ANOMALIES IN THE CBS "SQ" STEREO/QUADRAPHONIC SYSTEM

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1. Introduction

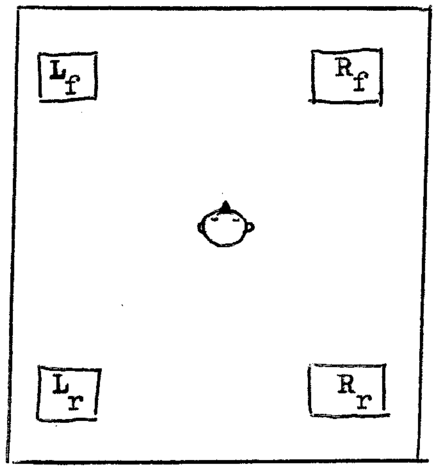
Of the various proposed systems of 2-channel 4-speaker stereo recording, the greatest interest has been excited by the CBS "SQ" system, on account of its excellent compatibility with mono and 2-speaker stereo reproduction, its initially impressive 4-speaker reproduction, and the degree of backing from serious commercial organisations such as CBS and **SONY**. It is the aim of this report to indicate certain serious anomalies in this system. Its apparent present success is due to: (i) the relative crudity of the present early state of the recording engineer's art in 4 channels, and (ii) the excellent engineering development work by CBS Laboratories in designing equipment to cope with the requirements of such crude recordings. However, a deep theoretical analysis indicates that the system has features which will render it incapable of coping with substantial improvements in the art of 4-channel recording beyond the present stage. It would be a serious matter if a 4-speaker stereo system were adopted that proved to be a great brake on further progress.

This account is not intended to be a criticism of the painstaking work of those involved in developing the "SQ" system, but to be a warning that the success of a devoted and competent research effort at the early stage of development of an art is no guarantee of its ultimate development into the best available means. It is clearly difficult to justify claims that a system cannot cope with future, and as yet untried, developments, and so it must be emphasised that the following comments are based on difficult methods of analysis using the full resources of modern mathematical theory. While the details justifying criticisms of the "SQ" system cannot be given here, a full theoretical analysis is available from the author in the preprint "Matrix Systems for Four-Speaker Stereo I".

2. Four-Speaker Stereo

For a number of good reasons, it has become customary to reproduce 4-speaker stereo via a more-or-less square or rectangular loudspeaker layout as in figure 1, using loudspeakers in the following positions: Left rear (L_r), Left front (L_f), Right front (R_f) , and Right rear (R_r).

Figure 1 :



The aims of 4-speaker stereo are three-fold:

(1). to reproduce sounds from the positions of each of the four speakers (i.e. the "gimmick" aim).

(2). to reproduce phantom sound images from other horizontal directions around the listener by making each of the sounds emerge simultaneously from more than one speaker at a time (i.e. the "surround sound" aim).

(3). to reproduce the effect of concert-hall ambience.

It is clearly easiest to accomplish these aims if the reproduced recording is made using four completely separate sound channels. Such a recording is termed "discrete", and each individual sound is recorded either on one channel only for aim (1), or in-phase on a neighbouring pair of channels for aim (2). In practice, aim (3) is proving to be the most subtle and difficult to achieve, although in principle one only need record each reflected concert-hall sound in its correct phantom position.

The critical listener to current 4-channel recordings will have noted that the most common shortfall from aim (2) has been the neglect of sound images lying at the two sides of the listener. It is common to record sounds at positions within the front side or within the back side of the square, but there has been a marked reluctance to exploit the full range of positions at each side. This has been particularly true of ambience information, which is often totally lacking at the sides.

The aims (2) and (3) can be accomplished by linear (so-called "matrix") systems using less than four channels, as there is no reason why a phantom image should not be produced by a sound emerging simultaneously from three or even four speakers, rather than just two. It can be shown that a 4-speaker system reproducing arbitrary horizontal directions needs to use at least three channels if all the sounds are to emerge in phase with one another, but if some degree of phase error between speakers is acceptable, then aim (2) can be achieved by a matrix system using only two channels of recorded sound. The CBS "SQ" system is such a 2-channel matrix system.

3. The CBS "SQ" System

The CBS "SQ" system proceeds by mixing the four channels of a discrete recording down into two channels via an encoder, and the resultant two--channel recording is played back via a decoder into four loudspeakers. If the 2-channel medium is, for sake of illustration, taken to be a gramophone record, then the sound of the front two channels L_f and R_f is recorded exactly as for ordinary stereo on the left and right groove walls (see figure 2). This is the basis of the "SQ" system's excellent compatibility with conventional stereo reproduction. Thus sounds recorded at front-centre appear in the groove as a horizontal (monophonic) stylus motion.

The rear channels L_r and R_r are recorded on the disc as clockwise and counter-clockwise helical stylus motions at ordinary audio frequencies. This is achieved by recording the L_r sound with equal intensity on both groove walls, but with a 90^o phase lag on the right one, and the R_r sound equally on both walls with the right wall having a 90^o phase lead. The relative recorded phases of the L_r and R_r sounds is arranged to be so that a centre-back sound appears on the disc as a vertical groove modulation (see fig. 2).

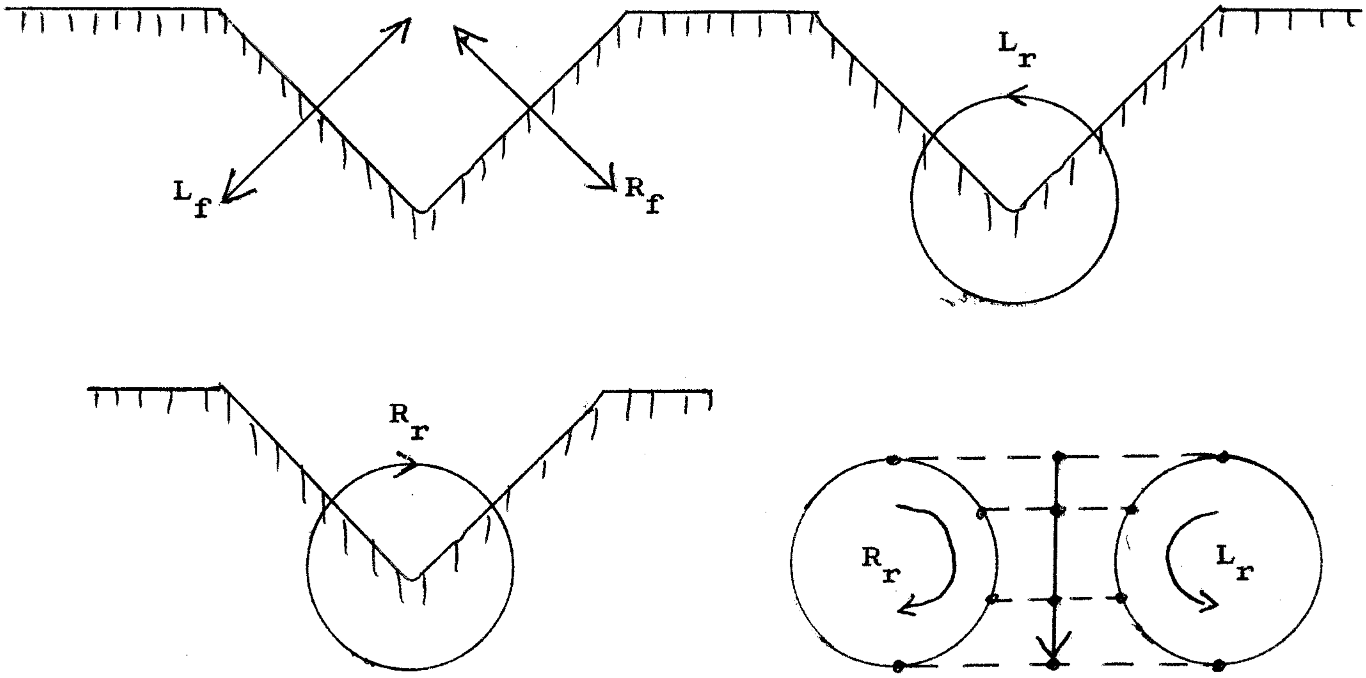


Figure 2. Stylus motions for the "SQ" system, showing how the rear channels' helical motions add to form a vertical modulation.

4. Other Two-Channel Systems

Other 4-speaker 2-channel systems of recording have been proposed by Hafler, Sansui, Scheiber, Electro-Voice and others. While recordings made for one of these systems may not be suitable for playback by another, they are all 'equivalent' systems in the sense that it is possible to design a matrix circuit (possibly involving phase shift circuitry) that will convert a 2-channel recording made for any one of these systems into a 2-channel recording suitable for playback via any given other of these systems. Thus, as far as the results of 4-speaker reproduction are concerned, there is no need to distinguish these systems, although each will differ in their compatibility, i.e. in the results given when played monophonically or via 2-speaker stereo. The CBS "SQ" system is not equivalent to these others.

An example of this class of systems is that of Sansui-type, which records the four sounds L_r, L_f, R_f & R_r as stylus motions at $67\frac{1}{2}^o$, $22\frac{1}{2}^o$, $-22\frac{1}{2}^o$ & $-67\frac{1}{2}^o$ to the horizontal, respectively as in fig. 3.

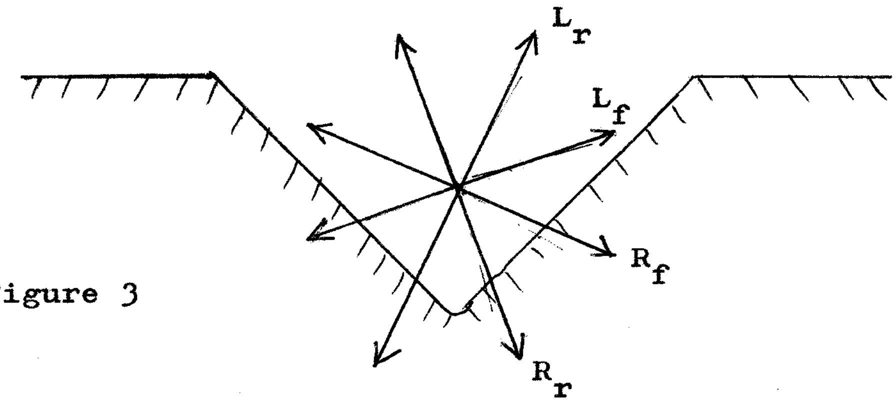


Figure 3

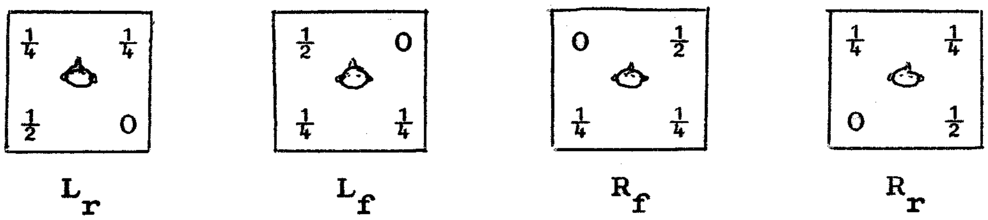
Sounds corresponding to intermediate reproduced directions are recorded in intermediate directions of stylus motion. Thus a front centre sound is recorded horizontally and a rear centre sound is recorded vertically.

5. Playback Matrices

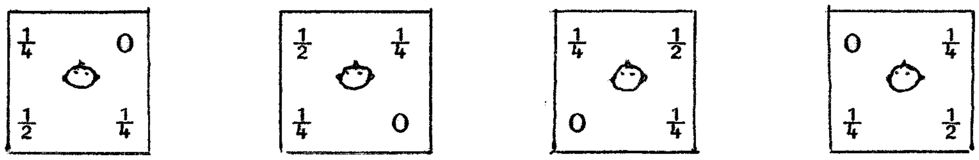
A 2-channel matrix system recording can be played through four speakers via many different linear decoding matrix circuits, and it may well be that more than one type of playback matrix will give an acceptable surround sound effect. Thus a factor in the choice of recording system used is its behaviour with a variety of playback methods, and not just the one that might initially have been proposed.

However, every matrix system of recording has a 'most natural' playback method associated with it, i.e. the one assigning each of the four corner sounds to their respective speakers with the minimum energy of cross-talk onto the other speakers.

With the CBS "SQ" system, a sound recorded in the four positions L_r, L_f, R_f & R_r will be reproduced via a minimum-cross-talk playback matrix with the following respective energies from the four loudspeakers:



For recordings of the Hafler/Sansui/Scheiber/Electro-Voice type, a minimum-cross-talk playback matrix will yield the following sound energies from the 4 speakers during playback of the indicated corner sounds:



L_r L_f R_f R_r

It is emphasised that other playback matrices may be used with either system, which may well give subjectively 'better' results, but which can be shown also to give more inter-speaker cross-talk.

6. False Ambience and 'Overlap'.

It is well known that the effect of reproducing a monophonic sound through more than one loudspeaker is not only to create a phantom image, but also to add a quality of 'richness', 'space' or 'openness'. This effect becomes very pronounced if a significant sound energy emerges from speakers almost directly opposite in direction to the phantom image, and is then known by the name overlap. The effect of a high degree of overlap is to add a quality that inexperienced listeners easily confuse with genuine ambience. However, initial tests using direct live/recorded comparisons of 4-channel systems fitted with a control to vary overlap indicate that critical listeners tend to find the effect of overlap rather unnatural.

Because many of the present relatively inexperienced discrete 4-channel recordings have an unnatural quality of recorded ambience, the addition of an ambience-like overlap effect may well be considered an actual improvement to the sound. However, the more overlap is inherent in a system of 4-speaker recording, the more difficult it will be to attain a high degree of realism from the ambience once 4-channel recording techniques improve.

By examining the speaker energy outputs in section 5 above, it will be seen that, for each recorded corner position, the CBS "SQ" system gives a large amount of sound energy from the speaker directly opposite. In contrast, systems of the Sansui family have a much lower degree of overlap. Any alternative playback matrix for the CBS "SQ" system that gives less overlap will simultaneously increase the amount of inter-speaker cross-talk.

7. The Front and Back

So far, only corner-position sounds have been examined, but it is also necessary to look at what happens to sounds in other positions. When a minimum-cross-talk playback matrix is used, the distribution of sound energy among the speakers for sounds recorded at the front and the back for the two types of system are:

$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{4}$	0.43	0.43	0.07	0.07
$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{4}$	0.07	0.07	0.43	0.43
front		back		front		rear	
CBS "SQ" system				Sansui-type systems			

Thus the "SQ" system has a high degree of overlap for front or back sounds; however, the relative phases of the sounds emerging from the speakers helps establish the correct directionality. Modifying the playback matrix to improve front/back cross-talk increases its complexity and inter-speaker cross-talk for corner sounds.

8. Directional Ambiguities and Errors

Whatever system is used, the process of encoding a discrete 4-channel recording into two channels results in an unfortunate effect called "directional ambiguity". This effect consists of sounds pan-potted between two speakers in the discrete recording being encoded into the two channels in a manner different to that ideal or correct way of encoding sounds that ensures that they are reproduced from the correct position. For example, in a Sansui-type recording (fig. 3), a sound pan-potted half-way between the 2 rear speakers is liable to be recorded as a horizontal stylus motion (see fig. 4), corresponding to a sound emerging from in front of the listener during playback, rather than the correct vertical stylus motion. In this example, the reproduced position is totally wrong, and we have a <u>directional error</u>.

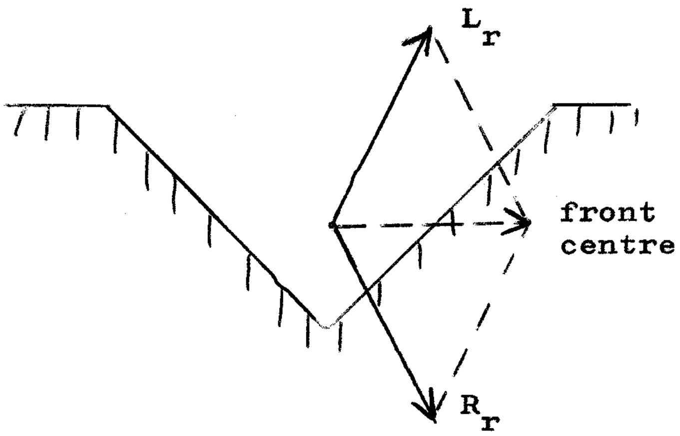


Figure 4 , showing how a rear centre sound can emerge from a Sansui-type encoder as a front-centre sound.

This directional error can be corrected by inverting the phase of one of the rear channels, but a direcectional error will then appear for sounds pan-potted at one of the two sides. Fortunately, in Sansui-type systems, such directional ambiguities can be rendered negligible by ensuring that each of the 4 corner sounds is recorded with a 45^{o} phase lag or lead with respect to its neighbours.

It can be shown that directional errors will always occur with the CBS "SQ" system unless the rear channels are recorded with a 90^{o} phase lag or phase lead with respect to the front ones. Because even a small alteration of the phase shift either way from 90^{o} causes directional errors, this means that CBS "SQ" recordings will be on the verge of having such errors near the positions of the two speakers lying on one of the diagonals. Which diagonal suffers from these directional ambiguities depends on whether the L_r channel is encoded via a 90^{o} phase lead or a 90^{o} phase lag with respect to the L_f channel.

This means that the "SQ" system has a strong left/right asymmetry, which affects sounds at the sides; this defect is thus unlikely to be shown up on the present rather primitive recordings which lack a range of side information. Near the affected pair of corners, the "SQ" system records a sound slightly to the right of a corner in almost <u>exactly</u> the same way as one slightly to the left. If an orchestra slightly wider than than the angle between the front speakers is recorded, then at least one of its edges is likely to be reproduced either 'folded-over' or with vague directionality.

The directional ambiguities in the encoder matrix also have the effect of reducing the side-to-side cross-talk of a side-left or side-right sound from the ideal -7.7 dB to -7.2 dB for a Sansui-type recording, and to -6.0 dB for a CBS "SQ" recording.

9. Gain Control 'Logic' Circuitry

The high inter-speaker cross-talk of 2-channel matrix systems can be reduced by using a decoder which incorporates variable gain circuits in each of the four outputs which automatically turn down the gain of those outputs primarily containing cross-talk. Such gain control circuits are operated by information already inherent in the 2-channel recording. Clearly, while this inherent information is sufficient to obtain a subjective improvement in cross-talk, it is nevertheless limited and incomplete. Thus there is a limit on what can be achieved by such circuitry with any given system.

There are two main categories of gain control method, namely those that preserve the intensity of <u>every</u> recorded sound, but merely alters the distribution of the sound among the speakers, and those that emphasise the outputs of the speakers handling most sound and de-emphasise the others. The first category of gain-control method stands less chance of suppressing important lesser-intensity sounds, but the second category makes fuller use of information inherent in the recording, and thus allows more flexibility in the design of gain-control circuitry. For Sansui-type systems, it can be shown that the first category of gain control substantially avoids any program-dependent shifting of the position of lesser--intensity sounds, whereas the other category will cause image--shifting with some types of program material, although careful design might minimise this. With the CBS "SQ" system, both categories of gain control method can cause images to shift by as much as 180°.

The first category of gain control method cannot improve the side--to-side cross-talk with either type of system, although this is in any case rather worse for the "SQ" system (-6.0 dB) than for the Sansui-type system (-7.7 to -7.2 dB). The first category is also incapable of improving the front/back cross-talk (-7.7 to -7.2 dB) of Sansui-type recordings, and such an improvement to the 0 dB front/back cross-talk of the "SQ" system can be obtained only if over 85% of the recorded sound energy is at front-centre (or, alternatively, at back-centre).

10. Microphone Techniques

Because of their simplicity, compactness and proven effectiveness for 4-speaker stereo, coincident microphone recording techniques are especially useful for the many aplications where the full resources of the studio are either impractical or undesirable: sound effects, location and documentary recordings, 'live' concerts, and conference recording. Coincident microphones are also useful for picking up ambience information or establishing a basic stereo image. There is a wide variety of such coincident microphone techniques, using readily available microphones, suitable for the Sansui-type systems, but no such practical coincident microphone techniques suitable for the CBS "SQ" system are available.

Spaced microphone techniques have given disappointing results with 4-speaker stereo, due to hole-in-the-middle effects (if spaced outward-pointing cardioid microphones are used) or to time-delayed sounds being picked up by microphones corresponding to a speaker in the direction opposite to the phantom sound image (if spaced omnidirectional microphones are used).

Multi-microphone techniques work with all systems, but often need an artificial source of reverberation. If some reverberation is recorded at side positions (as it should be), then the "SQ" system needs more stereophonic artificial reverberation devices than do Sansui-type systems in order to establish a full surround-reverberation effect.

11. Flexibility

While Sansui-type recordings are primarily designed for the usual square loudspeaker layout, they can equally be played with substantially correct directional effect via a diamond-shaped layout (with speakers at the front, the back, and both sides) as in the proposal of David Hafler, or via more exotic layouts (e.g. pentagon, hexagon), as long as suitably designed playback matrices are used. This is possible as Sansui-type systems possess the poperty of 'rotational symmetry', i.e. all recorded directions of sound are treated in a similar manner. Such modified loudspeaker layouts may well allow improvements to '4-speaker' stereo analogous to those obtained by using a centre-speaker with '2-speaker' stereo.

The CBS "SQ" system lacks rotational symmetry, and so is far less flexible in its choice of usable speaker layouts. For example, the obvious playback matrix for the diamond-shape layout will give the same distribution of energies among the speakers for both front left and rear left recorded sounds, and for both front right and rear right recorded sounds. The lack of rotational symmetry also means a loss of operational flexibility in the studio, as "SQ" recordings cannot be rotated in the 2-channel format.

12. Periphonic (with-height) systems

'Periphony' is the term used to describe those systems of sound reproduction that reproduce the effect of sounds coming from all directions around the listener, both horizontal and vertical. Trials of periphony at its best show that many listeners consider its benefits to go as far beyond 'ordinary' 4-speaker stereo as the latter at its best goes beyond 2-speaker stereo, but there are still problems to be solved in rendering periphony practical for domestic use. Previous proposals for periphony have involved 4 channels, and have usually used a tetrahedral loud-speaker layout of some description.

However, a group-theoretical analysis shows that there is one, and essentially only one, system of periphony using only two channels. This periphonic matrix system records horizontal sounds in the same way as systems of Sansui-type. Thus Sansui-type systems are the only ones that will be capable of adding the full periphonic height-effect when this becomes comercially and domestically feasable. The CBS "SQ" system contains no possibility of such development.

13. Compatibility

Although its 4-speaker performance is important, any 2-channel matrix system must also be compatible with (i.e. give good results via) both monophonic and 2-speaker stereo reproduction. This means that: (i) No sound should be unduly attenuated or exaggerated during mono reproduction, (ii) Ditto for 2-speaker stereo reproduction, (iii) the 2-speaker stereo image should be of reasonable width and without any undue geometric distortion, (iv) The 'difference' component of the 2 channels should not have a much larger energy than the 'sum', so as to prevent noisy mono and distorted or mistracked stereo.

The Scheiber, Hafler, Sansui and Electro-Voice systems differ from one another in compatibility, although they give similar 4-speaker results. All these systems, and the CBS "SQ" system, obey requirements (ii) and (iv) reasonably well. The best for condition (i) is the Scheiber system; the "SQ" system is not quite so good as centre-back sounds are not reproduced monophonically, sounds at one side are are attenuated, and centre-front sounds are exaggerated by 3 dB ; the Sansui & Hafler system obey (i) very poorly as rear quadrant sounds are severely attenuated in mono.

If few sounds are recorded at side positions, then an "SQ" recording will reproduce with full stereo width (condition (iii)), whereas Scheiber, Hafler or Sansui recordings will have a rather narrow stereo width. This is the basis for the claim that the "SQ" system has an excellent compatibility. However, if recordings involving orchestras rather wider than the angle between the front speakers are made, then the edges of the orchestra will be distorted or 'folded-over' via 2-speaker reproduction with the "SQ" system. In order to avoid such image distortions, and to avoid cramming the rear 270° of sound into the space between the 2 speakers, it is advisable to adopt a system in which the L_f and R_f sounds fill, say, $\frac{2}{3}$ of the 2-speaker stereo stage rather than all of it. Even when no direct sounds are recorded at the sides, the reverberation that should be recorded at the sides will help to fill up the edges of the 2-speaker image and create a sense of width.

A Sansui/Scheiber type of system with a reasonable width which obeys the compatibility requirements reasonably can be obtained by increasing the difference component of a Sansui-type (fig. 3) recording 3dB, & retarding the phase of the right channel by 45°. Such a recording is also reasonably compatible with Sansui, Hafler, Scheiber and, possibly, Electro-Voice reproduction!

A curious consequence of the left/right asymmetry of the CBS "SQ" system is that a sound recorded at side-right will be reproduced in mono with an attenuation of 5.3dB (relative to corner sounds) or 8.3 dB (relative to front-centre sounds), whereas a left-side sound will be boosted by 2.3 dB relative to the corners, and attenuated by 0.7 dB relative to front-centre.

14. Conclusions

Most current commercial 4-channel recordings exhibit a five-point directionality, i.e. most sounds are recorded only in the 5 positions L_r, L_f, front-centre, R_f and R_r. While this yields impressive results, the crudity of the resultant effect is analogous to the 'ping-pong' effect of much early stereo. In contrast, even if images are blurred by as much as 10^o, it is possible to record 36 distinct images around the listener, and with some recording techniques (e.g. using coincident microphones) a finer resolution is possible.

The "SQ" system has been designed to give the best possible results with '5 point directionality' recordings, as CBS's own demonstrations have shown. This performance is obtained by an almost maximal use of the information inherent in 2 channels, and thus little room is left for further substantial development. The '5 point' excellence has been bought at the expense of: (i) a misbehaviour of sounds near at least 2 of the corners (L_f & R_r in CBS's own encoder matrix), which seems to manifest itself as a very blurred corner image, (ii) a high degree of overlap during linear playback, especially for front-centre & rear-centre sounds, and (iii) a tendency for front-centre sounds to jump to the rear (& vice-versa) under the action of gain control logic circuitry.

The criticisms in this report arise from a fundamental conflict about what 4-speaker stereo should achieve - i.e. the '5-point directionality' approach versus the 'continuous 360^o image' approach. It appears that the best 2-channel matrix system for the former philosophy (i.e. the CBS "SQ" system) inherently prevents the aims of the latter philosophy from being fully achieved.