Ambisonics in Multichannel Broadcasting and Video*

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The FCC's effective deregulation of FM multichannel broadcasting standards, and the advent of multichannel audio via satellite, cable, and video systems, pose the question of the most effective use of 3 or 4 related audio channels. The Ambisonic UHJ hierarchy for transmitting total sound fields offers more varied mutually compatible applications than do other proposals (such as quadraphonics), with options up to and including full-sphere ("periphonic") directional reproduction. These options are detailed, including mono, stereo, 2-, 2½, 3-, and 4-channel horizontal surround encoding, 4-channel periphony, and a range of user sound field adjustments in stereo and psychoacoustically optimized surround-sound reproduction modes.

0 INTRODUCTION

Ambisonics is unique in being a total systems approach to reproducing or simulating the spatial sound field in all its dimensions. Conventional monophony and stereophony are subsystems of Ambisonics, as are so-called 4-channel systems that attempt to reproduce the directional sound field via four loudspeakers. Beyond this, Ambisonics provides for full upward compatibility to any number of loudspeakers in any reasonable configuration.

Ambisonics is not limited to any particular number of transmission channels; with greater the number, the higher is the obtainable directional resolution. With 4 transmission channels, full spherical portrayal of directionality—including elevation and declination—becomes practical. All options are fully compatible with one another. For example, a system employing 3 transmission channels will be correctly decoded to any number of loudspeakers by receivers designed for decoding either 2 or 4 transmission channels. The transmission options include the use of supplementary band-limited transmission channels.

The implications for a broadcast standard of such a systems approach are very significant. The extensive "intercompatibility" provided gives the broadcaster a virtually unlimited range of options. A broadcaster may choose to remain with the conventional 2-transmission-channel system, yet will still be assured of providing benefits to listeners with even the most sophisticated 4-transmission-channel decoders.

Additional broadcast or reception options include limited-bandwidth third-channel transmission (termed 2½-channel), full bandwidth 3-channel transmission, and full-bandwidth 4-channel transmission for either horizontal or full-sphere directionality.

Ambisonics is a unification and extension of prior art in sound field recreation. In order to encompass the wide range of international knowledge and experience in reproducing or simulating the spatial sound field, it was necessary to develop new notations and theoretical foundations.

Particular emphasis has been laid on optimizing the subjective directional illusion throughout the listening area. This involves decoding techniques that match the loudspeaker feeds to the precise layout of loudspeakers in the room and that handle different audio frequencies so as to match the differing directional behavior of the ears at low and high frequencies.

On the one hand, Ambisonics has led to a novel studio microphone technology [1]–[3] capable of unprecedented realism and accuracy. A commercial version of this "sound field" microphone has been made available by Calrec Audio. On the other hand, Ambisonics gives a new range of creative sound manipulation techniques such as full-range positional control (with no limitations) for both single sounds or whole sound fields, full control of image width, artificial surround reverberation, and even full-sphere directional panning. References [3]–[6] describe many aspects of this technology, much of which has been implemented

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by Audio & Design (Recording) in their Ambisonic mastering system.

The encoding specification used with Ambisonics is called Universal HJ (UHJ), which is described in detail in Appendix 1. This incorporates the BBC's HJ system [7]. UHJ includes a mono- and stereo-compatible surround-sound encoding using conventional 2-channel transmission techniques. By using multiplexing described in Appendix 2, an optional third channel, giving enhanced directional resolution, is put in quadrature modulation on the 38-kHz subchannel. For the optional effects of "loudspeaker emphasis" (often termed discreteness) or of full-sphere reproduction, an additional fourth channel can be conveyed on a 76-kHz double-sideband subchannel.

A further UHJ transmission option is to use a band-limited third channel. This would be useful where it is desirable to minimize any possible impact on existing usage of the multiplex signal.

1 ALL DIRECTIONS

A distinctive feature of Ambisonic technology is that it is based on a precise and completely unambiguous technical specification of how the encoding method should handle every direction of sound in space. This may be contrasted with the quadraphonic approach, in which the handling of only 4 loudspeaker directions is explicitly specified, with other directions left largely to chance.

While at first this "all-direction" approach might seem a mere technicality, in fact it has far-reaching consequences. In conventional quadraphonics, phantom images between the loudspeakers are usually created by using conventional stereo between each pair of loudspeakers. But it has long been known [8] that the quality of the phantom images is poor if the stereo loudspeakers subtend an angle at the listener of more than 60 degrees (Fig. 1). Quadraphonics angles the loudspeakers at an average of 90 degrees apart, giving a "hole in the middle" effect with unstable phantom imges. It is found that the stereo illusion breaks down completely for pairs of loudspeakers to the side of the listener. This problem has been demonstrated by at least six independent experimental studies in at least four countries (for example, see [8]–[13]).

However, in Ambisonics the precise method of encoding directionality has been chosen to permit much more stable images around the whole sound stage. While we describe this in more detail below, the result is that even when using just 4 loudspeakers for reproduction, the usable front and rear stages are much wider than the restricted 90-degree width possible with conventional pairwise quadraphonics (Fig. 2).

Moreover, Ambisonics defines the encoding of every direction. Thus it is possible to design decoders that handle every direction equally, rather than giving excessive emphasis to a few loudspeaker directions at the expense of phantom image directions. One particular consequence of this is that a wide range of loudspeaker layouts can be used with ambisonics, including different shapes of rectangular layouts [Fig. 3(a)] and 6 loudspeaker layouts [Fig. 3(b)]. Available Ambisonic decoders include a simple preset adjustment (rather like a conventional stereo balance control for the user) to adjust the decoder to give correct directionality with the loudspeaker layout used by the listener.

While most listeners are expected to use 4 loudspeakers, the 6-loudspeaker decoding option undoubtedly gives further improved results, especially for due side-sound positions. This is because although 4 loudspeakers can be made to give a much more accurate directional illusion than quadraphonics, certain types of sounds with spiky waveforms (such as applause,

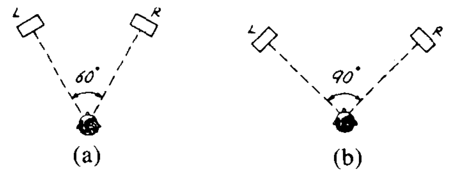

Fig. 1. Stereo gives good phantom images for a 60 degree loudspeaker angle (a), but poor phantom images with a hole in the middle for a 90-degree loudspeaker angle (b).

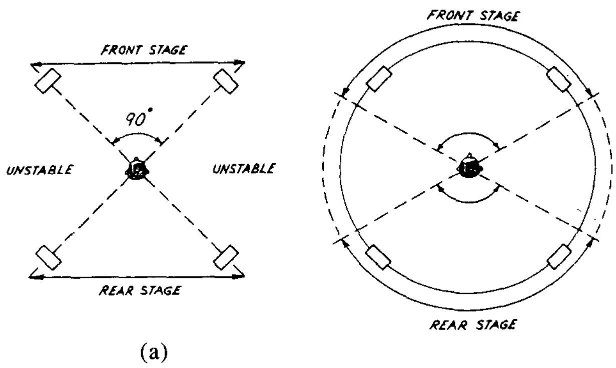

Fig. 2. (a) Conventional pairwise quadraphonics is restricted to a 90-degree wide usable front stage and rear stage. (b) Ambisonics can give much wider usable front and rear stages, even when using only 4 loudspeakers.

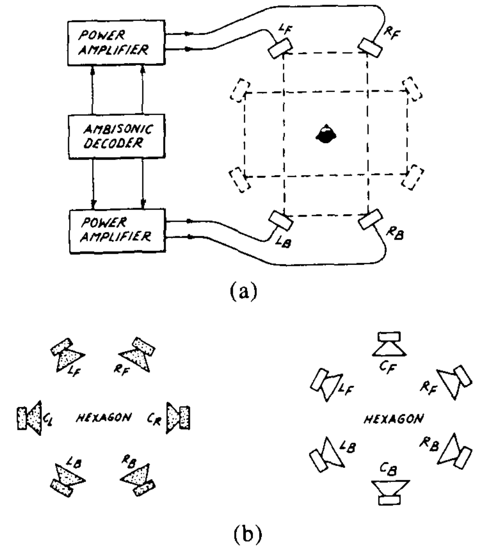

Fig. 3. Ambisonics can be decoded (a) via different rectangular loudspeaker layouts or (b) via various hexagonal layouts with correct directional effect.

harpsichords, and oboes) still tend to be drawn toward the 4 loudspeakers; 6 loudspeakers overcome this problem.

Clearly, the all-direction encoding used for Ambisonics gives a much wider range of creative possibilities for the producer, and a wider range of options for the listener at home, than do quadraphonic approaches. However, Ambisonic systems will also handle quadraphonically produced material, although one should not expect the inherent defects of conventional pairwise mixed quadraphonic material to be removed.

2 PSYCHOACOUSTIC DECODING

Before discussing UHJ encoding, it is helpful to understand the process of decoding in more detail. The original sound field, whether it is a live sound or one created at a mixing console, has an infinite number of possible sound directions. In the listener's room there are only a few loudspeakers in a few directions. Thus the recreation of the sound field from these loudspeakers must be an illusion created in the ears and mind of the listener.

The job of the decoder is to produce loudspeaker-feed signals that produce a convincing illusion of the intended directional sound field. There is no practical way of exactly recreating the original physical sound field over a large listening area, since information theory and physical acoustics show that this would require around one million transmission channels and one million loudspeakers.

For a system to be practically usable, it is essential that the directional illusion be convincing over a reasonably large listening area, and not just at one ideal "stereo seat." Moreover, the listener should have the freedom to face any direction, not just forward [14].

These complex requirements are difficult to satisfy for a 360-degree sound stage encoded into just a few transmission channels. It is necessary to have a very detailed understanding of human directional hearing to do such a design. In the years since quadraphonics was introduced, a considerable amount of the required experimental data on the directional psychoacoustics of human hearing have become available thanks to experimental studies in the United States, England, Germany, and Japan [9]–[13], [15]–[17]. Unfortunately the sheer volume and complexity of these data make it impossible to do optimum design work direct from the data.

Completely new technical tools were required in order to handle and analyze the experimental data. Essentially this involved the recognition that the ears use many different methods of localizing sounds. Thus a so-called metatheory of human hearing was developed [18]–[20], that is, a theory of possible theories of directional hearing. By putting the metatheory in a convenient mathematical form [18], [20], it became possible to isolate a few aspects of the sounds from the loudspeakers that affect many different mechanisms of human directional hearing. The computation of these few parameters for experimental data allowed a simplified presentation and understanding of these data. The various parameters isolated by the metatheory of directional hearing mostly correspond to easily learned audible qualities of sound, such as "phasiness," "in-the-head" quality, image instability under head rotation, low-frequency directionality, and high-frequency directionality.

Not only does the metatheory provide a language to describe many of the subjective qualities of sound localization, it also greatly simplifies the design of decoders [21]. This is because it has the sort of mathematical simplicity that allows a great many general theorems to be proved by mathematical argument. Several of these mathematical results combine to show that once a decoder has been designed to meet one type of requirement, known as the Makita theory, it can very easily be modified to meet many other important requirements of human directional hearing as well.

The Makita theory was originally used for analyzing all-around decoding by Cooper and Shiga [22] at the University of Illinois. This theory gives the precise apparent direction of a low-frequency sound if the listener turns his or her head to face the apparent source of sound.

A psychoacoustically optimized decoder designed using these principles has the basic form shown in Fig. 4 [21]. At the input a phase-amplitude matrix converts the transmission signals into three signals W, X, and Y, representing the omnidirectional part, the front-minus-back part, and the left-minus-right part of the reproduced sound field. (A full-sphere directional decoder would also produce a Z signal, representing up-minus-down information.) The relative frequency responses of these three signals are then adjusted by three shelf filters to match the different requirements of human directional hearing below and above about 700 Hz. (The head starts casting an acoustical shadow for sounds above 700 Hz.) Finally, an amplitude matrix is used to derive loudspeaker feed signals for the particular loudspeaker layout used. In particular, a simple potentiometer adjustment of this matrix compensates for the use of different rectangular shapes of loudspeaker layout. More refined decoders can be devised to cope with such things as the size of the loudspeaker layout and to optimize the relative preference given to the directional resolution of reproduction in different directions.

One of the most convincing aspects of the metatheory of directional hearing is that it allows many of the remaining weaknesses of particular decoder designs to be predicted. In other words, it not only predicts what is right about a decoder, but also what is wrong. Naturally no decoder creates an absolutely perfect illusion of all directions for all listener positions, but it becomes possible to minimize faults and to make careful trade-offs between those that inevitably remain.

Perhaps the most important consequence arising from this understanding of directional hearing is the following remarkable result [18], [19]. For decoders using 4 loudspeakers in a square or rectangular layout, the optimum number of transmission channels is only 3. The effect of a fourth nonredundant transmission channel is to degrade the quality of phantom image positions. Typically, the effect of a fourth channel is to emphasize the 4 loudspeaker positions, pulling other phantom images toward the loudspeakers (Fig. 5).

In general it is found that for any number of transmission channels, a larger minimum number of loudspeakers is required to give a convincing illusion of all phantom image directions. If too few loudspeakers are used for the number of transmission channels, the loudspeaker positions are overemphasized. This is analogous to what happens in a radio antenna if a circular array of dipoles contains too few dipoles—one loses circular symmetry and unwanted nulls appear. It turns out that 4 transmission channels require at least 6, and preferably 7 or more, loudspeakers to avoid "loudspeaker emphasis" completely for horizontal sound. For full-sphere sound with 4 transmission channels, at least 6 loudspeakers (in an octahedral layout) are required (Fig. 6). For 2, 2½, or 3 transmission channels, 4 loudspeakers are sufficient, although ideally 5 or 6 are even better.

In some cases it appears that people desire loudspeaker emphasis, such as given by quadraphonics, at the expense of good phantom images. There is no difficulty in UHJ of providing such encoding and decoding options if and when required (see Appendix 1).

To summarize, the metatheory of directional hearing provides a simple language for interpreting the results of otherwise indigestible complex experimental data. This language immediately suggests simple methods of optimizing the subjective performance of decoders under a wide range of listening conditions. Some aspects of such designs are detailed in Appendix 3. This Ambisonic know-how and technology can also be applied to so-called logic decoders if required. A consequence of this understanding of directional hearing is that for phantom image directions, 3 channels are better than 4 for 4-loudspeaker reproduction.

3 UHJ MULTIPLEX BROADCASTING

In order to get signals to the consumer, it is necessary to encode the complete Ambisonically produced directional sound field into a form that can be picked up as conventional mono or stereo, as well as being decodable to full surround sound. The UHJ system provides such an encoding scheme, suitable for broadcasting, cable, video, and analog or digital records and cassettes. For FM broadcasting, the UHJ approach includes specifications for multiplexing the audio signals (see Appendix 2).

As described in Appendix 1, the UHJ system encodes the directional sound field into four signals, denoted by Σ, Δ, T, and Q. The signals Σ and Δ are, respectively, the sum and difference of the conventional left and right stereo signals, but use phase-amplitude encoding to represent the complete 360-degree sound stage. Roughly speaking, the amplitude ratio of the left and right stereo channels is used (as in stereo) to represent the side-to-side directionality, whereas front-to-back aspects of directionality are represented by the phase difference between the left and right stereo channels.

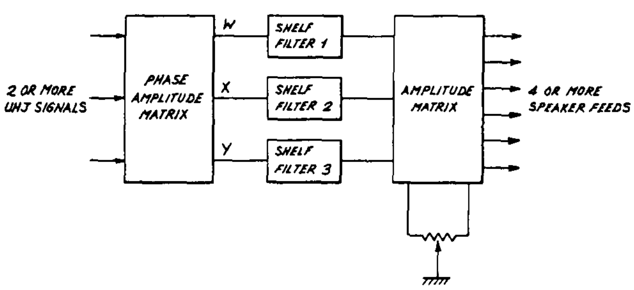

Fig. 4. Basic form of horizontal Ambisonic decoder.

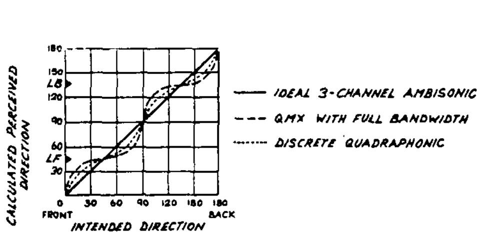

Fig. 5. Image position versus intended direction at high frequencies for (_____) Ambisonic 3-channel, (.....) pairwise quadraphonics, and (___) QMX 4-channel, all decoded via a square loudspeaker layout. Note the attraction of sounds using 4 transmission channels to the loudspeaker positions (indicated by triangles).

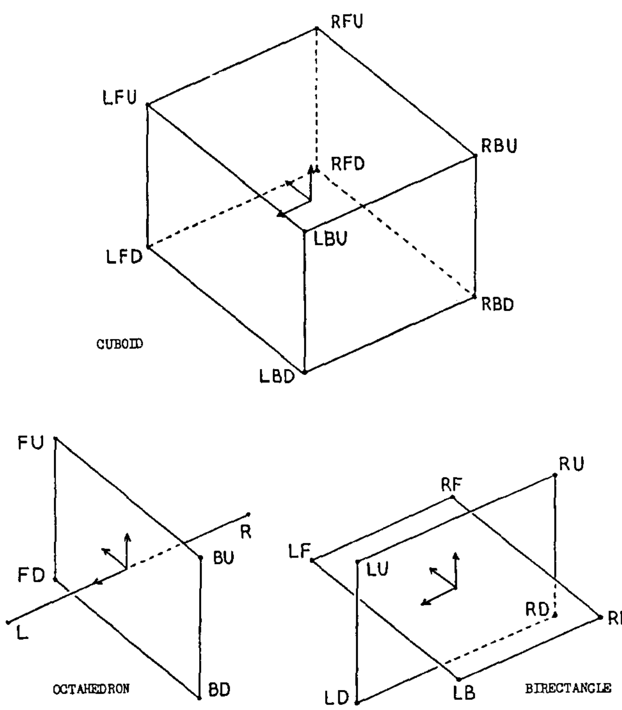

Fig. 6. Typical loudspeaker layouts for full-sphere reproduction. Other layouts are possible. Note that the cuboid and octahedral layouts occupy only four floor locations, and that the birectangular layout incorporates both a conventional stereo pair and a horizontal rectangular layout. Speaker designations: F—front; B—back; L—left; R—right; U—up; D—down.

Appendix 1 details the UHJ encoding equations.

The UHJ stereo signals are designed to ensure optimum compatibility with mono and stereo playback equipment. No system of encoding surround sound can offer perfect mono, perfect stereo, and perfect surround sound at the same time. Some designers of surround-sound systems have coped with this fact of life by declaring that certain types or uses of program material are "unimportant" and can be neglected. However, any encoding system coming into general use has to cope with a wide range of possible uses. Moreover, it has to be remembered that a successful system is likely to be in use for at least 25 years, and that preferred styles of program material can change drastically over such a period. For example, compare the styles of popular music at the start of stereo in 1957 with the sophisticated studio manipulations of today. For this reason it is considered vital to ensure that an encoding system should not fail to give adequate results with any reasonable program philosophy competently implemented [14].

It is vital that any chosen system of surround-sound encoding consistently give surround-sound results preferable to stereo, since otherwise there would be no point in departing at all from the excellent results that present-day stereo can give. UHJ has therefore placed emphasis on the possibility of uncompromised surround sound, within the inevitable limitations of the available number of transmission channels and reproduction loudspeakers. Mono compatibility will always be important, since small portable mono receivers are likely to remain in use indefinitely. Thus the UHJ mono signal incorporates all sound directions, including due back and all vertical directions, at a level within 5 dB of one another. This ensures that the mono intelligibility of important musical or speech lines will never be lost.

Since stereo is the most important present-day high-fidelity medium, the stereo results of UHJ have also been designed with care to give a high-quality full-width stereo stage on typical surround-sound productions. For quadraphonic productions limited to a 90-degree wide front stage, it has been suggested that this front stage should fill the stereo presentation as well. However, this would give serious problems of stereo compatibility for Ambisonic systems capable of a much wider usable front stage, since it would then be difficult to know where to put the edges of the front stage during stereo playback. To leave room for the full front stage when this is reproduced in stereo, the part of the stage within ±45 degrees of due front (that is, the part of the Ambisonic front stage that quadraphonics attempts to handle) is reproduced in stereo with a width of about 75% of the total distance between the loudspeakers.

The typical stereo presentation of UHJ is shown in Fig. 7. It will be seen that front-stage material is reproduced with sharply defined images occupying virtually the whole of the stereo stage, and that some sound positions can actually appear marginally beyond the loudspeakers. Rear-stage sounds appear with rather less well defined images between the stereo loudspeakers. The more "recessed" quality of these broader images helps to provide an audible distinction between front and rear sounds even in stereo, thereby reducing the artistic incompatibility arising with other stereo fold downs when sounds from different surround directions seem to come from the same stereo direction.

In practice, the apparent position and quality of sounds in stereo presentation depend somewhat on the nature of the sounds involved, the loudspeakers used, the listening conditions, and the listener position. UHJ stereo presentation has been designed to provide the best available trade-off obtainable with any surround-sound system. Although the very best that stereo can do (rarely achieved in current practice) is better, the improved studio technology of Ambisonics [1]–[6] normally gives better stereo via UHJ than does conventional studio stereo technique with conventional stereo. This situation is analogous to the introduction of color television in Europe. In theory, this ought to have degraded monochrome reception. However, in European practice it was found that the better cameras and studio equipment required to make color work well gave improved monochrome reception.

An additional aspect of UHJ stereo compatibility is the fact that it has been designed for exceptionally good handling of the stereo sense of distance and depth. An understanding of the factors responsible for these qualities is relatively recent, and as far as we are aware, no other system has been systematically designed to handle the spatial qualities of indirect as well as direct sounds. Indeed, in this respect, UHJ stereo is superior to prior stereo techniques, even ignoring any use for surround sound, as many reviews of commercial UHJ releases have noted.

Consumer surround-sound decoders can be designed to give very acceptable surround sound from just the two basic UHJ Σ and Δ channels. This mode is known as 2-channel UHJ, or BHJ. The term "channel" here refers to the number of transmission channels, since as we have explained, the number of loudspeakers is

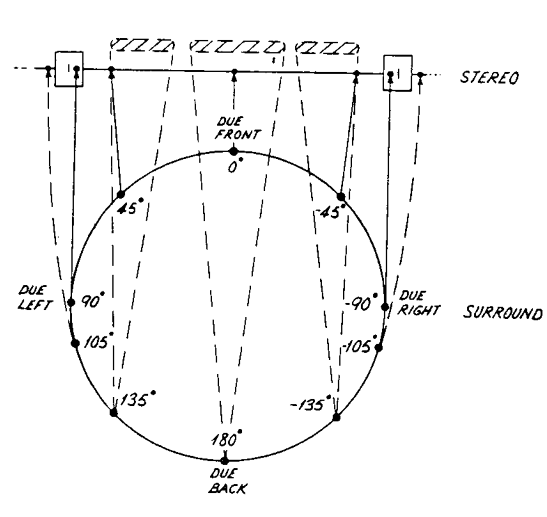

Fig. 7. Typical stereo presentation of UHJ material. The precise form of stereo presentation depends on the nature of the program material.

a consumer option, not directly the concern of the broadcaster.

A broadcaster wishing to give his or her public a greater refinement and accuracy of surround sound can transmit in addition supplementary channels for enhanced directional resolution. These supplementary channels were pioneered by Cooper in his UMX system [22], and UHJ has systematically refined his idea to cope with an even wider range of needs. The supplementary channels may be transmitted with no harmful effect on the users of either stereo or 2-channel UHJ surround-sound decoding equipment.

The range of options open to the broadcaster with the supplementary channels T and Q is shown in Figs. 8 and 9. These options include: just broadcasting the 2 basic UHJ channels for mono, stereo, and horizontal surround-sound reproduction; broadcasting the 2 basic UHJ channels plus a band-limited third channel T for mono, stereo, and improved horizontal surround; broadcasting 3 full-bandwidth channels for mono, stereo, and full horizontal surround; and broadcasting 4 channels for all possible modes of reproduction, including full-sphere surround sound.

As can be seen from Fig. 8, a receiver designed only for one of the more restricted modes (such as 2-channel horizontal surround sound) can work on broadcasts on any of the more expansive and all-inclusive modes. This gives full intercompatibility of modes between transmitter options and receiver options. In all (including mono, stereo, 2-channel UHJ, 2½-channel UHJ, 3-channel UHJ, 4-channel loudspeaker-emphasis UHJ, and 4-channel full-sphere UHJ) there are seven possible transmission and reception modes—yet the system design is such that this vast range of possibilities are fully intercompatible. This flexibility offers unprecedented capability of coping with all present and foreseeable future modes of broadcasting for multiloudspeaker reproduction. Further possible reception modes within UHJ are discussed in the next section.

The third channel T, in either band-limited or full-bandwidth form, is placed into the multiplex signal by quadrature double-sideband suppressed-carrier modulation of the 38-kHz subcarrier. The fourth channel Q is multiplexed using double-sideband suppressed-carrier modulation of a 76-kHz subcarrier. The indication of which mode is being broadcast can be conveyed to the receiver by means of a code carried by a submerged tone indication method, such as proposed by Dolby Laboratories. The spectrum of the multiplex baseband signal in 2-, 2½-, 3-, and 4-channel transmission modes is shown schematically in Fig. 9.

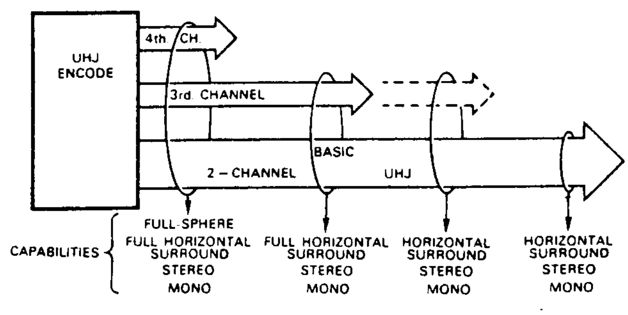

Fig. 8. UHJ is a hierarchy using 2-, 2½-, 3-, and 4-channel intercompatibility.

In the case of 2½-channel transmission, the audio modulation bandwidth of the 38-kHz quadrature double-sideband signal (the T subchannel) is approximately 5 kHz. In a 2½-channel receiver, a simple low-pass filter is used in the T audio signal path to minimize noise and crosstalk resulting from low-cost receiver design.

The UHJ system is the only encoding system so far proposed that satisfies all of the requirements for 2½- and 3-channel use. The encoding of the T channel has been chosen so that a 3-channel surround-sound decoder still gives basically correct directional reproduction as the T channel is faded out. (The basic design theory used to ensure this is summarized in [20].) By this means, a UHJ decoder for 2½-channel broadcasts decodes correctly not only the low-frequency range where 3 channels are present, and the high-frequency range where 2 channels are present, but also the intermediate frequency range where an intermediate degree of third channel is present. Also, the listener in a fringe area has the option of reducing the contribution of the third channel to his or her reception so as to reduce interference while obtaining most of the benefits of full 3-channel decoding.

A second feature of the UHJ T signal is that it is designed to have a 90-degree audio phase relationship to the mono signal for due front and due back sounds. This ensures [23] that typical pilot recovery misalignments in current stereo receivers do not produce a stereo channel imbalance when receiving 2½-, 3-, or 4-channel broadcasts. Any system employing a quadrature 38-kHz double-sideband subchannel without a 90-degree audio phase relationship to the mono audio signal will experience serious positional errors even with stereo receivers having only quite small pilot phase errors of a few degrees.

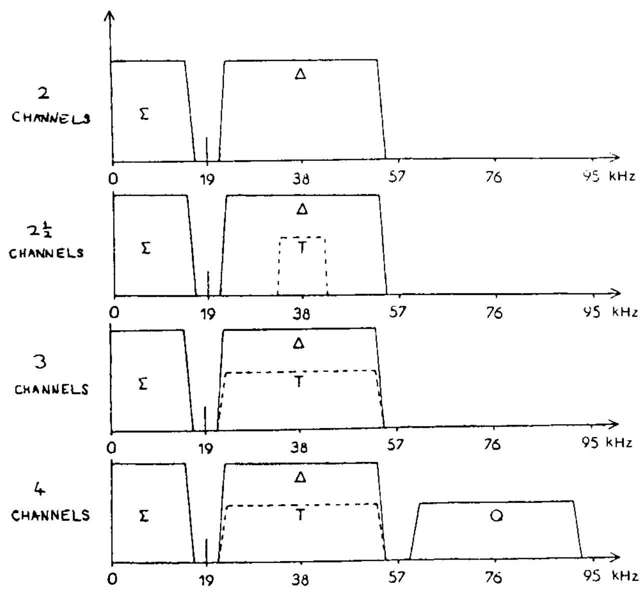

Fig. 9. Multiplex spectrum of UHJ broadcast options.

The 3-transmission-channel option, as explained earlier, will give the optimum illusion of all-around horizontal directionality via 4-loudspeaker decoders, and the 4-transmission-channel option comes into its own with the exciting future possibilities of full-sphere directionality. The 2½-channel option gives results that much more closely resemble the decoding of 3-channel UHJ than 2-channel UHJ. This option is particularly valuable when used with recording or cable systems which do not have the data capacity for 3 audio channels, but where a limited data capacity exists that can be used for a band-limited third channel. In addition, receiver design for 2½-channel reception is less critical than for 3-channel reception, since it avoids crosstalk effects caused by baseband low-pass filters often used in receivers to minimize Subsidiary Communications Authorization (SCA) interference.

The 2-, 2½-, and 3-channel UHJ modes allow broadcasters to continue using the conventional 67-kHz SCA subchannel. If a 95-kHz SCA subchannel proves acceptable, then the 4-transmission-channel UHJ mode will also allow use of SCA.

Thus the broadcaster can choose the UHJ option that suits his or her needs now and upgrade to a higher option later. For instance, 2-channel UHJ can be broadcast over existing 2-channel transmitters simply by using UHJ-encoded 2-channel software.

2½-channel UHJ can be used with software media having enough spare channel capacity to allow the addition of a 5-kHz band-limited audio channel. 3-channel UHJ is the best horizontal surround-sound option, and SCA can continue to be used. Finally, a broadcaster can go to the full 4-channel UHJ option if either there is a demand for loudspeaker emphasis reproduction or when full-sphere software becomes available.

Although the commercial availability of full-sphere sound is likely to be a long way off, due to the rather large number of loudspeakers needed, the technology of full-sphere reproduction has been demonstrated and developed. This "high-end" option of full-sphere (periphonic) directional reproduction can be used to provide the ultimate in either realism or effects capability of known systems. In applications where realism is important, periphony provides a substantial improvement in perceived tonal accuracy over the finest stereo or horizontal surround-sound reproduction systems, and a large number of commercial recordings now exist in a mastertape form which contains the full periphonic information of 4-channel UHJ. Besides such commercial music recordings, the BBC has done a number of periphonic radio drama productions [24], and studio equipment is available from professional equipment manufacturers that permits the studio production of periphony of either natural or studio-created effects. In addition the psychoacoustic Ambisonic decoding of periphony has been developed [25]. Despite periphony not being commercially viable in the short term, it would be unwise to adopt surround-sound system standards that will not permit the painless future introduction of this future step forward in the art of sound reproduction.

To summarize, the range of mutually compatible services offered by UHJ would appear to meet not only currently perceived needs of broadcasters, but a whole range of new possibilities that will help ensure that FM broadcasting will remain competitive with other media well into the future. The mature systems design of UHJ also offers the listener the option of his or her choice. All UHJ options include the basic mono, stereo, and 2-channel surround-sound possibilities.

4 VIDEO AND OTHER APPLICATIONS OF UHJ

Besides mono, conventional stereo, and the various surround-sound options detailed above, the fact that UHJ conveys a total directional sound field permits other kinds of reception option for the end user.

One use is in video media, where it has been suggested that 3 channels could be used to convey separate stereo-left (L), stereo-right (R), and center (C) signals so that the important "center" sounds should be locked in place at the television screen for all listening and viewing positions. If the L, R, and C signals are encoded into 3-channel UHJ at respective azimuths 75 degrees left of, 75 degrees right of, and at center front, then these signals can be decoded either via UHJ surround-sound decoders or as feeds to L, R, and C loudspeakers in a manner that is fully cross-compatible. In other words, a surround-sound decoder would respond appropriately to a L, R, C broadcast, and a 3-loudspeaker reproducer would respond appropriately to a full UHJ 3-channel surround broadcast. Mono and stereo reception in either case would be fully compatible.

In addition the use of UHJ with video media permits all directions of sound to be handled with full mono and stereo compatibility, unlike some cinema systems in which a monophonic "sound-effects" channel is added for nondirectional reproduction through loudspeakers surrounding the audience. In mono reproduction, the sound-effects channel in such systems is largely lost, but this problem does not exist for *any* position in the UHJ sound stage. Equipment for converting between UHJ and current cinema standards will be available for allowing cinema sound-track material to be converted to UHJ for domestic video release and TV broadcasting, where mono compatibility is a prime requirement.

Another application of UHJ is to provide listeners with a high degree of control over the reproduced mix of sound in all reception modes from mono to full-sphere sound. Elsewhere [2] methods have been described of mixing the W, X, Y, Z signals derivable from UHJ (see Appendix 3) to derive arbitrary stereo pair directional characteristics pointing in any direction, which could be used by stereo listeners to derive desired mixes from 3- or 4-channel UHJ transmissions. The same reference [2] describes techniques of sound field control that allow electronic modification of the total sound field without destroying those relationships between the component signals that are characteristic of actual sound fields. By this means it is possible for users of 3- or 4-channel UHJ to obtain the subjective effect of moving forward or backward, or in any other direction, by increasing the intensity of sounds in that direction and diminishing in the opposite direction, without affecting the psychoacoustic quality of surround-sound decoding given by Ambisonics. This sound field control has hitherto only been implemented on professional equipment, but domestic versions are feasible.

A similar possibility exists in decoding 2-channel UHJ also, and a commercial domestic decoder has been marketed incorporating a "zoom" control permitting subjective movement forward or backward within the UHJ surround-sound stage without losing the psychoacoustic qualities of Ambisonic decoding. As can be seen from the block diagram of this decoder (see Appendix 3, Fig. 14), this adjustment takes place entirely within the phase-amplitude matrix of the decoder. Besides this kind of zoom effect, all Ambisonic decoders can be modified in design to allow the user to rotate the reproduced sound field to "point" in any direction.

With these possibilities, UHJ becomes a medium permitting not only an accurate recreation of an intended sound field, but also the modification of this sound field to cope with wide differences in the tastes of individual listeners and their circumstances. For example, some listeners may wish for an "upfront" presentation emphasizing the frontal stage and deemphasizing ambience and rear-stage sounds, whereas others might prefer listening with a more distant perspective.

5 RECEIVING APPARATUS

Although the number of reception options for UHJ is extremely large, in practice the situation is likely to be simple for each class of user, since the designer and manufacturer of receiving equipment can take care of any complexities of technical option by automatic switching. Such automatic switching is simplified by the fact that several parts of an Ambisonic decoder are common to several different decoding modes.

The lowest cost apparatus, for in-car, music-center, and portable reproducers, may well consist of a simple 2-channel, 4-loudspeaker UHJ decoder with no mode switching. Such an apparatus is also likely to include features of the Ambisonic technology designed to make the benefits of the Ambisonic approach available to even the listener with a limited budget. These low-cost options include a means of correct 4-loudspeaker decoding using only 3 power amplifiers feeding 4 loudspeakers via a "loudspeaker matrix" (Fig. 10). In addition low-cost decoder networks using the minimum possible number of phase shifters are possible as described in Appendix 3. Both these cost-cutting options are also available to users of 2½- and 3-channel receiving apparatus, with virtually no sacrifice of subjective performance in comparison with normal design compromises in this class of equipment.

In medium-range high-fidelity equipment, relatively simple mode switching of a few resistors (and filters for the 2½-channel mode) will allow the user (by either manual or automatic operation) to use the best mode available. Again the above-mentioned cost-cutting options are available to receiver designers. Alternatively, a receiver incorporating 4 power amplifiers can include a 6-loudspeaker decoding option at virtually no extra cost (Fig. 10).

Fig. 10 shows the loudspeaker connections for 4-loudspeaker decoding using 3 amplifiers or for 6-loudspeaker decoding using 4 amplifiers. It will be seen that these arrangements do not depend on special loudspeaker impedances or the like, but merely use connecting wires between the loudspeaker terminals and the amplifier outputs.

All Ambisonic decoders, whatever their price level, depend on the principle illustrated in Fig. 11 [21], [18]. An initial phase-amplitude matrix converts the UHJ encoded input signals into three signals: W representing the acoustical pressure at the center of the listening area, a "forward velocity" signal X representing front-minus-back directional information, and a "leftward velocity" signal Y representing left-minus-right directional information. An "up-minus-down" signal Z is also used for decoders giving full-sphere reproduction.

These signals are then passed through shelf filters with different gains at low frequencies (below 700 Hz) and high frequencies (above 700 Hz) so as to compensate for the frequency-dependent properties of human hearing. These filters in practice are also used to ensure a flat overall frequency response for all directions, and full interchannel phase compensation. High-pass filters in the velocity signals compensate for the finite size of the loudspeaker layout. These affect only the very lowest audio frequencies, but their effect on the phase response of the X and Y signals can compensate for defects caused by loudspeaker proximity to the listener for certain types of signals.

The output of the Ambisonic decoder is an amplitude matrix specifically matched to the number of loudspeakers and the layout shape. For rectangular loudspeaker layouts, a potentiometer is to modify the amplitude matrix coefficients, so that it is a simple matter to adjust for the layout shape in much the same manner as one currently uses a balance control. Experience shows that the compensation for the particular loudspeaker layout in use is vital for the subtle sense of "correctness" of sound quality that makes good surround sound superior to stereo.

Using Ambisonic decoders, a number of interesting characteristics have emerged. It is found that removing the shelf filters not only degrades the precision of localization (as might be expected), but also alters the tonal quality of reproduction, making it less natural. This appears not to be a simple frequency response effect, since care is taken in the design of Ambisonic decoders to ensure a flat overall frequency response. (A tone quality change is also noted when switching between different decoding matrices having no shelf filters, which automatically have flat frequency responses.) The psychoacoustic metatheory [18] of human hearing used to design decoders in fact incorporates a method of analyzing some aspects of subjective tonal quality, and the optimized decoders are indeed found to be more accurate.

Another aspect of Ambisonic decoding is that the loudspeakers tend to be audibly "invisible," that is, with eyes shut, it is difficult to determine from the reproduced sound where the loudspeakers are located, since they tend not to draw sounds toward them [5]. Naturally this depends to some extent on the loudspeaker design, since it has been found that the requirements for loudspeakers for Ambisonics are not always the same as for stereo, just as in an earlier era it was discovered that good mono loudspeakers were not always good stereo loudspeakers.

6 CONCLUSIONS

We have described some aspects of what makes Ambisonics, and its associated UHJ encoding system, a unique development in surround sound. While Ambisonics developed via the knowledge acquired attempting to avoid the problems of quadraphonics, it has become a comprehensive systems approach to sound reproduction that is based on rational engineering design among known possibilities, rather than hopeful guesswork.

Quadraphonics, including its known limitations and weaknesses, can of course be handled via UHJ. This is important if only to rescue the large amount of program material existing in this form. However, the full advantages of UHJ can only be realized with program material and decoders using the new knowledge and techniques of the postquadraphonic generation. Ambisonics and UHJ should be thought of as the first systematic approach to handling and conveying to the listener a total sound field, rather than some arbitrarily chosen loudspeaker feeds. As such, it allows both the broadcaster and the listener to make their own choices (in terms of convenience and cost) of how good an approximation to the original sound field is to be obtained, without creating unnecessary restrictions on either current or future possibilities.

Unlike quadraphonics, which was an attempt to apply essentially stereo techniques to 4 loudspeakers, Ambisonics represents a major departure in the development

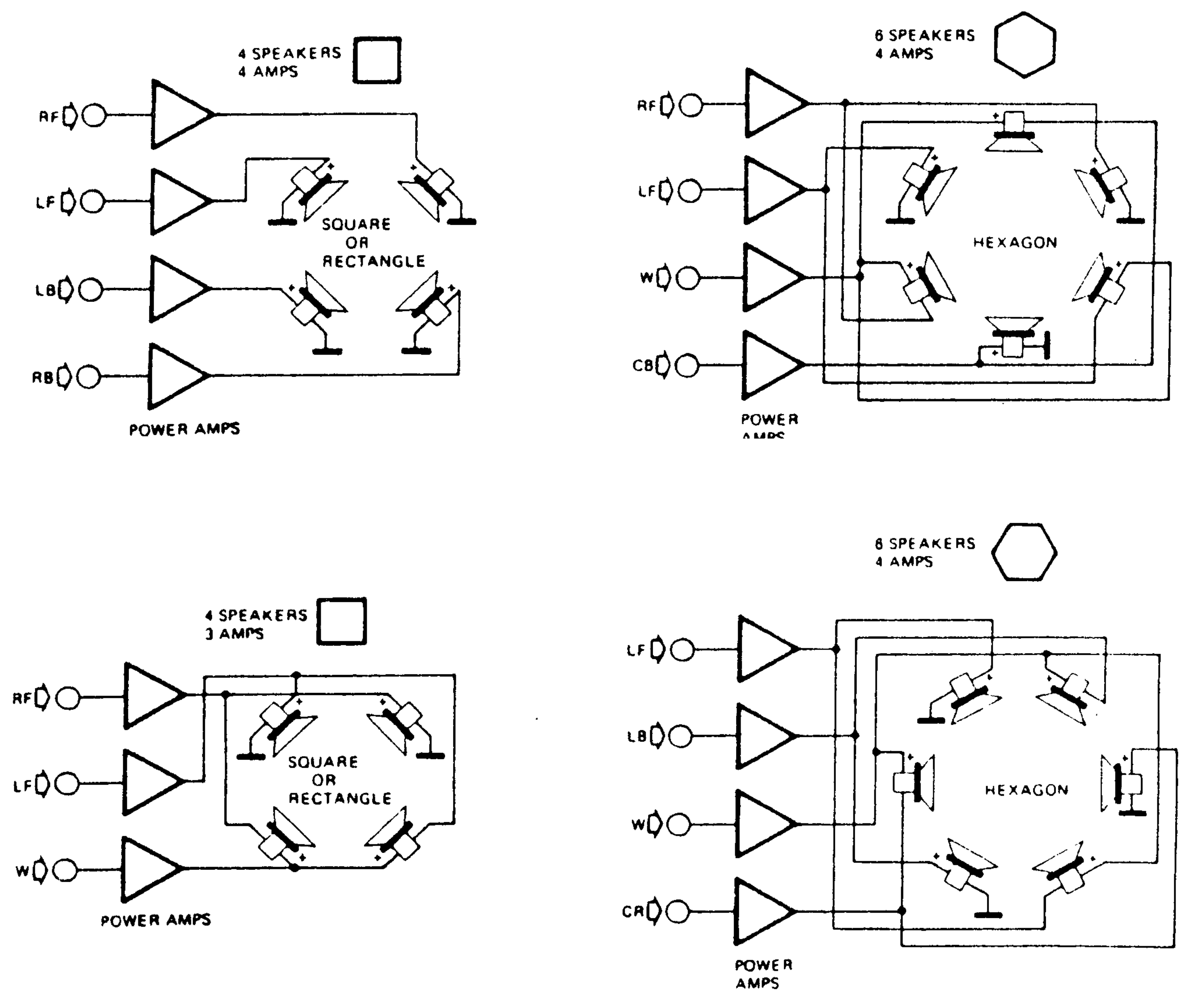

Fig. 10. Loudspeaker matrix arrangements for surround-sound decoding.

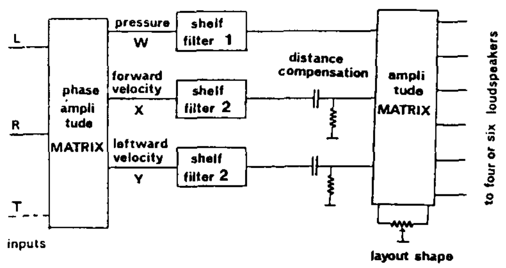

Fig. 11. Ambisonic decoder block diagram.

of high-fidelity sound comparable to the jump from mono to stereo. As such, it has its own language, concepts, and techniques. It will be recalled that the early days of stereo involved crude "ping-pong" attempts to treat stereo as just double mono. The quadraphonic attempt to treat surround sound as mere double stereo will in retrospect appear just as misguided.

7 ACKNOWLEDGMENT

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APPENDIX 1
UHJ ENCODING EQUATIONS

The Universal HJ (UHJ) system is a system of encoding sounds in all spatial directions into 2, 3, or 4 channels of audio. The two basic channels, L and R, are intended for use via conventional stereo media, conveyed via the respective left and right transmission channels. An optional third supplementary channel T is used to convey enhanced directional resolution for horizontal sounds, and an optional fourth channel Q additionally conveys elevation information (above or below horizontal) for periphonic (full-sphere) reproduction. The Q channel can alternatively be used to convey the "loudspeaker emphasis" effect.

The encoding equations for UHJ are conveniently described in terms of the signals $\Sigma = L + R$ and $\Delta = L - R$, rather than L and R. The latter may be recovered by the equations $L = \frac{1}{2}(\Sigma + \Delta)$ and $R = \frac{1}{2}(\Sigma - \Delta)$. The symbol $j = \sqrt{-1}$ is used in the following to indicate a broadband relative 90-degree phase advance.

UHJ encodes horizontal sound signals S from a direction θ (measured anticlockwise from due front) via the equations

$$
\begin{aligned}
\Sigma &= (0.9397 + 0.2624 \cos \theta)S \\
\Delta &= (-0.3420j + 0.7211j \cos \theta + 0.9269 \sin \theta)S \\
T &= (-0.1432j + 0.9209j \cos \theta - 1.0000 \sin \theta)S \ .
\end{aligned}
$$

Fig. 12 shows a *PQ* diagram [26] of 2-channel UHJ, that is, a plot for horizontal azimuths θ (at 22½-degree intervals) of $Q = \mathrm{Im}\,[(L - R)/(L + R)]$ against $-P = \mathrm{Re}[(R - L)/(L + R)]$. The diagram indicates the position occupied by a left-channel only sound by L and a right-channel only sound by R.

Let W, X, Y, and Z denote the four signals constituting the B format [4], [2], where W has gain 1 for sounds from all directions, and X, Y, and Z have figure-of-eight (cosine) responses with peak gain $\sqrt{2}$ pointing, respectively, forward, leftward, and upward. For sounds

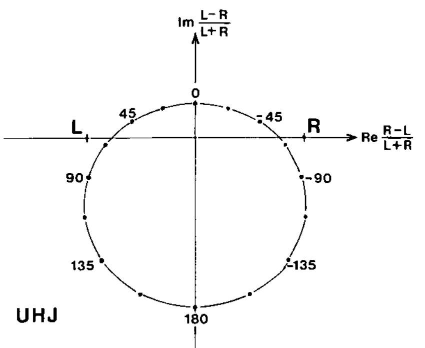

Fig. 12. *PQ* diagram of 2-channel UHJ encoding, showing for each azimuth θ the values of the real and imaginary parts of the ratio $(L - R)/(L + R)$. The points marked L and R correspond to the locations of sounds in, respectively, the left and right channels only.

from an azimuth θ (measured anticlockwise from due front) and at an elevation angle η above horizontal, the respective gains of W, X, Y, and Z are

$$
\begin{aligned}
&W: \ 1 \\
&X: \ \sqrt{2} \cos \theta \cos \eta \\
&Y: \ \sqrt{2} \sin \theta \cos \eta \\
&Z: \ \sqrt{2} \sin \eta \ .
\end{aligned}
$$

Then in terms of the B format, the full-sphere UHJ encoding equations are

$$
\begin{aligned}
\Sigma &= 0.9397W + 0.1856X \\
\Delta &= j(-0.3420W + 0.5099X) + 0.6555Y \\
T &= j(-0.1432W + 0.6512X) - 0.7071Y \\
Q &= 0.9772Z \ .
\end{aligned}
$$

Loudspeaker emphasis encoding for 4 channels encodes a sound S from the horizontal azimuth θ via the above equations for Σ, Δ, and T, and the fourth channel Q is encoded via

$$Q = (aj \sin 2\theta)S$$

where $0 \leq a \leq 1$ is the chosen degree of loudspeaker emphasis.

APPENDIX 2
MULTIPLEX EQUATIONS FOR UHJ FM BROADCASTING

The UHJ signals Σ, Δ, T, and Q are incorporated into the baseband multiplex signal for FM broadcasting via the equation

$$
\begin{aligned}
\Phi = [\Sigma] &+ [\alpha \sin \omega_p t + \Delta \sin 2\omega_p t] \\
&+ [\lambda T \cos 2\omega_p t] + [\beta Q \sin 4\omega_p t]
\end{aligned}
$$

where $\omega_p = 2\pi \times 19\,000\ s^{-1}$, t is time in seconds, $\alpha = 8$–10%, Φ is the signal modulating the FM carrier, 100% deviation is 75 kHz, λ and β are (possibly frequency dependent) positive gains, and the 4 signals Σ, Δ, T, and Q are all subjected to 75-μs preemphasis.

For 2-channel UHJ, the gains are $\lambda = \beta = 0$; for 3-channel UHJ, $\lambda = 1$ and $\beta = 0$; and for 4-channel UHJ, $\lambda = \beta = 1$. For 2½-channel UHJ, $\beta = 0$ and the positive gain λ is frequency dependent, lying between 0.9 and 1.1 between 30 Hz and 1.5 kHz, and between 0.5 and 1.1 between 1.5 and 4 kHz.

The frequency spectrum of the baseband multiplex signals for these options is shown schematically in Fig. 9.

APPENDIX 3
AMBISONIC DECODING EQUATIONS FOR UHJ

A variety of algorithms can be used to decode the various UHJ options, and it is not intended here to attempt a comprehensive account of all possibilities, but simply to examine some typical psychoacoustically optimized Ambisonic decoding algorithms. Future developments may well yield more refined algorithms. Aspects of information presented here and elsewhere in this paper are the subject of patents granted to NRDC.

A3.1 Horizontal Loudspeaker Layouts

All algorithms here derive so-called E-format signals W′, X′, Y′, and B′ by means of a phase-amplitude matrix acting on the UHJ input signals. These are then passed through shelf filters having accurately matched phase responses over the audio band, producing signals $W'' = k_1W'$, $X'' = k_2X'$, and $Y'' = k_2Y' + k'k_3B'$, where k_1, k_2, and k_3 are frequency-dependent positive gains, and where $0 \leq k' \leq 0.7$ is a fixed gain termed the forward preference of the decoder. Rectangular loudspeaker layouts with loudspeakers LB, LF, RF, and RB at the respective azimuths $\phi' = 180° - \phi$, ϕ, $-\phi$, and $-180° + \phi$ (measured anticlockwise from due front) are fed with respective signals

$$P_{\phi'} = \frac{1}{2}\left(W'' + \frac{1}{\sqrt{2}\cos\phi'}X'' + \frac{1}{\sqrt{2}\sin\phi'}Y''\right).$$

A regular polygonal n-loudspeaker layout feeds the loudspeaker at azimuth θ with

$$P_\phi = \frac{1}{\sqrt{n}}(W'' + \sqrt{2}\cos\phi\, X'' + \sqrt{2}\sin\phi\, Y'') .$$

A3.1.1 General horizontal UHJ decoding equations

$$\begin{aligned}
W' &= 0.982\Sigma + 0.197j(0.828\Delta + 0.768tT)\\
X' &= 0.419\Sigma - j(0.828\Delta + 0.768tT)\\
Y' &= 0.187j\Sigma + (0.796\Delta - 0.676tT)\\
B' &= -0.694j\Sigma + 0.140(0.828\Delta + 0.768tT)
\end{aligned}$$

where $0 \leq t \leq 1$ is the gain of the third channel T.

A3.1.2 Simplified UHJ decoding equations using three phase shifters

$$\begin{aligned}
W' &= 0.982\Sigma + 0.197j(0.828\Delta + 0.768tT)\\
X' &= 0.419\Sigma - j(0.828\Delta + 0.768tT)\\
Y' &= (0.827\Delta - 0.648tT)\\
B' &= 0
\end{aligned}$$

where $0 \leq t \leq 1$. When $t = 0$ (that is, for 2-channel UHJ), suitable shelf filter gains are as follows:

	Low frequencies	High frequencies
k_1	0.661	1.000
k_2	1.293	1.000

Fig. 13 shows the block diagram of a 2-channel UHJ decoder using these equations. A commercial implementation uses as few as 12 operational amplifiers to implement the whole decoder.

A3.1.3 2-channel UHJ decoding equations

$$\begin{aligned}
W' &= 0.982\Sigma + 0.164j\Delta\\
X' &= 0.419\Sigma - 0.828j\Delta\\
Y' &= 0.385j\Sigma + 0.763\Delta\\
B' &= -0.694j\Sigma + 0.116\Delta
\end{aligned}$$

where k_1, k_2, and k_3 are given by

	Low frequencies	High frequencies
k_1	0.646	1.000
k_2	1.263	1.000
k_3	0.775	1.000

This decoder has a substantially flat frequency response for all sound directions for all values of the forward preference k' between 0 and 0.7. The block diagram of a commercial implementation is shown in Fig. 14.

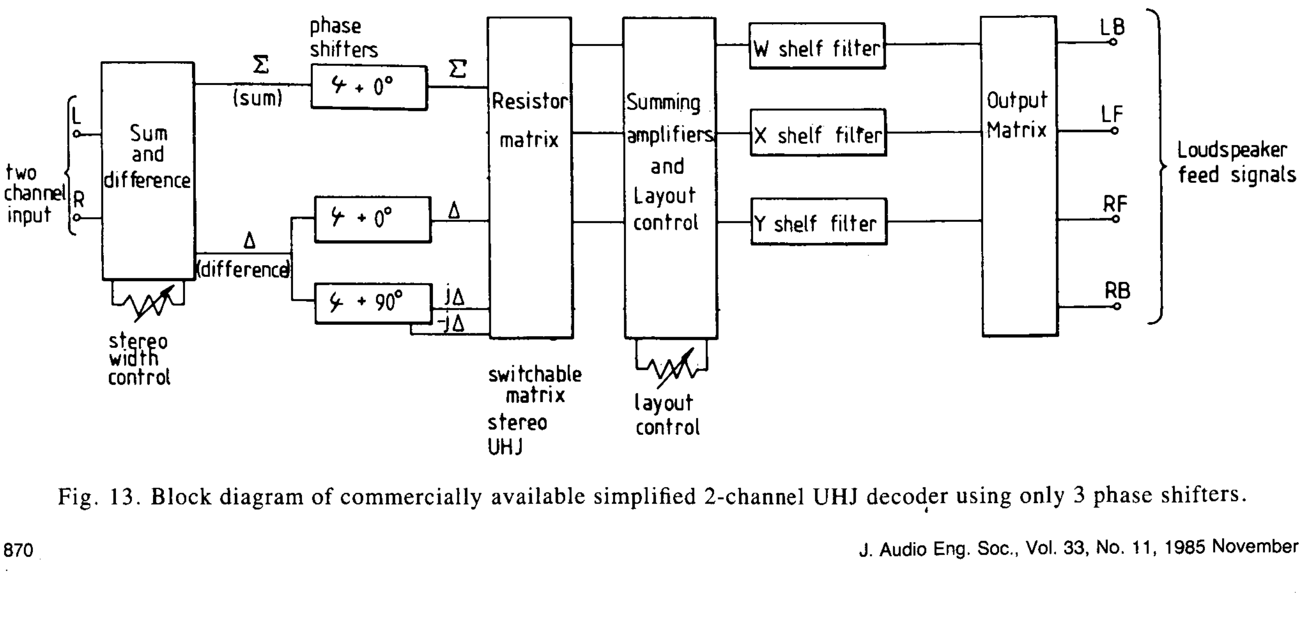

Fig. 13. Block diagram of commercially available simplified 2-channel UHJ decoder using only 3 phase shifters.

A3.2 Periphonic Decoding

Fig. 15 shows the block diagram of a typical periphonic UHJ decoder suitable for a variety of loudspeaker layouts, such as those illustrated in Fig. 6. The phase-amplitude matrix satisfies the equations

$$\begin{aligned} W &= 0.982\Sigma + 0.197j(0.828\Delta + 0.768T) \\ X &= 0.419\Sigma - j(0.828\Delta + 0.768T) \\ Y &= 0.187j\Sigma + (0.796\Delta - 0.676T) \\ Z &= 1.023Q . \end{aligned}$$

This matrix can be implemented using five phase shift networks, but a simplified decoder using only four phase shift network can be realized by replacing Y above with the signal

$$Y_2 = 0.827\Delta - 0.648T .$$

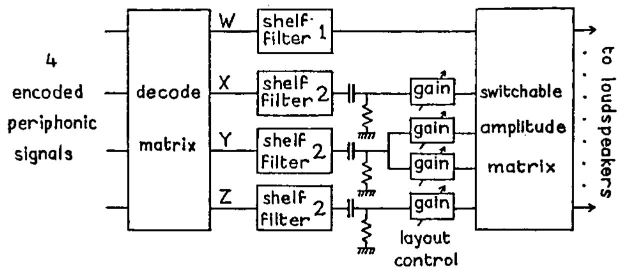

Fig. 15. Block diagram of periphonic decoder using equations of Appendix 3, suitable for use with loudspeaker layouts of Fig. 6.

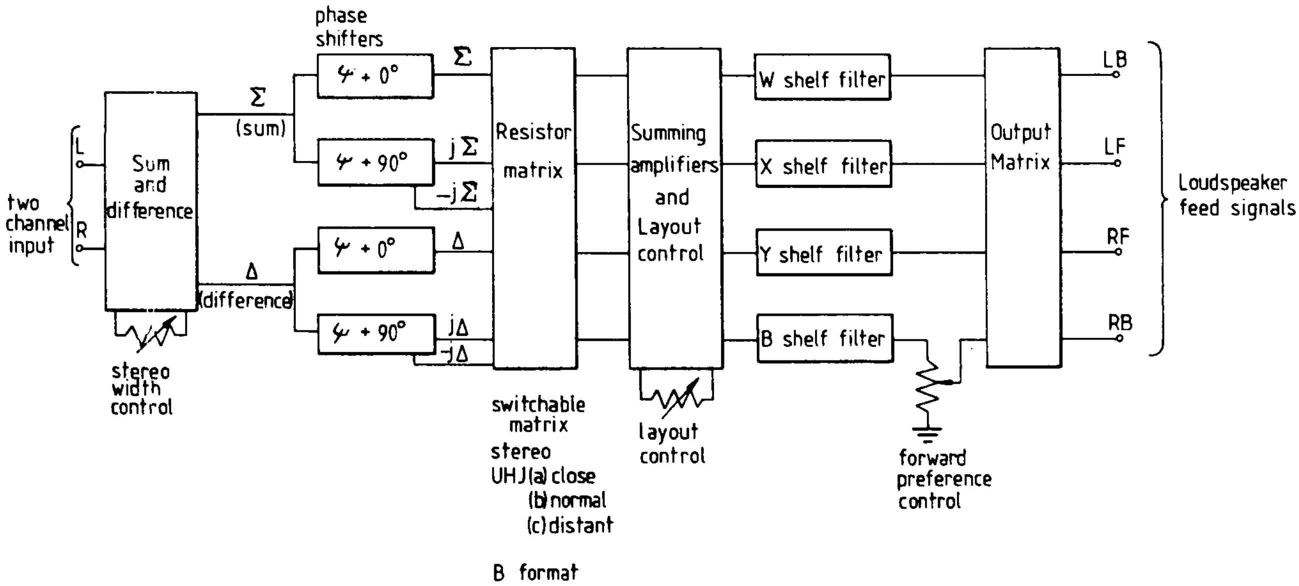

Fig. 14. Block diagram of commercially available 2-channel UHJ decoder using the 2-channel decoding equations of Appendix 3.

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Michael A. Gerzon received an M.A. degree in mathematics at Oxford University in 1967. Since completing postgraduate research in axiomatic quantum theory at Oxford University, he has been involved in research into the properties of linear and nonlinear multichannel systems, including analytic system theory.

One aspect of this work has been a study of surround sound recording and reproduction systems. This includes the abstract mathematical theory of these systems, the study of mathematical models for nondirectional and directional psychoacoustics, and the design of microphone arrays, studio processing equipment and decoders based on these studies. Since the start of 1974, much of this work has been carried out in connection with the British N.R.D.C. (National Research Development Corporation) and its Ambisonic systems of surround sound.

Mr. Gerzon has published over 15 papers and articles on the theory and practice of surround sound systems, as well as papers on a number of other audio topics. He is a member of the Audio Engineering Society.