the task of ensuring that all of the geometric acoustic principles are satisfied. However, the real acoustic result is modified by the diffraction effects at the lower end of the important stereo frequency range. The initial targets of -15dB and 15ms were shown to be not quite achievable in the experimental room.

Four installations based on Controlled Image Design have been completed. The first measurements showed that the main objectives of the design, the reduction of all reflected sound energy at the main listening position in the period up to about 15ms after the arrival of the direct sound to levels below -15dB relative to the direct sound, had essentially been achieved. However, an error in the fixing of the height of the loudspeakers had, in all cases, led to direct or nearly direct reflections from the main working surface of the mixing desks. After this had been corrected, the results showed that the objectives had been adequately achieved, even if there remained some minor shortfalls from the design specifications.

The problem of reflections from the mixing desk top surface is important, not only for the Controlled Image Design, and is complicated by the effects of diffraction over the top edge of the desk upstand.

10. REFERENCES.

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11. ACKNOWLEDGEMENT

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APPENDIX 1 - DIFFRACTION AND DESKTOP REFLECTIONS.

The usual form of construction of a mixing desk (console) incorporates a main working surface which is essentially planar, with a rear upstand to carry level-monitoring meters. Although the surface is broken by control knobs and other irregularities, it remains an effective reflector for sound energy components with frequencies between about 1kHz and 5kHz — those frequencies of most importance for stereophony. It is a simple matter to position the desk and loudspeakers such that a direct geometrical reflection is avoided. This usually requires the loudspeakers to be positioned fairly low down in the room and may rely on the desk upstand to provide a degree of screening. The separate sources of a loudspeaker must be considered individually — for this purpose the separate drive units do not act together to produce an overall response.

However, sound propagation is a wave function subject to diffraction effects. To some extent, the sound wavefronts will be distorted by the desk upstand so that they are deflected towards the main working surface. The geometrical 'shadow' zone may in fact reflect sound energy towards the listener. Conversely, in the 'non-shadow' zone, the sound energy levels will be less than they would be in the absence of the obstruction.

The subject of diffraction is too complicated for treatment here. However, some measurements were carried out to determine, in the context of a reflection from the top surface of a mixing desk, the approximate magnitude of the effects. For the case of the limiting angle, where the direct sound path just grazes the edge of the obstruction, it was found that diffraction reduced the level of the sound by about 5dB. This was reasonably independent of frequency over the range 1kHz - 10kHz. Thus, for a just geometric reflection the sound energy could be assumed to have an excess attenuation of 5dB, that is, in addition to the spreading loss and any loss at the reflection.

For the case where the obstruction projected into the direct sound path by 100mm (at a distance of 0.75m and for a listener-loudspeaker distance of 2.2m) the excess attenuation was about 10dB, although by that stage a moderate function of frequency (that is, −8dB up to 1kHz and then falling fairly uniformly to about −14dB at 10kHz).

APPENDIX 2 - MEASUREMENT OF TIME–FREQUENCY RESPONSES.

Audio systems are usually characterised by parameters which are functions of frequency. However, it is well known that the time domain function 'impulse response' theoretically contains all of the information necessary to specify a system fully (at least for a time-invariant one).

All of the meaningful interpretations of time domain events in the frequency domain (and indeed, most aspects of analogue circuit theory) are based on the Fourier Transform. This provides a means of translating between the two domains. It can be shown that the original time signal and a summation of the Fourier components are identically equivalent representations. For perfect frequency resolution the signal must exist, *and be available to the analysis*, for all past and future time. Conversely, an infinitesimal time event can carry no frequency information at all. In the real world, such ideal signals cannot exist. It is clearly sufficient to limit the time domain record to some reasonable length, such that the effects of the truncation are acceptable, in the context of the measurement. The product of time and frequency resolutions is a constant, approximately equal to unity.

The human hearing system is a complicated signal processing system, especially in the context of the stereophonic audio illusion. For reflections in a small room, the interval up to about 15ms is the most important. In the period up to 5ms reflections are not perceived directly but they can have an important influence on the sound quality because of interference with the direct sound.

Individual early reflections from room surfaces are likely to occur at about 3ms (from the ceiling), 7–8ms (from the side walls) and 15–20ms (from the rear wall). Thus, for measurement of the acoustical effects of early reflections in control rooms, it is desirable to be able to resolve time differences of the order of 1ms. Fortunately, the stereophonic illusion involves mostly the higher frequencies; the main image-forming frequencies are those from about 1000Hz upwards.

These factors lead to measurements based on time resolutions of about 0.5–2ms, resulting in frequency resolutions of the order of 0.5 to 2kHz. As a result, it is conceptually possible to identify and measure reflections with time and frequency resolutions high enough to be useful for the investigation of stereophonic systems.

There are two particularly useful measures of short-time responses — the so-called 'Energy-Time' response (ET) and the 3-dimensional Energy-Time-Frequency response (ETF). The first of these, the Energy-Time curve, is in fact the magnitude of the complex system impulse response. It is usually taken to represent 'instantaneous energy'. Although its precise theoretical interpretation is not that of "energy"[14], it does present a view of the time-domain response in which representations of discrete reflections are easily observed. In the ET results presented in this paper, the effective bandwidth of the measurement is approximately 500Hz to 8kHz and the plotted value is the *average response* over that frequency range.

The second useful measure of response is the 3-dimensional ETF, or 'waterfall' plot. For this, the start of a Fourier transform block is progressively shifted in time, to produce a series of frequency responses at different times. The resolution is limited by the length of the transform window, which must be short for reasonable time resolution and necessarily produces coarsely-quantised frequency-domain data. Despite these limitations, a useful display of reflections can be obtained. In the ETF results presented in this paper, the scale has been adjusted to show only the response down to -16dB relative to the direct sound. Also, a frequency-domain smoothing function, corresponding approximately to an one-third octave resolution, has also been applied, to reduce the 'comb filter' interference patterns. This makes the assumption that no features of the response involve effects with a bandwidth narrower than one-third octave.

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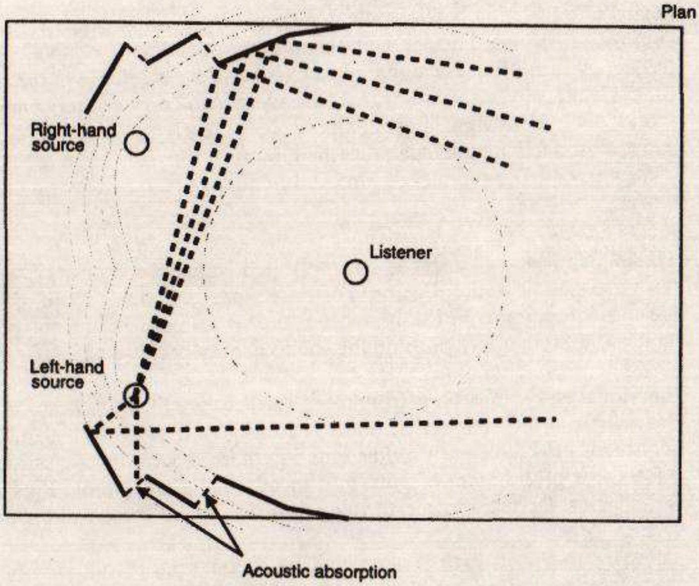

Fig.1 Controlled Image design for prototype room - plan view

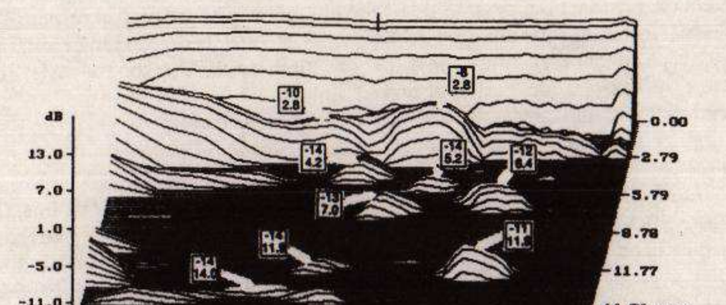

Fig. 2. Energy-Time-Frequency response of a typical control room design, based on acoustic absorption.

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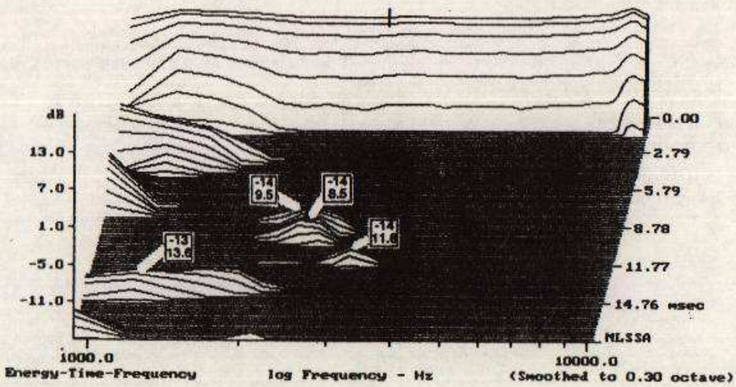
Fig. 3. Energy-Time-Frequency response of the prototype Controlled Image design room



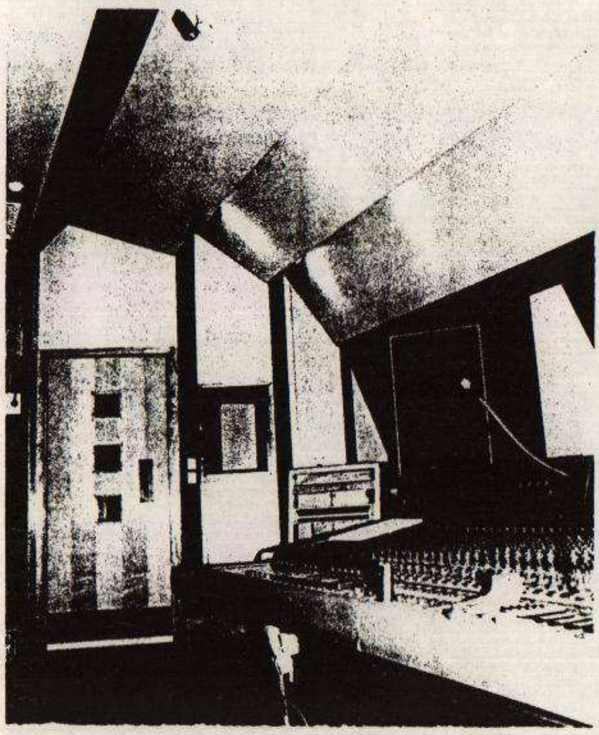
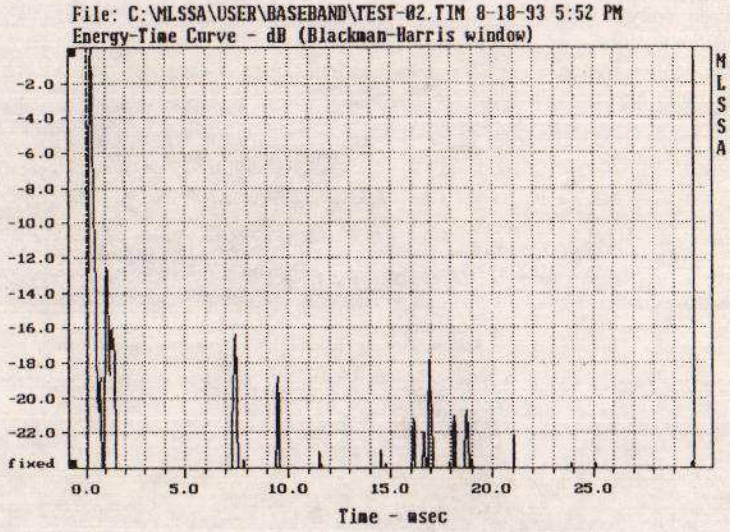


Fig. 4 Photograph showing part of a Controlled Image Design room in Broadcasting House.

Fig. 5. Energy-Time response of one room/loudspeaker, before change to loudspeaker height



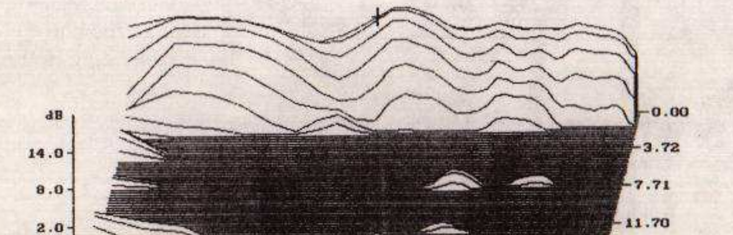


Fig. 6. Energy-Time-Frequency response of one room/ loudspeaker, before change to loudspeaker height

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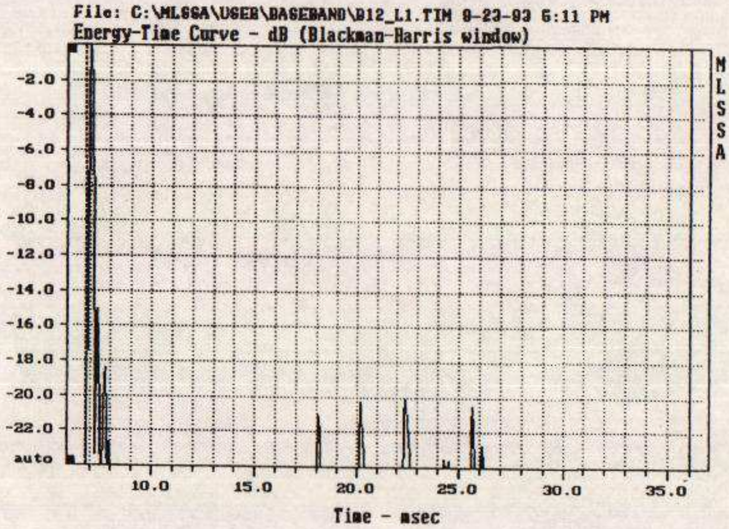
Fig. 7. Energy-Time response of one room/loudspeaker, after change to loudspeaker height



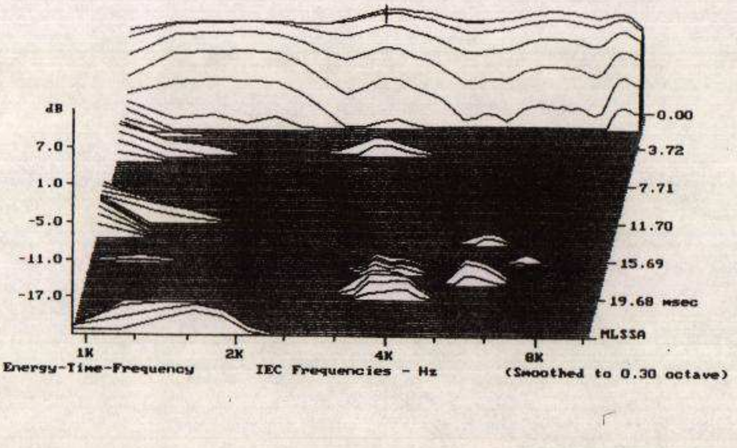


Fig. 8. Energy-Time-Frequency response of one room/ loudspeaker, after change to loudspeaker height