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QUADRAPHONY: techniques involved in four channel recording and reproduction

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QUADRAPHONY: TECHNIQUES INVOLVED IN FOUR CHANNEL RECORDING AND REPRODUCTION

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Summary

A series of tests has been carried out, and recordings made, to identify some of the problems that will be encountered in recording and reproducing quadraphonic programme material. Various microphone and loudspeaker arrangements have been evaluated with the main aim of re-creating, in the listening room, the acoustic qualities - ambience, spaciousness, etc. - of the original environment. In the case of orchestral music this aim is the re-creation of all the acoustic qualities of the best seat in a concert hall.

Recommendations are made with regard to future work on special microphones for quadraphonic use.

Issued under the authority of

Head of Research Department

Research Department, Engineering Division,
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QUADRAPHONY: TECHNIQUES INVOLVED IN FOUR CHANNEL RECORDING AND REPRODUCTION

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1. Introduction

Quadraphony, four-channel sound, is now considered commercially viable by recording companies and over the last eighteen months Research Department has been involved in a series of experiments to quantify the many different variables in a four-channel system. Some of these experiments are still unfinished but, as interest in quadraphony increases, it seems appropriate to discuss the problems that have already been encountered. This report covers only those problems which arose during the experimental work on recording and reproducing quadraphonic sound. Later reports will discuss properties of hearing relevant to quadraphony[1] and some of the problems of broadcasting four-channel material to the listening public.

Commercial quadraphonic recordings have exploited the two-dimensional (sometimes even three-dimensional) effects that the system is capable of producing, such as surrounding the listener with instruments or electronic noises, or even rotating instruments right around the listener's head. These effects are generally achieved by making a multimicrophone, multitrack recording and 'panning'* each instrument into the sound location that is required on reproduction. This produces a 'pan-pot' recording.

The orchestral recordings made by Research Department have been based on a different approach. The aim of these has been to re-create, in the home environment, the subjective balance of audio signals that exists in the best seats of a concert hall, with the orchestra in front of the listener and only reverberant information arriving from other directions. This has been achieved using a relatively simple microphone arrangement, i.e. a group of four, coincident, cardioid/hypercardioid microphones.

The same microphone arrangement has been used to record drama and the surround-sound effects of 'The Last Night of the Proms.' Such recordings, because of the microphone techniques used, are referred to in this report as coincident-microphone recordings.

Only one loudspeaker arrangement has been examined in detail. This is the square array, in which the loudspeakers are placed at the corners of a square, facing towards the centre. The listener sits at the centre of the square facing the mid-point of one side, which is conventionally regarded as the front of the sound stage. Other arrangements have been suggested, e.g. diamond and tetrahedral arrays,[2,3] but preliminary tests showed that they gave a quadraphonic performance inferior to that provided by the square layout. It is relevant to note that all commercial quadraphonic recordings are intended to be replayed using a square layout of loudspeakers.

This report discusses first the problems of accurate reproduction of quadraphonic material. It then covers the requirements of the recording equipment, particularly the microphones, with reference to the experience gained during the experimental recordings. Microphone techniques are one of the most important factors in the performance of quadraphonic systems, and the final section discusses a possible change to microphone characteristics which would produce an improvement in coincident-microphone recordings.

2. Listening conditions and equipment

2.1 Symmetry

A system of quadraphony can suffer from more intrinsic crosstalk between the four channels than is usual in stereo but because of the 'balance' of loudspeakers around the listener this cross talk need not be troublesome. If this balance is upset, however, the crosstalk can cause the images to shift from one point to another or even render the images so diffuse as to be unlocateable.

Multi-microphone recordings pan-potted down to four channels and played directly through four loudspeakers are not very critical with regard to the symmetry of the listening conditions. With a coincident-microphone recording, however, using microphones with cardioid responses, the unwanted crosstalk from the loudspeakers adjacent to that reproducing the wanted signal is only 6 dB down and, under these conditions, symmetry, for good placement of images, is more important. If a 4–2–4* matrix is involved in the system, crosstalk may be fed to

*A sound is 'panned' into a predetermined position in the reproduced sound field by mixing appropriate portions of the signal into the four master channels.

*'*l*–*m*–*n*' is a short hand notation indicating the number of signal channels at different points in a quadraphonic system. '*l*' is the number of source channels, '*m*' is the number of record/transmission channels and '*n*' is the number of output channels.

adjacent loudspeakers only 3 dB down on the wanted signal, independent of the origin of the material (i.e. pan-pot or coincident-microphone), and symmetry becomes essential. This symmetry applies to the loudspeakers, the listening position relative to the loudspeakers and the overall listening conditions.

2.2 Choice and placement of the loudspeakers

Experience with stereo has shown that sharp, well positioned images are obtained only if two, well matched, high quality loudspeakers are used; these are normally placed to subtend 60° at the listener (see Fig. 1).

In quadraphony each pair of loudspeakers subtends 90° at the listener, and the ears* are now called upon to create 'stereo images' at the sides and back of the head as well as at the front. Work already carried out on certain properties of hearing[1] has indicated that the 90° spacing has an adverse effect on image-sharpness and location. This does not cause gross errors in the front quadrant, except that a centre-front image tends to rise, from the horizontal, by some 20° to 30°, but the same work has also shown that the ear is not very effective in combining sounds from two loudspeakers at the side of the head (one towards the front, the other towards the rear) to form an image at the mid-point of the side.

*To avoid awkward expressions, 'ears' or 'ear' will be used to imply the combination of ear and brain.

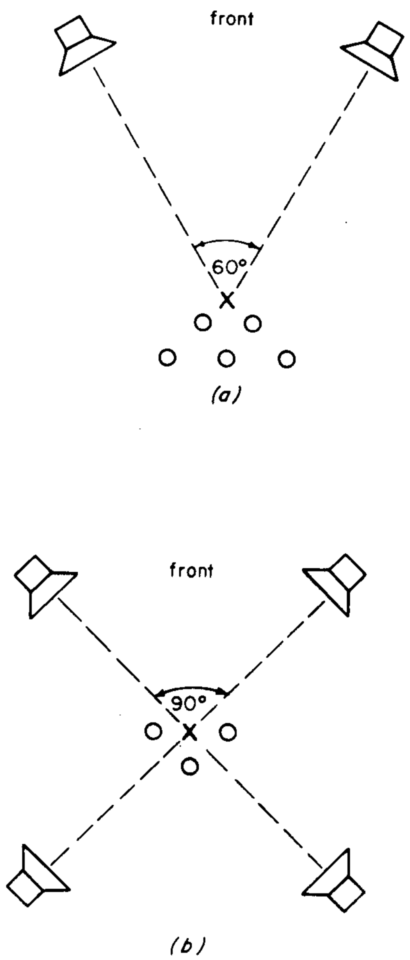


Fig. 1 - Optimum layouts for listening to stereo and quadraphony

(a) stereo (b) quad.

X = Best listening position

O = Other listening positions which do not upset the sound at X

NB: The number of these points will depend upon the size of the listening area, i.e. distance between loudspeakers.

Experience indicates that four identical* high quality loudspeakers should be used for the monitoring of all quadraphonic signals. This is especially important if a 4—2—4 matrix system is being used, because one of the unfortunate properties of such matrix systems is that they can generate rather large phase differences between the four decoded signals. At times during investigations involving 4—2—4 matrices the phase differences have been clearly audible on high-grade loudspeakers as unpleasant 'phasey' sensations in the reproduced quadraphonic sound. The author has attended commercial demonstrations, however, where the same material played through the same matrix equipment but reproduced on unknown loudspeakers has sounded quite acceptable; the loudspeakers (and perhaps the room in which they were placed) were apparently masking the defects of the matrix. This should not be taken as an excuse for lowering the specifications for studio monitoring conditions; on the contrary, it is a good reason for tightening standards if quadraphonic programmes are to match the high quality of present stereo productions.

Loudspeaker placement should also be carefully considered if meaningful results are to be obtained. As an extreme example of the problem, the sensations produced by quadraphony in a free-field room were found to be severely affected when one of the front loudspeakers was 5 cms (2 inches) too close to the listening position relative to a nominal 2·4 m (8 ft) radius for the other loudspeakers. This misplacement caused centre-front images to be shifted markedly towards the 'close' loudspeaker. When attempts were made to correct this by adjusting the relative signal levels it was found that an imbalance of 3 dB was needed to centralise the sound which produced a very phasey, diffuse image. Such a positional error would give rise to less than 0·2 dB difference in sound-pressure level at the listener and only 150 μs difference in time of arrival of the two sounds. It is, however, equivalent to a 90° phase error at 1·6 kHz, which would cause the unpleasant sound sensation.

Normal listening environments are not nearly as critical in their requirements as a free-field room, but consistent results can only be obtained when the loudspeakers are correctly placed.

2.2.1 Balancing quadraphonic loudspeakers

The best way to balance the four loudspeakers is an aural method (see Fig. 2). Loudspeaker A is first fed with a monophonic signal and adjusted to give a suitable listening level. The same signal is then also fed to B and

* Same make and model with well matched characteristics.

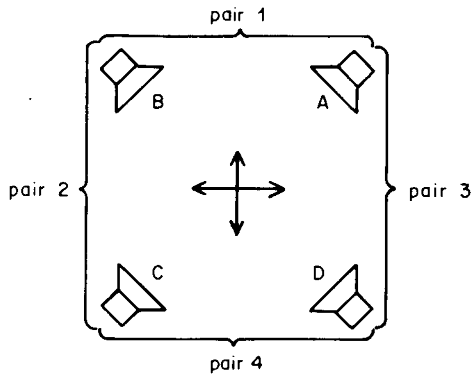


Fig. 2 - Balancing four loudspeakers

its level adjusted to generate a central image when listening on the centre line that divides the two loudspeakers. A is then disconnected and C energised; a balance is achieved as before, facing loudspeakers B and C. The same procedure is repeated for Pair 3 and if correct adjustments have been made Pair 4 should also give a similar result.

A method has been suggested in which the listener faces the front whilst balancing all four loudspeakers; however, for a centre-side image created by two loudspeakers, the ear appears to be more conscious of the front loudspeaker than the one at the back.* This method of balancing, therefore, is not recommended.

2.3 Listening position

Quadraphony in an absolute sense provides only one ideal listening position; with a square layout of loudspeakers this position is at the centre of the square. The quadraphonic sensation generated at this point is far superior to anything achievable elsewhere in the listening room, and it is to be recommended that any sound balancing engineer should be seated in such a position.

At other points in the quadraphonic square it is still possible to achieve a very pleasant quadraphonic effect but the directions of images are altered. In fact it is possible to stand on one side of the quadraphonic square and still receive the impression that the sound has retained its two-dimensional quality. Fig. 1 shows three secondary listening positions where a satisfactory effect is obtainable, but note these have been chosen specifically such that there is no-one directly between the best listening position and any of the loudspeakers; a head is extremely good at blocking out sound and ruining a quadraphonic balance.

2.4 Listening room requirements

As already mentioned, symmetry is the key to good reproduction and even the room can have a noticeable effect on the placement of quadraphonic images. In the early stages of the investigation into properties of hearing relevant to quadraphony, subjective tests were carried out both in a listening room and in a free field room. The listening room was designed to be acoustically similar to normal domestic lounge (reverberation time approximately 0·3 secs), but with the acoustic treatment more evenly distributed. The room is approximately 5·5 m (18 ft) long by 4·2 m (14 ft) wide by 3 m (10 ft) high and the bulk of the acoustic treatment is placed on three of the walls and the ceiling; there is also carpet on the floor. The fourth wall, at the back of the quadraphonic square, is the main source of asymmetry. There is a central window (1·2 sq.m., 13·7 sq.ft.) for visual communication with a control room, a door (1·8 sq.m., 20 sq.ft.) to the right of the window and a small amount of acoustic treatment (1·3 sq.m., 14 sq.ft.) to the left of the window. From the above description it can be seen that the listening room used for these quadraphonic assessments is more symmetrical than most domestic environments and certainly better than the normal control room associated with a sound studio. Even so, the effect of the window in the listening room has been detected and the quantitative results obtained have reflected the slight asymmetries.

A recommendation of perfect symmetry for control rooms dealing with quadraphonic signals would obviously be impractical, if not impossible, but gross asymmetries should be avoided. The loudspeakers, control desk and room should be arranged to be mutually symmetrical and if any imbalance has to be tolerated it is preferable to arrange this to be in the front-to-back direction rather than from left to right. Thus, for example, if a window is required between a control room and its studio, that window should be arranged to be in the centre of the front edge of the listening square, rather than on the left- or right-hand side of the square. Any large reflecting areas, e.g. equipment bays, ventilation trunking, should be avoided if possible, or separated from the listening area by acoustic screens. The latter arrangement will both prevent misleading reflections and afford a small degree of acoustic separation where the equipment bay is a source of interfering noise, e.g. transformer buzz.

3. Recording equipment

3.1 Tape recorders and associated equipment

Normally, at some stage of the production process, a four-track master of the quadraphonic material is produced; this may be derived directly from coincident microphones or from a particular balance of many microphones (in the latter case, an intermediate multitrack recording may be produced which is later balanced to four tracks).

There is, however, one main point to be borne in mind with regard to recording: this is that the signal-to-noise ratio should be maintained as high as possible, which implies, at the present time, that some form of noise-reduction technique be used to reduce the effect of tape hiss. During the early experimental recordings of quadraphony it was found that a disturbing level of tape hiss was reproduced over the rear loudspeakers in spite of

*See appendix

the fact that the rear-channel recordings had the same signal-to-noise ratio as the front channels. It was then noticed that, whilst facing the back of the quadraphonic square, the front loudspeakers, i.e. the ones that were now behind the listener, were those which subjectively produced the most tape hiss. This phenomenon was confirmed by several subjects and it is therefore concluded that the ears appear to accept a level of tape noise coming from in front which is higher than that which is acceptable from behind. To alleviate this problem later quadraphonic recordings were made using Type A Dolby noise-reduction units.

To find what effect the Dolby units might have on a quadraphonic recording eight Model 361 units were placed in series. Alternate ones were switched to the encode condition and the others were switched to the decode condition. Measurement of the phase and frequency responses gave results which were within the specification of 5° and ±1 dB per encode-decode. On a listening test, comparing a monophonic signal before and after it had been passed through this chain of units, there was a just perceptible change in the tonal quality of one item of music, but on other items of music and speech there was no noticeable difference. It was therefore concluded that the units tested performed their task of noise reduction with no significant side effects. This conclusion has been confirmed by all the subsequent recordings of quadraphonic material, including fourth generation copies of some test material.

One other problem which may arise in quadraphonic recordings is that of phase errors due to tape weave. There is a need for this to be investigated further, particularly with respect to its effects where channel reduction techniques are used, especially 4—2—4 matrices with 'logic' decoding.*

3.2 Microphones for quadraphony

Several aspects of microphone technique were briefly investigated** before experimental orchestral recordings were made at the 1972 Promenade Concerts. Two of these were the comparison of coincident versus spaced-microphone configurations and the effects of changing the directional characteristics of the microphones.

For all the preliminary work, four AKG C12A capacitor microphones were used. These were tested in a free-field room and their characteristics were found to be matched to better than ±½ dB from 50 Hz to 3 kHz and better than ±1 dB from 40 Hz to 16 kHz.

Fig. 3 shows some of the microphone configurations tested. These configurations were set up, in turn, in a studio and the amplified microphone outputs were fed directly to four monitoring loudspeakers in a separate listening room, great care was taken to ensure that each channel had exactly the same gain. An engineer walked

*'Logic' implies non-linear circuits used to enhance separation under specified conditions.
**This work was carried out by H.D. Harwood.

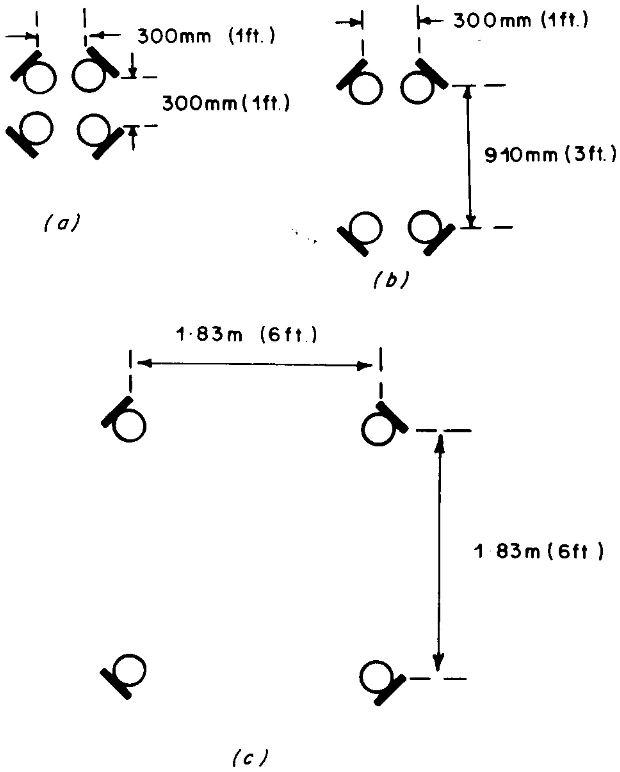


Fig. 3 - Microphone arrangements for the coincident v spaced microphone tests

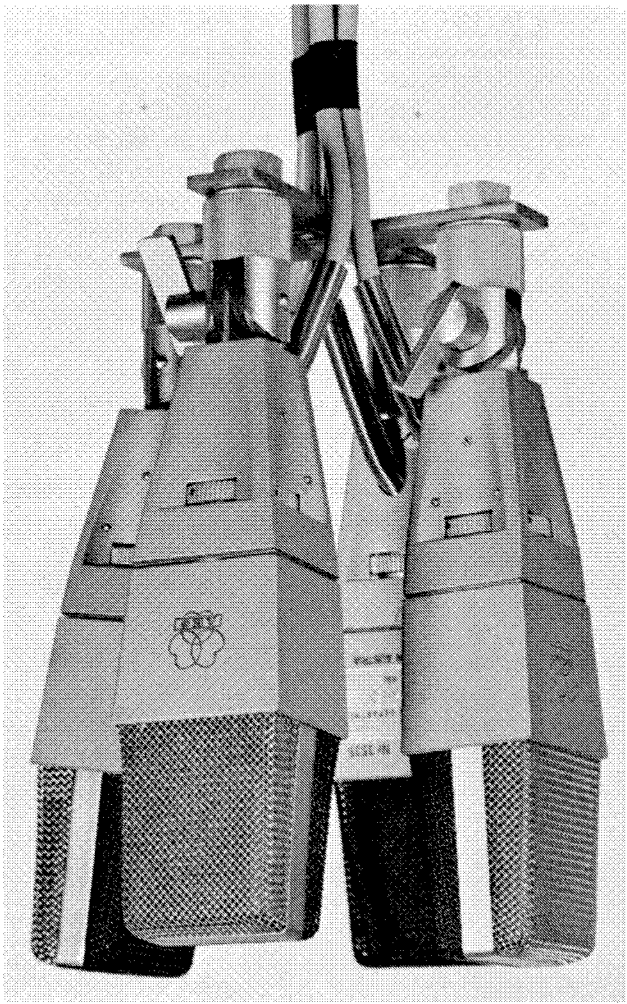
round the microphones on a 3 m (10 ft) diameter circle, reading from a script, and a note was made of the locus and quality of his image in the listening room. The tests were repeated for the different microphone placements and for different microphone polar-responses; omnidirectional, cardioid and 'cottage-loaf' responses were used.

The most accurate results were obtained using layout 'a' (Fig. 3) with the microphones switched to either the cardioid or cottage-loaf response. Under these conditions a listener was able to locate the position of the engineer anywhere around the microphones to within ±5° of the true location.*

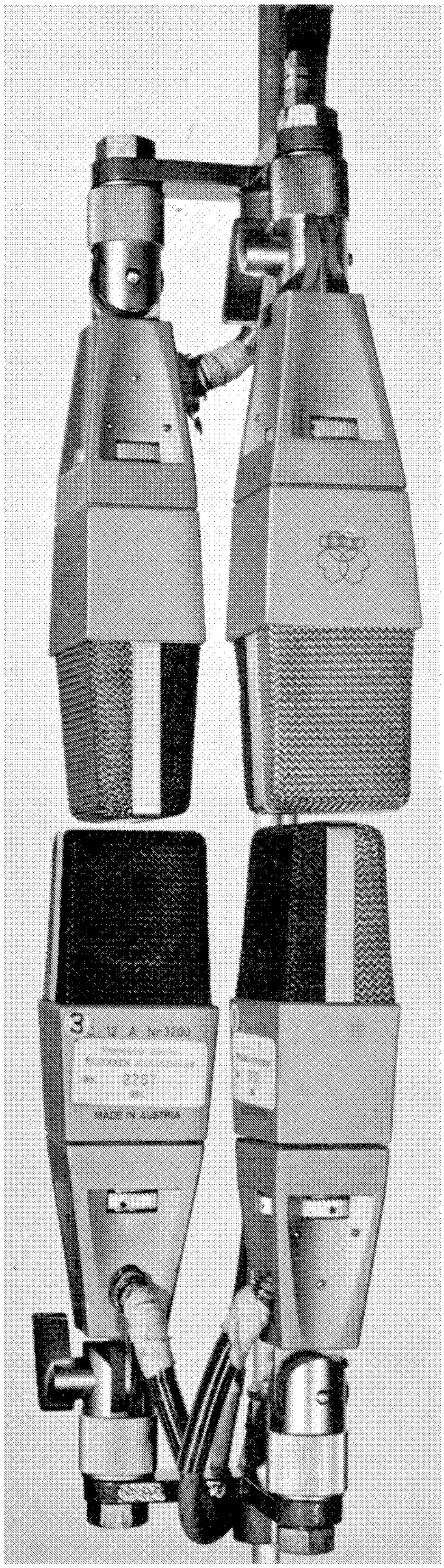
Both the spaced microphone layouts suffered from the same defect, namely that as the engineer walked around the circle embracing the spaced microphones, his sound image, which should have moved linearly between the corresponding loudspeakers, actually clung to the first loudspeaker until he was almost centrally placed. The image then moved rapidly to the second loudspeaker and stayed there until he was well beyond the axis of the second microphone; this is the well known stereo 'hole-in-the-middle' effect appearing in a quadraphonic form.

Based on these results it was concluded that coincident-microphone techniques produced better all-round results than spaced microphones. This was confirmed

*During these tests the listener was allowed to turn and face the sound image.



(a)



(b)

Fig. 4 - Microphone configurations
(a) Horizontal planar array (b) Two-plane array

by an orchestral recording made in the Town Hall at Barking where again coincident and spaced microphones were tested. Wherever the microphones were separated, the corresponding side of the quadraphonic square suffered a lack of positional discrimination during replay, whilst four coincident cardioid or cottage-loaf microphones gave a pleasant balance and distribution of sound images.

One property of the cottage-loaf response was however noted. The fairly large rear-lobe in the polar diagram (Fig. 6c) appeared to result in directional ambiguity across the diagonal of the square. The situation was a little confused by a full-width balcony in Barking Town Hall, relatively close to the microphone cluster. This gave rise to just audible reflections, even with cardioid microphones, but it was considered that the cottage-loaf recordings were slightly worse in this respect. Subsequent recordings, therefore, were made only with the cardioid microphone-response or with a response mid-way between cardioid and cottage-loaf,* and the diagonal ambiguity, although occasionally noticed by listeners with very acute hearing, has not proved to be a problem.

*The latter response will hereafter be referred to as the 'hyper-cardioid' response.

Having found that the coincident configuration gave the best quadraphonic results, two different clusters of microphones were tested during subsequent recordings, see Fig. 4. The horizontal square array was the first one to be devised. The cluster had a diagonal of 100 mm (4 inches), which is equivalent to a quarter wavelength at 825 Hz. The discrete (4–4–4) quadraphonic results obtained with this arrangement were very good but it was felt that systems involving 4–2–4 (and possibly 4–3–4) matrices might require even closer placement of the capsules. The two-plane array was therefore suggested, with maximum capsule spacing of 57 mm (2·3 inches), which corresponds to a quarter wavelength at 1·4 kHz. This was the microphone arrangement used throughout the Promenade Concert recordings.

3.3 Microphone placement and associated problems encountered during recording sessions

When using a coincident microphone array it is not always easy to find a position in the recording environment, the concert hall or studio, where a satisfactory balance of sound exists. For an orchestral recording, a satisfactory placement would be one in which a wide clear image of the orchestra was obtained together with a balance between direct and reverberant sound. In the case of the Prom-

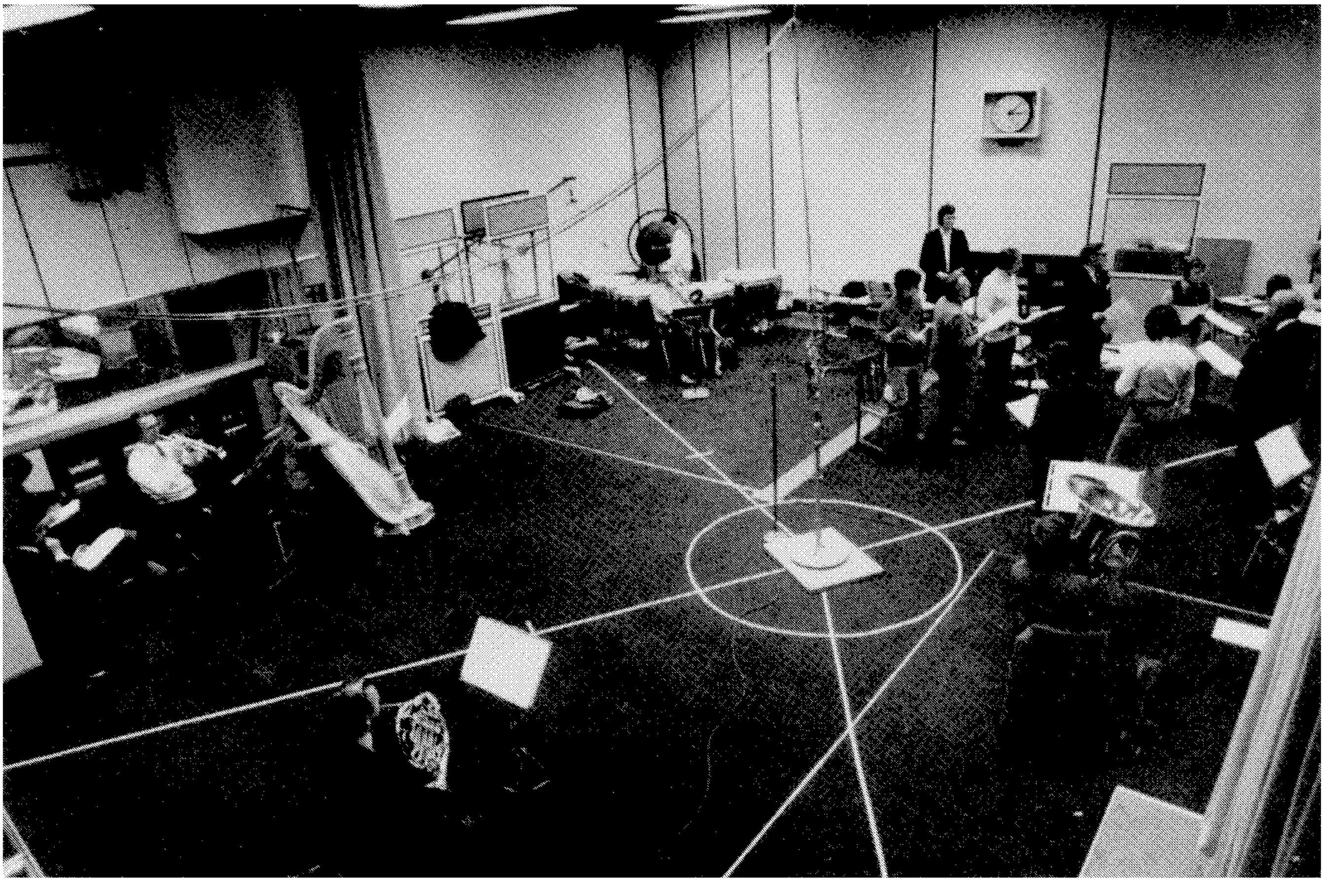


Fig. 5 - Recording of quadraphonic drama

enade Concerts three different microphone positions were tried before a satisfactory balance of direct and reverberant sound was obtained, and this, due to the distance of the microphones from the orchestra, slightly affected the orchestral image, which tended to be marginally narrower and more distant than in the equivalent stereo presentation. This will always be a problem, in certain environments, unless spot microphones are also used. It is considered, however, that this is an artistic rather than an engineering problem and so the use of additional spot microphones was not investigated.

The final position selected for the quadraphonic microphones at the Royal Albert Hall was approximately 7·2 m (24 ft) behind the conductor's rostrum and 6 to 9 m (20 to 30 ft) above the floor. This gave good recordings except for the previously mentioned point that the orchestra occasionally sounded rather distant. There is in the recordings thus obtained one factor which gives the listener a sense of participation in the concert, rarely achieved even by the best stereo production; that is audience reaction. The occasional cough from a member of the audience, coming from the correct direction during replay, gave the recording a sense of realism and, far from being distracting, seemed to add to the overall effect.

Unfortunately such all-round reception has the drawback that the microphones pick up unwanted sounds from all directions. This has not proved troublesome in the orchestral recordings, but a quadraphonic drama recording of 'Oedipus' (fig. 5) suffered from a high level of environmental noise; the collective effect of four microphones relative to one gives a 6 dB decrease in the ratio of signal to environmental noise. In the case of the Oedipus recording the situation was further worsened by the fact that the actors were further away from the microphones than is usual for a stereo drama production. The result was a recording with a relatively high level of low-frequency noise, picked up from the ventilation plant and other sources. The noise was easily removed from the recording by filtering out all signals below 70 Hz, but this indicates that close microphone techniques are required for drama unless much more stringent acoustic criteria are adopted from drama studios. Close microphone techniques imply that there will be very little room for movement by the actors, or even for placing actors in

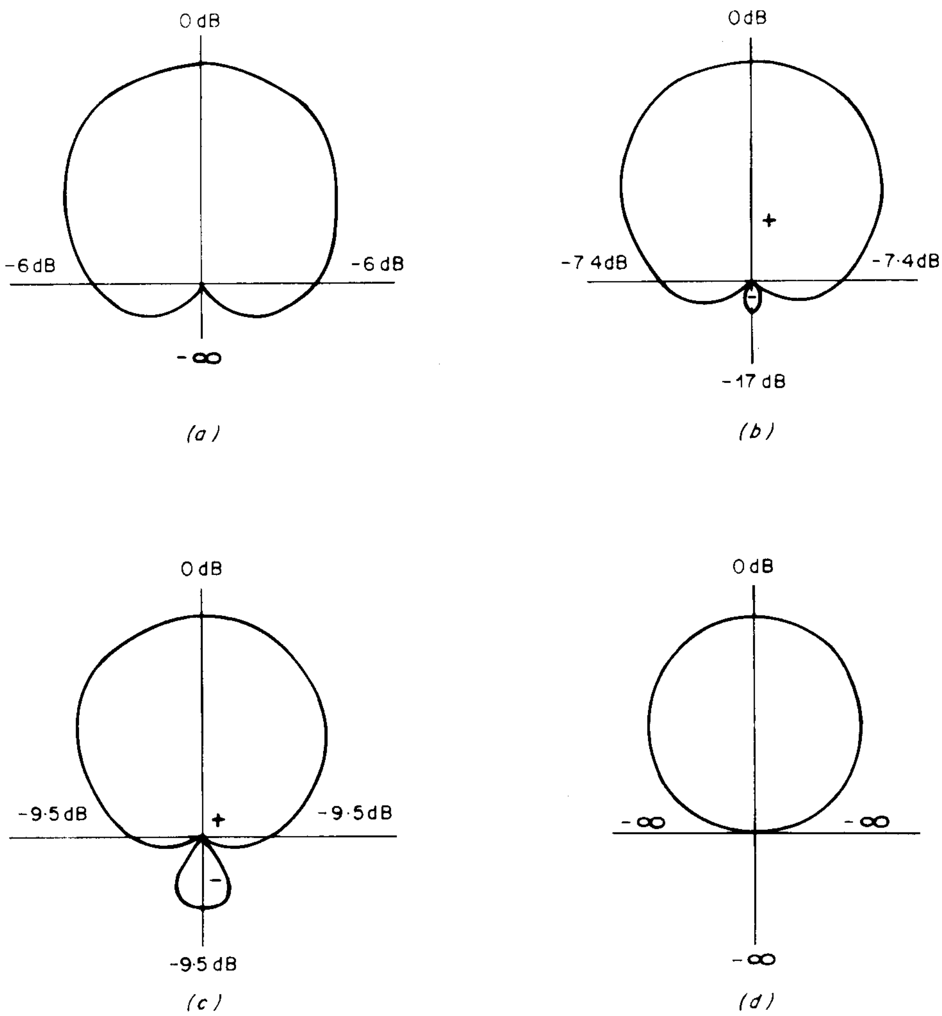


Fig. 6 - Analysis of microphone characteristics

(a) Cardioid: $V \propto 1 + \cos\theta$

(b) Hypercardioid: $V \propto 0{\cdot}75 + \cos\theta$

(c) Cottage loaf: $V \propto 0{\cdot}5 + \cos\theta$

(d) ½ figure-of-eight:

$V \propto \cos\theta$ *for* $-\frac{\pi}{2} < \theta < \frac{\pi}{2}$,

and $V = 0$ *for* $\frac{\pi}{2} < \theta < \frac{3\pi}{2}$

the correct location round the microphones, and thus pan-pot methods of image placement may be more favoured for future drama productions.

4. Microphones: future development

During the experimental recording work cardioid and hypercardioid microphone responses were used and it was noted that the adjacent-channel crosstalk, due entirely to the polar responses of the microphones, affected the subjective impression provided by the recordings. The effect was not one of mislocated images, as in this respect the recordings were satisfactory; the crosstalk tended to 'pull the sound image in' towards the listener relative to the impression created by a pan-pot recording.

As can be seen from Fig. 6(a) a cardioid response is only 6 dB down when the source is 90° off axis, i.e. a noise from the right-front of a sound stage will generate signals in the left-front and right-back microphones only 6 dB lower than that generated in the right-front microphone. A switch to a hypercardioid response, as shown in Fig. 6(b), improves the adjacent separation slightly but at the expense of an antiphase rear lobe. A cottage-loaf response, Fig. 6(c), worsens the overall performance because of the greater size of its rear lobe. Fig. 6(d) shows a microphone response that would be ideal for quadraphony in that its output is

$$V \propto \cos\theta \text{ for} -\frac{\pi}{2} < \theta < \frac{\pi}{2}$$

and

$$V = 0 \text{ for } \frac{\pi}{2} < \theta < \frac{3\pi}{2}$$

Four of these could adequately cover the quadraphonic sound stage giving coincident-microphone signals with the same interchannel separation as pan-pot signals. In fact if a sound source moved around a truly-coincident, cluster of this form, the signals would vary in the same way as if they had been generated using the sine/cosine method for the pan-pot placement of sound images.

A useful approximation to this characteristic may be made by using a second-order pressure-gradient microphone. The response of this type of microphone is shown in Fig. 7. It can be seen that this has the required shape of front-lobe and that the response behind the microphone is everywhere more than 18 dB below the axial response. Four of these in a quadraphonic cluster would give omnidirectional sensitivity (in the horizontal plane), as in the case of four cardioid microphones; therefore, signals obtained using such microphones would give equally good directional accuracy of image, with improved sharpness and possibly a more 'open' impression.

It should be noted that these improvements will only be valid if a four-channel transmission system is available. Coincident cardioid microphones already make full use of the channel separation available in a three-channel system. There may, however, be practical advantages to be gained with the new type of microphone, such as an increase in the ease with which the cluster can be used in an acoustically difficult environment (see section 3.3).

There is, however, no commercial microphone available at present with the desired characteristic and the development of one, covering the audio band with high signal-to-noise ratio, would require a considerable amount of work.

5. Conclusions

The experimental quadraphonic recordings have supplied a wide range of material for qualitative tests to be carried out on possible broadcast systems. The experience gained has pointed out some of the possible problems of quadraphony. It appears to be more critical than stereo with regard to listening position and to be less tolerant of listening environment, if images are to be accurately located; such performance should be the objective, although for normal domestic reproduction these factors are far less important. Pleasing results, even though they may to some extent be inaccurate, can be obtained in a wide range of circumstances.

Only the square loudspeaker layout is recommended if accurate image-location is required, and symmetry in the listening environment is also recommended.

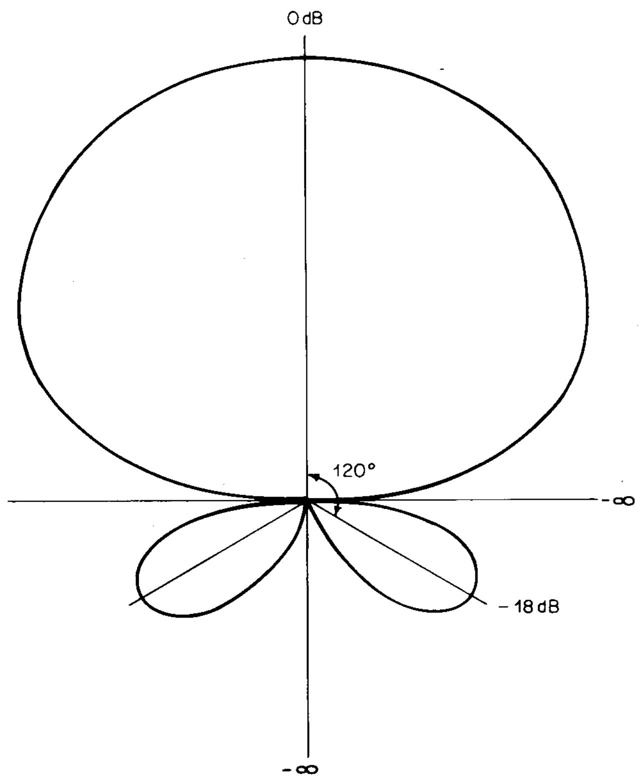


Fig. 7 - Polar response of second order gradient microphone
$V = v_o\,(1 + \cos\theta)\cos\theta$

With regard to signal origination, two techniques have been outlined, the pan-pot method, using several (or many) separate microphones, and the coincident-microphone method, although only the latter has been discussed in detail. If the coincident-microphone method is to be used in the long term, the development of a microphone with a more suitable polar characteristic would be a significant step forward.

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7. Acknowledgement

The author is grateful to many people in Radio O.B.s and Television O.B.s who co-operated in the making of recordings, at the 1972 Promenade Concerts and elsewhere.

Appendix

Work has been carried out to examine the properties of human hearing in order to determine what the ear/brain combination is capable of deducing from quadraphonic sound presentation. This work is to be reported in full in a later document.[1] One factor which is extremely relevant to this report, however, is the quality and position of the sound images generated at the side of the head by two equally energised loudspeakers, one towards the front and the other towards the back. Centre-side images have been found to be extremely sensitive to head movement and to shift rapidly with changes in the level-difference between the two loudspeakers. During tests in a free field room it was noticed that the side images were subjectively judged to be much further forward than expected. In fact on average the rear loudspeaker needed to be 10 dB louder than the front one to generate a centre-side image and a variation of $\pm½$ dB moved the image through $\pm 15^\circ$. This effect, however, is only applicable when the two loudspeakers are simultaneously energised by the same signal. Tests have also shown, that given an 'either/or' comparison, a listener can balance a loudspeaker at the front with one at the back to within 1 dB. Thus the ear/brain combination appears to exhibit a conditional directionality that only exists when identical sounds are presented in front of, and behind, the listener at the same time.

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