The Principles of Quadraphonic Recording
Part One: Are Four Channels Really Necessary?

By Michael Gerzon

THE recent growth of interest in quadraphony (i.e. sound reproduction via four loudspeakers) has encouraged the belief that four recording channels are necessary for a full quadraphonic effect. The author has recently published an account[1] of a method of four-speaker reproduction of ordinary two-channel stereo that can give a convincing all-round-sound effect, despite certain theoretical and practical limitations. This poses the problem of whether one really needs to record or transmit four channels of audio for four speaker quadraphonic reproduction.

The aim of this article is to give an elementary theoretical analysis which indicates that *three* recorded channels should be quite adequate for quadraphonic reproduction. The uses, advantages and limitations of this are discussed, and formulae are given which indicate how three-channel recordings can be reproduced via four loudspeakers, and how four-channel recordings can be reduced to three channels. The second part of this article is devoted to the use of these considerations in obtaining a system of *Periphonic* (Greek: *peri-*, around) sound reproduction, i.e. the reproduction of sound in all spatial directions, from in front, each side, behind, above and below.

While the author has used certain advanced mathematical techniques in deriving the material in this article, all the results are here stated only in terms of very elementary mathematics, and physical reasons are given for most of the phenomena. It is hoped that the information here will prove useful in designing multi-channel recording and reproducing systems, quadraphonic pan-pot circuits, and in other applications.

It is generally accepted that three speakers are not adequate for good surround sound, due to the limited listening area and the wide angle between the loudspeakers. This has led many people to assume that, because four loudspeakers are necessary for surround sound, therefore one needs to record four channels. The author has shown[1] that even two-channel recordings can be made to give a genuine surround sound (albeit with some defects), and this suggests that three channels might be quite sufficient to convey all the information required for quadraphonic reproduction.

There are strong arguments in support of deriving the sound for four loudspeakers from only three channels of recorded sound. The primary

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purpose of four speaker reproduction is to reproduce music realistically. It is generally recognised that the most natural recordings are obtained by coincident microphones, rather that spaced or multi-mike techniques. (It is true that the latter techniques may produce a more spectacular, 'pleasing' or analytic sound, but it is not the purpose of the present article to argue matters of taste.)

It may be thought that placing four coincident microphones with, say, cardioid directional characteristics pointing in different directions will give a reasonable four channel sound. For conventional quadraphony, which only conveys horizontal directional information, these microphones will normally have their axes pointing horizontally. However, it may not be generally known that, for microphones whose axes point horizontally, there are only three linearly independent microphone directional characteristics. Put another way, given four coincident microphones whose axes point horizontally, it is always possible to derive the audio output of at least one of the microphones by matrixing the outputs of the other three microphones together in suitable proportions. (Technically, this is expressed by saying that 'the space of horizontal microphone directional characteristics is three-dimensional'. This arises from the fact that all conventional microphone directional characteristics are linear combinations of zero and first order spherical harmonics. In future, high quality microphones may be developed whose directional characteristics involve second order spherical harmonics. Four such microphones would be capable of recording four independent channels for four speaker reproduction.)

This means that whenever a coincident microphone technique is used for sound to be reproduced over four loudspeakers arranged horizontally around the listener, as in **fig. 1** for example, only three microphones are actually needed to obtain all the audio information. The sound fed to each of the four

FIG. 1 QUADRAPHONIC SPEAKER LAYOUT

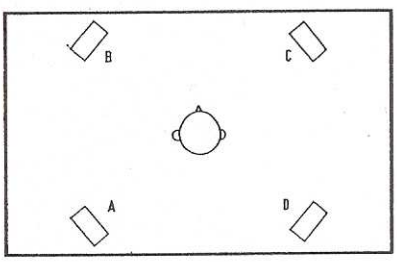
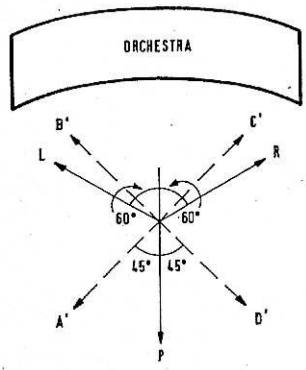


FIG. 2 COINCIDENT MICROPHONE ORIENTATION



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speakers can be derived by suitable matrixing of the three microphone signals. Thus, for many purposes, only three recorded channels are needed to convey all the information reproduced by the four loudspeakers.

In order to give this assertion concrete form, it is first necessary to describe the layout of the reproducing loudspeakers. In the standard quadraphonic system, the four loudspeakers are to the rear left, front left, front right, and rear right of the listener, in a square as illustrated. It is convenient to label these loudspeakers A, B, C and D respectively, and to use these letters to indicate the four audio signals which must be transmitted to the four loudspeakers.

Consider three identical coincident microphones with, say, cardioid directional characteristics pointing in the three directions indicated by solid arrows in **fig. 2**. Thus, one microphone points 60° to the left (giving an output L), one points 60° to the right (giving an output R), and one points backward (giving an output P). According to what was said above, it is possible to derive all other horizontally-pointing microphone outputs from L, R and P by matrixing. Also note that the signals L and R form a good stereo signal. The signals A′, B′, C′, and D′ fed to the four loudspeakers A, B, C and D could well be the outputs that would be given by cardioid microphones pointing in the four directions (broken arrows) labelled A′, B′, C′ and D′ in fig. 2, i.e. 135° to the left, 45° to the left, 45° to the right, and 135° to the right. Rather messy trigonometric computations show that A′, B′, C′ and D′ may be obtained from L, R and P by the matrixing described in **Table 1**.

If the microphones pointing in the directions L, R and P of fig. 2, have a given identical hypercardioid directional characteristic, then the signals A′, B′, C′ and D′ obtained by the matrixing of Table 1 will be the signals which would be obtained from identical hypercardioid microphones pointing in the directions A′, B′, C′ and D′ of fig. 2.

Thus, for coincident microphone recordings, we need only record the signals L, R and P given out by identical cardioid or hypercardioid microphones pointing in the directions of the three solid arrows in fig. 2. The signals fed to the four loudspeakers can be obtained by the matrixing of Table 1. This illustrates the principle that good quadraphony can be recorded using only three channels, although four loudspeakers are needed to reproduce it.

Having shown that coincident microphone recordings need only three channels, the question naturally arises whether other types of four-speaker audio can be recorded or transmitted using only three channels. Most of the four-channel material recorded at the moment consists of more or less independent sound on each channel, due to the use of widely spaced microphones. There is one obvious way of reducing genuine four-channel recordings to three channels. This is to derive the three signals, L, R, and P that would be picked up by imagined microphones pointing along the solid arrows in fig. 2 if the sound A, B, C, and D of the four channels were played through loudspeakers in the four directions A', B', C', and D' in fig.2. While we are only imagining 'make-believe' microphones picking up imaginary loudspeakers, the computation of the signals L, R, and P picked up by these microphones does give us a prescription for reducing four channels to three. Unfortunately, the signals L, R, and P thus obtained depend on the choice of directional characteristic of these imagined microphones. This illustrates the fact that there is no unique way of reducing four-channel material to three channels.

Table 2 gives the matrixing that converts four channels to three assuming that our fictional microphones are hypercardioids with a null response 135^o off axis, i.e. with a 15.31 dB front-to-back ratio.

Table 1
Converting three channels L, R, P to four channels (see fig. 2)

A' = 0.506 L - 0.311 R + 0.805 P
B' = 0.977 L + 0.161 R - 0.138 P
C' = 0.161 L + 0.977 R - 0.138 P
D' = -0.311 L + 0.506 R + 0.805 P

Table 2
Converting four channels A, B, C, D to three channels (in the manner of 135^o-null hypercardioid microphones).

L = 0.418 A + 0.724 B + 0.194 C - 0.112D
R = - 0.112 A + 0.194 B + 0.724 C + 0.418 D
P = 0.612A + 0.612 D

Table 3

Reproduction of four channels transmitted via three channels (as in Tables 2 and 1)

A' = 0.739 A	+ 0.306 B - 0.127 C + 0.306 D
B' = 0.306 A	+ 0.739 B + 0.306 C - 0.127 D
C' = -0.127 A	+ 0.306B + 0.739 C + 0.306 D
D' = 0.306 A	- 0.127 B + 0.306 C + 0.739 D

Table 4

Converting four channels A, B, C, D, to three channels (in the manner of cardioid microphones).

L = 0.445 A + 0.695 B + 0.262 C + 0.012 D
R = 0.012 A + 0.262 B + 0.695 C + 0.445 D
P = 0.604 A + 0.104 B + 0.104 C + 0.604 D

The four-channel material, with signals A, B, C, and D, can be transmitted or recorded via three channels, L, R, and P by the recipe of Table 2. The signals A', B', C' and D' for the four loudspeakers can be rederived by the recipe of Table 1. Of course, something is lost in the process of reducing four channels to three. **Table 3** give the signals A', B', C', and D' emerging from the loudspeakers in terms of the original signals A, B, C, and D, after these have been reduced to three channels L, R, P and been reconstituted according to Tables 2 and 1. It will be seen that the signal B' (say) emerging from loudspeaker B consists mainly of the signal B, plus the signals A and C each attenuated by 7.66 dB, plus an out-of-phase crosstalk of the signal D attenuated by 15.31 dB. However, this crosstalk should not seriously affect the directional characteristics of the reproduced sound, as satisfactory results are obtained with the much higher degree of crosstalk obtained when two-channel stereo is reproduced via four loudspeakers.[1]

Thus, while the three-channel transmission or recording of four-channel material causes little loss of directional effect, the sound does tend to spread out among the loudspeakers. The reconstituted sound may be thought of as a spatially blurred version of the original. This is illustrated by what happens to coincident microphone recordings. Suppose that A, B, C, and D were picked up by coincident hypercardioid microphones with nulls 135° off axis pointing along the broken arrows of fig. 2. Then the reproduced signals A', B', C' and D' obtained by reducing to three channels and reconstituting as in tables 2 and 1 will be the sound that would be picked up by *cardioid* microphones pointing along the broken arrows of fig. 2.

Thus a certain amount of information is lost even with coincident microphones in the process of converting from four channels to three, and back to four again. For both spaced and coincident microphone recordings, the degree of loss depends on the chosen imaginary microphone characteristic used to convert four channels to three. **Table 4** gives the reduction from four channels to three when the fictional microphones are cardioids. The reproduced channels are then as in **Table 5**, in which the degree of sound spreading on to adjacent channels is greater that in **Table 3**. However, crosstalk on to the opposite channel is eliminated, which is a desirable requirement with spaced microphone recordings.

Table 6 gives the reduction from four channels to three when the fictional microphones are hypercardioids with a null 120^{o} off axis (i.e. with a 9.54 dB front-to-back ratio.) Such a three channel signal will not be very suitable for reconversion to four channels by the recipe of **Table 1** in many cases, as the reproduced signals will be as in **Table 7**, in which the crosstalk on each channel from the opposite channel is a rather excessive -9.54 dB. However, if the signals A, B, C, and D originate from a coincident microphone system, then the reproduced signals A', B', C' and D' will be the same as A, B, C, and D.

This shows that, if four channels are reduced to three, conversion using an imaginary 120^{o} -null hypercardioid (Table 6) works best with coincident microphone recordings, conversion using a fictitious cardioid (Table 4) has desirable properties for spaced microphone recording in which no pan-potting is used, and conversion using an imaginary 135^{o}-null hypercardioid (Table 2) is a good intermediate compromise between these conflicting requirements.

Sounds which are pan-potted exactly half-way between two adjacent speakers can be conveyed without loss via three channels, as long as the conversion to three channels uses a fictitious 120^{o}-null hypercardioid (**Table 6**). For example, consider an audio signal X pan-potted halfway between speakers A and B. Then the four-channel signal is A = 0. 707X, B = 0.707X, C = 0, D = 0. After conversion to three channels via **Table 6**, one has L = 0.787X, R = -0.079X, P = 0.354X. The matrixing of **Table 1** reconstitutes the signals

A' = 0.707X, B' = 0.707X, C' = D' = 0. Similarly, a signal pan-potted half-way between speakers B and C, C and D, or D and A can be transmitted via three channels by putting, respectively, L= 0.604X, R = 0.604X, P = -0.146X or L = -0.079X, R = 0.787X, P = 0.354X or L = 0.104X, R = 0.104X, P = 0.854X.

All the above indicates that reasonable quadraphonic sound can be conveyed via three channels. It is therefore worthwhile to examine the various domestic recording and transmission media to see what advantages three- channel recording might have over four-channel recording.

Take the problem of transmitting four-speaker sound via FM radio. The author has recently proposed[2] a system of broadcasting three channels which involves the use of no subcarrier frequencies not already use for stereo. This system inherently has a much better noise performance, and causes less adjacent-station interference than any four-channel FM multiplex system. In the case of FM broadcasting, significant improvements in technical quality can thus be obtained if quadraphonic sound is conveyed via only three channels.

The use of only three channels also has significant advantages in domestic tape recording. Current proposals for quadraphony involve recording four channels side-by-side on 6.25 mm (quarter inch) tape. The width of each tape track on the best four channel tape heads is only about 1 mm. This means that the outer tracks are badly affected by dropout, and the hiss level is rather high.

Table 5

Reproduction of four channels transmitted via three channels (as in tables 4 and 1)

A' = 0.707 A + 0.354 B + 0.000 C + 0.354 D
B' = 0.354 A + 0.707 B + 0.354 C + 0.000 D
C' = 0.000 A + 0.354 B + 0.707 C + 0.354 D
D' = 0.354 A + 0.000 B + 0.354 C + 0.707 D

Table 6

Converting four channels A, B, C, D, to three channels (in the manner of 120°-null hypercardioid microphones).

L = 0.379 A + 0.733 B + 0.121 C – 0.233 D
R = -0.233 A + 0.121 B + 0.733 C + 0.379 D
P = 0.604 A - 0.104 B – 0.104 C + 0.604 D

Table 7

Reproduction of four channels transmitted via three channels (as in tables 6 and 1)

A' = 0.750 A + 0.250 B - 0.250 C + 0.250 D
B' = 0.250 A + 0.750 B + 0.250 C - 0.250 D
C' = -0.250 A + 0.250B + 0.750 C + 0.250 D
D' = 0.250 A - 0.250 B + 0.250 C + 0.750 D

If only three tracks had to be recorded, the track width would increase to 1.6 mm, which would improve the signal-to-noise ratio by at least 2 dB, and would dramatically reduce drop-out. The three-track format would also be compatible with half-track stereo recordings. Furthermore, the cost of reasonable quality multitrack heads is rather high, and three track heads would only cost about half as much as four-track heads of comparable quality.

Alternatively, it would be economic to record quadraphonic tapes using three tracks in each direction. The quality loss involved in this would be substantially less that when four tracks each way are used. Indeed, experience with 8-track cartridges indicates that eight tracks on 6.25 mm tape cause many severe problems, due to the difficulty of accurate track alignment. The wider track widths and guard bands possible with tapes using three channels each way should reduce these problems.

It is more difficult to see whether the use of only three channels gives any advantages with gramophone records, as one first has to consider how multi-channel gramophone records might be manufactured. To preserve the low cost of gramophone records, it is essential that any multichannel disc should be manufactured by the simple process of pressing a blob of vinyl, and this rules out adding channels by modulating the colour, the dielectric constant, the magnetisation, or other esoteric properties of the disc. Conceivably, two channels could be added to ordinary stereo by modulating the slope of each of the two groove walls, but there are numerous difficulties in designing a pickup to recover this information. In practice, it seems certain that additional channels will be added by modulating an ultrasonic subcarrier with frequency between 30 and 40 kHz.

Several companies are known to be working on multichannel discs using subcarriers, with reasonably promising results. Despite the very low amplitudes of such subcarriers (about the wavelength of light…) it appears that a fairly low noise level can be achieved, thanks to the ability of heated record cutting styli to reduce noise at high frequencies. By recording two modulated subcarriers, each causing a direction of stylus motion 90^{o} from that caused by the other, four channels can be carried on one disc. The crosstalk between the subcarriers will be poor, because of the poor channel separation of pickups at high frequencies, but even this can be minimised by recording the two subcarriers 90^{o} out-of-phase with respect to one another.

Back to seventy-eights?

However, at the current 33⅓ RPM rotation rate there is one severe problem with the subcarrier method. When the record is tracked, the pickup will produce fairly large amounts of harmonic distortion above 5 kHz. As the usual stereo tracks will be recorded at a much higher level than the subcarriers can be, distortion products of the audio will interfere badly with the subcarrier modulations. This problem can be partly overcome by using higher rotation rates, e.g. 45 or 78 RPM, but it is known that the distortion level in the vertical component of the stylus motion is larger than in the horizontal component. Thus the easiest way of reducing the distortion's interference with the subcarriers is to record the subcarriers horizontally only. But if this is done only one subcarrier can be recorded.

Thus the technical problems associated with using modulated carriers may mean that only three channels may be available on gramophone records. In such a case, it would again be desirable to convey quadraphony via three channels. Care will be needed to ensure that the polarity, phase and frequency response of the subcarrier channel matches that of the stereo channels, at least in the mid-frequency audio range, so that the matrixing of **Table 1** can be performed accurately.

While quadraphony can be conveyed over three channels, we have seen that four channels are capable of conveying sound with less spatial spreading of the sound onto adjacent channels. What, then, is the precise nature of the additional information conveyed by four channels?

In a four channel recording, there is one audio signal essentially independent of the three audio signals L, R, and P of **Tables 2, 4 or 6**, which conveys no directional information whatsoever. This is the 'focus' signal F defined by $F = \frac{1}{2}A - \frac{1}{2}B + \frac{1}{2}C - \frac{1}{2}D$.

This is the only combination of the four signals A, B, C, and D which is always zero for coincident microphone recordings. For any four channel recording, given the signals L, R, P, and F, it is always possible to rederive the original signals A, B, C, and D by means of matrixing. When the signal F is suppressed (i.e. when only L, R, and P are transmitted), a reasonable facsimile of the original directional effect can still be obtained by means of the matrixing of **Table 1**. Thus the essential difference between three and four channel quadraphony is the addition in the latter of the 'focus' signal, which conveys no directional information, but only information about how widely a sound appearing to come from a given direction is spread out among the four loudspeakers.

The question of when a four channel recording with signals A, B, C, and D is capable of being passed through three channels without alteration has a simple answer; this can be done if and only if the focus signal is zero, and the matrixing that achieves this is that of **Tables 6** and **1**.

Despite the fact that three channels are sufficient for quadraphony, commercial pressures make it likely that practical quadraphonic media will in fact convey four channels. However, we have seen that 'focus' information can be dispensed with without excessive losses of directional information. This prompts the thought that, in four-channel recordings, perhaps the focus information can be discarded, and other information smuggled into its place. The next part of this article will describe how, by this means, 'conventional' (!) quadraphonic recordings can be used to reproduce height information via suitable reproducing equipment.

REFERENCES

1) M.A. Gerzon: 'Surround Sound–From 2-Channel Stereo' Hi-Fi News, August.
2) M.A. Gerzon: 'QUART- A System of Multichannel FM Multiplex'. Hi-Fi News, May 1970.

