from quadro to surround sound

P. Fellgett and M. Gerzon

In previous articles ('Quadrille' and 'music of the spheres', Elektor 17, September 1976, p. 910) it was noted that 'Ambisonics' was perhaps the most promising of the quadrophonic systems proposed so far. This led to a reaction from Prof. P. Fellgett, pointing out (amongst other things) that he preferred to use the phrase 'surround sound' since 'quadrophonics' rather over-stresses the number four – quite apart from being a condemnable mixture of classic tongues. Since we had very little information on Ambisonics at our disposal, we took the opportunity to ask him to write a short article explaining the basic theory and philosophy of Ambisonics. His text reached us only three weeks later (!), and it is presented here in full. Where some further comments or explanation seemed necessary, we have given this separately as an 'editorial note'. But first let us see what Prof. Fellgett has to say.

The aim of sound reproduction is to give pleasure in listening. From the earliest days of mono it was appreciated that pleasure and realism go together. Not only did the pioneers strive to extend frequency-range and reduce non-linear distortion, but they sought to refine microphone techniques to give the sense of space and depth of live music. Yet realism was still marred by lack of the sense of direction of direct and reverberant sound. Stereophony was the first step in filling this gap, and in the hands particularly of A.D. Blumlein achieved great refinement of technique, and an open transparent sense of space of great beauty. Even this was incomplete because direction could be reproduced only over a limited stage in front of the listener. The final step has been taken in the present decade by the development of surround-sound technology capable of representing direction all around the listener.

Speech, and many natural and everyday sounds, can give listening pleasure, but music is unique in its power to sustain repeated listening. The first requirement of a surround-sound system suitable for recording is therefore to sound musical. It must be able to fulfil the needs of synthesized *avant-garde* or 'pop' music, and equally to reproduce the sonorities and ambience of all the music written for performance from earliest times through baroque, classical and romantic to the present day. This requirement is symbolised in figure 1. The test is not conformity with any artefact that is a technical means to an end, such as a mixdown or a 4-track master tape. The true criterion is comparison of what the listener hears with the original live or imagined music.

1

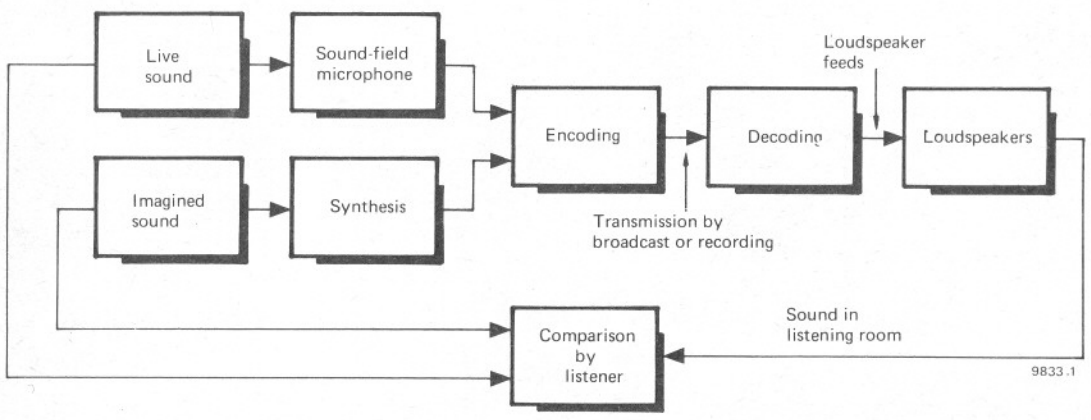
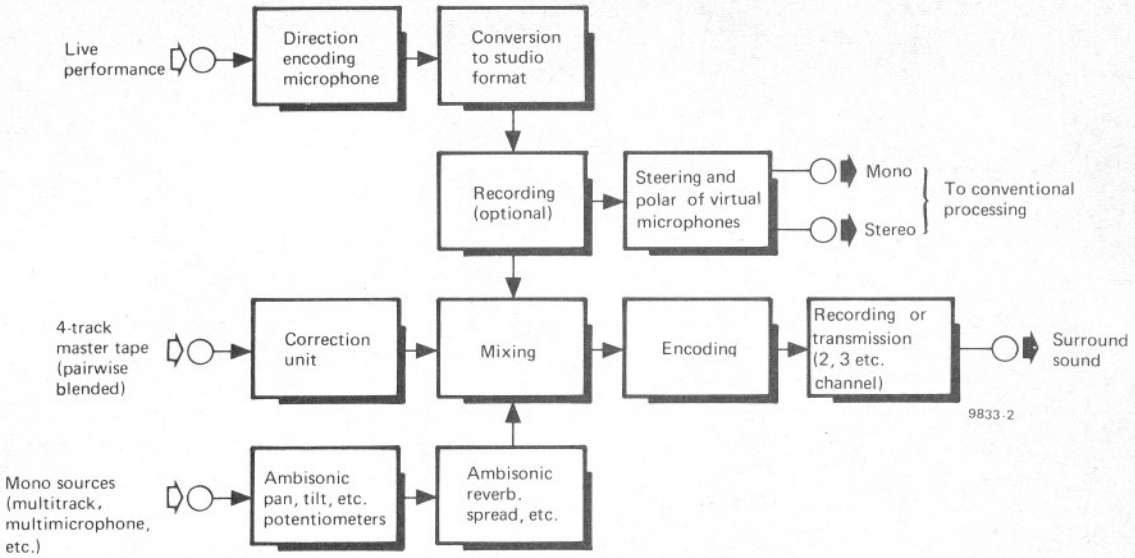
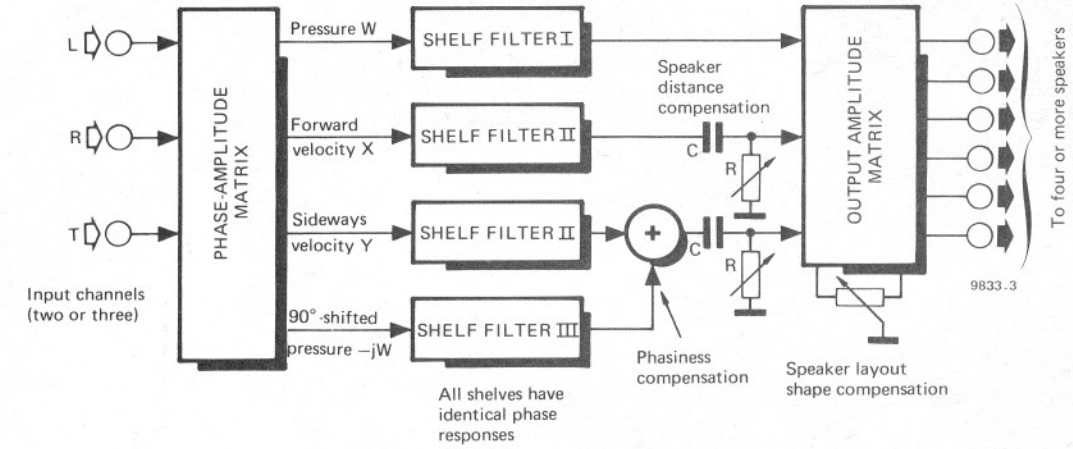


Figure 1. Block diagram to illustrate evaluation of a good surround-sound system.

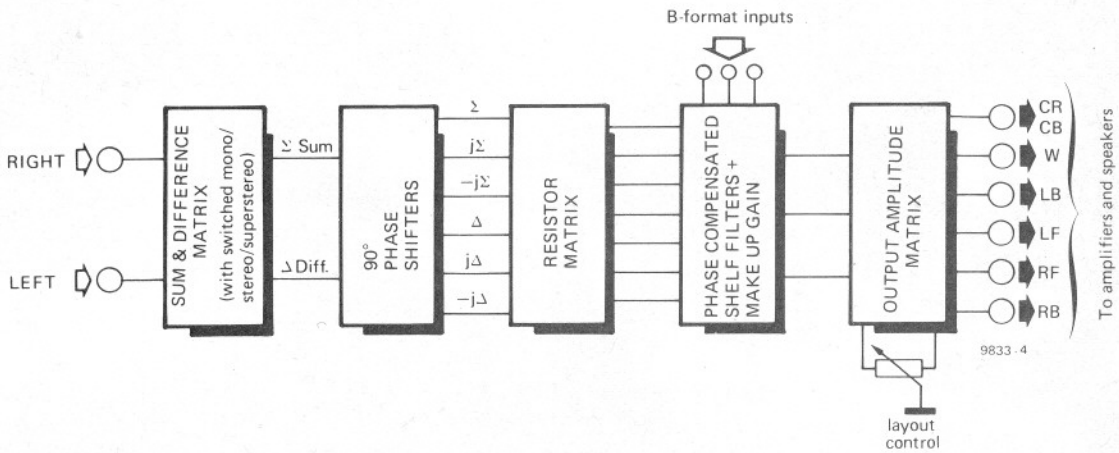
2


Live performance
Direction encoding microphone
Conversion to studio format
Recording (optional)
Steering and polar of virtual microphones
Mono
Stereo
To conventional processing
4-track master tape (pairwise blended)
Correction unit
Mixing
Encoding
Recording or transmission (2, 3 etc. channel)
Surround sound
9833-2
Mono sources (multitrack, multimicrophone, etc.)
Ambisonic pan, tilt, etc. potentiometers
Ambisonic reverb. spread, etc.

3


L
R
T
Input channels (two or three)
PHASE-AMPLITUDE MATRIX
Pressure W
Forward velocity X
Sideways velocity Y
90°-shifted pressure –jW
SHELF FILTER I
SHELF FILTER II
SHELF FILTER II
SHELF FILTER III
All shelves have identical phase responses
Speaker distance compensation
C
R
C
R
Phasiness compensation
OUTPUT AMPLITUDE MATRIX
Speaker layout shape compensation
9833-3
To four or more speakers

4


B-format inputs
RIGHT
LEFT
SUM & DIFFERENCE MATRIX (with switched mono/stereo/superstereo)
Σ Sum
Δ Diff.
90° PHASE SHIFTERS
Σ
jΣ
–jΣ
Δ
jΔ
–jΔ
RESISTOR MATRIX
PHASE COMPENSATED SHELF FILTERS + MAKE UP GAIN
OUTPUT AMPLITUDE MATRIX
CR
CB
W
LB
LF
RF
RB
To amplifiers and speakers
9833-4
layout control

Evidently no technology can pass this test unless it can handle live performance as well as synthetic pan-pot and echo-effects. It is found that live ambient material provides the most sensitive touchstone, for musicality is quickly lost if the loudspeakers are audible as separate sources of sound, or if ambience pools in particular directions instead of being smoothly distributed. The real problem is to leave the listener undisturbed by obtrusion of the technical means of radiating sound into his room. If this can be solved, it follows almost automatically that a wide range of synthetic effects, from the simplest to some of great subtlety, can be made available by artificial simulation of elements from the response to natural ambient sound.

The purely engineering requirements are also exacting. To be acceptable today, a technology for surround-sound must cover all essential needs from studio to listener. It must provide for the variety of microphone techniques and artificial processing, and be compatible with all valid philosophies and aims of recording. It must provide a compatible series of means of transmission beginning with a basic 2-channel implementation suitable for dissemination by existing stereo media (disc, tape, fm) and, extending to it, effective use of multi-channel media. Very desirably it should enable the basic version to be enhanced by adding a third channel of reduced bandwidth or amplitude suited to carrier-disc or enhanced fm stereo broadcasting. The base-band signals must have good mono and stereo compatibility. The listener should not be restricted to having his loudspeakers in a square (a shape to which few domestic rooms are suited), and he should have freedom to enhance his system by using more than four loudspeakers if he wishes.

Figure 2. Some facilities in ambisonic technology.

Figure 3. Block diagram of a generalised ambisonic decoder (courtesy MAG).

Figure 4. Block diagram of a domestic ambisonic decoder of medium complexity for 2-channel (45JB) material. This will accept 2-channel or 3-channel B-format inputs and deliver mono, stereo, superstereo or 45JB decoded outputs. It can drive rectangular or regular hexagon loudspeaker layouts via 3 or 4 power amplifiers. Loudspeaker distance and psychoacoustic compensation are provided.

It goes without saying that any design which is free from compromise is over-engineered. A most important requirement is a body of theory competent to show how specific design aims can be realised in a minimal design, and to enable rational engineering choices to be made in accordance with stated priorities among competing requirements.

The earlier so-called 'quadrophonic' proposals for surround-sound fell short of fulfilling many of these demands, and indeed made no attempt to meet some of them. They were conceived before sufficient systematic understanding was available to avoid arbitrary choices, and a proliferation of mutually incompatible systems resulted. A new approach was needed.

Second generation surround-sound

The first of the new generation of surround-sound systems commercially available was the UMX system developed by Professor D. Cooper (University of Illinois) and Dr. Shiga of the Nippon Columbia Company, who marketed the system.

To this has been added extensive theoretical work and experiment carried out at the Universities of Oxford and Reading under the auspices of the British National Research Development Corporation, who hold extensive patents in many countries on the inventions which have resulted. The complete technology is called 'Ambisonics', and within it a compatible series of signal formats known as 45J (a development running number) has been internationally agreed. This engineering standard is the subject of current submissions to appropriate standards authorities in a number of countries.

There is no simplistic 'secret' of Ambisonics. Its capability of high performance is due to clearly formulated engineering and aesthetic aims and a body of experimentally validated theory which places the realisation of these aims whithin normal methods of engineering design. Some unique features may however be especially noted.

Ambisonics is not an isolated 'system' but a comprehensive technology centering around engineering specifications of the signals for public distribution. Specification 45J includes a basic 2-channel format, designated 45JB, which is of itself a carefully designed surround-sound implementation with well formulated and balanced mono and stereo compatibility. This is the lowest member of a compatible series which includes members using 3 channels, or with a 4th channel which may convey height information for periphony (spherical surround). Particular attention has been given to fulfilling the need for '2½-channel' specifications in which the 45JB basebands are enhanced by a third channel of restricted bandwidth or amplitude suited to carrier disc or fm broadcasting.

In the studio . . . . .

Ambisonic studio technology includes the soundfield microphone for natural sound, and a wide range of pan-pot, reverberation and spread effects conforming to an accurate specification. Correctly designed ambisonic pan-pots are actually simpler than pairwise 'quadrophonic' pan-pots, or can be made more versatile. Existing pairwise pan-pots can be converted by additional circuitry. There is provision for using archive material recorded in pairwise format, including a comprehensive range of choices for the producer to optimise the compromises inseparable from this inferior method of encoding direction.

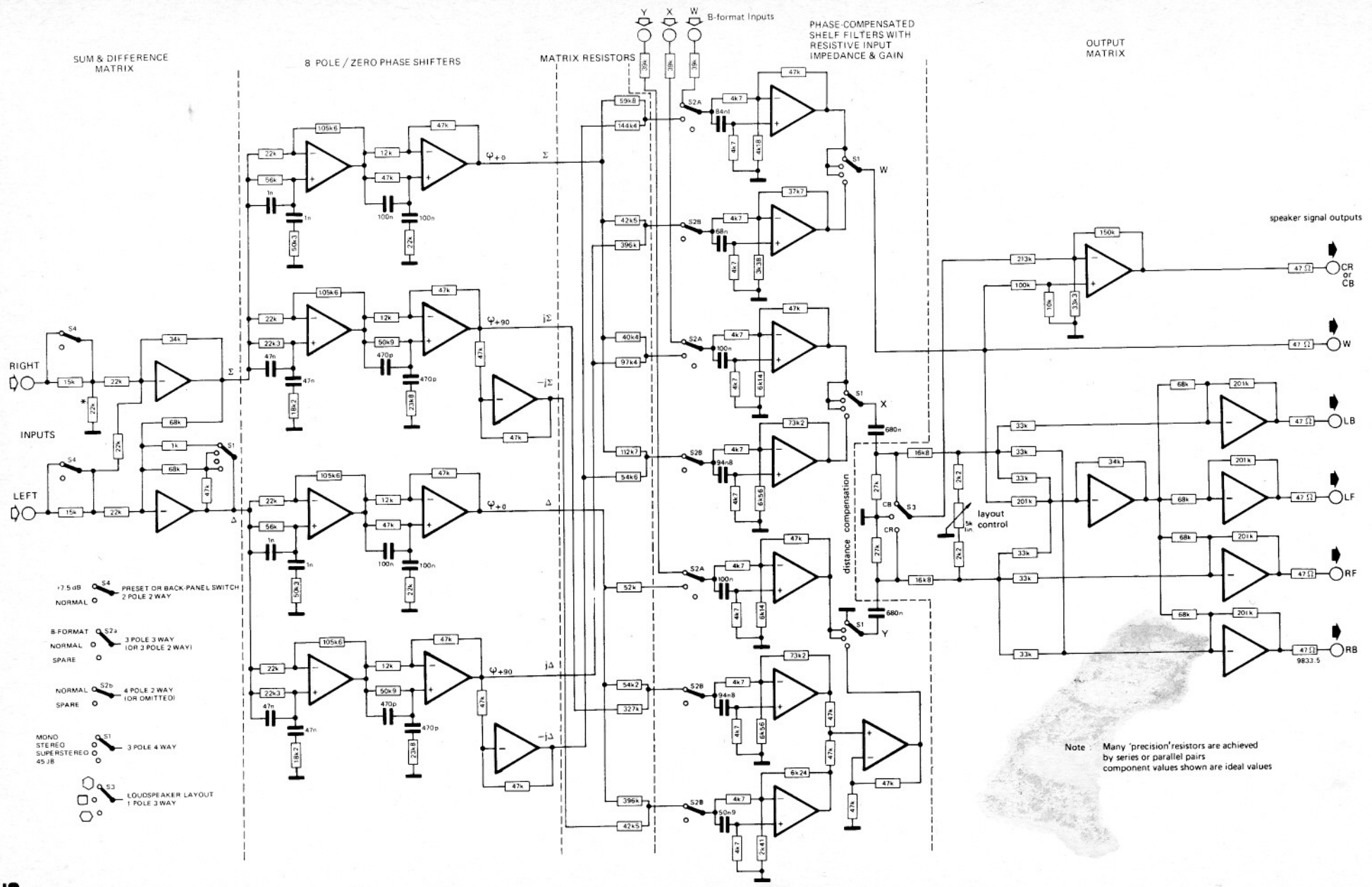
A studio format, known as B-format, is recommended which facilitates processing and reduces sensitivity to small errors of amplitude or phase, especially in recording. An attraction of this format is that material held in it can be encoded at a later date into *any* reasonable surround, stereo or mono form for distribution, so the risk of obsolescence is minimised. Figure 2 illustrates some of the facilities available in ambisonic technology.

. . . . . and at home

The ear and brain do not locate sound by only one mechanism, but by many. The goodness of localisation, and the impression of naturalness and correctness of sonority and tone, are found to improve when different mechanisms agree. Ambisonic decoders are designed to give correct localisation by as many spectral (frequency domain) and bi-spectral (first order non-linear) mechanisms of the ear as possible. Decoders for 45JB include a 'front preference' option to cater for material in which frontal sources are predominant. Any number of loudspeakers in any layout (within reason) can be used. Decoders for four loudspeakers include 'layout' and 'distance' controls permitting adjustment for the ratio of length to breadth of rectangular layouts, and for size of room. Decoders can be provided for trapezoidal layouts, or for five, six or even more loudspeakers if wished. The inter-relations between loudspeaker feeds demanded by psychoacoustic criteria produce the useful bonus that four loudspeakers can be fed from only three power amplifiers, or six loudspeakers from four amplifiers.

Since the mechanisms of the ear, and therefore the psychoacoustic criteria, change with frequency, all decoders (except the most basic for the lower end of the market) employ special phase-compensated shelf filters. This frequency-dependence improves not only localisation but also the subjective tonal quality in comparison with naive decoders lacking this feature.

Loudspeaker emphasis and signal-dependent gain devices can be incorporated in ambisonic decoders for those occasions when a more gross effect may be deliberately sought. Ambisonic



Note : Many 'precision' resistors are achieved by series or parallel pairs
component values shown are ideal values

5

45J-encoded material can if wished even be played through the Sansui 'Variomatrix' decoder, with simple added circuitry. An ambisonic decoder with signal-dependent gains has been designed having improved conformity with psychoacoustic requirements. Figure 3 is a block diagram illustrating a generalised ambisonic decoder; of course not all of the features need be present in a particular consumer product.

These features of ambisonic decoders are more or less realisable (by suitable modifications of circuitry) with source material encoded in any reasonable way, although best results require correct 45J (or equivalent) encoding. BBC 'Matrix H' encoding is close enough to 45JB to be playable directly into ambisonic 45J decoders with psychoacoustic enhancement of performance. There is effective compatibility with Nippon Columbia 'Denon' UMX, and a simple switching enables RM, QS and SQ material to be handled with a degree of approximation depending on the source encoding. A 'stereo decode' mode is available. This does not deliberately give a synthetic pseudo-surround effect, but enables localisation in the frontal stereo stage to be improved by the use of four (or more) loudspeaker playback.

Figure 4 is a block diagram of a domestic decoder of medium complexity for 2-channel (45JB) material. The blocks are expanded into actual circuit configurations in figure 5 and these are in turn shown in more detail in figure 6 (a), (b), (c) and (d). Figure 7 shows various ways of using the outputs for four or six loudspeakers using three or four power amplifiers.

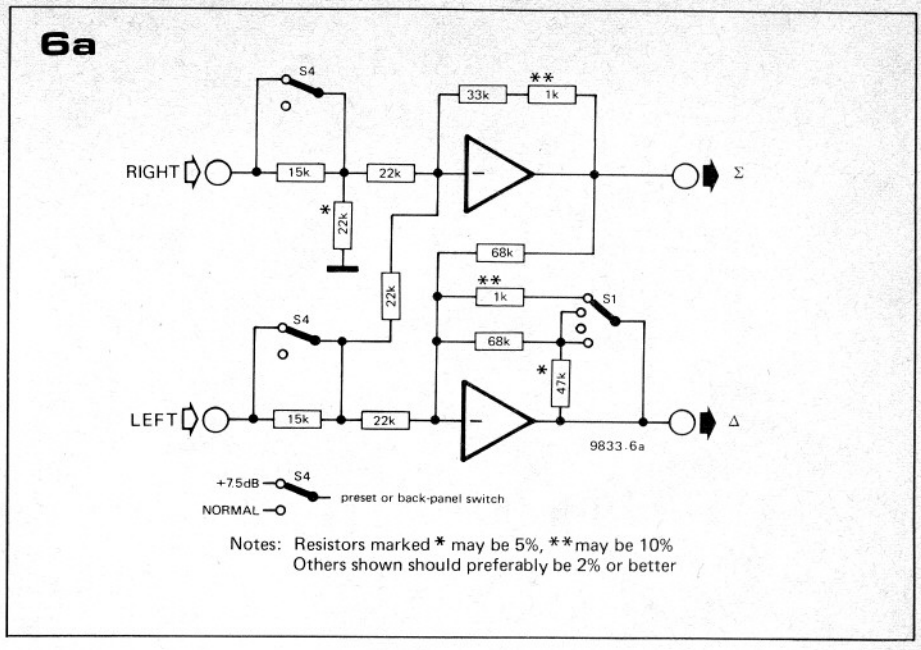
Decoder functions

The decoder circuit given here has a four-position mode switch, labelled 'mono', 'stereo', 'superstereo' and '45JB'. It should be noted that the 'mono' and 'stereo' positions are not obtained by simply switching off unwanted channels or shorting outputs together.

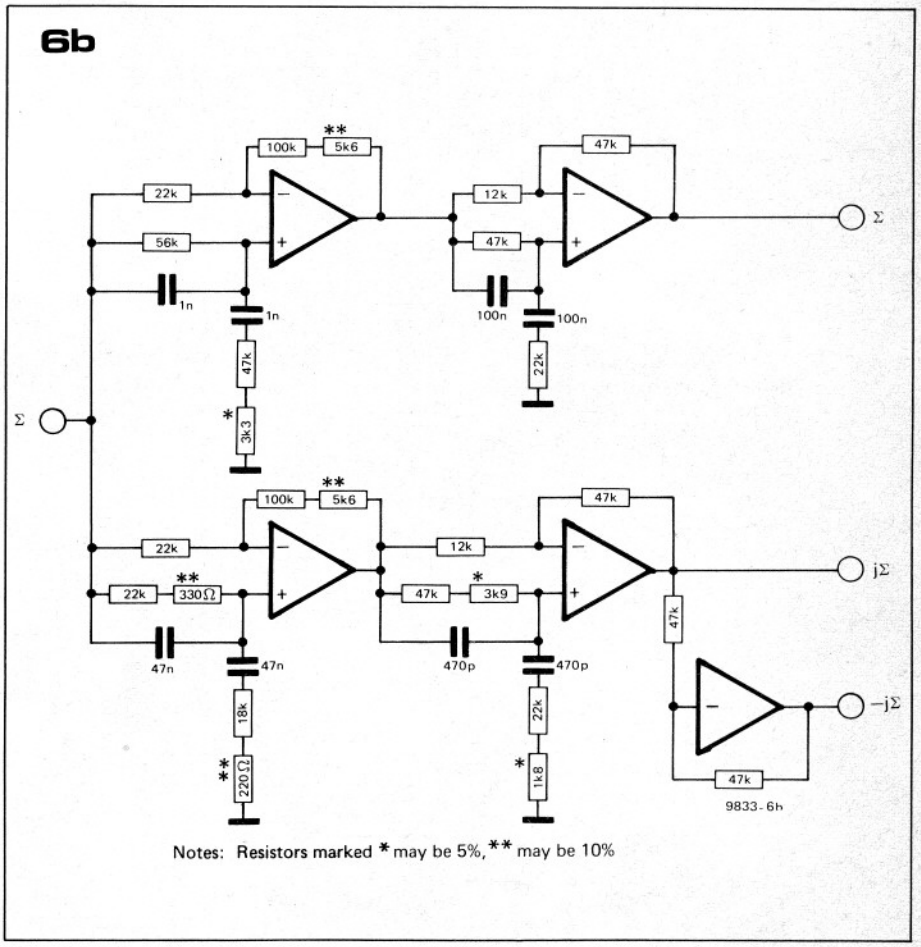
Mono reproduces mono material through 4 or 6 loudspeakers so that the sound image appears to be straight ahead, but at a larger distance than the speaker distance. It avoids the 'coming from a box' effect of single-speaker mono reproduction, and the 'in-the-head' and tone-colour distortions associated with 2-speaker mono reproduction. In practice, 'mono' decode helps unlock the spacious quality contained in good mono recordings.

Stereo reproduces conventional stereo material over the conventional front-quadrant stereo stage, but uses the extra speakers to reduce undesirable qualities of 2-speaker stereo reproduction – notably excessive speaker prominence, unstable images and tone-colour distortions. 'Stereo' decode does not enhance the quality of badly-recorded stereo material (but neither does it worsen it). Good material will obtain a further sense of spaciousness without any gimmickry of directional effect. The effect is almost completely unobtrusive and yet capable of considerable reduction of listener fatigue through presenting the ears with a more natural sound. 'Stereo' decode also tends to enhance the reproduction of SQ-encoded records.

Superstereo gives a wider frontal stage from stereo material for those who wish for a more spectacular effect, without descending to mere gimmickry. This position also provides excellent decoding



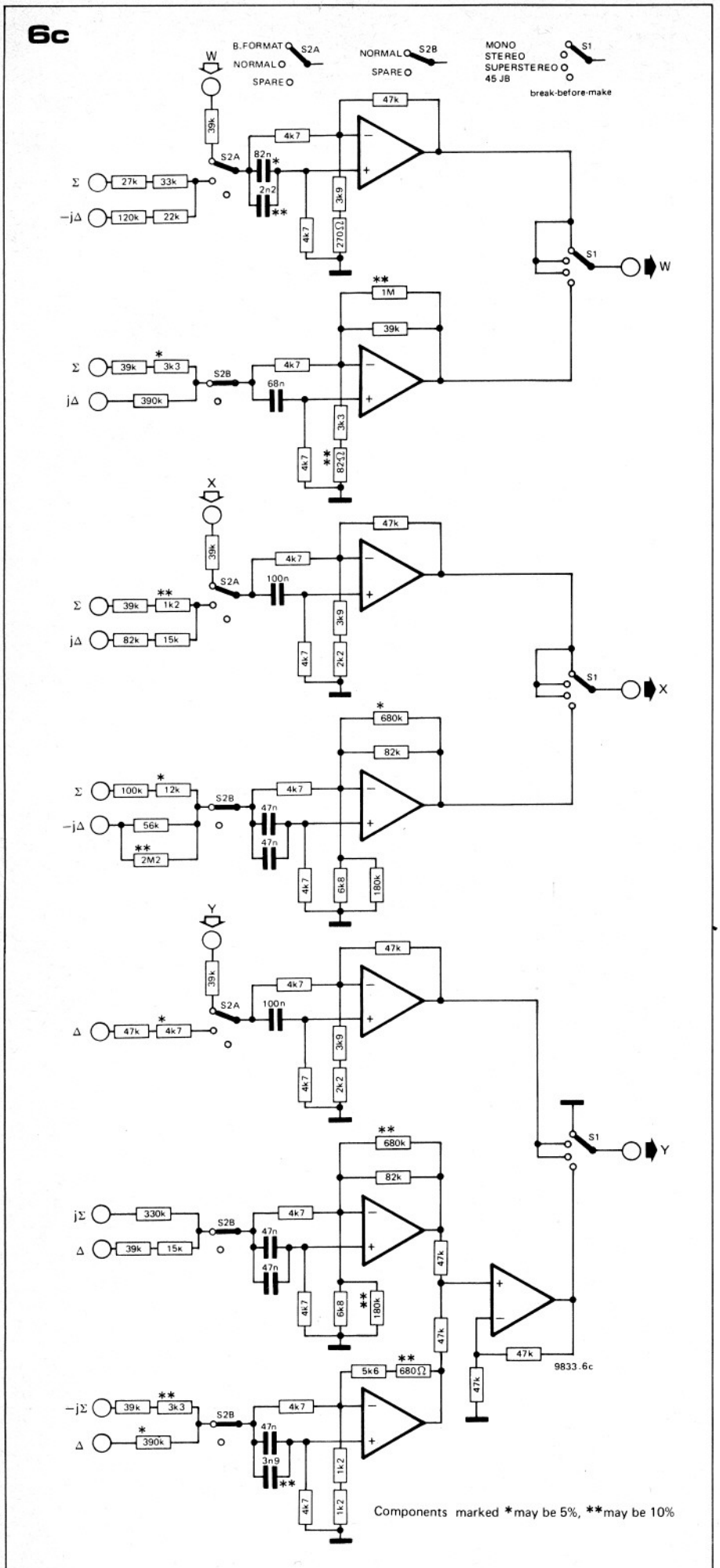
Notes: Resistors marked * may be 5%, ** may be 10%
Others shown should preferably be 2% or better



Notes: Resistors marked * may be 5%, ** may be 10%

Figure 5. Overall circuit diagram of domestic ambisonic decoder corresponding to the block diagram of figure 4.

Figure 6a. Detailed circuit of input stages (sum/difference matrix).
6b. Detailed circuit of phase shifter stage. Two of these stages are required, one for the Σ and one for the Δ signal. Nominal performance: phase shift 90° ± 1⅓° from 30 Hz to 16 kHz. A 2% component spread gives 90° ± 3° over this range. Stage gain is 1.33 dB.



of Regular Matrix encoded records, with a full 360° reproduced stage.

45JB decodes system 45J recordings and broadcasts. It is also suitable (but not optimised) for decoding 'Matrix H' for good ambient reproduction, and it is reasonably compatible with BMX recordings.

B-format enables those with a 4-channel recorder to get optimal studio-quality reproduction from master recordings made in the ambisonic B-format studio mode.

Editorial notes.

Let's be honest: we are impressed by the capabilities of ambisonics. To sum it up briefly:

- an ambisonic system will accept practically any input.
- an ambisonic system makes the fullest use of the available number of transmission channels.
- an ambisonic system can drive almost any loudspeaker layout, using a minimum number of power amplifiers.
- the designers of ambisonics have evidently done their homework.

Great!

Now let's be practical. At the moment, no ambisonics recordings are commercially available. There is very little point in building an ambisonics decoder until some record company starts supplying these recordings, or until some broadcasting corporation starts transmitting in ambisonics. From a technical point of view (please note: *not* necessarily a commercial or even a consumer point of view) we wish that this situation were different.

In theory, and even – as we have heard on first-hand authority – in practice, a surround-sound demonstration using ambisonics is unbelievably convincing. Speaking only from the theoretical point of view, we are prepared to go along with this: we have favoured UD-4 so far, since this system seemed to make full use of the available transmission capabilities. In our opinion, ambisonics is an extension of UD-4: technology and mathematics have been complemented with psycho-acoustic research. We have tried to give all systems an equal chance in the pages of this magazine, and we have noted the good points of each system. I previous articles we have even noted th there may be room for more than one system. However, if only one system is to be chosen for universal application, our money is on ambisonics – on a purely technical and theoretical basis. We can't wait to hear a practical demonstration!

Finally, some comments on this article. It is, of course, incomplete. It is sufficient to whet the appetite – without giving something to bite on. The author explains that they are still negotiating with various parties and cannot release more information.

The circuits are quite basic, but they are approved by the inventors. There are no alignment points, to our relief, so we don't need to give alignment instructions. So long as there are no commercial releases of ambisonic recordings, we do not feel obliged to offer a printed circuit board.

For that matter, Mr. Gerzon (who designed this decoder within 48 hours!) has pointed out that there is room for improvement and simplification. When the time seems ripe for a constructional article with a p.c. board, we hope to take him up on this. However, the circuit shown here does give an idea of what an 'ambisonics' decoder looks like, and that is sufficient for the present.

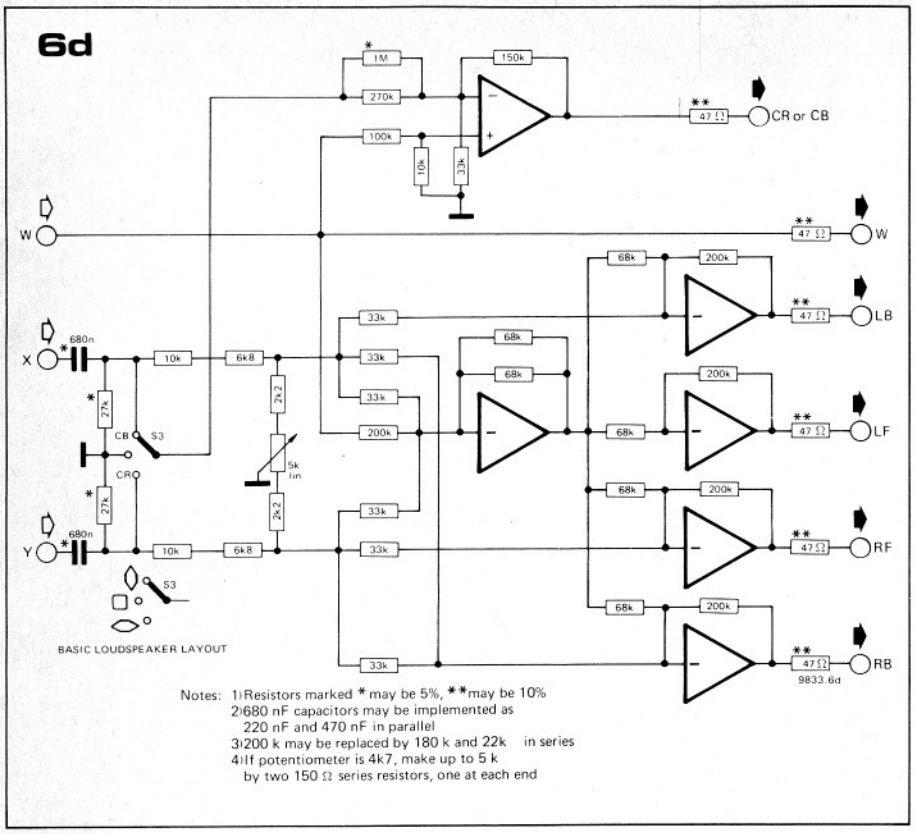


Figure 6c. Detailed circuit of resistor matrix + shelf filter stage.

Figure 6d. Detailed circuit of output stages, including loudspeaker distance compensation, loudspeaker layout control and amplitude matrix.

Figure 7. Three or four of the outputs from figure 6 may be fed to power amplifiers to drive four- or six-loudspeaker layouts. The '+' sign indicates the positive loudspeaker terminal in each case.