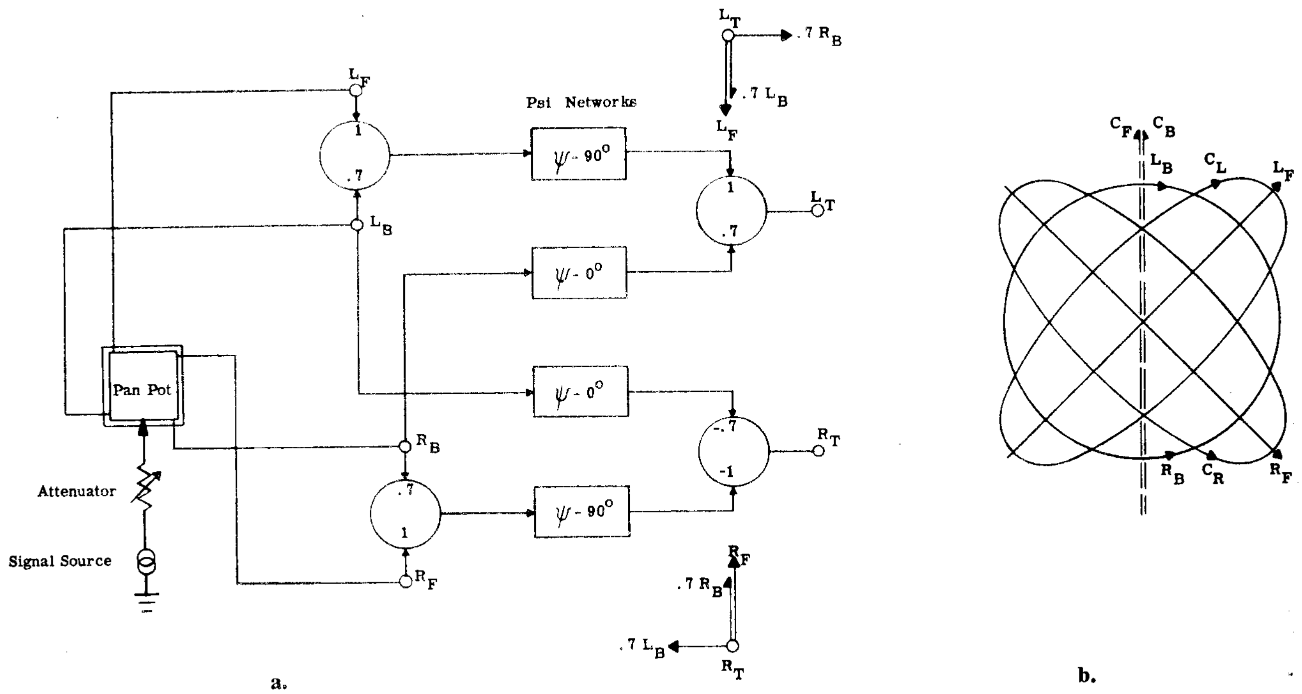

Fig. 4. "Forward-oriented" encoder and modulations.

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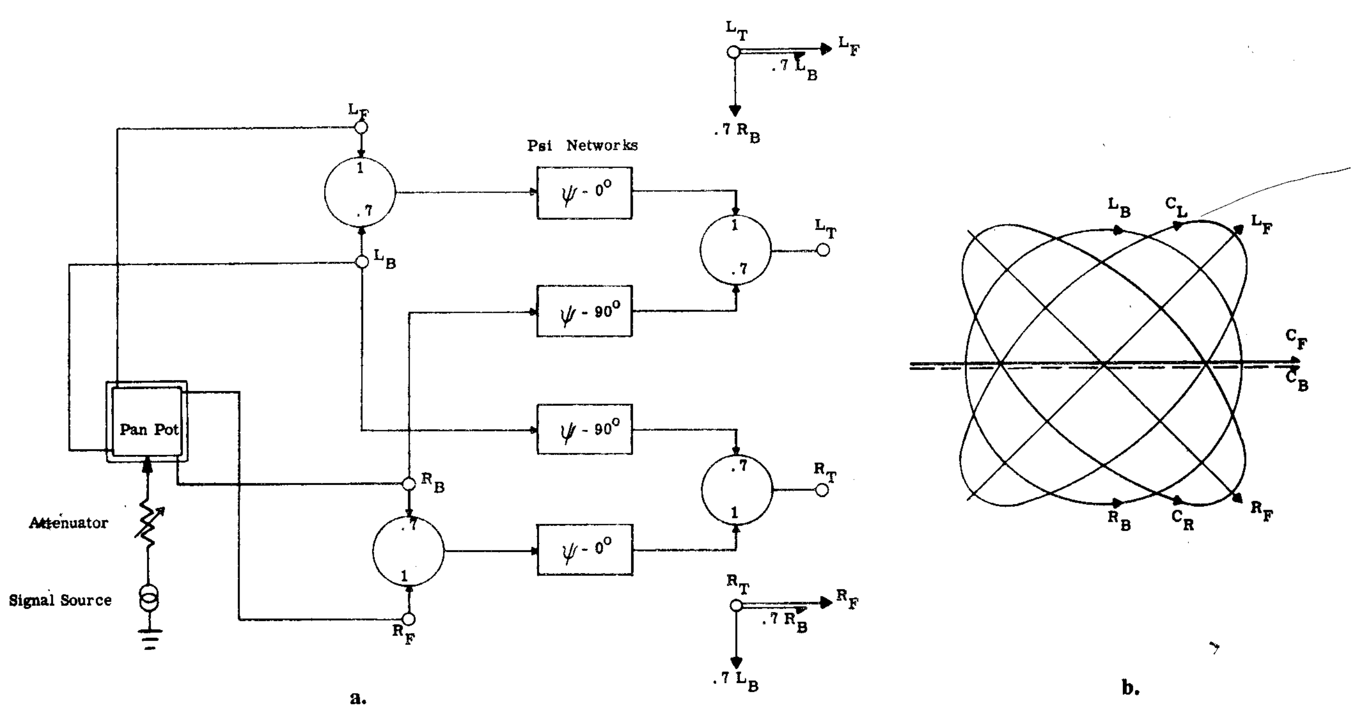

Fig. 5. "Backward-oriented" encoder and modulations.

not transmitted in monophonic systems (even if such a signal is correctly decoded in the Center Back of a quadraphonic array)[2], the use of Center-Back direction is discouraged with the SQ system. In effect, the above set of modulations defines the basic SQ matrix system.

It is shown in [1] that during reproduction the SQ-encoded signals are "decoded" into a set of four-channel signals which retain infinite interchannel separation between the front and the back channel pairs, provide 3 dB interchannel separation between the side channel pairs, and 0 dB separation between Center-Front and Center-Back signals. By using a "blend matrix" decoder or, especially a "matrix-plus-logic" decoder—the latter to be described in a companion paper—the side channel and the front-back separation can be increased to as much as 20 dB or more, resulting in a four-channel reproduction which compares very favorably with the original, discrete, four-channel master tape.

Among the important attributes of the SQ system is its full compatibility with existing stereophonic and monophonic phonographs and with all AM and FM transmission systems. This is ensured in the first instance by the complete separation of the front channels and by a favorable "folding" of back-channel signals in a stereophonic field, and by in-phase relationship of all front-channel-panned signals. In the second instance, the double helix allows the back corner signals to be transmitted in the monophonic mode with the same relative levels as the two front corner signals. This is noted from the fact that the projections of L_F and R_F in Fig. 1**a** upon the horizontal axis are equal to the diameter of the helixes. This code is the only one proposed thus far which possesses all the above characteristics.

As to practical significance of the above-mentioned attributes, it should be remembered that the capability of correctly transmitting the corner signals in the monophonic mode is requisite, as all AM and probably 90% of all FM radio listening are monophonic, and 80% of all phonographs currently available in some important markets—Europe, for example,—still are monophonic. The ability of retaining full front channel separation ensures that a symphony orchestra, for instance, spans the full space between loudspeakers in the stereo mode, and is an indispensable attribute of good stereo compatibility.

In the monophonic mode, the Center-Front (C_F) signal is transmitted at a +3 dB level, as in the case of stereo recording.[3]

OPTIMUM SIDE MODULATION AND DIAGONAL SPLITS

The basic set of SQ modulations in Fig. 1**a** does not define the set of modulations for producing Center-Left (C_L) and Center-Right (C_R) signals. These are not frequently encountered in real life recording except for reverberant energy pickup. Nevertheless, some producers have expressed a desire to place performers on the sides of the audience. By analyzing the decoder action, we have determined that for optimum results, side signals should be encoded in the form of two elliptical helixes with 2.42:1 major/minor axes ratios with the major axes coincident with the L_F and R_F signals, respectively, and sequenced to rotate oppositely with respect to each other in the manner shown in Fig. 1**b**. When playback signals corresponding to these elliptical modulations are applied to a basic SQ decoder, the decoded signals yield channel separations of 7.6 dB between the left and right pairs of channels, which is sufficient to make a side-to-side separation-enhancing logic superfluous. Encoder circuits to implement these side modulations are described later in this paper.

For the moment, it is sufficient to note that all the modulations shown in Fig. 1**b** are inscribed within the square joining the ends of the vectors L_F and R_F. They do not alone occupy more lateral or vertical modulation space than the two basic front channel signals.

It is further noted, without proof, that elliptical modulations equal in magnitude to those shown for C_L and C_R, but rotating in directions opposite to the arrowheads will decode in an SQ decoder into signal pair "splits" L'_F and R'_B and R'_F and L'_B, respectively, with a 7.6 dB channel separation relative to the signals transferred to their respective cross-diagonal pairs.[4]

ENCODING SQ RECORDS

The simplest procedure for encoding an SQ record is to prepare a suitable four-channel master tape, and to apply it to the four input terminals of an SQ encoder. The signals which appear at the two output terminals are conveyed directly, or via an encoded master tape, to a conventional stereophonic disc cutter. The producer soon learns from experience which placement of sounds in the quadraphonic master tape produces the most effective decoded program, which he can approve by auditing the decoded signals. Most of the existing SQ records have been produced in this manner. Nonetheless, with the advance of quadraphonic mastering techniques and the desire of artists and producers to introduce special effects, a number of procedural and encoder refinements have been evolved which are described in the following pages.

[2] The RM matrix (see Appendix) also places the Center-Back signals in the vertical modulation mode.

[3] From time to time in the past, it has been suggested that conventional stereophonic signals should be recorded or transmitted through relative 90° phase-shift psi networks in order to prevent the 3 dB buildup. Fortunately, this procedure has never gained significant popularity, and it is hoped that it will enjoy a quiet passing. Any extraneous phase shifts introduced into a stereophonic program will adversely affect its capability to play compatibly through quadraphonic decoders.

[4] It is also noted in the Appendix that the RM system does not define a diagonal splits capability.

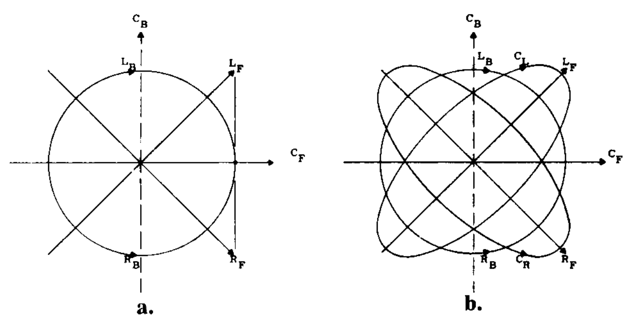

Fig. 1. SQ vectors **a.** basic modulations and **b.** complete set with optimum side modulations added.

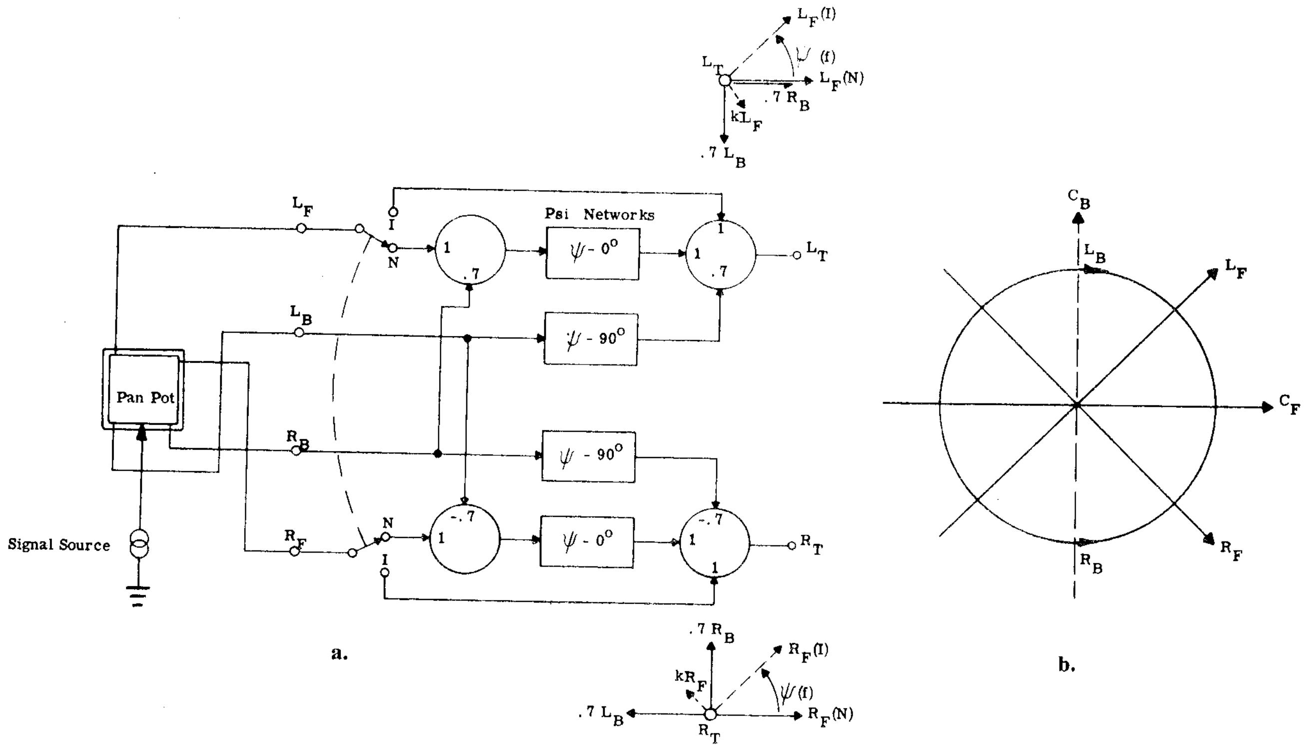

Fig. 2. SQ model 4200 encoder and modulations.

BASIC SQ ENCODER

The basic Model 4200 SQ encoder is shown in Fig. 2**a**. The encoder employs four Ψ networks, two of which are reference networks defining a phase shift Ψ-0°, and two 90° networks, with phase shift Ψ-90°. Considering each of the signals L_F, L_B, R_B, and R_F as a reference, the phasor relationships at the output terminals are portrayed by the phasor groups, L_T and R_T, which define the basic SQ modulations delineated in Fig. 2**b**. The encoder provides "omnidirectional fidelity," i.e., both the encoded and the decoded signals retain constant total power throughout a 360° pan pot action [1]; it does not, however, produce the optimum side-channel modulations, C_L and C_R, previously described. The application of equal signals to L_F and R_B terminals produces an ideal modulation for a diagonal split. The application of R_F and L_B signals, however, results in an effect opposite to that desired. To produce an R_F—L_B split, a second Model 4200 encoder sequenced in reverse (i.e., left inputs and outputs connected to the respective right inputs and outputs, and vice versa) can be used.

Notice should be taken of a "Normal-Interior" (**N-I**) switch in the Model 4200 encoder, and the purpose of this switch will now be explained. While, in general, the front and back sets of input signals are incoherent, presenting no signal buildup problems in encoding, sometimes coherency is present; for example, when the back channel microphones used to pick up the reverberation in a concert hall are spaced less than a wavelength of the lowest frequency of interest apart from the main front microphones, or when a pan pot handle is somewhat elevated from its periphery. This is illustrated in the phasor groups L_T and R_T in Fig. 2**a**, where phasors kL_F and kR_F which originate from the same source as L_F and R_F find their way into the L_B and R_B channels. It is noted that the sum of L_F and kL_F in this instance is greater than the sum of R_F and kR_F, and this leads to buildup of signal in the left channel. This problem usually can be satisfactorily resolved by positioning the **N-I** switch to "I" which allows the front channels to by-pass the Ψ-0° networks and thus to appear directly at the output terminals, L_T and R_T. In this manner, a phase shift Ψ, which is a function of frequency f, is interposed between the front and the back channel outputs, in effect "randomizing" the relative phase angles between the direct signals and the leakage signals. The appropriateness of the "I" position in every instance should be verified by auditing the encoded signal through a suitable "full logic-type" SQ decoder.

ACROPERIPHONIC RECORDING

"Acroperiphony" is the recording of an umbrella of

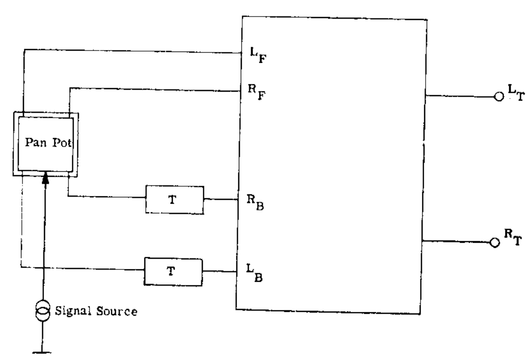

Fig. 3. Acroperiphonic recording. T = 10-20 ms time delay.

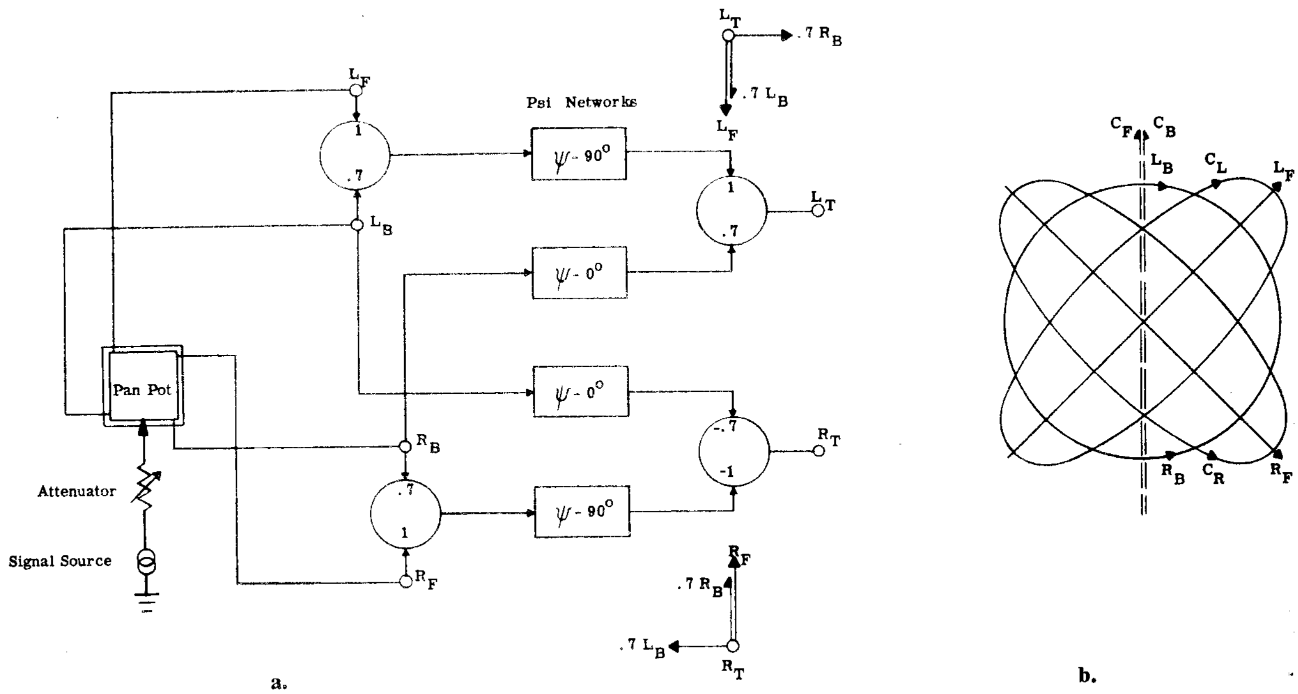

Fig. 4. "Forward-oriented" encoder and modulations.

elevated sounds. In some cases it is desired to "pan" the signal anywhere within the quadraphonic sound field, or above the heads of the audience. It is known, of course, that voices of artists coming from the ceiling are quite unusual in real life. Nevertheless, this capability has been requested by a number of producers, and CBS Laboratories has investigated various encoding methods for achieving this type of display in the decoded record. The presence of elevated sounds, of course, results in coherency between the front- and back-channel signals, and the effect of small amounts of front-back coherency are readily overcome with the **Interior Switch** position, as explained in the preceding paragraph. In a more universal sense, acroperiphony with a Model 4200 encoder can be obtained by placing two delay lines, T, between the pan pot and the back channels, as shown in Fig. 3. A value of T between 10 and 20 ms is satisfactory with 15 ms being near optimum. To obtain sharp definition of a Center-Back channel, the two delay elements should provide equal delays. However, since Center-Back signals usually are not purposely applied to the encoder, a high degree of precision generally is unnecessary. With the

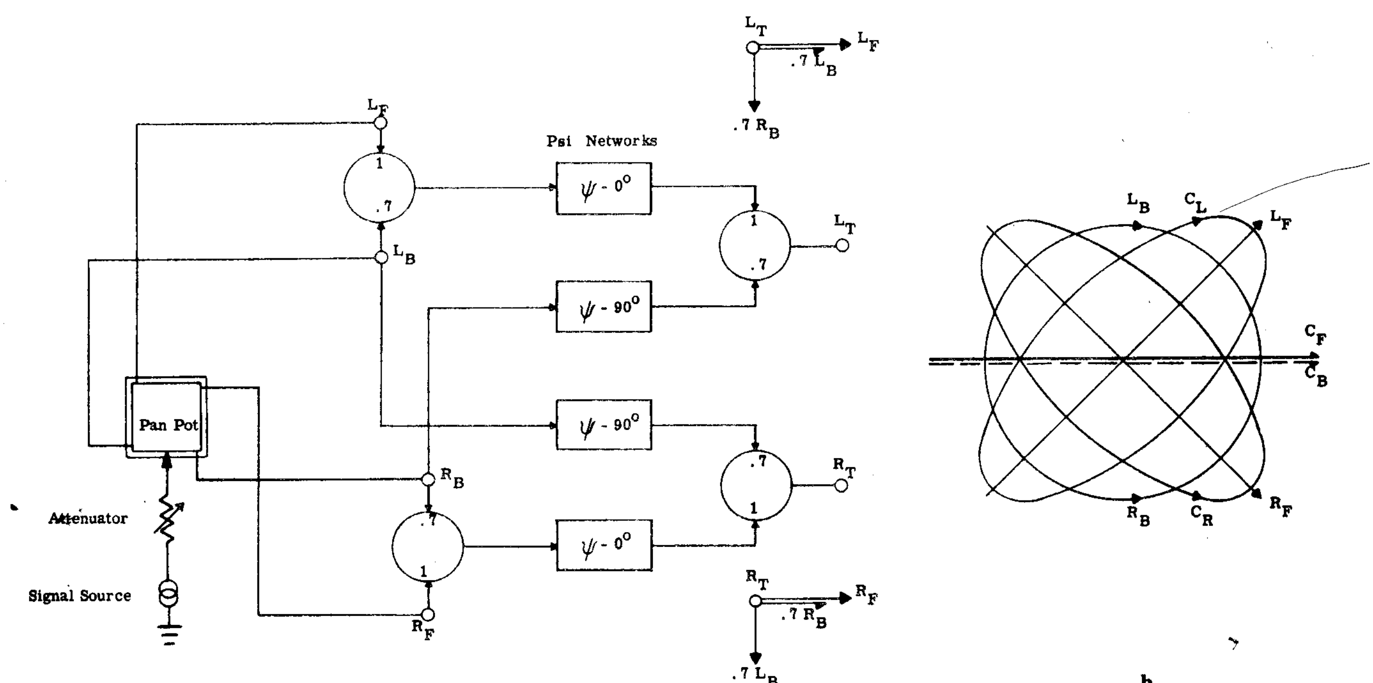

Fig. 5. "Backward-oriented" encoder and modulations.

arrangement shown in Fig. 3, the producer has complete freedom to pan the signal above the listener anywhere in the room, with the proviso that monitoring of the decoded signal should be employed to verify the result.

FORWARD-ORIENTED ENCODER

To take into account specialized situations, a number of encoder forms have been developed which, when properly applied, meet the requirements of the SQ code. One arrangement, currently being evaluated, called, "forward-oriented encoder," is depicted in Fig. 4**a**. The output signal phasors, L_T and R_T, are structured differently with respect to each other than those in Fig. 2**a**; their orientation, nevertheless, being such that the SQ code is fully and correctly produced for all signals except those in the back quadrant. As seen in 4**b**, the L_F, C_F, R_F, L_B, and R_B modulation vectors are in their proper geometric orientations. The Center-Left and Center-Right (C_L and C_R) signals produce modulations in the shape of oppositely sequenced ellipses with ratio of 2.42:1 aligned with their respective Left-Front and Right-Front modulations. Therefore, they define optimal Center-Left and Center-Right signals. Analysis shows, however, that when applied with a conventional pan pot these two signals are approximately 2.3 dB higher in level than they should be for uniform power transmission. Therefore, an attenuator is needed to adjust the intensity of C_L and C_R as desired.

It may be readily shown that with the forward-oriented encoder, suitable diagonal splits, L_F—R_B and R_F—L_B are produced; albeit, resulting in a decoded channel separation of 4.8 dB with respect to the cross-diagonally transferred signals instead of the optimal 7.6 dB.

Setting the pan pot to Center Back causes the modulation to revert to lateral as depicted by the broken-line arrow, C_B, which, in turn, causes it to "decode" as a Center-Front signal. Thus, the forward-oriented encoder cannot be used by itself for around-the-clock pan pot action; however, this property does have a significant advantage in broadcasting four-channel tape programs which may not have been properly edited to conform with quadraphonic matrix characteristics. Any Center-Back solo signal erroneously present will be heard at normal level in stereophonic and monophonic receivers, even though it will be transferred to the front of the quadraphonic array on decoding.

BACKWARD-ORIENTED ENCODER

Another interesting encoder form undergoing field evaluations for a specialized purpose is shown in Fig. 5**a**. Especially useful for exploring the signal positions in the back half of the quadraphonic field, this encoder has been named a "backward oriented encoder." An examination of the phasor groups at the terminals L_T and R_T shows that the L_F, R_F, L_B, R_B, C_L, C_R, and C_B signals are ideally and properly encoded as shown in Fig. 5**b**. However, the Center-Front signal also takes on the form of vertical modulation, thus, the front quadrant in this decoder is not normally used.

The backward-oriented encoder provides the producer and the recording engineer with a tool which is useful in the production of "extra stereophony" in records in which the back-channel sounds appear to spread beyond the confines of the loudspeakers in the stereophonic

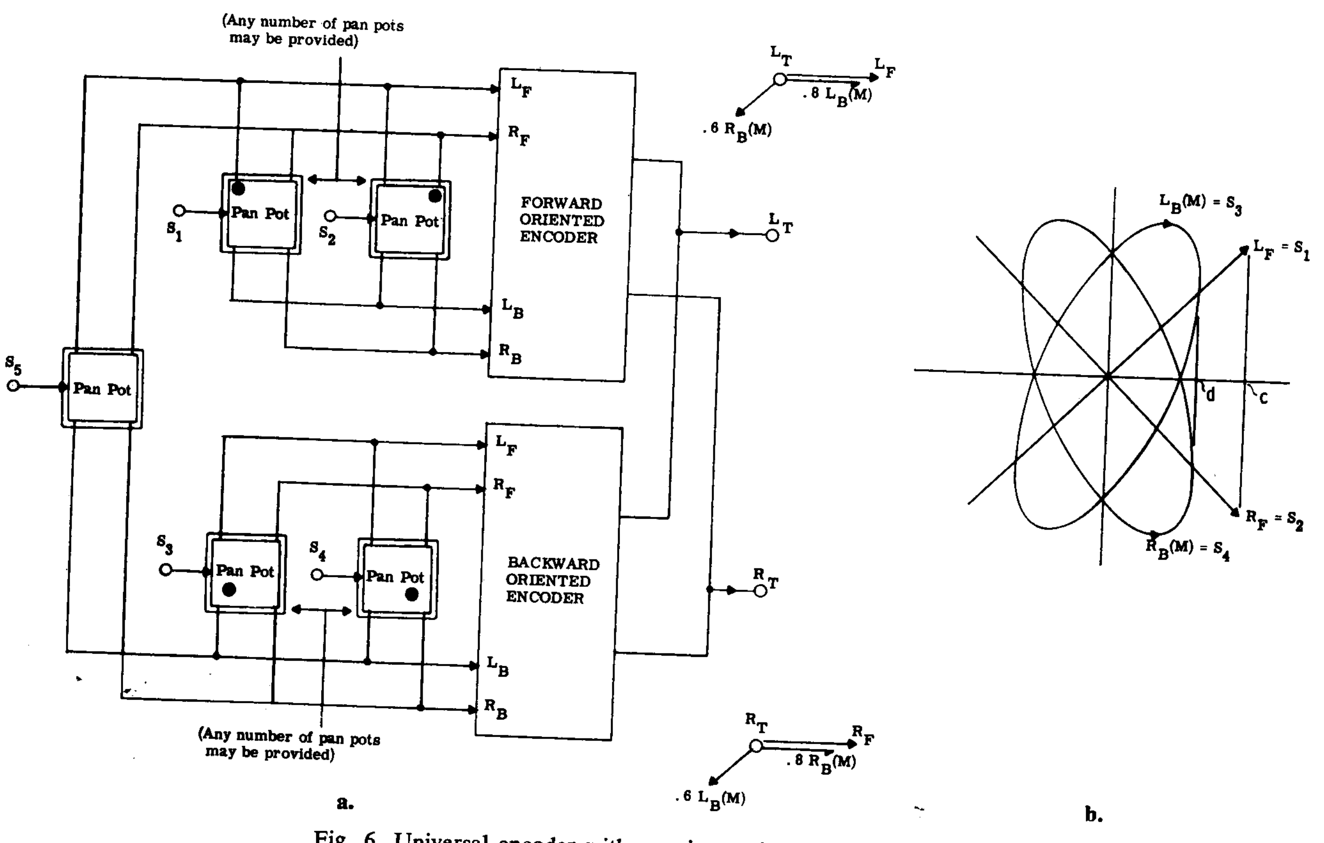

Fig. 6. Universal encoder with panning option for "wide stereo."

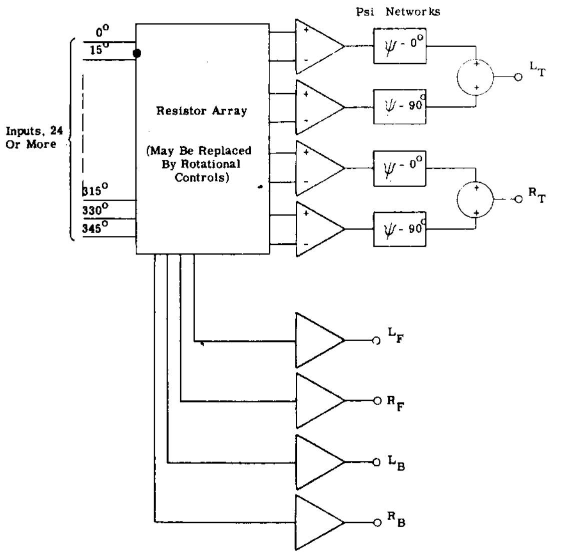

Fig. 7. Block diagram of SQ position encoder.

reproduction mode as described below.

UNIVERSAL ENCODING SET

An experimental arrangement combining the forward- and backward-oriented encoder modes into a "universal" encoding set is shown in Fig. 6a. A forward-oriented and a backward-oriented encoder are connected together for a common output feed. Each encoder may be supplied from any number of pan pots, as shown, only two pairs being illustrated. These are supplied from four signal sources, $S1$ and $S4$, which may be the outputs of the original multichannel tape, or an already encoded quadraphonic master tape.

It should be noticed that in this example the two upper pan pots are "panned" to the Left-Front and Right-Front positions, respectively, resulting in the Left-Front and Right-Front modulations shown in Fig. 6**b**. Signals $S3$ and $S4$, instead of being at the "corners" of the array, are panned on the diagonal approximately halfway toward the center of the pan pot, as denoted by the position of heavy black dots on the lower pan pots. The resulting signal phasors, L_B(M) and R_B(M), form back-channel modulations in the shape of two elliptical patterns, defining the modified back-channel signals L_B(M) and R_B(M). The modified signals will "decode" as back-channel signals brought in toward the center of the room.

Because of the angular relationship between the phasors L_B and R_B, the back-channel signals tend to spread beyond the confines of the loudspeakers when the disc is reproduced in a stereophonic mode. This provides an impression of "extra-wide stereo," which while shunned by most is preferred by some producers. It should be noted that because of the elevated inclination of the ellipses, the projection of the back channel modulation upon the horizontal axis, at the point d, is some 30% shorter than that of the L_F or R_F at c, resulting in about 3 dB loss of back channel transmission through monophonic circuits.

One or more pan pots may be provided for panning a signal around the periphery of the quadrant by connecting them in the manner indicated for the signal $S5$.

"POSITION" ENCODER INTEGRATION

As have been shown earlier, several modifications of the SQ encoder are possible, each suited for a specialized application, without departing from the basic SQ code concept and retaining full compatibility with all SQ decoders. The logical extension of these specialized devices is the creation of a single position encoder which allows the encoding format for every direction of sound to be optimal. Such a position encoder requires access to the original multitrack master tape since each component of the final musical mix must be individually encoded to conform with the intended spatial allocation. (Already existing four-channel tapes can be handled with the position encoder by configuring the device for one of the SQ codes previously described.)

As has been demonstrated, within the SQ code there is a unique amplitude and phase relationship for each spatial position in the listening area. During mixing, each independent source of sound is assigned to one or more of these specific spatial positions by the producer. The encoder then must transform these spatial positions into two channels with amplitude and phase relationships yielding, upon decoding, the maximum identity with the original spatial allocation. Such an SQ encoder is shown in Fig. 7. The encoder has a large, but necessarily limited, number of inputs which correspond to specific locations within the listening area. Alternately, a lesser number of inputs can be utilized each having a continuous range of positional adjustments.

The encoder has six outputs: two are the SQ encoded outputs, L_T and R_T, for making the two-channel disc transfer master, and the remaining four are the L_F, R_F, L_B and R_B channels for producing a cartridge master tape used for duplicating quad-8 tape cartridges.

Looking first at the output amplifiers, we see L_T and R_T each formed by the addition of two inputs corresponding to (Ψ-0°) and (Ψ-90°) networks. Each network, in turn, is fed from an amplifier providing either

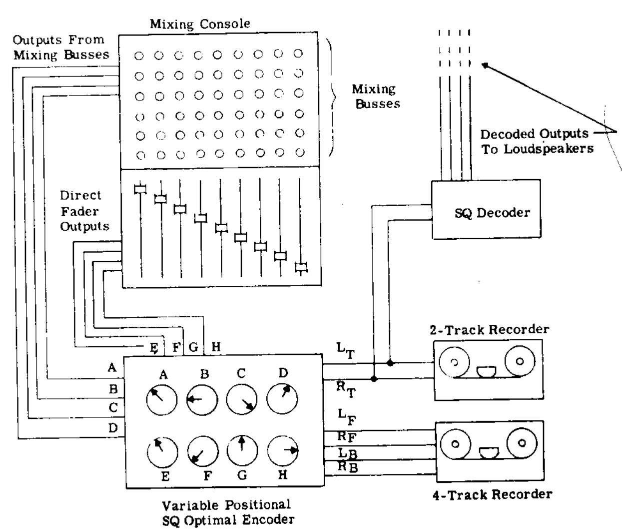

Fig. 8. Integration of the SQ position encoder into the studio complex. Typical mix positions: **a.** Left-Front (315°). **b.** Center Left (270°). **c.** Right Back (135°). **d.** Right of Center Front (30°). **e.** Left of Center Front (330°). **f.** Left Back (225°). **g.** Center Front (0°). **h.** Center Right (90°).

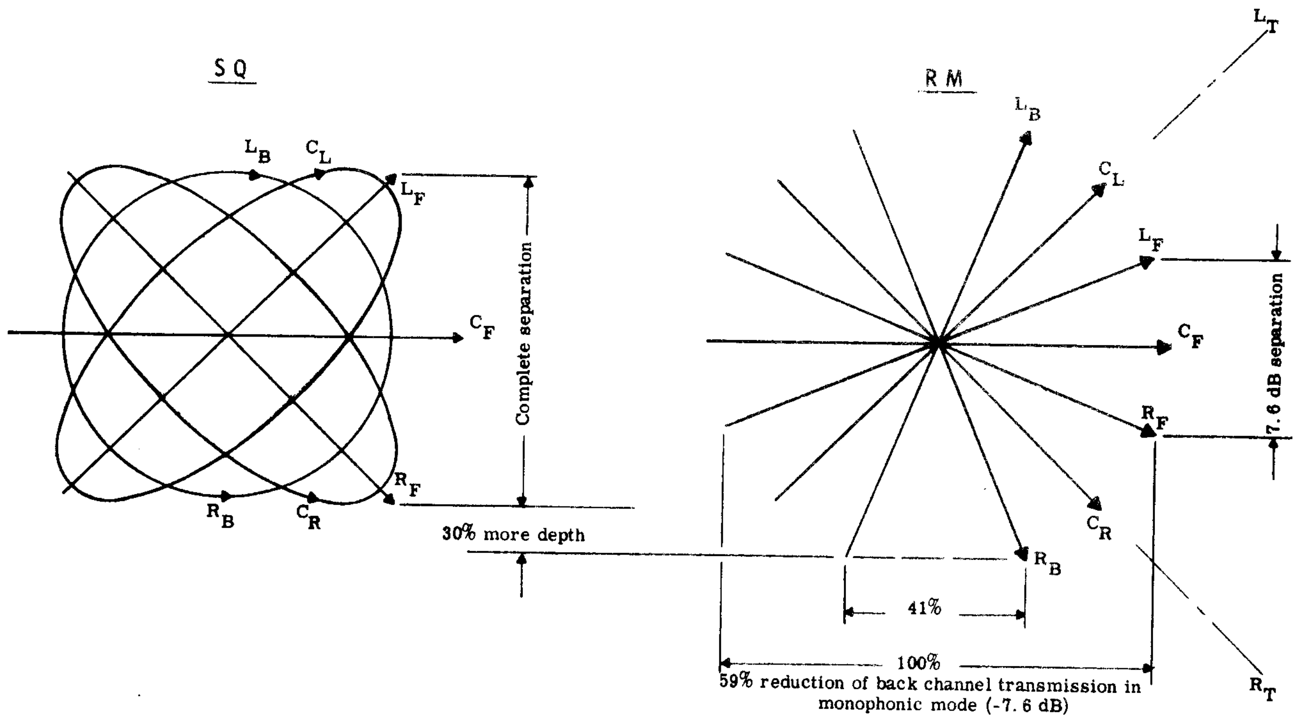

Fig. 9. Comparing SQ and RM modulations.

a direct or inverted output at relative amplitudes determined entirely by a resistor array.

By properly choosing the values of resistors in the array and specific designation of the summing amplifier input terminal, a signal at any relative phase and amplitude corresponding to any combination of previously described encoded signals may be synthesized to produce the optimum modulations for any angular position in space. Also, with the position encoder, coherent inputs applied to diagonal corners can be made to appear predominantly decoded at the particular corners.

A typical integration of the position encoder is shown in Fig. 8. The encoder inputs connect to mixing busses following any faders on the mixing console. (Eight or more busses are generally available on the averaging mixing console.) The busses are used where more than one sound is intended for a particular location, exemplified by inputs designated *A*, *B*, *C*, and *D* on the encoder. Where single sounds are to be separately positioned, the encoder is fed directly from the specific fader, as illustrated by inputs *E*, *F*, *G*, and *H*. The two-channel encoder outputs feed directly the two-track recorder and the four-channel outputs are applied directly to a four-track recorder. The two tapes can be recorded simultaneously during mixdown.

Those wishing to encode an already existing four-track master may utilize the new encoder by assigning each track to its respective input or panning to that location.

CONCLUSION

While the basic SQ encoder provides a satisfactory means for converting conventional four-channel tapes to encoded disc form, specialized requirements have arisen which have led to more advanced encoding techniques. Recent innovations in SQ encoder configurations give the recording engineer and producer a new freedom to create quadraphonic records fulfilling every demand of four-channel sound. The capabilities of the SQ system include the means for optimal panning around the horizontal periphery and positioning the sound anywhere in the elevated mode. Optimum side splits and diagonal splits become possible, and extrastereophonic reproduction may be provided. The resulting discs conform to all the requirements of the basic SQ code, maintain full stereophonic and monophonic compatibility, and decode with precision on all SQ decoders.

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[1] B. B. Bauer, D. W. Gravereaux, and A. J. Gust, "A Compatible Stereo-Quadraphonic (SQ) Record System," *J. Audio Eng. Soc.*, vol. 19, pp. 638-646 (Sept. 1971).

[2] Engineering Committee Standard, "SQ Matrixed Disc Records," Engineering Committee of Japan Phonograph Record Association, 8-9, 2-Chome Tsukiji, Chuo-ku, Tokyo, Japan (April 13, 1972).

[3] Engineering Committee Standard, "Regular Matrixed Disc Records," Engineering Committee of Japan Phonograph Record Association, 8-9, 2-Chome Tsukiji, Chuo-ku, Tokyo, Japan (March 23, 1972).

APPENDIX

In addition to the SQ Matrixed Disc Record Standard issued by the Engineering Committee of the Japan Phonograph Record Association, the Committee has also issued a Regular Matrix Disc Standard, [3], popularly known as "RM," whose modulations in its idealized form are shown on the righthand side of Fig. 9 for comparison with the SQ groove modulations at left. For clarity, the vertical modulations, generally not used because of monophonic incompatibility, are omitted in both vector systems. The RM Standard notes that as the sound source nears the center of the array, the vector locus turns to an ellipse, and finally to a circle, however this detail is not shown here; but we note that these "center" sounds will be decoded as Left-Back signals in an SQ decoder. Phase dissymmetry is present since all the ellipses and circles in the RM system code turn in a clockwise sequence. The Standard does not describe any encoders for producing the RM modulations, nor does it define a modulation form which can be decoded to diagonal splits.

According to the RM code, the Left-Front and Right-Front modulations are oriented at 22½° with respect to the L_T and R_T axis. This is equivalent to 7.6 dB front channel separation. Thus, a symphony orchestra recorded in between the front channels, upon replay as a stereophonic record will shrink to approximately one-half the space in between the loudspeakers. The back channels, L_B and R_B, comprising antiphase L_T and R_T components, in a stereo display give to a central observer an illusion of being positioned beyond the confines of loudspeakers; but because of this, transmission in the monophonic mode causes the back channel level to diminish down to 41% of that of the front channels, which corresponds to a loss of 7.6 dB.

Another practical consideration respecting the L_B and R_B channels in the RM mode is that they require 30% more cutting depth in recording than do the corresponding channels in the SQ code. In order to accommodate the added depth, the RM disc with heavy back channel modulation generally has to be recorded 2.3 dB lower in level than the SQ disc.

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Benjamin B. Bauer, Vice President, Acoustics and Magnetics at CBS Laboratories, graduated from Pratt Institute in 1932 and received the degree of Electrical Engineer from the University of Cincinnati in 1937 at which time he joined Shure Brothers, Inc., as development engineer, later becoming director of engineering and vice president. He went to CBS Laboratories in 1957, where he has been responsible for a broad range of major developments in acoustics and magnetics.

The author of numerous papers and recognized for his contributions to acoustical developments, Mr. Bauer holds more than fifty patents.

He is a Fellow of the Institute of Electrical and Electronic Engineers, a founder and former National Chairman of its Audio and Electroacoustics Group, from which he received the Group's Achievement Award in 1955. Mr. Bauer is a Fellow of the Acoustical Society of America and the Audio Engineering Society, as well as former president, and winner of the Society's Potts Memorial Award in 1963.

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Gerald A. Budelman became a member of the CBS Laboratories staff after his graduation from Cornell University, where he received the B.S.E.E. degree in 1968. During his stay at Cornell, he was associated with commercial Radio Station WVBR-AM&FM, being responsible for its operation and programming as General Manager in his final year there. Since joining CBS Laboratories, Mr. Budelman has headed all of its diverse data survey field efforts, and has successfully completed numerous acoustics and hydroacoustic research missions in many parts of the United States. Most recently, he was the principal investigator in the State of Connecticut's pioneering study of noise pollution on Connecticut highways. He supervises CBS Laboratories' advanced Data Reduction Facility, responsible for all phases of data analysis and interpretation. He is also playing a key role in the development of a new multi-channeled data acquisition system for acoustic, seismic and hydroacoustic work. Mr. Budelman is a member of Pi Delta Epsilon.

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Daniel W. Gravereaux joined CBS Laboratories in 1964 after service in the U. S. Army in the Active Reserve program. He graduated from the University of Connecticut in 1963, earning a B.S.E.E. degree and has pursued postgraduate studies at the institution.

At CBS Laboratories, he has been involved in diverse phases of audio engineering and research. His many accomplishments include contributions to the development of magnetic film striping used in CBS Electronic Video Recording System (EVR) and developing the method and equipment for reliable high-density disk recording for CBS Laboratories' AVS-10 Audio Visual Training Machine. He filled a key role in the development and implementation of the CBS Laboratories MRS series voice-time-data onboard recorder which flew all the manned missions in the Gemini space program.

Mr. Gravereaux has published articles covering such subjects as turntables, phonograph arms, phonograph pickups and the dynamic range of disk and tape records. He is a member of the Audio Engineering Society and is an active radio amateur.