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Cooper

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[54] **MULTIDIRECTIONAL SOUND REPRODUCTION**

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[51] **Int. Cl.**... **H04r 5/00**
[58] **Field of Search** ....179/1G, 179/1 GQ, 15 BT, 100.4 ST, 179/100.41 K, 100.1 TD

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Analysing Phase Amplitude Matrices by Scheiber, Audio Engineering Society Preprint, Oct. 5–8, 1971.

[57] **ABSTRACT**

Multidirectional audio sound signals are encoded in transmission signals employing phasor matrixing coefficients varying in amplitude and phase as a continuous function of the bearing angle or direction of each signal source. The transmission signals are decoded to provide presentation signals for loudspeaker placement patterns which may be selected by the listener. Exemplary matrixing or encoding apparatus and rematrixing or decoding apparatus are described.
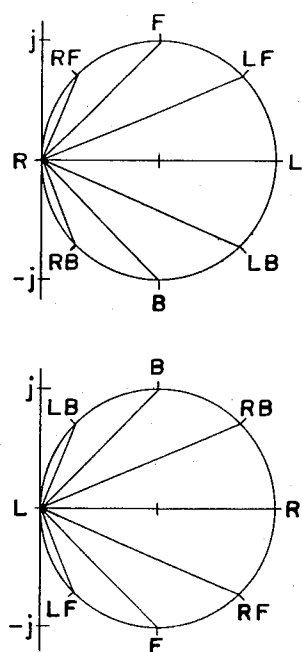
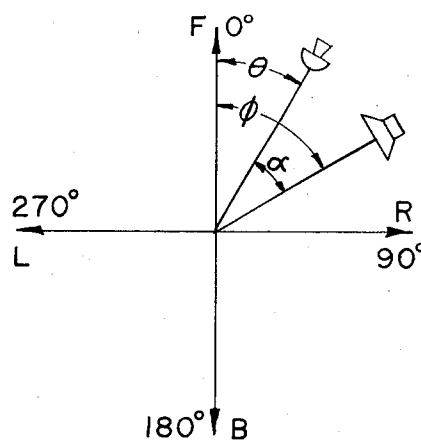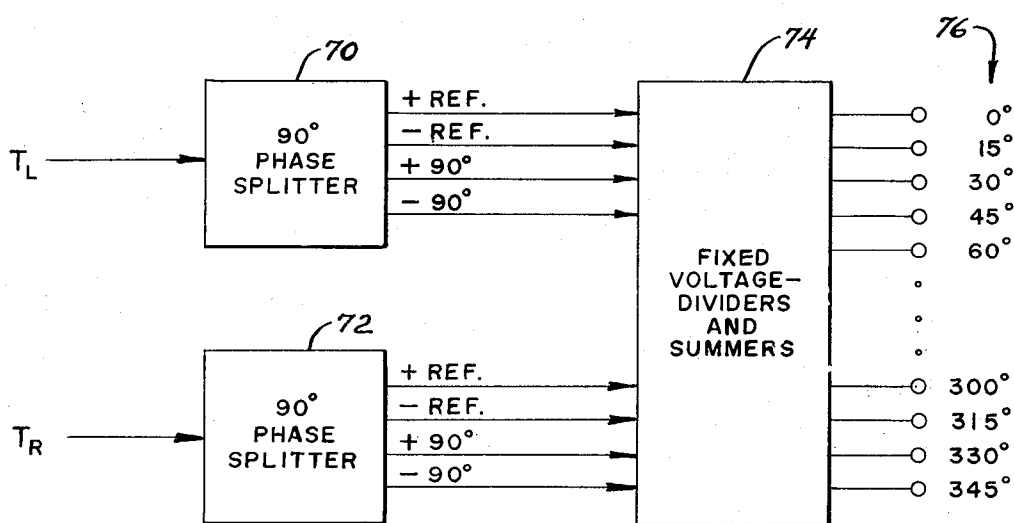**17 Claims, 10 Drawing Figures**

Fig. 1

Fig. 2

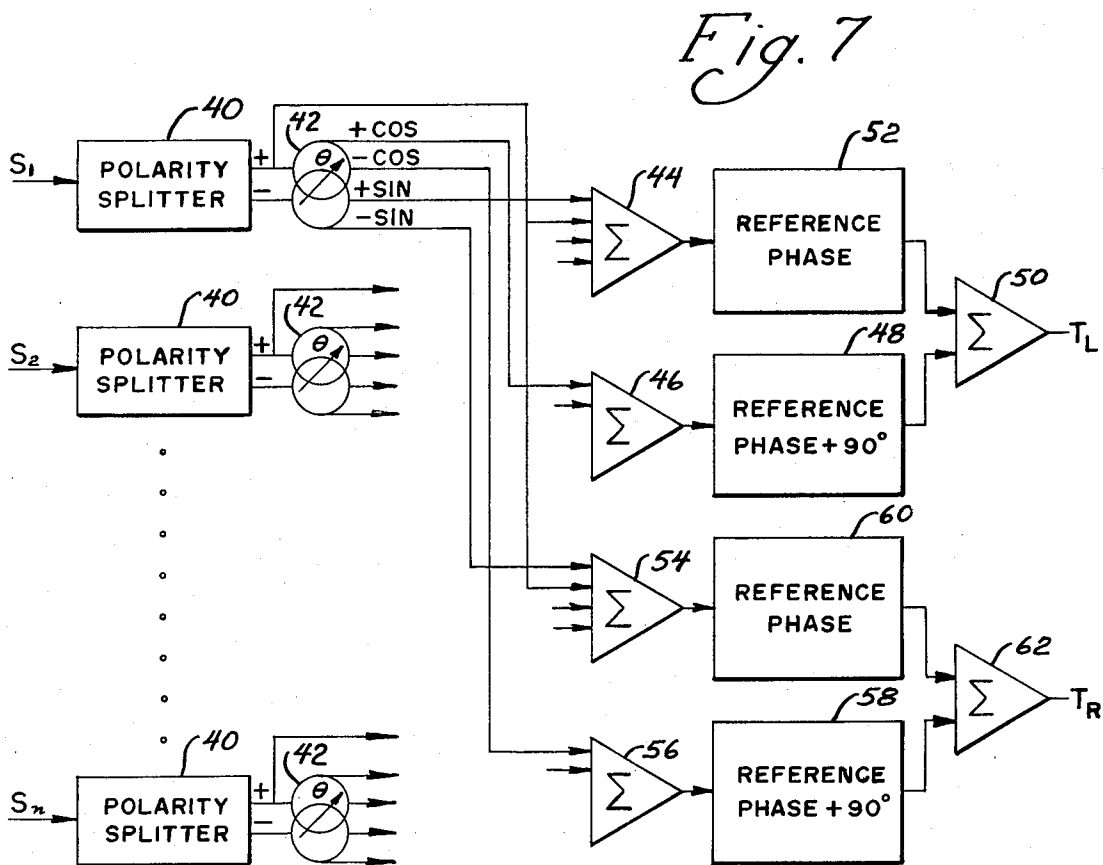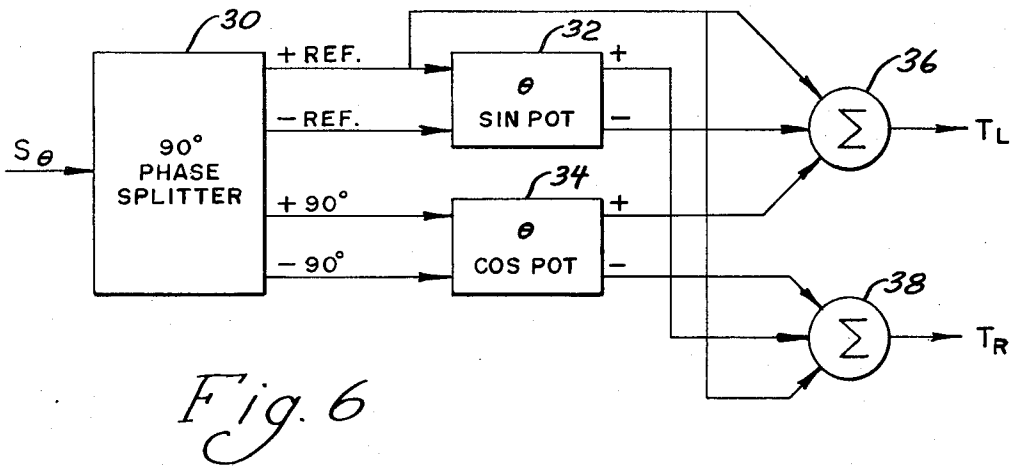*Fig. 3*
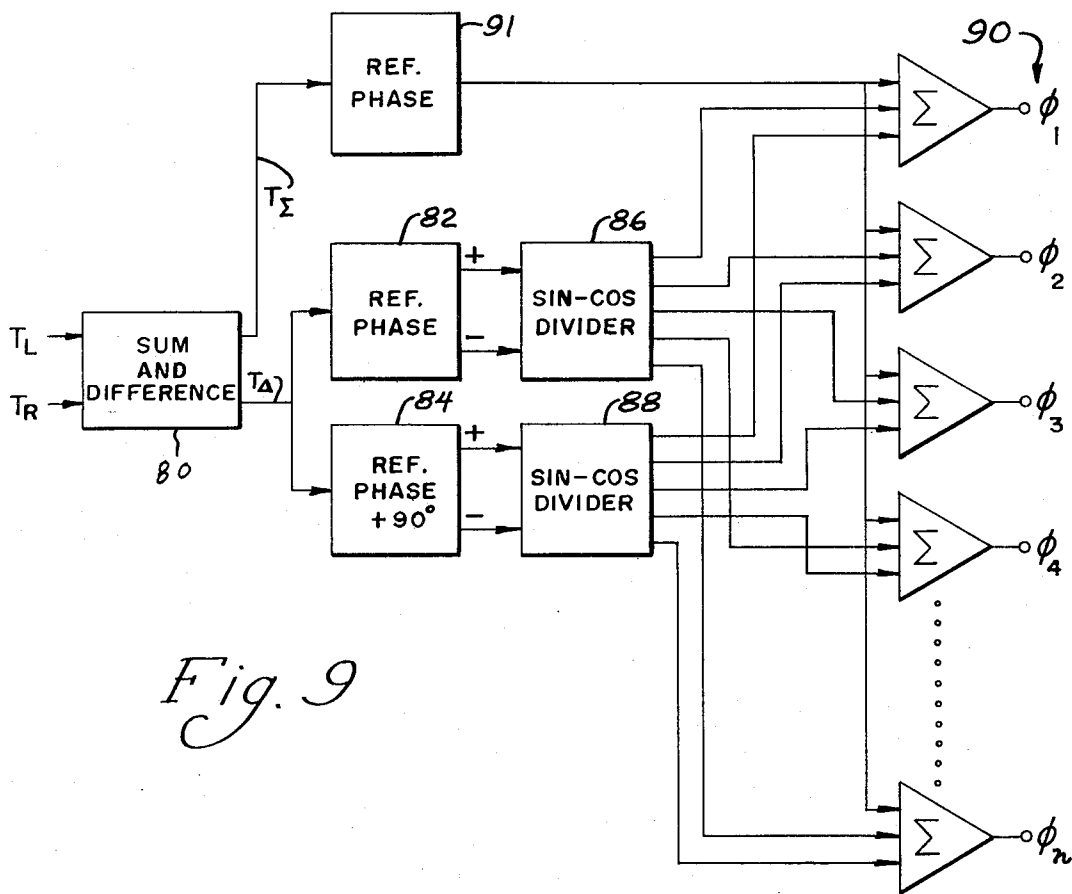
Fig. 5
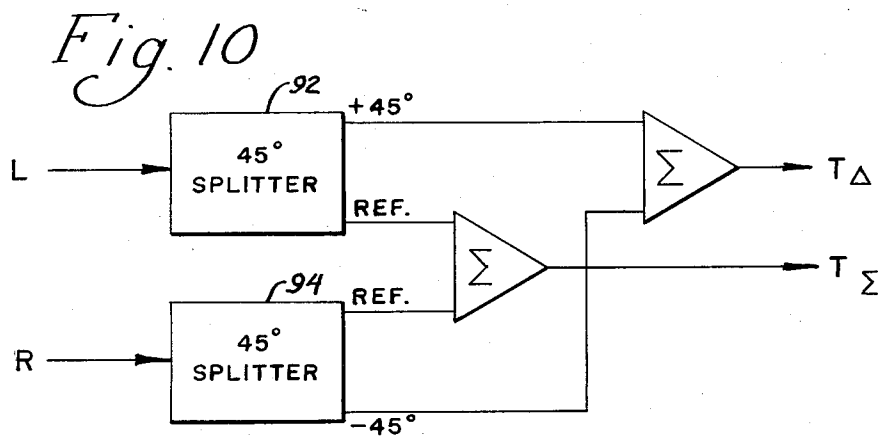

Fig. 4

Fig. 8

Fig. 6

Fig. 7

Fig. 9

Fig. 10

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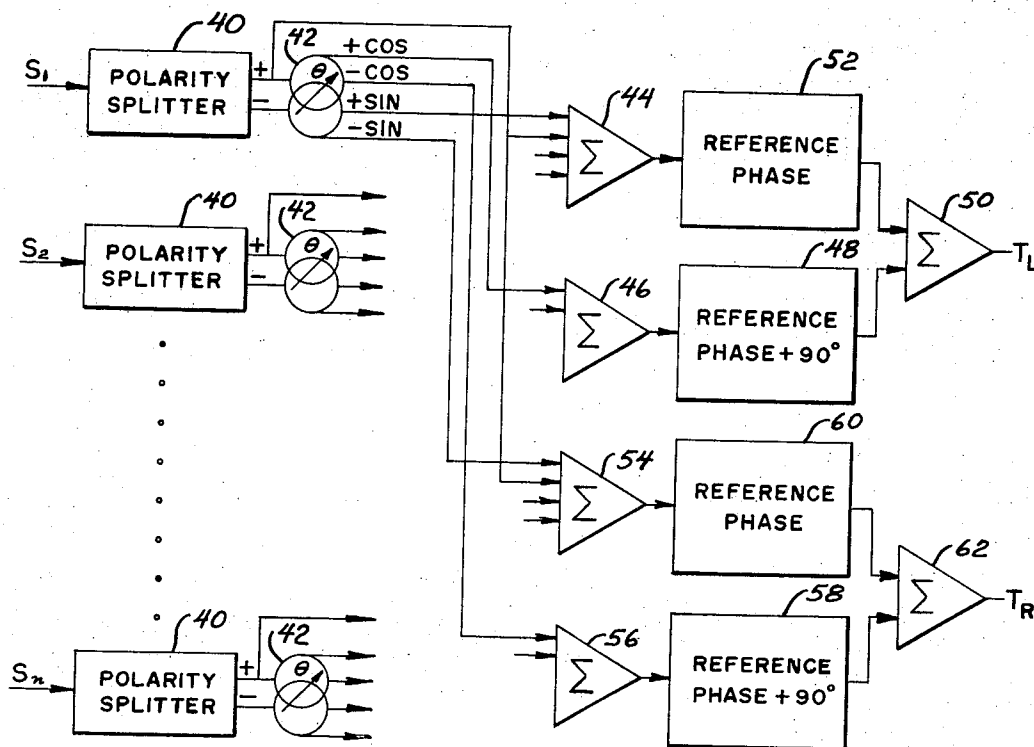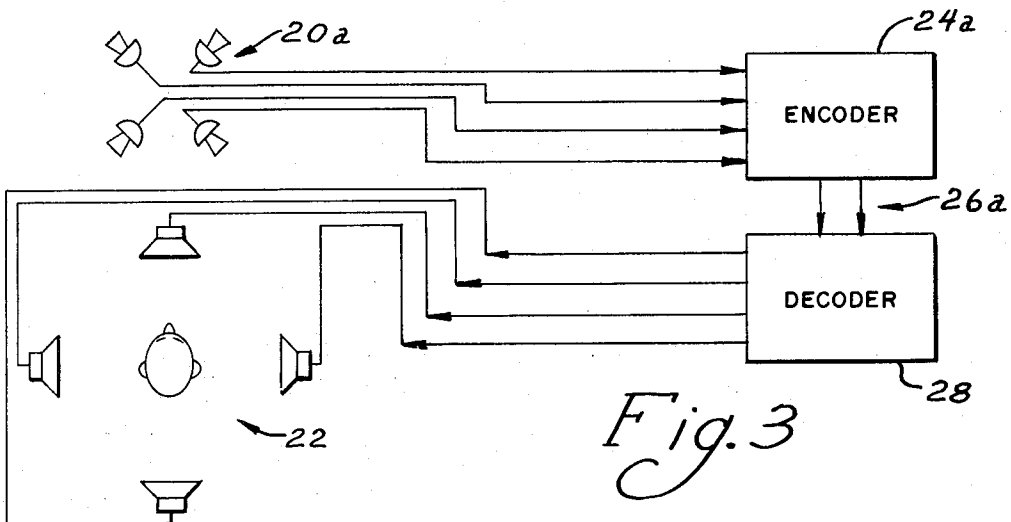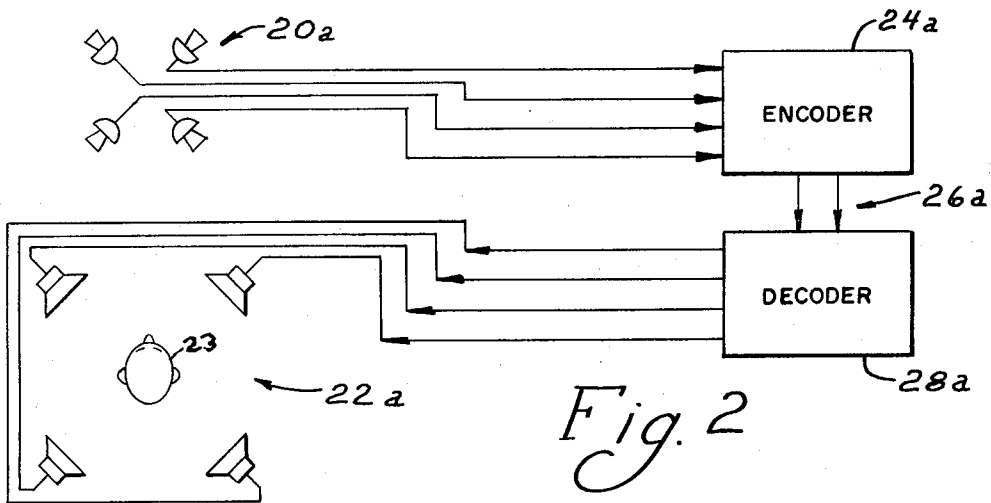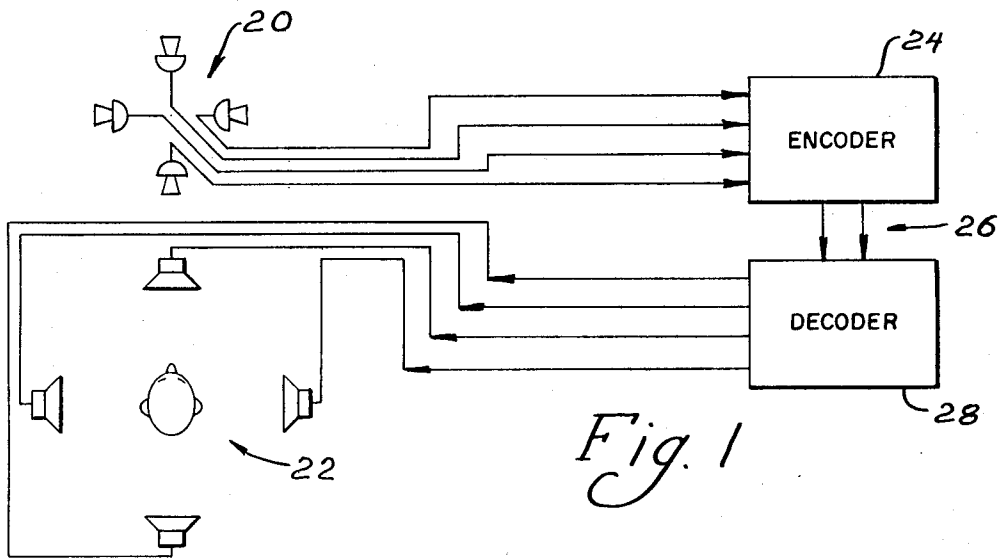
MULTIDIRECTIONAL SOUND REPRODUCTION

This invention relates to reproduction of multidirectional audio program material with greater directionality and ambience than those of conventional stereo reproduction, and to the recording and/or transmission of program material for such reproduction. More particularly, the invention relates to the coding or mixing of directional sound information into a number of recording or transmission channels smaller (at least normally) than the number of sound sources to be reproduced and decoding or signal treatment and distribution of the content of these channels to reproducers differing in number or location from the sound-source locations for reproduction simulating presence at the original performance in psychoacoustic impression.

Although the invention in its broader aspects is not limited to any specific number of sound sources (typified by microphones) or reproducers (typically loudspeakers), it will most readily be understood by initial reference to the type of reproduction which has become popularly known as "quadrasonic" or "quad," an extension of two-speaker stereo techniques to the reproduction of multidirectional program material with four loudspeakers to increase the sensory illusion of presence or ambience. The term "quadrasonic" originated to describe systems wherein exciting or presentation signals for individual reproducers are maintained in separate and discrete form as separate signal channels, as in four-speaker reproduction from four-track tape. However the term is now commonly used, and is used herein, to include what have sometimes been called "pseudo" four-channel systems, wherein four (or more) original directional sound-source channels are mixed or combined by encoding into two signal channels, and thereafter decoded to produce four presentation signals for feeding the speakers. It is impossible, in such a manner, to produce exact or pure correspondence between the excitation of each loudspeaker and the output of a correspondingly located microphone. But it has been known for some time that results which are psychoacoustically reasonably simulative of transmission through four discrete channels can be obtained by such "4 to 2 to 4" signal processing or matrixing. (There also exist systems wherein no directional information whatever is added to conventional stereo signals, the latter being processes, with preselected delay, etc., to feed one or more back speakers in addition to the conventional front speakers, thus producing wholly synthetic psychoacoustic impressions of added directional effects, but the present invention is not directly concerned with these.)

A present requirement for widespread adoption of any quadrasonic system is that of compatibility with continued use of existing reproducing equipment, monaural and stereo. Stated otherwise, it is generally recognized that recordings made for quadrasonic reproduction are desirably capable of satisfactory reproduction by monaural record-players and conventional stereo record-players, and quadrasonic FM transmissions (whether live or from recordings) must similarly be reproduced as monaural or stereo material by existing receivers.

A number of encoding and decoding systems compatible with mono and stereo equipment have been proposed, and some have been the subject of experimentation and preliminary forms of commercialization.

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A recent publication on the subject is the paper of Peter Scheiber in *Journal of the Audio Engineering Socity*, Volume 19, page 267 (April, 1971) describing such a system. A number of other systems have been devised by or for various producers of phonograph records, signal-processing equipment, etc. All of these are found on analysis to have various drawbacks or objections. The relative importance of the weaknesses or inadequacies of each of such known systems is differently estimated by their proponents, but none of the 4–2–4 systems heretofore proposed has been sufficiently close to the performance of discrete four-channel reproduction to result in adoption as a standard system of encoding and decoding for use in stereo disc recordings and stereo FM broadcasting equipment.

The present invention flows from study of the weaknesses or inadequacies of the systems heretofore proposed, and lies in the devising of novel methods and apparatus of encoding and decoding multiple-source and multiple-reproducer signals which not only involve a minimum of sacrifice of the performance obtained with the respective reproducer signals maintained in separate channels throughout, but additionally provide much greater flexibility than previous systems afford.

Full details of the fairly numerous two-channel matrixing systems recently proposed or introduced by the record and equipment manufacturers mentioned above do not appear to be publicly available, but the general nature of their imperfections in performance are observable. In any such system, including the present system, a sound which emanates from a single point (notably a point located to activate only a single microphone) is ultimately reproduced not from a single loudspeaker, but from a plurality of differently located loudspeakers, excited from the same original source but with an excitation amplitude relation such that from a psychoacoustic standpoint reproduction from a single direction is satisfactorily simulated. However, in the systems heretofore devised, the satisfactoriness of this illusion of directionality is not uniform for all directions. The nature of the anomalies or directional ambiguities in signals intended to appear to the listener to come from particular directions in the prior art systems is not wholly identical in each case, nor are the sound directions from which the prior art matrixing systems produce such anomalous results the same. Typical examples, however, are opposite-phase reproduction from rear speakers and similar anomalies which result in more faithful reproduction of front-oriented sounds than rear-oriented sounds. In some cases, the anomalies are more or less negligible in psychoacoustic impression with most program materials, but become highly noticeable with materials with "sound effects" specifically designed for quadrasonic reproduction, wherein rear sounds are not merely supplementary.

It is the principal object of the present invention to provide an encoding and decoding system for quadrasonic or similar reproducing systems which avoids such flaws or imperfections of previous systems, and thus more closely approaches the psychoacoustic simulation of systems employing completely separate and discrete signal channels for the excitation of each reproducer. In addition to achieving this principal object, however, the invention provides methods and apparatus whereby it is unnecessary to maintain, for satisfactory performance, a single predetermined set of positions of the

loudspeakers with respect to the listener to produce satisfactory reproduction. The systems of the prior art (including transmission in four discrete channels) require a single specific orientation of the loudspeakers with respect to the listener. In most cases, a pair of back speakers is added to the front speakers of a conventional stereo system to form a "2 plus 2" array. In at least one case, however, the speakers are to be arranged in the form of a diamond or "1–2–1," i.e., at opposite sides of the listener and at the center front and back. With all these prior art systems, the required speaker orientation is specified in connection with the directions represented by the four discrete transmission channels or with the coding used in the two-channel transmission or recording, and no manner is provided, so far as is known, for using different speaker orientations, or a different number of speakers, while retaining satisfactory reproduction.

Unlike the encoding and decoding systems of the prior art, the encoding and decoding of the present invention is capable of producing the same reproduction characteristics for all directions, and may be described as "directionally symmetrical." The meaning of this term as herein used may be most easily understood by considering the simple example of the reproduction of a sound whose source is successively moved to actuate each of four orthogonally located microphones in succession. In a system with directional symmetry, a listener who turns through corresponding successive 90° angles hears the sound source in wholly identical fashion as it is correspondingly moved through the four positions. This property is inherent in a quadrasonic system with a separate signal channel for transmission of each microphone output but is not obtainable with prior art "4–2–4" matrix systems. As indicated above, this is particularly important in permitting use of new types of program material wherein there is to be conveyed a realistic impression of an independent sound source (a voice or chorus for example) at a localized location rearward of the listener.

In addition to eliminating this limitation on utility, the directional symmetry of the matrixing, as a further aspect of the invention, permits simple signal-conversion whereby the geometry of a loudspeaker system may be "rotated" with respect to the loudspeaker geometry assumed in the signal-production to permit wholly satisfactory reproduction of (for example) a recording or FM transmission designed for "2-plus-2" speaker orientation by a reproducing system with speakers arranged in the "1–2–1" form of a diamond, or vice versa. Indeed, the invention provides methods and apparatus whereby the number and arrangement of speakers to be used in reproduction is essentially unidentified in the signal transmission, which is "universal" and may be decoded into presentation signals for feeding any desired number and orientation of speakers. The two encoded transmission channels may be decoded to produce, for example, six speaker-feed signals, with the speakers disposed in the form of a hexagon, the resultant listener sensation approximating that obtained with discrete six-channel transmission. As will later appear, the principles of the invention may also be employed to provide analogous flexibility in reproduction of signals transmitted in more than two channels.

The invention accordingly provides decoders producing readily selectable presentation signals for the

number and pattern of the array of loudspeakers preferred by the listener, as well as equipment whereby encoding of multi-directional sound into a plurality of channels, and selection of directional effects, may be simply performed by a recording studio or record manufacturer or broadcaster without limitation to expected use by only those listeners having a specific loudspeaker arrangement.

The universal or rotatable aspect of the relation between encoding and decoding of the transmission signals of the invention is obtained by the employment of mixing coefficients which alter both the phase and amplitude of each source signal, in encoding, and of each transmission signal, in decoding, in a manner producing an overall reproduction matrix wherein the phase and amplitude of appearance of any source-signal in any presentation signal is entirely a function of the angular relation between the azimuthal location of the source and the azimuthal location of the speaker for which the presentation signal is formed, i.e., of the difference in bearing angles of the source and the reproducing loudspeaker.

The invention will be best understood by referring to the explanatory illustrations and embodiments of the invention in the attached drawing, in which:

FIG. 1 is a schematic illustration of one type of quadrasonic sound reproduction system;

FIG. 2 is a similar illustration of a variant type of quadrasonic sound reproduction system;

FIG. 3 is a similar illustration, but differing from the previous Figures in the employment of non-corresponding source-signal and reproduction locations;

FIG. 4 is a schematic view illustrating certain angular relations employed in the invention;

FIG. 5 shows phasor diagrams of transmission signals formed in accordance with the invention;

FIG. 6 is a block diagram of an exemplary single-signal encoder embodying the invention;

FIG. 7 is a block diagram of a "universal" encoder for numerous sound signals embodying the invention;

FIG. 8 is a block diagram of one form of decoder incorporating the invention;

FIG. 9 is a block diagram of another form of decoder of the invention; and

FIG. 10 is a block diagram of an adapter circuit for employing the decoder of FIG. 9 with conventional stereo signals.

In FIGS. 1 through 3 there are shown basic forms of quadrasonic sound systems which may advantageously employ the invention. FIGS. 1 and 2 show systems which are, except for the matrices for encoding and decoding transmission signals, the same as certain systems of the prior art. These exemplary systems are illustrated and described to facilitate understanding of the advantages and broad utility of the encoding and decoding (alternatively called matrixing and re-matrixing) of the present invention to be later described.

The systems of FIGS. 1 and 2 are alternate forms of quadrasonic systems heretofore employed with various matrixing systems. In each case, there is shown an array or pattern of orthogonal microphones 20 or 20a at a program location with a corresponding orthogonal array or pattern of loudspeakers 22 or 22a in the listening space surrounding a listener 23. In the system of FIG. 2, the microphones 20a are arranged to receive

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sounds from, and the speakers 22a are arranged to reproduce sounds from, locations at the left front (LF), right front (RF), right back (RB), and left back (LB) portions of the program and listening spaces, respectively, while in FIG. 1 the locations 20 and 22 are at front (F), right (R), back (B) and left (L).

Encoders or matrixers 24 and 24a produce two transmission signals at 26 or 26a which are then decoded or rematrixed at 28 or 28a to produce presentation signals for driving the speakers at the corresponding locations.

Although the representations of speaker locations at LR, LF, LB and RB in FIG. 2 and at L, F, R and B in FIG. 1 are more or less truly representative of locations actually used in practice in what are called "2-plus-2" and "1-2-1" quadrasonic orientations, the corresponding showings of the microphones will be recognized by those skilled in the art as considerably simplified showings of actual microphone placements normally used for quadrasonic reproduction, particularly in making recordings. Although simple systems such as illustrated, i.e., four directional (cardioid-pattern) microphones, can be and are sometimes used, for example at a normal listener location in a concert hall, it is more common to employ more complex microphone arrangements and to blend the outputs of various microphones for effects judged most pleasing; indeed, as in the case of ordinary stereo recording-studio and broadcast-studio techniques, the multidirectional signals may be synthesized or assembled from a much larger number of sound tracks of individual instruments or groups of instruments. It will accordingly be understood, both in connection with the drawing and in connection with further discussion herein, that an audio signal representative of the sound from a particular direction may be wholly synthetic as regards directional information. As later seen, the present invention additionally provides simple means for such synthesis.

As will also be understood by those skilled in the art, the illustrations of FIGS. 1 and 2 represent signal-formation and processing operations which may be carried out in a manner producing instantaneous reproduction of live program material but more normally involve some form of storage, i.e., recording, of the signals at one or more points in the sequence. Typically, the two transmission signals are the "left" and "right" groove-walls of an ordinary disc recording or the corresponding audio channels of a stereo broadcast; it is of course the two-channel limits presently imposed by these media which creates the greatest necessity for encoding and decoding, rather than direct transmission in discrete channels.

The matrixing or coding of the present invention is advantageously employed in even a simple fixed-position system such as that of FIG. 1 or FIG 2 because of the directional symmetry which the invention affords. However, a further advantage of the present matrixing method and apparatus is its breadth of utility. The present matrixing is not only readily adapted to use in the systems of both FIGS. 1 and 2, but permits decoding for highly satisfactory use of loudspeaker geometries or orientations which are not in any way "matched" to the source-signal geometry or orientation. One example of such an overall system is shown in FIG. 3, where outputs of the microphone system (or synthesized directional signals representative of sound sources) 20a and encoder 24a of FIG. 2 are reproduced by the decoder 28 and loudspeakers 22 of FIG. 2. As will be seen below, the present matrixing or coding and decoding system not only gives excellent reproduction from all angles with such "rotated" geometries but per-

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mits employment of even more diverse source-signal and reproduction geometries, such as the employment of any number of loudspeakers desired by the listener.

FIG. 4 illustrates, for identification, certain angular relations employed in the matrixing and re-matrixing or coding and decoding of the invention. In the present invention, the magnitude and phase with which each source signal appears in each presentation signal is determined wholly and solely by the angular relation between the direction or location represented by the source signal and the direction or location of the loudspeaker to which the presentation signal is to be fed. Where the overall reproduction matrix (the product of the encoding and decoding matrices) is such that the magnitude and phase of each source signal (relative to its original magnitude and phase) in each presentation signal is everywhere a function of only this angular relation, complete directional symmetry is achieved in any system like that of FIGS. 1 to 3. The angle between any given sound source (actual or synthesized microphone placement) and loudspeaker location may be designated as α, shown in FIG. 4. It will be seen that all values of α are the same in FIG. 1 and FIG. 2, and identical overall matrices for both of these geometries are accordingly produced by the invention, as later seen. However, the encoding matrices at 24 and 24a in the respective Figures are not numerically the same but are desirably selected in a manner preserving stereo compatibility, i.e., capability of stereo reproduction on equipment having no decoder. This is done, as hereinafter amplified, by determining the encoding matrix coefficients at 24 or 24a in accordance with an angle θ defining the bearing angle of each source with respect to a laterally neutral (front or back) direction and determining the matrix coefficients of the decoder 28 or 28a in accordance with the bearing angle ϕ of each loudspeaker with respect to a laterally neutral position in forming the presentation angle ϕ of each loudspeaker with respect to a laterally neutral position in forming the presentation signals. As shown in FIG. 4, and as adopted in the further description of the invention, the laterally neutral reference position is considered the front position and angles are measured clockwise; but reference herein to "left," "right," and similar terminology will be understood to be used for convenience of expression rather than specific limitation, the effects of reversals, etc., being obvious.

As will be obvious, no matrixing and re-matrixing can produce an overall matrix which is "perfect" in the same sense as perfection can be obtained where there is no necessity of compressing the number of signal channels for transmission. However the requirements of a perfect overall matrix are mor closely met than heretofore known by employing matrices of the present invention.

A "universal" encoding matrix for forming two transmission signals T_L and T_R from any number, n, of sources is:

$$T_L = \sum_{k=1}^{n} S_k(1 + e^{j(\theta_k + \pi/2)}) = \sum_{k=1}^{n} S_k(1 - \sin \theta_k + j \cos \theta_k)$$

(1)

$$T_R = \sum_{k=1}^{n} S_k(1 - e^{j(\theta_k + \pi/2)}) = \sum_{k=1}^{n} S_k(1 + \sin \theta_k - j \cos \theta_k)$$

where S_k is the k-th source signal, θ_k is the bearing angle between the sound location thereby represented

and a laterally central reference location and j is the square root of -1.

It will of course be understood that the equality symbol hereinafter refers to proportionality, uniform changes in absolute magnitude in signal-processing being irrelevant.

The phasor coefficients of the respective transmission signals T_L and T_R are shown in FIG. 5 for the particular source positions previously discussed. Signals from (i.e., to appear to be "from" upon reproduction) the left, L, are reproduced in the full amplitude and original phase in the T_L signal, but are zero in the T_R signal, and vice versa. The signals from other bearing angles appear in both transmission signals but always in quadrature phase relation, one leading and one lagging the reference phase, which is preserved in the L and R signals. The magnitude of each component is diminished with increase of its relative phase angle (positive or negative), reaching zero at each 90° phase angle (180° difference in source location). The mixing equations below, calculated from the "universal" matrix above, may be employed for utilizing the invention with fixed four-microphone placements, with or without the addition of other signals such as the "on-mic" touch-up signals frequently added for solosits and other special effects. For the 1–2–1 source orientation, numerical values of the mixing equations are:

$$T_L = S_L + 0.707\ S_F\ \underline{/+45°} + 0.707\ S_B\ \underline{/-45°}$$
$$T_R = S_R + 0.707\ S_F\ \underline{/-45°} + 0.707\ S_B\ \underline{/+45°}$$

For the 2-plus-2 source orientation, numerical values of the mixing equations are:

$$T_L = 0.924\ S_{LF}\ \underline{/+22½°} + 0.383\ S_{RF}\ \underline{/+67½°} + 0.383$$
$$S_{RB}\ \underline{/-67½°} + 0.924\ S_{LB}\ \underline{/-22½°}$$
$$T_R = 0.383\ S_{LF}\ \underline{/-67½°} + 0.924\ S_{RF}\ \underline{/-22½°} + 0.924$$
$$S_{RB}\ \underline{/+22½°} + 0.383\ S_{LB}\ \underline{/+67½°}$$

Fixed circuits for producing the desired mixing for one or both these fixed microphone placements may be constructed if so desired, with or without employment of microphone directional patterns. Additional insertion of signal material may then be made to simulate performance at any location by employment of additional mixers such as shown in the schematic diagram of FIG. 6.

As shown in FIG. 6, the input signal S is fed to a 90° phase splitter 30 which produces a positive and a negative reference-phase signal and a positive and a negative 90° phase-shifted signal. The reference signals and the phase-shifted signals are attenuated (and reversed in polarity where appropriate) in sine and cosine potentiometers 32 and 34 set to the bearing angle at which the signal S is to be simulatively inserted. The positive reference signal and the potentiometer outputs are mixed in summers 36 and 38, the outputs of which are then inserted as components of the signals T_L and T_R, respectively, in accordance with the basic encoding equations earlier stated.

In principle, a mixer such as shown in FIG. 6 may be employed for each sound-source direction. However where a substantial number of microphones or soundtracks are desired to be recorded or broadcast in readily selectable angular positions, the number of phase shifters required may be greatly reduced by employing a construction such as shown in FIG. 7. As there shown, each of the signals S_1, S_2, etc. is fed to a polarity splitter (phase inverter) 40. The positive or in-phase and negative or opposite-phase signal are fed to a sine-cosine potentiometer producing positive and negative signals of amplitude and polarity determined by the angle of potentiometer setting. The unattenuated positive signals and the negative sine signals (which are of course in positive phase for angles having negative sine values) from all sources are mixed in a summer 44. The positive cosine-amplitude signals (negative in phase for angles having negative cosine values) are mixed in a summer 46. The output of the latter is advanced in phase by 90° at 48 with respect to the output of the summer 44 and the two are mixed or summed at 50 to form the signal T_L. (As will be recognized by those skilled in the art, the output of the summer 44 must be fed to the summer 50 through a reference-phase portion 52 of the phase shifter 48, the phase-shift of presently available frequency-independent phase-shifters being the difference in phase between the phase-shifted output and the output of a reference-phase channel such as shown at 52, rather than the phase difference between output and input.)

In similar fashion, the positive input signals and the positive sine-function signals from all sources are mixed in a summer 54 and the negative cosine function signals in a summer 56. The latter summed output is advanced in phase by 90° at 58 relative to the reference phase 60 of the output of summer 54, and these are likewise summed at 62 to form the transmission signal T_R.

Persons skilled in the art will immediately recognize that the functions performed by certain of the elements shown in FIG. 7 as circuit elements may be carried out by employment of other techniques which are well-known as equivalents for performing such functions in recording and broadcast practice. For example, microphone sensitivity patterns of well-known types may readily be employed in substitution for the indicated attenuation potentiometer networks of some or all of the signals S_1, S_2, etc., in the signal-mixing system of FIG. 7. Orthogonally positioned dipole microphones may be employed to produce directly the signals attenuated in accordance with the sine and cosine of the azimuthal angle of the incident sound sources, with a closely adjacent single omnidirectional microphone employed to produce the unity or unattenuated components.

As earlier indicated, the transmission signals T_L and T_R may either be recorded on any conventional medium, notably a stereo disc or tape recording, or used for instantaneous reproduction, as in quadrasonic FM broadcasting employing the two audio channels provided for ordinary stereo.

The manner of decoding of the signals of FIG. 5 may now be considered. The decoding closely resembles the encoding, except that the coefficients applied to the transmission signals in the forming of each presentation signal are functions of the angle ϕ, the listening-space

bearing-angle of the loudspeaker for which each presentation signal is formed. Each presentation signal P_i is formed from the transmission signals by mixing in the amplitude and phase relation

$$P_i = T_L [1 + e^{-j(\phi_i + \pi/2)}] + T_R [1 - e^{-j(\phi_i + \pi/2)}]$$

$$= T_L (1 - \sin \phi_i - j(\cos \phi_i) + T_R (1 + \sin \phi_i + j \cos \phi_i) \quad (2)$$

where ϕ_i is the bearing angle between the presentation location and a laterally central reference location and j is the square root of -1. Thus each presenation signal is formed by multiplying each transmission signal by the complex conjugate of the multiplier or coefficient used (or which would have been used) in inserting signal from that bearing angle in forming the transmission signal, and the resulting respective products are then added. Each resultant presentation signal P_i is thus:

$$P_i = \sum_{k=1}^{n} S_k (1 + e^{-j(\phi_i - \theta_k)}) = \sum_{k=1}^{n} S_K \cos \frac{1}{2} (\phi_i - \theta_k)$$

$$\underline{e^{-j(\phi_i - \theta_k)/2}} \quad (3)$$

The presentation signal P_L for a speaker at the left position is thus the signal T_L as illustrated in FIG. 5, unaltered, and T_R is likewise presented unaltered in forming a presentation signal for a speaker at R (if there is one). Presentation signals for other positions are exactly the same in appearance of phasor diagrams, except that the locations represented are intermediate between the 180° relation shown in FIG. 5 for the L and R signals. Except for a source signal diametrically opposite the presentation point, all source signals appear in every presentation signal, but with a magnitude which varies continuously from maximum to zero as a function of magnitude of the angle between the signal source direction and the presentation direction.

For the 1–2–1 speaker orientation, numerical values of the decoding equation (2) are:

$$P_L = T_L \; \underline{/0°}$$
$$P_F = 0.707 \, T_L \; \underline{/-45°} + 0.707 \, T_R \; \underline{/+45°}$$
$$P_R = T_R \; \underline{/0°}$$
$$P_B = 0.707 \, T_L \; \underline{/+45°} + 0.707 \, T_R \; \underline{/-45°}$$

For the 2-plus-2 speaker orientation, numerical values of the decoding equation (2) are:

$$P_{LF} = 0.924 \, T_L \; \underline{/-22\,\frac{1}{2}°} + 0.383 \, T_R \; \underline{/+67\frac{1}{2}°}$$
$$P_{RF} = 0.383 \, T_L \; \underline{/-67\frac{1}{2}°} + 0.924 \, T_R \; \underline{/+22\frac{1}{2}°}$$
$$P_{RB} = 0.383 \, T_L \; \underline{/+67\frac{1}{2}°} + 0.924 \, T_R \; \underline{/-22\frac{1}{2}°}$$
$$P_{LB} = 0.924 \, T_L \; \underline{/+22\frac{1}{2}°} + 0.383 \, T_R \; \underline{/-67\frac{1}{2}°}$$

It may be noted that the overall transmission or reproduction is not affected by the choice of transmission signals T_L and T_R to correspond to left and right directions, identical results being obtained with any choice of diametrically opposed directions for transmission in original phase and amplitude in the two respective channels. Association of the transmission signals with the left and right directions, however, provides compatibility with ordinary stereo equipment.

Playback equipment permitting selection of an indi-

vidual speaker location at any desired angle whatever may be devised along the same lines as the signal-preparation equipment earlier described. However such provision is in general superfluous, since practical speaker placements are not nearly as diverse as microphone placements, in which balance as between front and back, right and left, etc., is optional rather than a requirement. The fixed presentation-signal outputs for the eight positions illustrated suffice to cover the needs and preferences of users of four-speakers systems, while intervals of 15° are wholly adequate for virtually any practical use.

There is shown in FIG. 8 one construction for a decoder which may be employed with a very wide variety of speaker geometries. The respective transmission signals T_L and T_R are fed to 90° phase shifters 70 and 72, each of which has positive and negative reference-phase and phase-shifted outputs. These outputs are fed to a fixed mixing network 74 consisting of voltage-dividers attenuating the input signals and distributing the signals so attenuated to summers producing outputs in accordance with equation (2). Fixed output terminals 76 are provided for presentation through suitable amplifiers by loudspeakers at any selected multiple of 15° intervals (or any other intervals for which outputs are provided). The number of placement of speakers may thus be selected in accordance with the preference (including economic limitations) of the user. In general, the speakers are normally preferred to be equally spaced in bearing-angle and equidistant from the listening position, i.e., disposed in the form of a square or regular polygon. However room shape and acoustics and personal preferences may result in other arrangements in many cases.

Another form of decoder with selectable fixed-location output terminals is shown in FIG. 9. The transmission signals T_L and T_R are fed to a sum and difference circuit 80 to produce a sum signal T_ϵ and a difference signal T_Δ. The difference signal is treated in the same manner as at 70 or 72 of FIG. 8, the separate phase-shifter channels for the reference phase 82 and the shifted phase 84 being again shown in FIG. 9. The respective polarities of the reference and phase-shifted difference signal T_Δ are fed to fixed voltage dividers at 86 and 88 and the attenuated outputs are fed to summers 90 along with the sum signal T_ϵ from the reference-phase channel 91 producing output presentation signals for the pre-selected angles ϕ_1, ϕ_2, etc., for which the taps on the attenuators or dividers 86 and 88 are designed.

Where the invention is employed in standard stereo FM broadcasting, the function of the sum and difference circuit shown in FIG. 9 at 80 is performed in the standard stereo matrixing, and the circuit 80 may be omitted in decoding. It will be observed that such sum and difference signals T_ϵ and T_Δ may be directly formed from source signals and employed as transmission signals without formation of signals T_L and T_R, being formed substantially as follows:

$$T_\Sigma = \sum_{k=1}^{n} S_k$$

$$T_\Delta = \sum_{k=1}^{n} S_k (j \cos \theta_k - \sin \theta_k) = \sum_{k=1}^{n} S_k e^{j(\theta_k + \pi/2)}. \quad (4)$$

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The transmission signal pair T_L and T_R contains exactly the same information as the transmission signal pair T_ϵ and T_Δ, and these signal sets are readily convertible from one form to the other in either direction without any alteration of the available information content. Although these two forms of the same signal information are normally the most useful and simplest in equipment implementation, other transmission signal pairs identical in overall information content and ready convertibility to and from these specific forms may be devised and will be understood to be included in the expressions above.

If so desired, individual presentation signals may, after formation, be "touched up" in accordance with listener preference. For example a particular listener may find the overall effect more pleasing with further phase shifting of one or more of the presentation signals after the formation thereof (not shown). As another example, directional effects may be emphasized by auxiliary signal treatment of the same type heretofore employed with other coding and decoding systems, such as varying the amplification of amplifiers feeding particular loudspeakers to increase apparent "contrast" or sound-source localization for certain types of sounds.

It will be observed that the encoded transmission signals are readily useable with existing reproduction equipment having no provision for decoding of multidirectional signals. The sum of the two transmission signals is the simple sum of all of the source signals in their original phase. Thus employment of the transmission signals in the sum-and-difference mono-compatible matrixing of stereo FM broadcasting, or reproduction of an encoded stereo disc recording on a monaural phonograph, produces perfect monaural reproduction. The employment of the two encoded channels as the left and right channels of conventional stereo reproduction produces only slightly less apparent left-right separation than a conventional stereo recording (as in prior systems for quadrasonic encoding and decoding with two-channel transmission).

If so desired, provision may be made in the decoder for artificially encoding ordinary stereo signals containing no directional information, so that such program material is reproduced in the multidirectional speaker system in a manner generally resembling the reproduction of signals wherein the further directional information is encoded. Ordinary stereo signals correspond to source signals at left front, LF, and right front, RF. There is shown in FIG. 10 an adapter which may be substituted for the sum and difference circuit **80** of FIG. **9,** for example by a switch on the decoder, to produce a listener effect or sensation similar to that of direction-encoded signals having source-signal components only from these directions. The ordinary stereo signals are fed to respective 45° phase slitters **92** and **94** to produce a sum signal T_ϵ in reference phase and a difference signal T_Δ in quadrature phase.

It has previously been mentioned that the selection of the two transmission signals for direct reproduction at L and R locations, respectively, is of significance only for compatibility with conventional stereo equipment having no decoding provision. In its broader aspects, the invention may be employed in applications wherein stereo compatibility is unimportant. For example, the invention may be used for the sole purpose of conserving tape space, and thus extending playing time, in the

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general type of recording now done in four or more discrete tape channels. By compressing the information into two recording channels and then expanding in playback, much greater utilization of tape space is made. In such use of the invention the reference direction of the bearing-angles used in encoding may be chosen more or less arbitrarily, and the directions represented by the two transmission signals are accordingly equally arbitrary, so long as they are selected in diametric opposition.

The particularized embodiments of the invention thus far described are confined to those designated for use with the two-channel transmission systems which are currently standard for stereo broadcasting and disc recording. However the broader aspects of the invention are of wider application. The two-channel transmission thus far described is merely a specific application of principles which may be advantageously employed for reproducing directional audio information with larger numbers of channels than two. By employment of the invention, the results obtainable with transmission limited to the two channels used in conventional stereo reproduction are otpimized. However, in further accordance with the invention, a larger number of channels may advantageously be employed. A primary use for a larger number of channels is to sharpen the directionality pattern for any given speaker array, i.e., to reduce the cross-talk which is an unavoidable consequence of employment of a number of loudspeakers larger than the number of transmission channels. But the invention in its broader aspects may be employed even where the number of transmission channels is equal to or greater than the number of required presentation signals, for the purpose of permitting "rotation" of presentation signals, such as in reproduction of a four-track tape recording recorded for "2-plus-2" loudspeaker presentation on loudspeakers arranged in a "1–2–1" orientation, as later seen.

Understanding of the application of the invention to numbers of channels greater than two will be facilitated by first considering certain aspects of the performance and underlying theory of the two-channel system already described. It may be seen upon study that the essence of the advantageous novelty stems from the fact that the sum of all products of the function of θ applied to the source signals at bearing angles θ in formation of each transmission signal and the function of ϕ applied to that transmission signal in the formation of each presentation signal at bearing angle ϕ is a single-variable 360° repetitive function of the difference between the angles θ and ϕ having a maximum absolute value at a reference difference angle, a relatively absolute value at the diametrically opposite difference angle, and absolute values at intermediate angles symmetrical with respect to the axis thus defined. It is this characteristic which imparts the "rotatability" or "universality" of the loudspeaker patterns for which the transmission signals may be decoded.

It will be obvious that all functions which satisfy these criteria are not of wholly equal merit as regards simulation of discrete-channel direct reproduction in psychoacoustic effect. All other factors being equal, it is desirable that the amplitude or absolute value of the overall reproduction function have a zero or null at 180° from the maximum. Likewise, all other factors being equal, it is desirable that the amplitude pattern decrease as rapidly as possible from its maximum value, which oc-

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curs where θ equals ϕ, i.e., where the difference angle α is zero. Further, again with all other factors being equal, it is desirable that phase differences between the appearances of any given source sound in the various presentation signal be minimized, i.e., that the overall reproduction have a minimum of relative phase difference.

The relative importance of these three factors in producing the illusion of presence at the actual performance is a psychoacoustic matter which is presently incapable of quantitative evaluation. It has been experimentally established that the reproduction produced by the two-channel matrixing of the above-described embodiments is more satisfactory than with other matrices for the same purpose. The performance may be described in terms of the factors of merit above by the following: The pattern demonstrates a complete null at 180°, an amplitude reduction of −3 dB at 90° (and of course 270°, these being a convenient point of reference for measuring pattern "sharpness"), and no component is presented with a phase difference of as great as 180° from any other, any components which are reproduced with a difference of phase approaching 90° from their original relative phase being essentially negligible in amplitude. The employment of overall functions which are better in one respect, but at the sacrifice of another, is accordingly within the broad purview of the invention, although it can be shown from information theory and sampling theory that the reproduction information given by mixing and re-mixing coefficients determined as above is as accurate as is possible with only two transmission channels.

The characteristics or performance factors just described can be substantially further improved by applying the same general principles in the construction of transmission signals for three or more transmission channels. Such applications of the principles of the invention may be roughly divided into two categories in their relation to the two-channel embodiment already described: (1) systems employing one or more auxiliary channels or transmission signals in addition to the two transmission signals already described and (2) systems which employ three or more transmission signals which display the same type of mutual symmetry as the T_L and T_R signals of the two-channel system.

Three-channel (and further multiple-channel) systems of the first type mentioned above may be described as "compatible" with the two-channel system. A typical current utility of such embodiments of the invention is in the production of threetrack or four-track tape recordings which may be played back, with suitable decoding, with any desired multiple array of speakers or may, alternatively, be played back as ordinary stereo recordings by equipment which cannot utilize the auxiliary recorded channel or channels. At such future time as disc recording and broadcasting may be provided with more than two signal channels, such auxiliary signals may likewise be employed in these media for similar purposes.

To maintain the ability to decode for varying speaker arrays, the encoding and decoding of the auxiliary channel must be such as to maintain the above-described essential characteristics of the overall transmission or presentation function. In principle, it may be possible to devise third-channel transmissions which may be decoded along with the two primary or basic transmission signals by devising complex decoding for all three channels which departs completely from the two-channel decoding in producing a desirable overall playback function in which the difference angle α is the sole variable. However it is found possible to preserve the same general manner of decoding of the two channels T_L and T_R and merely add to each presentation signal the auxiliary information contained in the coded and decoded auxiliary transmission signal. In order to do this, it is necessary that the encoding and decoding of the auxiliary transmission signal (or signals) produce an added component for the presentation signal which is itself a function solely of the difference angle. The simplest and most desirable manner of utilizing a third channel is to employ an encoding function of θ for production of the third transmission signal which, when multiplied by the conjugate decoding function of ϕ, itself produces a product which is a single-variable function of the difference angle and which, when added to the presentation signal function which results from the two-channel transmission, increases the sharpness of the amplitude maximum in the pattern. These requirements for the auxiliary channel are met by the employment of an appropriate exponential function of ϕ in encoding and its conjugate function of ϕ in decoding. The addition of a third transmission signal T_T using a mixing coefficient proportional to $e^{-j[\theta + \pi/2]}$ for each siganl S_θ and a remixing coefficient proportional to $e^{j[\phi + \pi/2]}$ in forming the added component for each presentation signal P_ϕ produces a product function of the difference in angles which, when added to the basic two-channel presentation function, substantially sharpens the directional effects. The overall presentation signal is

$$P_i = \sum_{k=1}^{n} S_k [1 + 2\cos(\phi_i - \theta_k)]. \qquad (5)$$

With this overall playback function, all sound sources are produced in all speakers in their original relative phase, and the amplitude for an angle difference of 90° (or, of course, 270°) is about 10 dB less than the maximum at 0°.

The auxiliary signal T_T thus formed may be employed with either the T_L and T_R transmission signals of equations (1) or the transmission signals T_ϵ and T_Δ of (4) above. The overall playback function thus obtained, although improving the pattern in the respects just mentioned, produces a signal component at 180° of the same magnitude as the signal component at 90°, i.e., about −10 dB from the maximum at 0°. This "backlobe" may be eliminated by a simple alteration. Considering the T_ϵ and T_Δ form of transmission, of the T_Δ and the T_T signals are attenuated by the square root of one-half, but without change in T_ϵ, and decoding by conjugate functions of ϕ is carried out, the resultant overall transmission function is

$$P_i = \sum_{k=1}^{n} S_k \left[\cos \frac{1}{2} (\phi_i - \theta_k) \right]^2.$$

This overall reproduction function produces presentation signals free of phase shifts and with a null at 180°, the magnitude at 90° being down 6 dB from the maximum at 0°. The same result is of course obtained with appropriate partial blending of the T_L and T_R signals

previously described, and the same attenuation of T_T. Where the basic pair of transmission signals is thus modified, the performance on equipment not capable of utilizing the third channel is obviously impaired. Accordingly, the recorded or broadcast sets of transmission signals will not normally include this alteration. The modified set of transmission signals is preferably generated in the decoder from the unmodified signals as recorded or broadcast.

The overall transmission or presentation equation set forth above resulting from the modified transmission signals has a coefficient expression shown in brackets which may also be written as

$$1 + \cos (\phi_i - \theta_k)$$

This will be seen to be of the same form as the equation (5) coefficient for the unmodified three transmission signals, each overall presentation signal being expressable as

$$P_i = \sum_{k=1}^{n} S_k[1 + 2m \cos (\phi_i - \theta_k)] \qquad (6)$$

where m is the square of the attenuation factor used in forming the modified T_Δ and T_T. Appreciable variation in details of reproduction characteristics is obtained by selection of m. As m is varied in the range from 0.5 to 1.0, the "backlobe" earlier mentioned is re-introduced, but the "90° separation" is simultaneously improved as indicated numerically earlier. With m having an intermediate value of 0.707, the 90° separation is 7.66 dB and the backlobe level is 28.3 dB below the 0° maximum. The choice of the constant m thus involves a tradeoff of desirable pattern characteristics which is incapable of evaluation as regards psychoacoustic effectiveness to the listener, and the three-channel decoder is desirably provided with means for adjustment by the user of the factor m above defined within the range of 0.5 to 1.0. It will be observed that where the factor $\sqrt{m}$ is introduced into the transmission signals at the decoder, and the conjugate functions thereupon immediately applied for decoding, the latter also of course including the factor $\sqrt{m}$, the two successive attenuations by the factor $\sqrt{m}$, may be replaced by a single attenuation by the factor m, as by ganged attenuator potentiometers at the inputs for the unmodified T_Δ and T_T signals, whereby the user may select a value of m between 0.5 and 1.0.

The same general principle may be employed in further adding a fourth channel for still further increasing the "contrast" between the amplitude of reproduction of a source signal from a loudspeaker in a position corresponding to the original position of the source and the amplitude of its reproduction from other loudspeakers, i.e., in further sharpening of the overall presentation signal functions of (5). A fourth channel addition to the three channels described above which meets the criteria already described is the transmission signal T_Q formed as follows:

$$T_Q = \sum_{k=1}^{n} S_k e^{2j(\theta_k + \pi/2)}.$$

Such a function may be produced by summing the outputs of two quadrupole microphones (each with one

dipole pattern opposed in phase to the other dipole pattern) relatively rotated by 45°, with the output of one quadrupole shifted in phase by 90°. Alternatively (or as a supplement) mixing circuits obtained by appropriate modification of those previously described may be employed. An attenuation factor equal to the square root of a constant m may be applied to the transmission signals T_T and T_Q in the formation and conjugate-function decoding of these auxiliary transmission signals. The overall presentation signals are in this case of the form:

$$P_i = \sum_{k=1}^{n} S_k(1 + e^{-j(\phi_i - \theta_k)} + m e^{j(\phi_i - \theta_k)}$$

$$+ m e^{-2j(\phi_i - \theta_k)}) \qquad (7)$$

$$= \sum_{k=1}^{n} S_k e^{j(\phi_i - \theta_k)/2} \left[\cos \frac{1}{2} (\phi_i - \theta_k) \right.$$

$$\left. + m \cos \frac{3}{2} (\phi_i - \theta_k) \right].$$

The phase relations of the source-signal components in each presentation signal are the same as in the two-channel case. However the 90° separation is vastly improved, as now seen.

The effects of variation of m with the fourth channel added are in broad terms generally similar to those of the corresponding variation in the three-channel case already discussd. For a value of m of 0.333, the pattern is of the cardioid type but the 90° separation from the maximum at 0° is 9 dB. For a value of m of 0.5, the null at 180° is preserved but very small backlobes (−23.9 dB) appear in the adjacent regions; the 90° separation is 12.6 dB. With a value of m of 1.0, nulls appear at both 90° and 180°, but there are noticeable magnitudes (−11.3 dB) at about 130° in each direction from the 0° maximum. The factors involved in selection of m by the listener are generally similar to those in the three-channel case, and it is desirable to provide the listener with adjustment of this factor in the range from 0.33 to 1.0.

As will be evident, the principles of the invention may be further extended to still higher numbers of channels while preserving the two basic transmission signals T_L and T_R for reproduction on equipment not capable of using the auxiliary channels.

In addition to such addition of auxiliary channels for the two-channel system first described herein, which may be considered as "compatible" additions to the basic two-channel system, the principles of the invention may be employed for multiple channels which are all associated with particular bearing angles in the same general manner as the signals T_L and T_R are identified with the directions "left" and "right."

Understanding of this aspect of the invention will be promoted by first considering further theory of the basic two-channel embodiment earlier described. In the discussion up to this point, bearing angles θ and ϕ have been considered as measured from the front center (or rear center) position. As already described this produces slightly different encoding functions for the "left" and "right" transmission signals T_L and T_R, which are unaltered in producing presentation signals for speakers at these opposed side locations. If there be considered an angle θ' for each sound source, measured from the "left" direction or bearing angle for T_L and from the "right" direction or bearing angle for T_R,

the encoding function or mixing coefficient function for both of these transmission signals may be expressed as:

$$1 + \cos \theta' + j \sin \theta' = 1 + e^{j\theta'}$$

For reasons shortly apparent, this may advantageously be now rewritten in the form

$$\tfrac{1}{2} + \tfrac{1}{2} \cos \theta' + \tfrac{1}{2}j \sin \theta'$$

(It may have already been observed that this fractional representation has merely been disregarded for simplicity heretofore even in instances where its presence would be required for rigorousness, for example in dropping a multiple "2" in deriving equation (3) from equations (1) and (2)).

The above expression for the forming of each transmission signal from source signals, using the direction to which the transmission signal corresponds as the reference for the bearing angle of the source, may be designated f_2 (θ'), where the subscript indicates the encoding function for each of two channels.

In similar fashion, the encoding function f_2 (ϕ') for each transmission channel in forming each presentation signal may be stated as

$$\tfrac{1}{2} + \tfrac{1}{2} \cos \phi' - j \sin \phi'$$

where ϕ' is the bearing angle of the presentation signal with reference to the direction to which the transmission signal corresponds. Th overall or summed presentation signal function is of course not affected by this alteration of reference point used in the encoding and decoding, being the same as the encoding function except for the difference-angle argument α.

Similar encoding functions (and conjugate decoding functions) may be employed for larger numbers of transmission signals corresponding to equally spaced directional angles. For three channels, at 120° intervals, the encoding function is

$$f_3 (\theta') = \tfrac{1}{3} + \tfrac{2}{3} \cos \theta'$$

and the decoding function of ϕ' is identical (the function having no imaginary term). The overall presentation signal function is again identical with the encoding function except for the difference-angle argument. It will be seen that this overall function is exactly the same as that obtained with the unmodified "compatible" three-channel system set forth above at (5). It may be demonstrated that the "compatible" and "equal-spaced" transmission signals are each linear combinations of the other, i.e., derivable from each other by reversible methods of linear combination which produce no change in the information content.

For four channels or transmission signals (primary transmission signals at each 90°) the encoding function for each is

$$f_4 (\theta') = \tfrac{1}{4} + \tfrac{1}{2} \cos \theta' + \tfrac{1}{4} \cos 2\theta' + \tfrac{1}{4}j \sin 2\theta'$$

and again the overall reproduction is the same as with the "compatible" four channel system (unmodified) earlier discussed which is related by linear transformation.

Such encoding is particularly useful in the making of discrete-signal four-track recordings, which can be played back with any desired speaker array.

It may be shown that further extension of this specific method of encoding and decoding in accordance with the invention may be made to any number n of chan-

nels representing equally spaced bearing angles by the expression, for any odd number of channels,

$$f_n (\theta') = (2/n)[\tfrac{1}{2} + \cos \theta' + \cos 2\theta' + \ldots + \cos (n-1/2) \theta']$$

and by the expression, for any even number of channels,

$$f_n (\theta') = (2/n) [\tfrac{1}{2} + \cos \theta' + \cos 2\theta' + \ldots + \cos (n-2/2)\theta'] + (1/n) [\cos (n/2)\theta' + j \sin (n/2)\theta']$$

As will be apparent, the larger the number of channels available, the larger the variety of particular encoding and conjugate decoding functions which may be devised for practicing the basic aspects of the invention, and the embodiments described above are merely illustrative of the simplest, particularly with numbers of transmission channels greater then 2. More complex functions, employing numerical factors in coefficients of various components more or less analogous to the single factor m earlier discussed, may be devised, as well as the forms of linear combinations.

Persons skilled in the art will accordingly readily devise many further variants of the specific embodiments of the invention herein selected for illustration and description. The protection to be afforded the invention should thus extend to all utilizations thereof as defined in the appended claims, and equivalents thereto.

What is claimed is:

1. A signal-processing apparatus for use in the production or reproduction of multidirectional audio signals comprising matrixing means for producing a set of output signals from a set of input signals, each signal of at least one of said sets being identified with a different sound-direction bearing angle, means for mixing the input signals with mixing coefficients defined for each respective value of a 360° repetitive single-variable function of bearing angle for each output signal to provide the respective output signals, said single-variable functions having the characteristic that when each output signal is multiplied by the complex conjugate of the respective function of another bearing angle and all such products are added, the sum produced thereby is a sum of input signals each multiplied by a coefficient that is a function solely of the difference between both bearing angles.

2. A method of reproducing directional audio information from a plurality of source signals to form a plurality of presentation signals, comprising the steps of: matrixing source signals representative of sounds from different bearing angles θ, each measured from a source reference direction, to form transmission signals having encoding mixing coefficients, at least one of said transmission signals having encoding mixing coefficients substantially corresponding to values of a given single-variable function of the bearing angle θ of the respective sounds, re-matrixing the transmission signals to form signals for presentation at bearing angles ϕ, each measured from a presentation reference direction having a specific angular relation to said source reference direction, by multiplying each transmission signal by a decoding mixing coefficient substantially corresponding to the vlaue of a single-variable function of ϕ for each presentation bearing angle, said function of ϕ being the complex conjugate of the function of θ defining the encoding mixing coefficients for each transmission signal, and adding the resultant product signals to form each presentation signal, so that the sum of all

products of the function of θ applied to source signals in formation of each transmission signal with the function of ϕ applied to that transmission signal in the formation of each presentation signal is a 360° repetitive single-variable function of the difference between the angles θ and ϕ having a maximum absolute value at a reference difference angle, a relatively small absolute value at the diametrically opposite difference angle, and absolute values at intermediate angles symmetrical with respect to the axis thus defined.

3. In a method of reproducing directional audio information from a plurality of source signals to form a plurality of presentation signals, wherein the source signals are representative of sounds from different bearing angles θ, each measured from a source reference direction, and are matrixed to form transmission signals having encoding mixing coefficients, at least one of said transmission signals having encoding mixing coefficients substantially corresponding to values of a given single-variable function of the bearing angle θ of the respective sounds, the steps of re-matrixing the transmission signals to form signals for presentation at bearing angles ϕ, each measured from a presentation reference direction having a specific angular relation to said source reference direction, by multiplying each transmission signal by a decoding mixing coefficient substantially corresponding to the value of a single-variable function of ϕ for each presentation bearing angle, said function of ϕ being the complex conjugate of the function of θ defining the encoding mixing coefficients for each transmission signal, and adding the resultant product signals to form each presentation signal, so that the sum of all product signals of the function of θ applied to the source signals in formation of each transmission signal with the function of ϕ applied to that transmission signal in the formation of each presentation signal is a 360° repetitive single-variable function of the difference between the angles θ and ϕ having a maximum absolute value at a reference difference angle, a relatively small absolute value at the diametrically opposite difference angle, and absolute values at intermediate angles symmetrical with respect to the axis thus defined.

4. In a method of producing signals with directional audio information from a plurality of source signals which includes matrixing of said source signals representative of sounds from different bearing angles θ to form transmission signals capable of bein re-matrixed for production of a plurality of presentation signals at bearing angles ϕ, the bearing angles θ being measured from a source reference direction and the bearing angles ϕ being measured from a presentation reference direction having a specific angular relation to said source reference direction, said method comprising the steps of mixing the source signals with mixing coefficients defined for each respective value of a given 360° repetitive single-variable function of the bearing angles θ for each transmission signal to provide said transmission signals, the respective single-variable functions having the characteristic that when each transmission signal is multiplied by the complex conjugate of the respective function of the bearing angle ϕ and all such products are added, the sum produced thereby is a sum of input signals each multiplied by a coefficient that is a function solely of the difference between said bearing angles θ and ϕ, and has a maximum absolute value at a reference difference angle, a relatively small absolute

value at the diametrically opposite difference angle and absolute values at intermediate angles symmetrical with the respect to the axis thus defined.

5. An audio recording having transmission signals formed from the matrixing of a plurality of source signals representative of sounds from different bearing angles θ and capable of being re-matrixed for production of a plurality of presentation signals at bearing angles ϕ, the bearing angles θ being measured from a source reference direction and the bearing angles ϕ being measured from a presentation refererence direction having a specific angular relation to said source reference direction, at least one of said transmission signals including the sum of mixed signals each formed by mixing the source signals with mixing coefficients defined for each respective value of a given 360° repetitive single-variable function of the bearing angles θ for each transmission signal, and said given single-variable function has the characteristic that when it is multiplied by the complex conjugate of said function of the bearing angle ϕ and all such product functions are added, the sum produced thereby is a function solely of the difference between said bearing angles θ and ϕ, and has a maximum absolute value at a reference difference angle, a relatively small absolute value at the diametrically opposite difference angle and absolute values at intermediate angles symmetrical with respect to the axis thus defined.

6. In the method of reproducing directional audio information which includes producing source signals corresponding to sound emanating from locations at bearing angles differing in side-to-side and front-to-back orientation with respect to a listener, the steps of encoding and mixing the source signals in accordance with first sets of predetermined amplitude and phase coefficients said first sets of coefficients being defined by 360° repetitive functions of said source bearing angles to produce a number of transmission signals smaller than the number of source signals, there being a respective function for each transmission signal, and decoding and separating the transmission signals in accordance with second sets of predetermined amplitude and phase coefficients said second sets of coefficients being defined by complex conjugates of said respective functions of a presentation bearing angle to produce presentation signals corresponding to angular positions of greater number than the number of transmission signals, each presentation signal comprising a plurality of source signals mixed in accordance with third sets of amplitude and phase coefficients constituting sums of products of said first and second sets, the coefficients of the third sets representing the proportion with which each source signal component is represented in each presentation signal, said coefficients of said third set being defined by functions of the bearing angles between the source direction and the presentation direction and all of said functions being identical for all such third set coefficients, whereby the presentation signals are directionally symmetrical.

7. A signal-processing system for producing or reproducing directional audio information comprising encoding means for matrixing source signals representative of sounds from different bearing angles θ, each measured from a source reference direction, to form transmission signals having encoding mixing coefficients, at least one of said signals having encoding mixing coefficients substantially corresponding to values of

a given single-variable function of the bearing angle θ of the respective sounds, decoding means for re-matrixing the transmission signals to form signals for presentation at bearing angles ϕ, each measured from a presentation reference direction having a specific angular relation to said source reference direction, said decoding means having means for multiplying each transmission signal by a decoding mixing coefficient substantially corresponding to the value of a single-variable function of ϕ for each presentation bearing angle, said function of ϕ being the complex conjugate of the function of θ defining the encoding mixing coefficients for each transmission signal, and means for adding the resultant product signals to form each presentation signal, so that the sum of all products of the function of θ applied to the source signals in formation of each transmission signal with the function of ϕ applied to that transmission signal in the formation of each presentation signal is a 360° repetitive single-variable function of the difference between the angles θ and ϕ having a maximum absolute value at a reference difference angle, a relatively small absolute value at the diametrically opposite difference angle, and absolute values at intermediate angles symmetrical with respect to the axis thus defined.

8. In a signal-processing apparatus for reproducing directional audio information from a plurality of source signals to form a plurality of presentation signals, wherein the source signals are representative of sounds from different bearing angles θ, each measured from a source reference direction, to form transmission signals having encoding mixing coefficients, at least one of said signals having encoding mixing coefficients substantially corresponding to values of a given single-variable function of the bearing angle θ of the respective sounds, said apparatus comprising decoding means for re-matrixing the transmission signals to form signals for presentation at bearing angles ϕ, each measured from a presentation reference direction having a specific angular relation to said source reference direction, said decoding means having means for multiplying each transmission signal by a decoding mixing coefficient substantially corresponding to the value of a single-variable function of ϕ for each presentation bearing angle, said function of ϕ being the complex conjugate of the function of θ defining the encoding mixing coefficients for each transmission signal, and means for adding the resultant product signals to form each presentation signal, so that the sum of all products of the function of θ applied to the source signals in formation of each transmission signal with the function of ϕ applied to that transmission signal in the formation of each presentation signal is a 360° repetitive single-variable function of the difference between the angles θ and ϕ having a maximum absolute value at a reference difference angle, a relatively small absolute value at the diametrically opposite difference angle, and absolute values at intermediate angles symmetrical with respect to the axis thus defined.

9. The method of claim 4 for producing two transmission signals wherein the transmission signals are formed as one of the following pairs:

$$T_L = \sum_{k=1}^{n} S_k(1 + e^{j(\theta_k + \pi/2)})$$

$$T_R = \sum_{k=1}^{n} S_k(1 - e^{j(\theta_k + \pi/2)})$$

and

$$T_\Sigma = \sum_{k=1}^{n} S_k$$

$$T_\Delta = \sum_{k=1}^{n} S_k e^{j(\theta_k + \pi/2)}$$

where S_k is the k-th source signal, θ_k is the bearing angle between the sound location thereby represented and a laterally central reference location and j is the square root of -1.

10. The method of claim 3 for producing presentation signals from two transmission signals T_L and T_R wherein each presentation signal P_i is formed from the transmission signals by mixing thereof in the amplitude and phase relation

$$P_i = T_L [1 + e^{-j(\phi_i + \pi/2)}] + T_R [1 - e^{-j(\phi_i + \pi/2)}]$$

where ϕ_i is the bearing angle between a presentation location i and a laterally central reference location and j is the square root of -1.

11. The improved method of claim 6 wherein said function is proportional to the quantity $1 + e^{j\alpha}$, where α is the angle between the source direction and the presentation direction and j is the square root of -1.

12. The improved method of claim 6 for stereo-compatible and mono-compatible reproduction wherein there are two transmission signals T_L and T_R formed from n source signals substantially as follows:

$$T_L = \sum_{k=1}^{n} S_k(1 + e^{j(\theta + \pi/2)}) = \sum_{k=1}^{n} S_k(1 - \sin\theta_k + j\cos\theta_k)$$

$$T_R = \sum_{k=1}^{N} S_k(1 - e^{j(\theta + \pi/2)}) = \sum_{k=1}^{n} S_k(1 + \sin\theta_k - j\cos\theta_k)$$

where S_k is the k-th source signal, θ_k is the bearing angle between the sound location thereby represented and a laterally central reference location and j is the square root of -1.

13. The improved method of claim 6 for stereo-compatible and mono-compatible reproduction wherein there are two transmission signals T_ϵ and T_Δ formed from n source signals substantially as follows:

$$T_\Sigma = \sum_{k=1}^{N} S_k$$

$$T_\Delta = \sum_{k=1}^{n} S_k(j\cos\theta_k - \sin\theta_k) = \sum_{k=1}^{n} S_k e^{j(\theta + \pi/2)}$$

where S_k is the k-th source signal, θ_k is the bearing angle between the sound location thereby represented and a laterally central reference location and j is the square root of -1.

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14. The method of claim **6** for reproduction of four source signals corresponding to mutually orthogonal sound locations by presentation to a listener from these same mutually orthogonal locations wherein each presentation signal contains the corresponding-location source signal plus each of the adjacent-location source signals, both of the latter being reduced to 0.707 in relative amplitude, and one of them being advanced in relative phase by 45° and the other being retarded in relative phase by 45°, with respect to the corresponding location signal.

15. The method of claim **11** wherein the sound locations are at left, front, right and back, the corresponding source signals being S_L, S_F, S_R and S_B, and the corresponding presentation signals being P_L, P_F, P_R and P_B, respectively, and the transmission signals being T_L and T_R, the first sets of coefficients being:

$$T_L = S_L + 0.707\ S_F \underline{/+45°} + 0.707\ S_B \underline{/-45°}$$
$$T_R = S_R + 0.707\ S_F \underline{/-45°} + 0.707\ S_B \underline{/+45°}$$

and the second sets of coefficients being:

$$P_L = T_L \underline{/\ 0°}$$
$$P_F = 0.707\ T_L \underline{/-45°} + 0.707\ T_R \underline{/+45°}$$
$$P_R = T_R \underline{/\ 0°}$$
$$P_B = 0.707\ T_L \underline{/+45°} + 0.707\ T_R \underline{/-45°}$$

16. The method of claim **14** wherein the sound loca-

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tions are at left front, right front, right back and left back, the corresponding source signals being S_{LF}, S_{RF}, S_{RB} and S_{LB}, and the corresponding presentation signals being P_{LF}, P_{RF}, P_{RB} and P_{LB}, respectively, and the transmission signals being T_L and T_R, the first sets of coefficients being:

$$T_L = 0.924\ S_{LF} \underline{/+22½°} + 0.383\ S_{RF} \underline{/+67½°}$$
$$+\ 0.383\ S_{RB} \underline{/-67½°} + 0.924\ S_{LB} \underline{/-22½°}$$
$$T_R = 0.383\ S_{LF} \underline{/-67½°} + 0.924\ S_{RF} \underline{/-22½°}$$
$$+\ 0.924\ S_{RB} \underline{/+22½°} + 0.383\ S_{LB} \underline{/+67½°}$$

and the second sets of coefficients being:

$$P_{LF} = 0.924\ T_L \underline{/-22½°} + 0.383\ T_R \underline{/+67½°}$$
$$P_{RF} = 0.383\ T_L \underline{/-67½°} + 0.924\ T_R \underline{/+22½°}$$
$$P_{RB} = 0.383\ T_L \underline{/+67½°} + 0.924\ T_R \underline{/-22½°}$$
$$P_{LB} = 0.924\ T_L \underline{/+22½°} + 0.383\ T_R \underline{/-67½°}$$

17. The signal-processing apparatus of claim **1** comprising an encoder having input sound-source signals of various bearing angles and output transmission signals.

* * * * *

UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

PATENT NO.   : 3,856,992
DATED   : December 24, 1974
INVENTOR(S) : Duane H. Cooper

It is certified that error appears in the above—identified patent and that said Letters Patent are hereby corrected as shown below:

Column 6, line 44   "reference" should read --references--.

Column 6, line 54   "mor" should read --more--.

Column 9, line 14   "presenation" should read --presentation--.

Column 10, line 10   "four-speakers" should read --four-speaker--.

Column 10, line 27   "of" should read --and--.

Column 10, lines 40, 48 and 59; Column 11, lines 3 and 57; Column 14, lines 46, 53 and 55; and Column 22, line 52 (Claim 13), "T_ϵ" should read --T_Σ--, each occurrence.

Column 11, line 56   "slitters" should read --splitters--.

Column 13, line 5   "signal" should read --signals--.

Column 13, line 51   "threetrack" should read --three-track--.

Column 14, line 23   "ϕ" should read --θ--.

Column 14, line 26   "siganl" should read --signal--.

Column 17, line 29   "Th" should read --The--.

Column 18, line 63 (Claim 2) "vlaue" should read --value--.

Column 19, line 48 (Claim 4) "bein" should read --being--.

PATENT NO. : 3,856,992   Page 2

DATED   : December 24, 1974

INVENTOR(S) : Duane H. Cooper

It is certified that error appears in the above—identified patent and that said Letters Patent are hereby corrected as shown below:

Column 22, line 43 (Claim 12) and Column 22, line 57 (Claim 13) the "N" above the summation symbol should read --n--, each occurrence.

The formulas at Column 9, lines 5-10 should read

$$--P_i = T_L(1+e^{-j(\phi i + \frac{\pi}{2})}) + T_R(1-e^{-j(\phi i + \frac{\pi}{2})})$$

$$= T_L(1-\sin\phi_i - j\cos\phi_i) + T_R(1+\sin\phi_i + j\cos\phi_i)--.$$

The formulas at Column 9, lines 21-25 should read

$$--P_i = \sum_{k=1}^{n} S_k(1+e^{-j(\phi_i-\phi_k)})$$

$$= \sum_{k=1}^{n} S_k\cos 1/2(\phi_i-\phi_k) e^{-j(\phi_i-\phi_k)/2}--.$$

Signed and Sealed this

second Day of *September 1975*

[SEAL]

Attest:

RUTH C. MASON
Attesting Officer

C. MARSHALL DANN
Commissioner of Patents and Trademarks