Experimental Tetrahedral Recording: Part One

By Michael Gerzon

IN the September 1970 *Studio Sound*, the author proposed a new system of four-channel recording using the skew tetrahedral loudspeaker layout shown in **fig. 1**, which is essentially a conventional square four-speaker layout with the front left (LF) and rear right (RR) speakers raised to the ceiling, and the front right (RF) and rear left (LR) speakers lowered to the floor. By this means it was hoped to capture the original directional effect of all sounds around the listener, both horizontally and vertically.

Recently, an experimental live relay and recording was arranged using this system. Considerations governing the design of the experiment will be described next month. The following confines itself to a description of the experimental set-up and an account of some impressions obtained by listeners.

The relay and recording was of a rehearsal and public concert given by the Schola Cantorum of Oxford, conducted by Andrew Parrott, of unaccompanied and accompanied choral music, in the chapel of Merton College, Oxford, on May 8. This location has a distinctive 'church acoustic'

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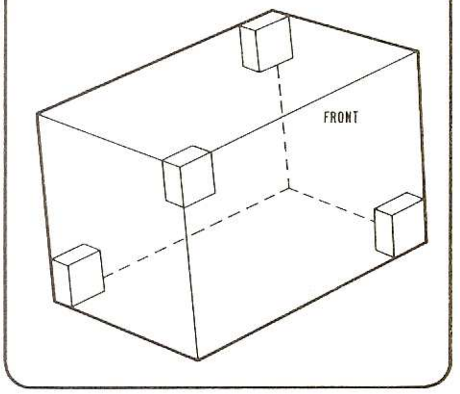
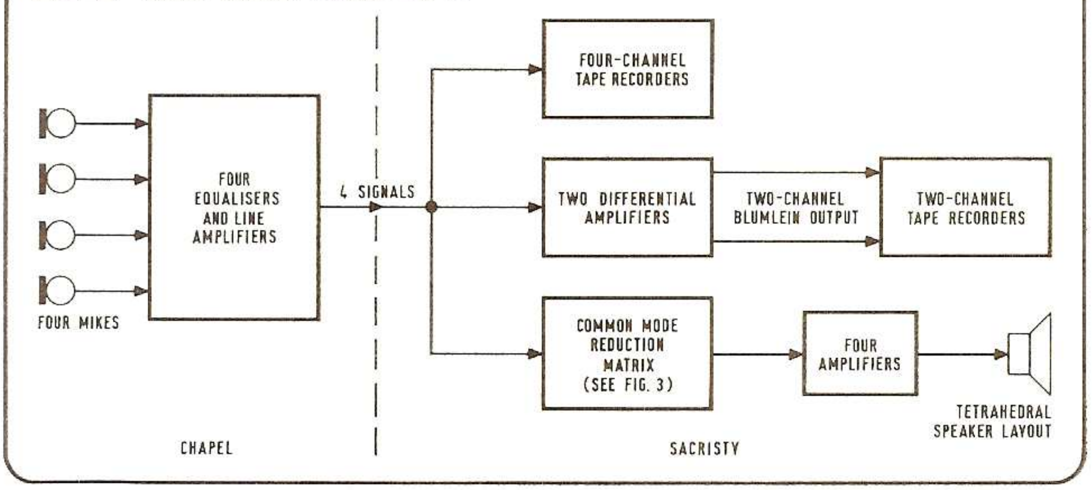
and the experimental aim was to determine how realistically this could be reproduced.

FIG. 1 SKEW-TETRAHEDRAL LOUDSPEAKER LAYOUT



The following set-up was used for the experiment (see also **fig. 2**). Four coincident Calrec 652 cardioid microphones, pointing along the four axes of the chosen tetrahedron of fig. 1, were placed in the middle of the audience in the chapel at just above ear level so as to provide an accurate comparison between the sound as heard live and as reproduced. These were fed into a four channel equaliser/line amplifier and this fed cable to the Sacristy adjacent to the chapel. In the Sacristy, the signal was split to feed two four-channel tape recorders, a 6.25 mm *Crown* loaned by Carston Electronics and brought by Bob Arthurton, and a 12.5 mm *Scully* loaned by Granada Recordings and brought by David Martin. The four signals were also fed via Quad valve amps

FIG. 2 BASIC EXPERIMENTAL SET-UP



into a tetrahedral monitoring set-up consisting of two floor level Quad electrostatic speakers and two Spendor *BC1* monitors placed 2.5m up on the top of stepladders. The floorplan of the speakers was about 3m square. The four channel signals were fed to the monitoring amps via a matrix circuit which allowed the cardioid microphone outputs to be converted into hypercardioids at the turn of a knob.

The four-channel signal was also taken to a pair of differential amplifiers which produced a crossed figure-of-eight Blumlein stereo output for simultaneous two-channel recording.

A relatively small speaker layout was used to simulate domestic conditions and to minimise the effect of the acoustics of the rather large Sacristy. As only four people could be seated comfortably within the tetrahedron, only a small number of people were able to take part in the experiment. Among these were Sid O'Connell and Granville Cooper, whose previous experience of other tetrahedral systems proved invaluable in pinpointing strengths and weaknesses of this system. It was possible to compare the reproduced sound with the real thing by passing through the door to the chapel.

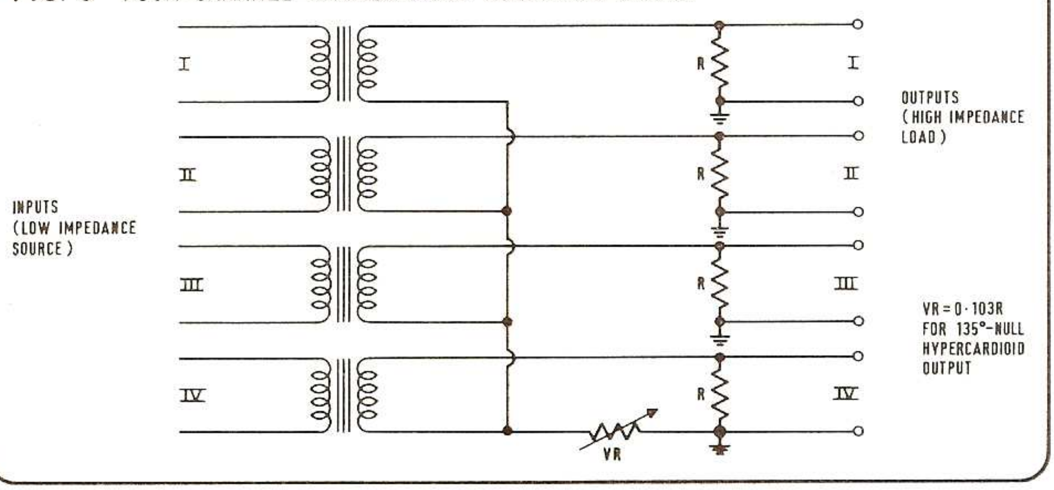
The initial setting up of speaker phasing and levels was found to be somewhat difficult and small errors in the channel gains were found to have a considerable effect on the reproduced sounds. When these were correctly adjusted, the basic stereo image was found to be reasonably correct in its directional effect, and sounds arriving at the microphones from above, below, the sides, the front and the back of the microphones were reproduced from these positions also.

When the skew tetrahedron of fig. 1 was first proposed, the author and others were worried that the front stereo image might not appear flat, but would instead tilt downwards from left to right. It was in fact found that a good horizontal stereo image was obtained in all sensible listening positions once levels had been adjusted. The general three dimensional sound picture was judged to be about the most accurate yet heard, and considerably superior to the stereo picture obtained with other systems.

There were two really important flaws heard. The first defect, given the name 'overlap' by Rex Baldock at the time, is the effect obtained when the sound corresponding to one direction emerges to some degree even from speakers in the opposite direction. Overlap is familiar to those who have tried Hafler reproduction with the rear speakers turned up a little too high. Just as a mono sound gains in richness from being reproduced from two speakers, so does a sound gain even more richness if it is reproduced from all four speakers. This extra quality was described as 'openness' by the one listener who liked it but other listeners felt that the richness caused by the overlap was rather unnatural and some found that sounds seemed to be coming from both in front and behind at the same time.

Calculations show that a sound arriving from the front at the cardioid microphones will be picked up by the rear microphones only 11.4 dB down relative to the front microphones. This degree of overlap can be reduced by using hypercardioid microphones. In the experiment, hypercardioids were simulated by using a common mode reduction circuit to reduce the common mode (i.e. omnidirectional) component of the four cardioid signals. The circuit used is illustrated in **fig. 3**, and a setting of the variable resistor VR at about 0.1R was found to give a considerable reduction of overlap; this setting corresponds to using hypercardioid microphones whose nulls are 135^{o} off-axis, and increases the front-back separation from 11.4 dB to around 20 dB. The pick-up of front sounds by the rear channels can theoretically be eliminated by putting VR=0.183 R, corresponding to 125.3^{o} null hypercardioids, but this is found to cause a lot of out-of-phase overlap for sounds coming from the sides of the orchestra. It was found subjectively that the least overlap corresponded to VR=0.1R very approximately. The result of these preliminary tests was that cardioids give too much overlap, and 135^{o} null hypercardioids, obtained by matrixing, give a much better effect.

FIG. 3 FOUR-CHANNEL COMMON MODE REDUCTION CIRCUIT



The other important flaw in the tetrahedral reproduction is far more difficult to rectify. As readers of this journal are aware, the *ELS* and *BC1* speakers used are among the most uncoloured available. They were chosen for precisely this reason, as fidelity to the live sound was the most important consideration. Unfortunately, it was considered impractical to mount *ELS*s on stepladders, and only two Spendors were available. As an *ELS* and a Spendor have been found to work well as a stereo pair, being surprisingly similar in sound, it was decided to use two of each as described earlier. However, it was found difficult to match their outputs for the tetrahedral reproduction.

Even when the levels were set optimally, it was found that the coloration from the four speakers caused a very disturbing side-effect. Although the basic stereo image was distributed horizontally, the four loudspeakers were heard as separate and very distracting sources of coloration. The coloration from the Spendors tended to pull LF and RR sounds upwards, and the *ELS* coloration tended to pull the RF and LR sounds downwards. These sources of coloration greatly disturbed the overall impression of a homogeneous sound field around the listener, and this is certainly the most serious problem to be solved with this system. Its seriousness is indicated by the observation that the *ELS* is probably the least coloured loudspeaker available and that the *BC1* is generally regarded as approaching it; yet the tetrahedral system made the Spendors seem tremendously prominent as a separate source of coloration and even the Quads were shown up to a lesser extent. If this experiment is anything to go by, tetrahedral reproduction as in fig. 1 is an ideal way for loudspeaker designers to assess so-called ‘subtle’ colorations ─ there is clearly an enormous amount of progress yet to be made in loudspeaker design.

The energetic members of Oxford University Tape Recording Society who had done all the hard work of the experiment decided that a mixed Spendor/Quad system was unsatisfactory. The next day they set up a tetrahedral playback system in a domestic room consisting of four *ELS*s, two placed on the floor, and two strapped precariously at ceiling level on stepladders, angled downwards towards the listener to avoid the loss of treble up top (literally!). This set-up gave much better results. The channel levels were found to be less critical, although the bass output of the ceiling *ELS*s had to be reduced to obtain a balance. With this system, the speaker coloration was found to be less disturbing, although its effects were still noticeable. The high degree of overlap given by cardioids was found to be more objectionable than with the earlier system.

The acoustics of the Sacristy had to some extent obscured the subtleties of the Spendor/Quad tetrahedral playback and it was found that, with the all-Quad system in the domestic room, the original acoustics of the chapel were audible with great clarity, even though the sound was being played back from a rather hissy tape. It was possible to analyse the acoustics in the same detail as if one were there live; with careful listening, one could pick out the precise position of a lectern which had obstructed some of the reverberant sound near the microphones. The separate effects of various parts of the ceiling and walls of the chapel were clearly distinguishable, and the whole experience strongly argued against those who claim that four channels need only pick up a generalised reverberant richness and nothing more.

There are many who regard the height effect as an altogether unnecessary luxury and, at first sight, our choice of music with virtually no vertical spread seems to suggest they are right. Yet the listening tests showed quite the opposite – the height effect on the reverberation added very considerably to the realism. Indeed, several listeners standing *outside* the tetrahedron still found the spaciousness of the recording to be superior to that obtained from most conventional four-channel recordings *within* the square of speakers. Another index of the improved realism is that listeners outside the playback room heard a sound that gave a quite uncanny imitation of emerging from a chapel.

Some of the orchestral playing in the concert had been rather scrappy and this was found to be very disturbing musically on two-speaker stereo playback. It was interesting to note that such flaws were far less noticeable on tetrahedral playback which, like the live sound, made it easier to listen though such performance errors to the music. The purely musical value of tetrahedral reproduction should not be underestimated.

This catalogue of enthusiastic initial impressions indicates the tremendous potential of tetrahedral reproduction but it must not disguise the serious problems that remain. When set up carefully, the overall impression is that of a basically realistic sound with a lot of spurious distractions added. Speaker coloration is the most serious and perhaps the tetrahedral system needs to wait until loudspeakers have attained the required standards. Alternatively, coloration might be rendered less disturbing by sharing it out among more loudspeakers, say a cube. The requirement that the amount of overlap must be kept down means that the choice of microphone arrangement is more critical than with other systems, although this problem would not exist with pan-pot multimike recordings.

It seems that the relative balance between the four channels must be accurately maintained right from the live sound to the playback speakers, as a small imbalance can shift a sound farther that with the narrowly angled speakers of two-speaker stereo. It is important to point the microphones accurately, as a 5^{o} or 10^{o} rotation of the image can make the sound seem terribly lopsided. This is especially important since the speakers become more prominent as distinct sources of sound when one's head is not pointing forward.

Another problem is that there is a partial 'hole in the middle' effect at the front, two sides and back (and, one presumes, above and below, although this was not evident in the absence of such direct sounds). The stereo image is certainly there, but it is less rigidly locked in place between the speakers than in the corners. The overall stereo effect does vary with listening position, although the orchestra tilts only near the corners, or if there is a channel imbalance. When one rotates one's head, one has an impression that the sound rotates with it, although the sound tends to lock into a position not far from its original one a little while after the head rotation stops. This rotation was less pronounced for hypercardioids than cardioids, and no rotation occurred when direct sounds surrounded the listener, as with audience applause.

When channel balance was out, it could be quite difficult to determine the precise relative positions of sounds, especially when there was too much overlap. It was also difficult to obtain a good distance effect, and the sound seemed to stop short at the loudspeaker distance, even when the live sound was closer. This disappointing distance effect is puzzling, as I have heard generally inferior systems reproduce all distances, both close and distant, with great fidelity.

These have been some initial reactions to skew-tetrahedral reproduction. It offers a tantalising glimpse into what audio could be like, and one becomes depressingly aware of the overwhelming deficiencies of even the best conventional four-channel stereo. It, or something like it, is clearly the system of the future, but how far in the future is anyone's guess as the practical problems still seem formidable. What is now needed is much more experimental investigation of this and related systems. It is only by patient research, by trial and error, that many of the difficulties can be resolved.

Meanwhile, it seems desirable for commercial recordings to be made containing height information where possible. Tetrahedral recordings made for the skew-tetrahedral layout of fig. 1 are directly suitable for playback over the conventional square loudspeaker layout, although the height effect is then lost. The situation seems to be that tetrahedral recordings can be issued in any genuine four-channel medium, but cannot be played back properly as yet. It should be observed that, if necessary, it will always be possible to rematrix a recording made for one tetrahedral system for playback via another.

A four-channel 12.5 mm tape has been recorded in the above experiment. This tape is available for copying or playback by anyone interested, although deficiencies in the recording set-up have given it rather a dull treble.

Tetrahedral systems can be varied in so many ways that it is essential for experimenters to understand the principles before they start. A naive outlook can render experiments fruitless. For this reason, the second part of this article will deal with the principles, setting-up procedures and uses of tetrahedral recording.

Experimental Tetrahedral Recording: Part Two

By Michael Gerzon

LAST month we described the actual set-up for a recent experimental tetrahedral recording and noted initial listener reactions. Perhaps more important than describing any one particular experiment is to indicate the problems facing anyone trying out similar experiments, and their solutions.

It is first necessary to choose the type of tetrahedral loudspeaker layout that it is intended to use for the playback. Four layouts have been proposed, and these are illustrated in **fig. 1**. The first such system was proposed by Granville Cooper (see ref. 1), and is shown in **fig. 1a**. A second system, using a skew tetrahedral layout, has been proposed by the author (ref. 2) and is shown in **fig. 1b**. A third playback system due to Jerry Bruck (ref. 3) is shown in **fig. 1c**, and a fourth 'sword of Damocles' tetrahedral layout has also been suggested.

A theoretical analysis indicates that the Cooper, Bruck and 'Damocles' layouts suffer from some important disadvantages resulting in an unsatisfactory distribution of stereo images around the listener. The most obvious disadvantage is that if the layouts lie on a regular tetrahedron, all these layouts require some loudspeakers to lie at large angles above or below the horizontal from the viewpoint of the listener (54.7° for the Cooper layout, 70.5° for the Bruck, and 90° for the 'Damocles'). Also, if room height is the smallest room dimension, then all these layouts include a much smaller volume than that of **fig. 1b** (35% for the Cooper layout, 54% for the Bruck, and 69% for the Damocles). These practical considerations make it necessary to 'squash' the tetrahedron vertically to obtain a reasonable listening area. Also, in order to prevent a hole-in-the middle at the front with these systems, it is necessary to narrow the angle between the front stereo pair of speakers from 109.5° to around 70°. The result of all these distortions of the loudspeaker layout is that is that sounds coming from directions not close to any loudspeaker (e.g. the sides) will not have an accurate stereo location. In the author's opinion, these practical compromises largely negate the whole reason for tetrahedral sound, i.e. to reproduce sounds from all horizontal and vertical directions from their original direction around the listener.

Perhaps even more serious is that in the Cooper, Bruck and Damocles systems, the loudspeakers

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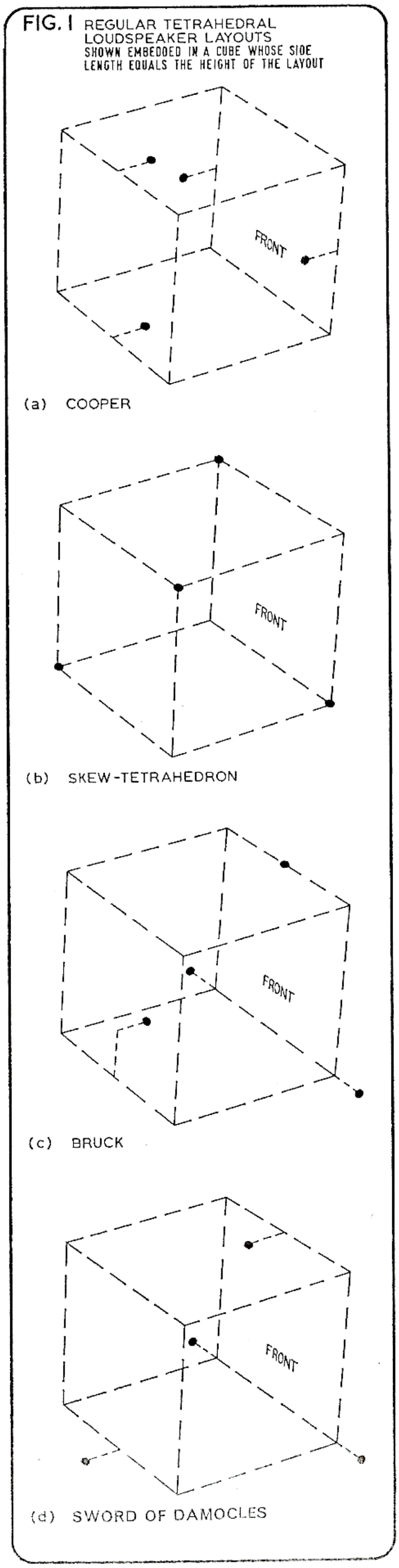
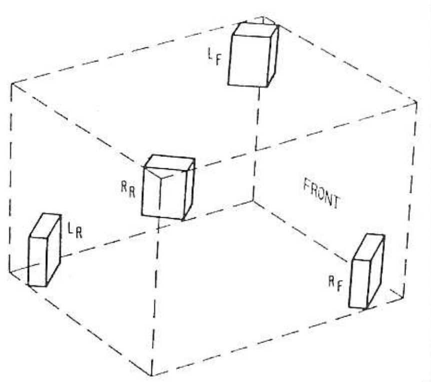


contributing the height information lie in the plane of symmetry of the listener's head, whereas the ordinary stereo speakers lie closer to the axis of the ears. As the ears are directional in the treble, this means that the height speakers contribute much less treble than the 'stereo' speakers, which must inevitably degrade the height effect and cause a poor stereo location of non-frontal images. On the other hand, the skew tetrahedral system of **fig. 1b** has all speakers lying at the same angle off the ears' axis, and would therefore stand a better chance of forming good non-frontal stereo images. Its large volume for a given room height makes 'squashing' much less necessary, no speaker lies more that 35.3° from the horizontal, and location of sounds at the side should not be affected by any squashing. It can also be shown (ref. 4) that it is less liable to hole-in-the-middle, and provides more realistic information to human stereo location mechanisms using small head movements, as compared to other tetrahedral layouts.

It is for these reasons that the skew tetrahedral layout was adopted for experimental investigations, despite its rather odd appearance and its unsuitability for reproducing two-channel stereo. The skew tetrahedral layout of **fig.1b** may be thought of as a conventional square layout, with the left front (L_F) and rear right (R_R) speakers raised to the ceiling, and the right front (R_F) and left rear (L_R) ones lowered to the floor. The simplest way of visualising the layout is to imagine the speakers as lying on four alternate corners of a cube. Of course, there is no reason why the mirror-image tetrahedral layout should not work just as well but it is thought advisable to standardise on the L_F speaker being high up, to avoid needless incompatibility between recordings. When setting up the loudspeaker layout, care should be taken to ensure that their floor plan is accurately square, although it is a legitimate experimental aim to investigate the effects of distorting the tetrahedron. As explained last month, it is advisable to use four identical speakers of low coloration, and it would be a good idea to point them towards the listener, possibly as in **fig 2**.

FIG. 2 TYPICAL SKEW-TETRAHEDRAL LOUDSPEAKER ARRANGEMENT



The would-be experimenter should be warned against attempting to make A-B comparisons between tetrahedral and conventional four-channel sound by adding another two speakers at the other two floor-level corners of the cube to make a floor-level ‘conventional’ square layout. Such a comparison would be unfair to the conventional system, which sounds worse when its speakers are very low or very high than when they are at, or just a little above, ear level. A fair A-B comparison requires the four speakers for each system to be placed at the positions optimum for that system.

The one big disadvantage of the skew tetrahedron system is that speaker colorations emerge from directions quite different from those associated with direct sounds, whereas the Cooper, Bruck and Damocles systems have their coloration-producing speakers placed near the likely sources of direct sounds. A fruitful area of investigation is to determine ways of overcoming this coloration problem, and possibilities range from using cubic or octahedral loudspeaker layouts to placing four outwards-firing miniature loudspeakers pointing along the four tetrahedral axes round the head of the listener, so that the stereo image is reconstructed from the diffuse sounds reflected from the walls and ceiling.

Now we must deal with the tricky problem of microphone technique. As explained in ref. 2, it is possible to make tetrahedral recordings with multimike pan-pot techniques, although this requires more elaborate matrix circuitry than is used currently. When only crude directional effects are required, as in much pop music, it is possible to use ordinary two-channel pan-pot techniques to make sounds come from straight above, straight below, from either side, from straight behind or directly in front (ref.2)

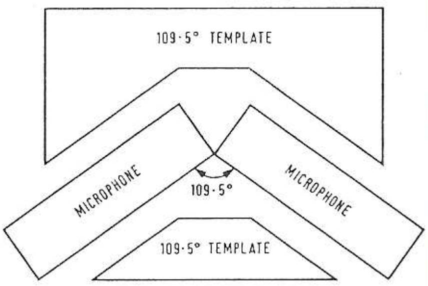
A profound philosophical problem with tetrahedral recording is where to put the microphones. If the tetrahedral system fulfils its aim of reproducing the live sound, then placing microphones several metres up is liable to make the poor listener seem to float high in the air; at least one listener has found Cooper's recording of the *Messiah* disconcerting just because the microphones had had to be placed 10m up. For experimental purposes, placing the microphones at a sensible listening height will allow the realism to be evaluated more effectively. If tetrahedral recording ever becomes commercial, one can be sure that this will be a perpetual source of controversy.

In principle, the coincident microphone arrangement is simple, merely consisting of four cardioid or hypercardioid microphones pointing in the four directions of the cube corners in **fig. 2**, placed as coincidently as possible. The picture of the experimental microphone arrangement used for the Oxford recording last May shows that the reality looks a good deal more confusing (see **fig. 3**).

Fig. 3 Experimental tetraphonic array using Calrec capacitor microphones

The subsequent discussion assumes that the microphones used have a cylindrical shape with the capsules mounted at one end, as in the AKG *C451*, Calrec *652* and Calrec *1050* microphones. The simplest way of making such microphones 'coincident' is to make them face into one another, but this would cause a tetrahedral cavity to be formed between them which would cause coloration. To avoid this it was deemed necessary (perhaps wrongly!) to use the type of 'coincidence') shown in the photo, in which the V-shape formed by one pair of microphones (as in **fig. 4**) interlocks with the V formed by the other pair of microphones. In the view from the front, one of these V's is formed by the two leftward-pointing microphones and the other by the right-pointing microphones. This choice was made so that any microphone spacing that remains will tend to simulate the left-right spacing of the ears. There are also good arguments for the two

FIG. 4 V-SHAPE FORMED BETWEEN PAIR OF TETRAHEDRAL MICROPHONES SHOWING ALIGNMENT TEMPLATES



alternatives, i.e. using an upward-pointing V and a downward-pointing V, or a forward-pointing V and a backward-pointing V.

Whichever arrangement is chosen, there is some difficulty in setting up. It is possible to obtain adequate flexibility of adjustment by mounting the microphones in a fiendishly complex arrangement of laboratory clamps, but the design of a proper mounting jig is beyond my spatial visualisation. The actual setting up procedure is basically by trial-and error adjustment, although it helps to mount the left pair of microphones on a separate framework (e.g. of laboratory clamps) from the right microphones, and to arrange that each framework can be adjusted in height, direction and angle to the vertical. The actual setting up uses the following facts:

1. The angle between every pair of microphones should be 109.5°, which can be checked using 109.5° angle templates as illustrated in **fig.4**. The lower template in **fig. 4** has its angle vertex cut off to permit use when the other pair of microphones is in place.
2. The plane containing the left-pointing microphones is tilted 45° upwards towards the front, whereas the plane containing the right-pointing microphones is tilted 45° downwards towards the front.
3. When viewed with one eye precisely from the front, precisely from the side, or precisely from underneath, the bodies of the microphones should appear to form an X with arms at 90° to one another. It is very easy to find the position from which the X looks best, and the eye is very good at recognising even small deviations from 90°; this makes this test particularly useful in the final stages of adjustment.

With a bit of time and patience, all angles should be accurate within a degree or two. The procedure is easier for stereo microphones (such as the *C24*) in which one capsule is mounted above the other. One uses two such stereo microphones, and angles the capsules in each 109.5° apart. The bodies of the two stereo microphones are then crossed to form a vertical X with arms at 45° to the horizontal; one stereo microphone is made to point forward and the other backwards.

The choice of what microphones are to be used must be governed by their physical size and their directional characteristics. It is only possible to make the microphones very nearly coincident if they are small. A high degree of coincidence is desirable, as only then is it possible to obtain by a suitable matrixing of the four output signals *any* possible cardioid or hypercardioid output pointing in *any* possible direction. If the microphones are appreciably spaced, such matrixing will no longer have the desired effect, due to wavelength effects. It was by such matrixing that it was possible to convert cardioid microphone outputs to hypercardioid in the experiment described last month. The four capsules should certainly lie within a sphere of 5 cm diameter, and preferably less, in order to ensure that phase effects do not upset the matrixing. As will be described in detail next month, it is possible to rematrix a tetrahedral recording to be suitable for any four-channel playback system, and this flexibility depends on getting the microphones very coincident.

However, it is just as important that all the microphones should be as similar to one another as possible, and if possible, they should be identical. To give a correct reproduced directional effect, the directional characteristics of the microphones must be identical and should be either accurately cardioid (i.e. 2.5 dB down 60° off axis, 6 dB down 90° off axis, 12 dB down 120° off axis) or accurately hypercardioid. It does not matter if the microphones are not quite hypercardioid enough, as they can always be rendered more hypercardioid by the common mode reduction circuit described in Part 1. A polar response which is irregular or too directional in the treble should be avoided.

Matrixing the outputs of the microphones can only give good results if they also have a good polar phase response, i.e. do not introduce spurious phase shifts into off-axis sounds. Unfortunately, it is difficult to measure polar phase response and one can only make intelligent guesses as to how good this will be. As a guide, a microphone is likely to have a poor polar phase response if it is a dynamic type, has two units, uses reflection plates, or has an irregular frequency or polar response at high frequencies. The closer frequency and polar response measurements conform to the ideal theory, the more suitable the microphone is likely to be for use with matrixing circuits. On this basis, the AKG *C451* and Calrec *CM652* or *CM1050* cardioids seem particularly suitable.

Because of the stringent requirements on the technical specifications, it is unwise to choose microphones on the basis that they give a good sound when used for ordinary stereo.

One can make a simultaneous two-channel Blumlein (i.e. 90°–angled crossed figure-of eight) recording by feeding the L_F and R_R signals into a differential amplifier for the left output, and the R_F and L_R signals into a second differential amplifier for the right output, as in **fig. 5**. Such differential amplifiers

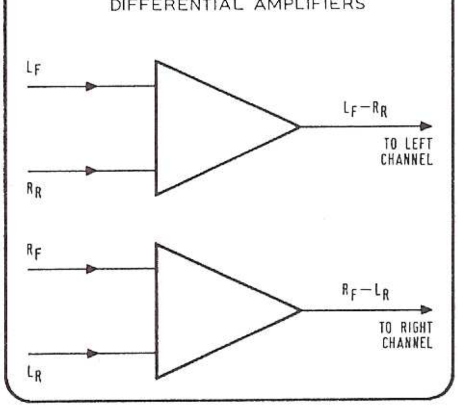


FIG. 5 DERIVATION OF 2-CHANNEL BLUMLEIN OUTPUT USING DIFFERENTIAL AMPLIFIERS

are also invaluable for matching the sensitivities of the four microphones. If the differential amplifiers are constructed with high tolerance components, then the following 'nulling' method is used: place two of the microphones right next to one another, pointing them in the same direction. Feed them into the line amplifiers with which they will be used during the recording, and take the line amp outputs into a differential amplifier. Monitor the output of the differential amplifier on a speaker, and talk in front of the two microphones. Adjust the gain presets on the line amplifiers until the sound from the speaker is minimised. The two microphones are then matched. This procedure should be repeated retaining one of the microphones as a reference standard and nulling it against the other two microphones in turn, each fed into its own line amplifier. One thereby ensures that the four tetrahedral microphones are accurately matched. If there is some doubt about the accuracy of the differential amplifier used, each nulling should be performed twice, interchanging the two inputs to the differential amplifier between the two nullings. The correct gain preset is half-way between the settings thus obtained.

The four microphones should be fed to the following four tape tracks: L_F (pointing left front upwards) to track 1, L_R (pointing left rear downwards) to track 2, R_F (pointing right front downwards) to track 3, and R_R (pointing right rear upwards) to track 4. This agrees with the usual quadraphonic convention.

It is relatively unimportant whether the microphones are cardioid or hypercardioid as matrixing can manufacture the optimum polar diagram. As yet, the optimum characteristic is not known, although the initial tests reported last month suggest something near 135° null hypercardioids. One problem is that if four cardioids are recorded on tape, and the matrixing to hypercardioids is performed during playback, then there will be a loss of 2 dB in signal-to-noise ratio, because of the loss of common-mode signal energy. In the Oxford experiment, it was considered advisable to record the original cardioids rather than matrixed hypercardioids despite the extra noise, so that the nature of the signal on the tape was known precisely. One would thus be able to calculate exactly what microphone characteristics and technique is produced by any matrixing on playback. Any pre-record matrix used in tetrahedral experiments should be built with high tolerance components, so that the matrix is accurately known.

For the same reasons, all four tape channels were recorded with precisely the same gain. It is helpful to record test tones at the start of all four tracks, so that any difference in channel gains can be corrected during playback. If the microphones are placed at a normal audience distance from the orchestra, then it is likely that the peak energies on all four tracks, front and rear, will be similar, although the rear tracks will sound quieter. If a higher gain is considered necessary on tracks two and four, then test tones are vital. Because of the need to match the four channels accurately, the gain of the rear channels should *never* be varied independently of the front. Remember that the rear channels provide not only ambience, but also stereo information to make the front sound horizontal. The recording engineer for the *Messiah* tetrahedral recording had altered the front-rear balance at several points, and at the playback last November at the University of Surrey it was fascinating to see listeners not knowing this become restless and perturbed at 'something wrong' at those points where the balance had been altered.

The final test for tetrahedral sound is whether it reproduces the overall musical impact of the live sound when technicalities are ignored. For this reason, no compression of dynamics was applied during the Oxford recording. Otherwise, a true comparison with the live sound would have been impossible. Any departure from reality will be far more obvious with tetrahedral sound than with two-channel stereo. The last part of this article next month will deal with methods of matrixing tetrahedral recordings

1. Granville Cooper, Tetrahedral Ambiophony, *Studio Sound*, June 1970
2. Michael Gerzon, Principles of quadraphonic recording, Part 2, Studio Sound, September 1970
3. Jerry Bruck, Interview, *Studio Sound*, December, 1970
4. M.A. Gerzon, Recording techniques for multi-channel stereo, *B.K.S. & T. Journal*, June 1971

Experimental Tetrahedral Recording: Part Three

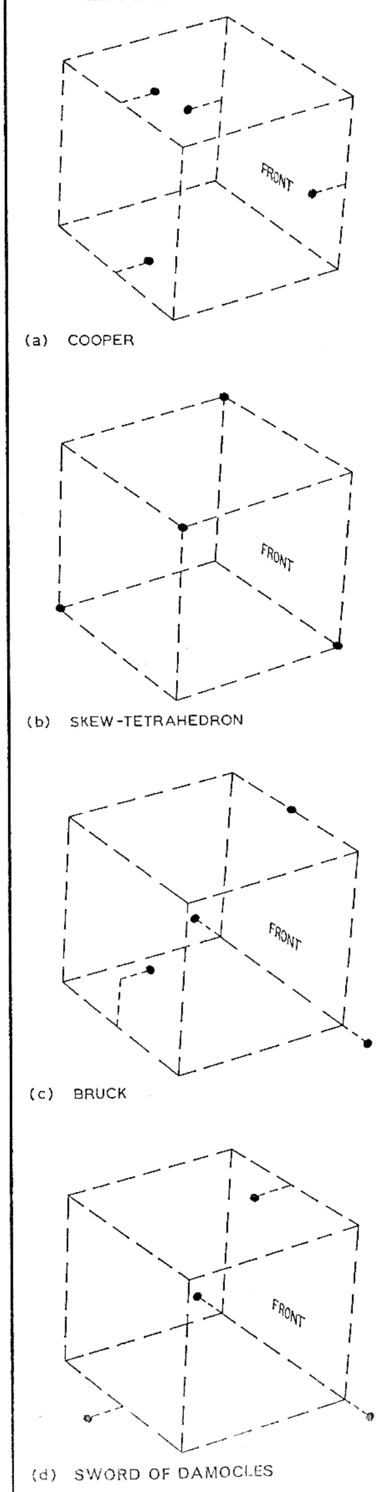
By Michael Gerzon

IN the previous two parts of this series, the method of making tetrahedral recordings was described. This last part describes the possible uses of such recordings in a wide variety of playback experiments.

If the precautions outlined in Part Two have been followed, the recording should consist of four coincident cardioid (or hypercardioid) signals pointing to the four corners of the cube shown in **fig. 1b**: L_R to rear left downward, L_F to front left upwards, R_F to front right downwards, and R_R to rear right upwards. By matrixing these four signals, it is possible to obtain *any* conventional microphone characteristic output pointing in *any* direction.

A possible adjustable matrixing circuit, in this case with four inputs and two outputs, is illustrated in **fig.2**. As many extra outputs as desired may be added, as long as the input impedance does not become too low for the input signals. The gain of each of the inputs on a given output is varied between +1 unit and -1 unit by means of the potentiometers VR and the phase controls S. While transformers are shown in the schematic of **fig. 2**, transistorised

FIG. 1 REGULAR TETRAHEDRAL LOUDSPEAKER LAYOUTS SHOWN EMBEDDED IN A CUBE WHOSE SIDE LENGTH EQUALS THE HEIGHT OF THE LAYOUT



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phase-splitter circuitry is cheaper and potentially better. A considerable loss of voltage is caused by the isolating resistors R (about 12 dB with four outputs) and it is recommended that an amplifying stage be incorporated at each output unless low capacitance signal leads are used. It is not recommended that the gain controls be placed between the + and - lines of the input transformers, although this would obviate the need for a phase switch as it would either decrease the input impedance or increase the non-linearity and interaction of the controls, or both.

By this or suitable alternative means, it is possible to derive any combination of the four input signals, and the coefficients of each input signal can be set directly on the controls VR. This allows the matrixing circuit to be adjusted instantly for any possible experimental requirement, as long as the coefficients that should occur in the matrix are known. For this reason, most of the rest of this article is devoted to giving the matrixings required to derive various different types of signals from the standard tetrahedral recording.

For reasons of space and convenience of presentation, we shall use standard matrix notation for this. For those not familiar with matrix notation, a given signal in the left column of these tables is equal to that combination of the signals in the right column with the coefficients in the given signal's row of numbers. (In addition, negative numbers have been indicated here by underlining instead of by the more usual minus sign.) Thus, for example, in **Table 1c**, the signal L_B is given by:
$L_B = 0.663\ L_R + 0.544\ L_F + 0.245\ R_F - 0.452\ R_R$ and in **Table 3** the signal A_6 is given by:
$A_6 = 0.483\ L_R - 0.483\ L_F + 0.629\ R_F + 0.371\ R_R$.

Table 1 gives the matrixings required to convert a skew tetrahedral recording with signals L_R, L_F, R_F, R_R as in **fig. 1b** into a recording intended for reproduction via one of the other tetrahedral layouts. The matrixings given synthesise microphone outputs pointing along the relevant tetrahedral axes with the same microphone directional characteristic as used for the original recording.

The outputs L_C (front left), R_C (front right), A_C (rear above) and B_C (rear below) for the Cooper tetrahedral speaker layout of **fig. 1a** may be derived as in **Table 1a**. The outputs T_B (front top), L_B (front left), R_B

(front right) and B_B (back) for the Bruck speaker layout of **fig. 1c** are derived as in **Table 1c**. The outputs T_D (top), L_D (front left), R_D (front right) and B_D (back) for the 'sword of Damocles' layout of **fig. 1d** may be derived as in **Table 1d**. The outputs L_R*, L_F*, R_F*, R_R* for the skew tetrahedral system with speakers in the *lower* front left and right rear positions, and in the *upper* left rear and right front positions, may be derived as in **Table 1b**.

Those with a knowledge of matrix algebra should note that the matrices of **Table 1** are orthogonal, so that to convert the other way (e.g. from a Cooper to a skew tetrahedral recording), the inverse matrix may be obtained simply by writing down the transpose, i.e. interchanging rows and columns. Similarly, to obtain the matrixing from one of these systems to another (e.g. Cooper to Bruck), simply compute the matrix $B\ C^T$, where C is the matrix given in **Table 1** for the system (e.g. Cooper) which is being converted, and B is the matrix in table for the system (e.g. Bruck) to which it is being changed. To facilitate such computations, all coefficients have been given to three decimal places.

It may prove necessary to rotate the stereo image because of inaccurate microphone placement, or to bring sounds to the front of the listener. **Table 2a** gives the matrixing for the skew tetrahedral system that rotates the image horizontally around the listener by an angle θ clockwise. If θ is made negative, then the image is rotated anticlockwise. Note that a clockwise rotation of the image is also produced by an *anticlockwise* rotation of the original microphones. **Table 2b** gives the matrixing for the skew tetrahedral system that rotates the stereo image by an angle θ upwards at the front about the axis running through the listener's ears. This should prove useful with recordings made with high-up microphones. **Table 2c** gives the matrixing for the skew tetrahedral system that rotates the stereo image by an angle θ clockwise about the front-back axis. This should prove useful for correcting tilted microphones.

Again, by applying matrix algebra methods, it is possible to compute the method of rotating the sound for recordings made for the Cooper, Bruck or Damocles layouts. For example, if H is the matrix corresponding to the desired rotation in **Table 2**, and if B is the conversion matrix corresponding to the Bruck system in **Table 1c**, then the matrix producing the same rotation for Bruck-system recording is BHB^T.

Besides tetrahedral methods of playback, the four-channel 'tetrahedral' recording can also be used for playback over more complex loudspeaker layouts. For example, the sound can be played over a cube of eight speakers, placed at the cube corners of **fig. 1b**, by feeding to them the eight signals L_R, L_R*, L_F, L_F*, R_F, R_F*, R_R and R_R* (see **Table 1b**) in the obvious manner (see also ref. 1).

Another method of playback is over six loudspeakers arranged to form a regular octahedron around the listener. While there are many possible octahedral speaker layouts, the best stereo image will be obtained only if all six speakers lie at the same angle off the axis through the two ears of the listener. This suggests that the octahedral loudspeaker layout of **fig. 3** should be used (or else its mirror-image). The signal fed to each loudspeaker will be the signal that would have been picked up by a cardioid microphone pointing in its direction. If the six loudspeakers are labelled A_1 to A_6 as illustrated, then their signals may be derived from the usual skew tetrahedral recording by the matrixing given in **Table 3**.

With the possibility of such loudspeaker layouts, it will be seen that the name 'tetrahedral stereo' is rather a misnomer, for the only way that a tetrahedron enters into such recordings is in the tetrahedral axes that happen to be chosen for the signals fed to the four tracks of the tape. There are many possible ways of storing the four parameters of information that determine the three-dimensional direction effect around the microphones, of which an alternative method would be to record the outputs of an omnidirectional microphone and that of three mutually perpendicular figure-of-eights. Because tetrahedra are involved only in describing the *way* the information is stored on the tape, and have nothing to do with the *content* of this information, the author has proposed that systems of recording the full directional effect around the microphones, including height, should be called *periphonic systems* (*peri*-, around, Greek).

The reader will see that, in principle, any regular or almost regular loudspeaker layout can be used for periphonic reproduction—tetrahedron, octahedron, cuboctahedron, dodecahedron, icosahedron, or even 62 speakers placed on the 31 axes of icosahedral symmetry. I do not propose to give the matrixing for the latter here. Perhaps the most important area of research is to determine methods of reproducing the correct directional effect over non-regular loudspeaker layouts, as only such irregular layouts stand a chance of fitting conveniently into a wide variety of domestic furnishing schemes.

All the matrixings of **Tables 1, 2** and **3** have the effect of converting four signals picked up with four identical cardioid or hypercardioid microphones pointing in four different directions into new signals which are effectively picked up by the same cardioid or hypercardioid characteristic pointing in four (or six) new directions. It may be desired to change the shape of the microphone pick-up characteristic to reduce overlap (see Part One). In this case, one uses the matrixings given in, or computed from, **Tables 1, 2** and **3**, except that a small constant is added to or subtracted from every coefficient in the matrixing. For example, if one wishes to convert from cardioid to 135°-null hypercardioid, while performing one of the operations described in tables 1-3, one uses a matrixing in which every coefficient is 0.073 smaller that it would be if a cardioid characteristic were retained. Similarly, if the original recording is made with four 135°–null hypercardioids (possibly due to pre-record matrixing) then 0.104 must be added to each matrix coefficient to restore cardioid outputs. To convert a cardioid recording to, respectively, 150°, 135° and 125°–null hypercardioids, one must subtract 0.033, 0.073 and 0.107 from every matrix coefficient in **Tables 1, 2** or **3**.

It is possible to rematrix tetrahedral recordings to throw away the height information (see ref. 1). This may be useful if it is desired to determine the subjective importance of the height information, and the relevant matrixing is given in **Table 4a**.

There is the related problem of playing 'conventional' four-channel recordings via a skew-tetrahedral speaker layout so that all sounds come from a horizontal direction. This also entails throwing out the spurious height information, but the matrixing of **Table 4a** cannot be used in this case, as it would cause undesirable out-of-phase images because conventional four-channel recordings are not properly 'conditioned' for the requirements of tetrahedral playback. The matrixing of **Table 4b** is a compromise that may allow

conventional four channel recordings to be reproduced tetrahedrally.
Table 4c gives a matrixing that may allow a conventional four channel recording to be reproduced over the octahedral layout of **fig. 3**.

We may play two channel stereo recordings via the skew tetrahedral or octahedral layouts by using the matrixings of **Table 4b** or **4c**, treating the stereo signal as if it were the front two channels of a four channel recording. Hafler-style surround-sound reproduction of two channel recordings is also possible. **Tables 4d** and **4e** give matrixings that may produce approximately horizontal surround-sound reproduction of two channels via the skew-tetrahedral and octahedral layouts.

Besides experiments with surround-sound and periphony, the other main use of tetrahedral recordings is in the study of ordinary two channel stereo microphone techniques. A tetrahedral recording made with coincident microphones contains within its four tracks sufficient information for any conventional coincident microphone recording to be reconstructed by matrixing. Thus, for the first time, it is possible to perform repeatable objective comparisons between the different microphone techniques, something which has not been done up to now as far as I am aware.

Table 5 gives the matrixings required to derive the left (L) and right (R) signals of various two channel recording techniques from a skew tetrahedral recording. Thus such a recording provides all the advantages of variable characteristic microphones, except that adjustments can be made after the recording, and a greater variety of adjustments are possible.

If a tetrahedral recording has been made with microphones that are spaced apart significantly, then much of the above matrixing will no longer work, and one is restricted to reproduction via one particular loudspeaker layout which may well prove to be non-optimum. Slightly modified matrixings could well give adequate results if the microphone spacing is moderate. A disadvantage of highly coincident microphones is that they tend to interfere with one another acoustically at high frequencies, but this is considered to be a relatively small price to pay for experimental flexibility.

The above account has only indicated a few of the many possible experimental uses of tetrahedral recordings, but nevertheless indicates just how much information is contained in the four channels. In a precisely definable sense, tetrahedral recording makes much more efficient use of four channels than any other current proposal. So great is the system's flexibility that a full appreciation of its uses and possibilities requires a more profound analysis than is possible in these pages. This flexibility is equally great whether coincident or multimike recording techniques are used (see ref. 1) A great deal of experimental work remains to be done before the system is ready for domestic use, as is apparent from the very large number of possible playback methods.

The intention of this series of three articles has been to set out the requirements and possibilities involved in tetrahedral recording, so that others should be encouraged to experiment with this technique. Like any new technology, the new recording system requires some unlearning of old tricks and the learning of new ones. With the extreme newness of even 'conventional' four channel stereo, it is hardly surprising that many of the old methods that worked with two channel stereo are still being applied erroneously to four channel systems. It is hoped that a study of ref. 1 and of this series of articles will have given some understanding of the special requirements of periphony. Finally, one must acknowledge the value of the pioneering tetrahedral recordings of Granville Cooper (ref. 2), whose hard-won experience has proved so useful in formulating the problems in doing experimental recordings.

References

1. Michael Gerzon, Principles of Quadraphonic Recording, part Two, STUDIO SOUND, September 1970
2. Granville Cooper, Tetrahedral Ambiophony, STUDIO SOUND, June 1970

[Tables 1-4 and Figures 2 and 3 are on the following pages]

TABLE 1 Matrixings converting standard skew tetrahedral signals of fig. 1b into other tetrahedral systems.

1a: Conversion to Cooper system.

$$\begin{bmatrix} L_C \\ R_C \\ A_C \\ B_C \end{bmatrix} = \begin{bmatrix} \cdot354 & \cdot854 & \cdot146 & \underline{\cdot354} \\ \underline{\cdot354} & \cdot146 & \cdot854 & \cdot354 \\ \cdot146 & \cdot354 & \underline{\cdot354} & \cdot854 \\ \cdot854 & \underline{\cdot354} & \cdot354 & \cdot146 \end{bmatrix} \begin{bmatrix} L_R \\ L_F \\ R_F \\ R_R \end{bmatrix}$$

1b: Conversion to mirror-image skew tetrahedron.

$$\begin{bmatrix} L_R^* \\ L_F^* \\ R_F^* \\ R_R^* \end{bmatrix} = \begin{bmatrix} \cdot500 & \cdot500 & \underline{\cdot500} & \cdot500 \\ \cdot500 & \cdot500 & \cdot500 & \underline{\cdot500} \\ \underline{\cdot500} & \cdot500 & \cdot500 & \cdot500 \\ \cdot500 & \underline{\cdot500} & \cdot500 & \cdot500 \end{bmatrix} \begin{bmatrix} L_R \\ L_F \\ R_F \\ R_R \end{bmatrix}$$

1c: Conversion to Bruck system.

$$\begin{bmatrix} T_B \\ L_B \\ R_B \\ B_B \end{bmatrix} = \begin{bmatrix} \underline{\cdot303} & \cdot803 & \underline{\cdot014} & \cdot514 \\ \cdot663 & \cdot544 & \cdot245 & \underline{\cdot452} \\ \underline{\cdot044} & \underline{\cdot163} & \cdot952 & \cdot255 \\ \cdot683 & \underline{\cdot183} & \underline{\cdot183} & \cdot683 \end{bmatrix} \begin{bmatrix} L_R \\ L_F \\ R_F \\ R_R \end{bmatrix}$$

1d: Conversion to 'sword of Damocles' system.

$$\begin{bmatrix} T_D \\ L_D \\ R_D \\ B_D \end{bmatrix} = \begin{bmatrix} \underline{\cdot183} & \cdot683 & \underline{\cdot183} & \cdot683 \\ \cdot544 & \cdot663 & \cdot254 & \underline{\cdot452} \\ \underline{\cdot163} & \underline{\cdot044} & \cdot952 & \cdot255 \\ \cdot803 & \underline{\cdot303} & \underline{\cdot014} & \cdot514 \end{bmatrix} \begin{bmatrix} L_R \\ L_F \\ R_F \\ R_R \end{bmatrix}$$

TABLE 2 Matrixings rotating skew tetrahedral signals

2a: Horizontal clockwise rotation by θ.

$$\begin{bmatrix} L_R \\ L_F \\ R_F \\ R_R \end{bmatrix}_{\text{out}} = \begin{bmatrix} \frac{1}{2}(1+\cos\theta) & -\frac{1}{2}\sin\theta & \frac{1}{2}(1-\cos\theta) & \frac{1}{2}\sin\theta \\ \frac{1}{2}\sin\theta & \frac{1}{2}(1+\cos\theta) & -\frac{1}{2}\sin\theta & \frac{1}{2}(1-\cos\theta) \\ \frac{1}{2}(1-\cos\theta) & \frac{1}{2}\sin\theta & \frac{1}{2}(1+\cos\theta) & -\frac{1}{2}\sin\theta \\ -\frac{1}{2}\sin\theta & \frac{1}{2}(1-\cos\theta) & \frac{1}{2}\sin\theta & \frac{1}{2}(1+\cos\theta) \end{bmatrix} \begin{bmatrix} L_R \\ L_F \\ R_F \\ R_R \end{bmatrix}_{\text{in}}$$

2b: Rotation about ears' axis by θ upwards at front.

$$\begin{bmatrix} L_R \\ L_F \\ R_F \\ R_R \end{bmatrix}_{\text{out}} = \begin{bmatrix} \frac{1}{2}(1+\cos\theta) & \frac{1}{2}(1-\cos\theta) & -\frac{1}{2}\sin\theta & \frac{1}{2}\sin\theta \\ \frac{1}{2}(1-\cos\theta) & \frac{1}{2}(1+\cos\theta) & \frac{1}{2}\sin\theta & -\frac{1}{2}\sin\theta \\ \frac{1}{2}\sin\theta & -\frac{1}{2}\sin\theta & \frac{1}{2}(1+\cos\theta) & \frac{1}{2}(1-\cos\theta) \\ -\frac{1}{2}\sin\theta & \frac{1}{2}\sin\theta & \frac{1}{2}(1-\cos\theta) & \frac{1}{2}(1+\cos\theta) \end{bmatrix} \begin{bmatrix} L_R \\ L_F \\ R_F \\ R_R \end{bmatrix}_{\text{in}}$$

2c: Rotation clockwise about front–back axis by θ.

$$\begin{bmatrix} L_R \\ L_F \\ R_F \\ R_R \end{bmatrix}_{\text{out}} = \begin{bmatrix} \frac{1}{2}(1+\cos\theta) & -\frac{1}{2}\sin\theta & \frac{1}{2}\sin\theta & \frac{1}{2}(1-\cos\theta) \\ \frac{1}{2}\sin\theta & \frac{1}{2}(1+\cos\theta) & \frac{1}{2}(1-\cos\theta) & -\frac{1}{2}\sin\theta \\ -\frac{1}{2}\sin\theta & \frac{1}{2}(1-\cos\theta) & \frac{1}{2}(1+\cos\theta) & \frac{1}{2}\sin\theta \\ \frac{1}{2}(1-\cos\theta) & \frac{1}{2}\sin\theta & -\frac{1}{2}\sin\theta & \frac{1}{2}(1+\cos\theta) \end{bmatrix} \begin{bmatrix} L_R \\ L_F \\ R_F \\ R_R \end{bmatrix}_{\text{in}}$$

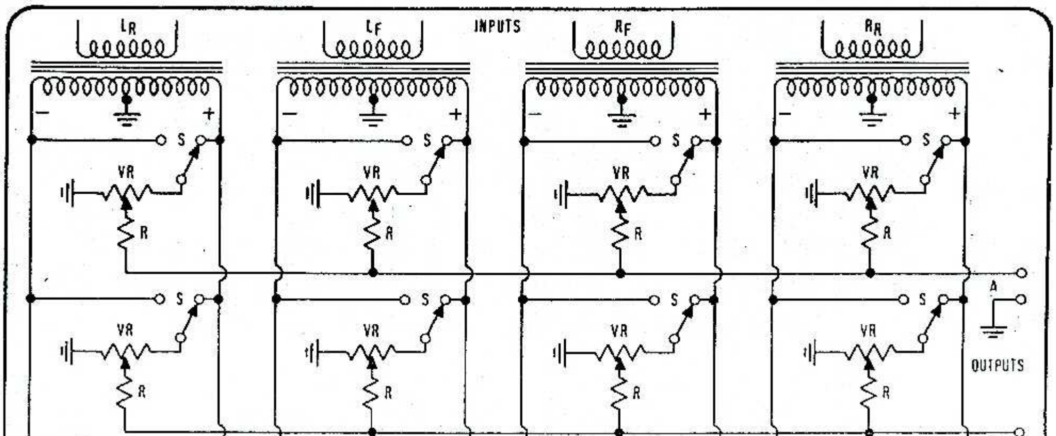

FIG. 2
FULLY VARIABLE MATRIXING CIRCUIT R MUST BE GREATER THAN 10 VR

FIG. 3 OCTAHEDRAL LOUDSPEAKER LAYOUT
ALL DISTANCES SHOWN AS A MULTIPLE OF THE STRAIGHT-LINE DISTANCE BETWEEN ADJACENT SPEAKERS.
SPEAKERS A_2 AND A_5 LIE STRAIGHT ABOVE A_3 AND A_6 RESPECTIVELY

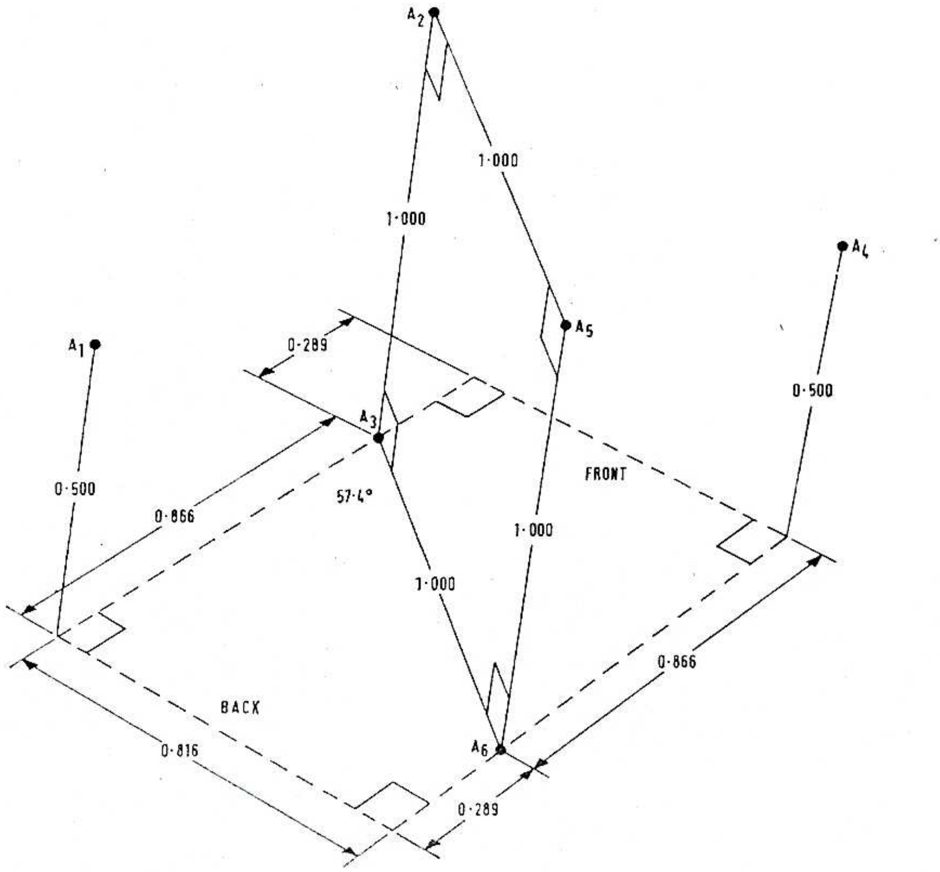

TABLE 3 Conversion from the skew tetrahedral system of fig. 1b to the octahedral system of fig. 3.

$$\begin{bmatrix} A_1 \\ A_2 \\ A_3 \\ A_4 \\ A_5 \\ A_6 \end{bmatrix} = \begin{bmatrix} {\cdot}854 & {\cdot}146 & \underline{{\cdot}354} & {\cdot}354 \\ {\cdot}017 & {\cdot}983 & \underline{{\cdot}129} & {\cdot}129 \\ {\cdot}629 & {\cdot}371 & {\cdot}483 & \underline{{\cdot}483} \\ \underline{{\cdot}354} & {\cdot}354 & {\cdot}854 & {\cdot}146 \\ \underline{{\cdot}129} & {\cdot}129 & {\cdot}017 & {\cdot}983 \\ {\cdot}483 & \underline{{\cdot}483} & {\cdot}629 & {\cdot}371 \end{bmatrix} \begin{bmatrix} L_R \\ L_F \\ R_F \\ R_R \end{bmatrix}$$

TABLE 4 Matrixings for reproducing 'conventional' recordings via skew-tetrahedral and octahedral speaker layouts

4a: Suppression of height information in tetrahedral recordings.

$$\begin{bmatrix} L_R \\ L_F \\ R_F \\ R_R \end{bmatrix}_{\mathrm{out}} = \begin{bmatrix} 1 & {\cdot}333 & \underline{{\cdot}333} & {\cdot}333 \\ {\cdot}333 & 1 & {\cdot}333 & \underline{{\cdot}333} \\ \underline{{\cdot}333} & {\cdot}333 & 1 & {\cdot}333 \\ {\cdot}333 & \underline{{\cdot}333} & {\cdot}333 & 1 \end{bmatrix} \begin{bmatrix} L_R \\ L_F \\ R_F \\ R_R \end{bmatrix}_{\mathrm{in}}$$

4b: Matrixing for tetrahedral playback of 'conventional' 4-channel recording.

$$\begin{bmatrix} L_R \\ L_F \\ R_F \\ R_R \end{bmatrix}_{\mathrm{out}} = \begin{bmatrix} 1 & {\cdot}414 & \underline{{\cdot}172} & {\cdot}414 \\ {\cdot}414 & 1 & {\cdot}414 & \underline{{\cdot}172} \\ \underline{{\cdot}172} & {\cdot}414 & 1 & {\cdot}414 \\ {\cdot}414 & \underline{{\cdot}172} & {\cdot}414 & 1 \end{bmatrix} \begin{bmatrix} L_R \\ L_F \\ R_F \\ R_R \end{bmatrix}_{\mathrm{in}}$$

4c: Matrixing for octahedral playback of 'conventional' 4-channel recording.

$$\begin{bmatrix} A_1 \\ A_2 \\ A_3 \\ A_4 \\ A_5 \\ A_6 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & {\cdot}172 \\ {\cdot}121 & {\cdot}707 & 0 & 0 \\ {\cdot}121 & {\cdot}707 & 0 & 0 \\ 0 & {\cdot}172 & 1 & 0 \\ 0 & 0 & {\cdot}121 & {\cdot}707 \\ 0 & 0 & {\cdot}121 & {\cdot}707 \end{bmatrix} \begin{bmatrix} L_R \\ L_F \\ R_F \\ R_R \end{bmatrix}_{\mathrm{in}}$$

4d: Surround-sound reproduction of 2 channels via a skew tetrahedron.

$$\begin{bmatrix} L_R \\ L_F \\ R_F \\ R_R \end{bmatrix} = \begin{bmatrix} 1 & \underline{{\cdot}414} \\ 1 & {\cdot}414 \\ {\cdot}414 & 1 \\ \underline{{\cdot}414} & 1 \end{bmatrix} \begin{bmatrix} L \\ R \end{bmatrix}$$

4e: Surround-sound reproduction of 2 channels via an octahedron.

$$\begin{bmatrix} A_1 \\ A_2 \\ A_3 \\ A_4 \\ A_5 \\ A_6 \end{bmatrix} = \begin{bmatrix} {\cdot}888 & \underline{{\cdot}460} \\ {\cdot}674 & {\cdot}214 \\ {\cdot}674 & {\cdot}214 \\ {\cdot}460 & {\cdot}888 \\ \underline{{\cdot}214} & {\cdot}674 \\ \underline{{\cdot}214} & {\cdot}674 \end{bmatrix} \begin{bmatrix} L \\ R \end{bmatrix}$$