A PRACTICAL BINAURAL RECORDING SYSTEM*

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SUMMARY

A practical binaural recording unit was designed and manufactured to extend the present day high quality sound recording-reproducing equipment development so as to utilize some of the benefits inherent in a stereophonic system.

A review of theoretical factors involved in binaural sound recording and reproduction is presented, with a description of the technical equipment developed to provide a high quality binaural system consistent with reasonable overall equipment cost. Some novel problems and effects encountered in the development program, as well as experiences with binaural recording techinques in the fields of radio transmission, court room recording, and test instrumentation, are described.

BINAURAL HEARING - DESIGN OBJECTIVE

Binaural hearing ability has been granted to most living creatures in order that they may be well adapted to fitting into a three-dimensional world and to provide them with sufficient protective mechanisms to increase their chances of survival. Binaural hearing is a valuable sense which furnishes the listener with not only direction of sound origin and a measure of the distance to the source, but also a general perception of the environmental surroundings in which the listener finds himself when the sound is emitted.

Present day high quality sound systems are nearing the peak of monaural perfection. It was believed that considerable public interest could be developed if an enhanced method of listening were provided. It was therefore decided to produce a simple, practical, low-cost commercial binaural recording-reproducing system.

THE MECHANISM OF AUDITORY PERSPECTIVE

It is to be noted that a human's ears and brain constitutes a directional computing system based upon their phase and amplitude sensitivity. This dual system has a sensitivity versus frequency cross-over area determined as follows: the average low frequency ear phase sensitivity is from the lowest frequency of sound detection up to approximately 800 to 1000 cycles per second. The sensitive transducers of each ear furnishes data to the brain computing system, which allows a perception of sound origin or directivity by binaural phase comparison over this frequency range. Above this frequency range, the wave lengths of sound are so short that the ear phase discrimination falls off rapidly and no comparison above 1000 cycles is possible. The amplitude of a low frequency sound below 800 to 1000 cycles per second is nearly equal at both ears since these long wave lengths readily pass around the cranium obstruction without amplitude loss. This means that

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the effective ear-mental sensitivity to amplitude differential falls off rapidly below 1000 cycles per second. In the region above 800 to 1000 cycles per second, the amplitude sensitivity of each ear becomes important. The physics of sound propagation is such that frequencies above 1000 cycles are attenuated by passing around the cranium. The ears' amplitude sensitivity range continues up to the highest frequency perception limit, which allows directional computation by amplitude comparison between the two ears. The amplitude sensitivity range of the ear is of course defined by the dynamic volume range shown in the standard Fletcher-Munson hearing curves, modified by the room masking level (Reference #1).

The overall computing system for direction is therefore quite effective from the lowest frequency to the highest frequency of sound perception. Figure 1 shows diagrammatically that high frequencies strike the nearest ear to the sound source with full amplitude, but effectively pass by the cranial obstruction without striking the far ear. There is a loss in the order of 30db at 10 kilocycles between the near and the far ear for sounds originating on the axis of the ears. Low frequency sound striking the near ear passes readily around the cranial obstruction so that there is only a 3db loss between the near ear and the far ear.

It may be shown that the portion of the normal auditory perspective due to phase sensitivity, is related to the distance between the human ears. Under the conditions that an observer has a between the ears distance of 6.78" and with a speed of sound in air of 1130 ft/sec., then the maximum frequency f, that the ears may compare phase on, without redundancy, is equal to a half wave length λ ; which is the distance between the ears.

$$\text{If } \lambda = 6.78 \times 2/12, \text{ then } f = \frac{1130}{\lambda} =$$

$$\frac{1130}{6.78} \times 2/12 = 1000 \text{ cycles per second}$$

This then is the maximum possible frequency for binaural phase detection. Average sound sources possess frequencies both below and above the cross-over range of 800 to 1000 cycles. The listener therefore locates the direction of such a combination sound source by both phase and amplitude methods. This enables one to derive a very accurate angular localization.

Two methods are also available for measuring the distance from the listener to the sound source. Since the phase shift of sound of a given frequency is a function of both angular location as well as distance to the binaural listener, a measure of the distance to the sound source is available to the mental computer when the source to listener distance is small. Experience in listening results in an ability to measure the distance to a sound source; the mental computing mechanism calculates the distance by comparing the ratios of the amplitude and the phase of the direct sound to reverberant sound reaching the ears. This is, of course, dependent upon room acoustics. Experience in a given room, or "awareness" of its characteristics allows the ratio to be measured automatically.

LISTENING METHODS

The human being, who has been given this wonderful sense of binaural hearing, achieves a false auditory perspective when monaural recordings are played back. Re-creation of an original sound field varying in amplitude and phase is accomplished by means of stereophonic recording and reproduction. This term "stereophonic" was developed to describe a system for re-creating at any plane in space, the passage of an original sound field with both correct amplitude and phase relationships. Many years of research and experimentation have shown that a very satisfactory re-creation of sound could be achieved through the use of a recording system utilizing three microphones and three sound tracks, which is then reproduced at a later time through a sound system terminating in three loud speakers. The mechanisms of such a system are currently well known, however, because of costs and technical complexities, they are not in present use to any great commercial extent. True stereo sound is quite difficult in technical achievement, and is comparatively costly in the forms which have been demonstrated to the public to date. Both stereo and binaurally reproduced sound have the characteristic of apparently placing the listener in the original sound field. It is this psychological effect which contributes so much to the realism of the reproduced sound.

Earphone sound possesses more binaural enhancement and apparent fidelity than does binaurally reproduced loud speaker sound due to the inherent sound isolation given to the ears by earphones. Experiments and tests with binaural loud speaker reproduction were carried out, and while it was found that some stereo deterioration occurred, it was possible through careful direction and placement of the loud speakers to achieve a considerable improvement over monaural reproduction. Excellent loud speaker listening can be accomplished by spacing the two reproducer loud speakers and the listener at the corners of an isosceles triangle, of perhaps 8 to 12 feet on a side. A somewhat larger listening audience may be accomodated by spacing with as much as 25 foot per triangle side; however, as the distance is increased, the effective sound directivity decreases, so that binaural listening suffers due to the lack of isolation between the sound channels.

Listening tests with such a system brought to light an interesting phenomenon due to the mental correlation of the strictly random background noise pulses ("hiss") present in the separate sound channels. The result of the mental correlation was that focused listening attention was directed toward apparent spacially localized noise sources. This resulted in the subjective raising of the background noise level and a coarsening of the apparent noise source. The random nature of the original white noise was effectively disturbed by false phase and amplitude coincidence, as correlated by the brain to produce apparently localized sources of noise.

SPACIAL DISTORTION

Spacial distortion, a form of distortion which is rarely mentioned and seldom commented upon, is the spacial distortion of a spacially disposed multiple sound source. Focused listening attention may be directed toward spacially disposed sources so as to sort out sound as much as 13db below the general noise background so as to secure intelligibility. Listening tests on monaurally reproduced sound shows that it is difficult to concentrate to the point of detecting the intelligence content of a single sound present in a generally noisy background.

A SIMPLE BINAURAL SYSTEM

Figure 2 shows a binaural sound system complete from sound origination in microphones, through amplifier including pre-equalizer, recorder, tape, playback amplifier including post equalization, loud speaker system, and listener. Microphone placement techniques for binaural recording vary somewhat at the present due to notable divergencies of opinions. This is in part caused by characteristic variations of both microphones and loud speakers, as well as the effect of the acoustics of both the pickup point as well as the reproduction room.

The simplest binaural system for obtaining correct results should obviously use microphones whose pickup patterns approach that of a normal, human ear. This can be accomplished by using so-called non-directional or semi-directional microphones, which actually do have some directional pattern, and mounting them pointing slightly outward on either side of an acoustic septum, which represents the cranium obstruction. This microphone system is the equivalent of a theoretical binaural listener and faithfully picks up sound for binaural storage in a tape recording system; the signal reaching each microphone being stored separately. The techniques of modern tape recording are such that a number of commercial machines are currently using half the area of 1/4" plastic base magnetic tape for high quality speech and music recording. This means that each half of the tape can be used for storing the information derived from a single microphone and amplifier channel, which allows a true binaural recording system to be developed.

A dual amplifier system was built to record or reproduce using this mechanism. When the recorded material is rewound and played back through the two amplifiers, which are also maintained as entirely separate channels, and the outputs are fed independently to speakers, a complete binaural recording and reproduction system is obtained. A second method of audible reproduction is provided for by connecting each reproducing channel to a single earphone in an especially designed binaural headphone set.

THE TAPE TRANSPORT

The development of a binaural tape transport from a standard Magnecord PT63-A was possible, because this basic unit incorporates an assembly of three magnetic heads. The tape passes in succession over an erase head, recording head, and a tape monitor head. The full track recording and tape monitor heads were simply replaced with half-track recording heads arranged to record on opposite edges of the tape. This, of course, sacrificed the facility of monitoring from the tape while recording. However, this was not thought to be a serious loss because of the reliable nature of magnetic recording. It was possible to add the 60kc recording bias circuit of the second recording head in series with the erase and the first recording head without materially changing the circuit impedance and upsetting the 60kc bias oscillator circuits. This was allowable because the main impedance of this series circuit is the erase head, the recording bias winding being a very small impedance. Using this arrangement, it was therefore only necessary to supply proper pole pieces and to reconnect the tape transport's internal wiring in order to accomodate the second recording channel. The existing plug and receptacle arrangements were such as to automatically maintain channel identity between tape transport and amplifier units. The half-track recording pole pieces were made by cutting away slightly more than half of the standard Mumetal pole pieces and soldering into place an equivalent size brass insert to fully support the tape.

THE AMPLIFIER UNIT

A new portable dual record-reproduce amplifier unit was designed, incorporating the characteristics of existing recording equipment amplifiers, except that miniaturization techniques were employed in order to package this unit in the same space as previously occupied by a single channel amplifier. The special features of this dual amplifier unit include individual illuminated VU meters for each channel, individual channel gain controls, and a single (dual) overall master gain control which simultaneously controls the gain of both channels, a special binaural headphone receptacle, and a single panel mounted monitor speaker with a unique volume control. This volume control is so arranged that the speaker is off when the control is at its center position. Maximum loud speaker volume for the one channel is obtained with clockwise control rotation, and maximum volume for the other channel is obtained with counter-clockwise rotation.

The individual amplifier tube lineup consists of two 5879's followed by a dual triode 12AX7, the second half of which is an inverter driving a pair of push-pull 6AQ5 tubes. A multiple section shielded selector-switch switches the equalization and input-output connections simultaneously for both amplifiers in order to change the unit function from record to playback. A full wave selenium rectifier provides DC filament power for the input tubes. The two independent 10 watt amplifier outputs are provided with nominal impedances of 4 and 16 ohms, as well as a 600 ohm balanced connection at plus 4dbm. Pre-and-post equalization is used in order to yield a flat response from 50 cycles to 15kc, plus or minus 2 db at 15 inches per second tape speed. An optional equalization facility is provided to allow operation at 7-1/2 inches per second with a 50 cycle to 7.5kc plus or minus 2db response. A signal to noise ratio of 50db may be achieved with this equipment. A 35db signal to cross-talk ratio between channels caused by magnetic coupling occurs at 50 cycles, but drops with frequency increase until it is below the tape noise at around 100 cycles per second.

Since accurate binaural localization depends to a considerable degree upon amplitude comparisons, a means of electronic balancing of both the recording and reproducing circuits is provided through the use of a calibration button which introduces a 60cps signal simultaneously into the first stage of each of the amplifiers. The individual channel gain controls may then be adjusted to yield equal VU meter readings. When recorded, this calibration signal allows balancing of the playback amplifier gains in a similar manner.

EQUIPMENT APPLICATIONS

The first binaural experimental units were built for an automobile manufacturer for laboratory and field use. Additional units were built for demonstration use to acquaint the public with this new medium and to "feel-out" the possible market applications of the equipment. In the first public demonstrations of binaurally reproduced music and sound, it was not possible to present the technical usefulness of this device and to poll the research workers properly since such a large group of music lovers invariably gathered so as to completely prevent adequate demonstration of the equipment to technical personnel. It has therefore been necessary to carry out considerable specialized work investigating the different fields of application. These endeavors are described in the following paragraphs:

POLICE WORK

Police and Secret Service Departments have begun to make use of binaural recording techniques for surreptitious recording since this method overcomes all accepted methods of masking voice intelligibility. A monaural recording system cannot overcome background noises, the running of water, the turning up of radio volume, etc. A binaural system permits spacial location of the masking source and allows focused listening attention to be directed to the intelligence source so as to achieve intelligibility under all of these conditions. It has been found that it is possible to obtain complete transcripts from recordings made under conditions where previously nothing useful could be obtained.

COURT ROOM REPORTING

Court reporting is an exceedingly important application of binaural recording equipment which assures accurate court records, including making a positive identification of persons in the court room. A study of monaural court reporting has been carried out by Mr. Ray Hurst (Reference # 6), who has clearly shown that court records are often at variance with what actually transpires because court clerks are unable to follow testimony fast enough to accurately transcribe it as it is presented. Often the clerk may hear something wrong and can also be guilty of making obvious mistakes. On one occasion, to our knowledge, it has been necessary to reverse a written court record which occurred due to a stenographic error. We have followed up this original monaural recording work by making binaural recordings in the State of Wisconsin Circuit Courts. The results achieved in recording actual court room procedures were more than gratifying. By properly disposing the microphones, excellent binaural recordings were made, which resulted in 100% intelligibility on playback, even when as many as three people were talking at once., e.g., the State's Attorney, the defense attorney, and the regular court reporter, who was inquiring concerning something which he had not heard well.

Experimental court room set-ups for the microphone locations resulted in placing one slightly in front of the intersection of the Bench and the witness's chair, and the other at the corner of the counsel table about 15 feet from the first microphone. This located the judge and witness near one microphone, while the two attorneys' positions were relatively close to the second microphone. The usual court room distractions went on throughout the recordings; extraneous noises included the building radiator noises, rattling of papers by court reporter and judge, coughing of people throughout the room, etc. The excellent results obtained have caused other courts to begin preliminary studies of this medium.

RECORDING OF HEARINGS

Another use of the binaural recording method is found in recording the proceedings of large Commissions where discussions may be originated from any position throughout a large group of people. Tests were made in hearings before the Public Service Commission of Wisconsin, in a room,perhaps, 25 x 50 feet in size. Speeches came from all parts of the room. The microphones were placed in one end of the room about 15 feet apart, near to the presiding member of the Commission. It was found in these tests that complete understanding was had during playback of every speech made throughout the Appearances with the exception of speeches which camefrom the court reporter. This man did not speak plainly, and could not be understood in the room at the time when the original recordings were made. All speeches, even those coming from the rear of the room, showed a high degree of intelligibility, which was not found when only monaural reproduction of the recordings was made.

SYMPHONIC AND ORCHESTRAL RECORDINGS

Excellent recordings have been made of large University bands; experimental recordings have been made of the University of Wisconsin band as well as of the University of Illinois band. An interesting occurance took place during a reproduction of one of the recordings which had just been completed in a large music hall. One of the caretakers approached, slipped on a headphone set and with a very startled look, wheeled around and stared at the empty stage. The "three-dimensional" listening effect had fooled him into believing that the band was still on the stage. Such involuntary reactions are a tribute to the effectiveness of binaural recording. From a music lover's standpoint, the improvement in realism with binaurally reproduced music is the most important improvement factor of such a system. Indications to date are that the additional complexity and cost of such a system as is described here are very acceptable in view of the results obtained.

RADIO BROADCASTING

In order to test public acceptance of this "new medium", experiments have been conducted utilizing simultaneous broadcasts over radio stations having both AM and FM facilities. Spot announcements and newspaper advertisements giving careful instructions to listeners were provided throughout the days preceding the broadcast concerning the fact that separate microphones were to be fed into the AM and FM channels so as to achieve a binaural effect. Instructions were issued telling the listener how to set-up his AM and FM receivers for the best listening effect. Very gratifying results have been achieved on radio stations WGN and WGNB, in Chicago. Sufficient interest in this "new medium" has been stirred up so that AM-FM binaural broadcasts have also been carried on experimentally by WJR in Detroit, WGAR in Cleveland, WQXR in New York, and elsewhere. It has been found that considerable listening enhancement in the home may be had using a quality FM receiver for one channel and a small "kitchen variety" AC-DC set for the AM channel. The reaction of music lovers to the improvement has been astounding. The only additional facilities required by a radio station for such a binaural broadcast are the use of a second microphone and separate amplifiers for the separate channel inputs to their respective AM and FM facilities. Since most radio stations have these facilities already, no additional expenditure is required for a direct binaural broadcast. Delayed broadcasts, and "canned" music of course may be handled directly by the binaural recorder described in this article.

In tests conducted in conjunction with a broadcast of the Chicago Philharmonic Orchestra, it was found that the introduction of individual reverberation chambers into the separate binaural channels detracted considerably from the quality of the transmission, to the point of almost completely destroying the binaural effect. The directorial staff assigned to production were in the habit of using reverberation for enhancement of their regular monaural symphony broadcasts. However, experimentation demonstrated that there was no question but that the binaural effect provided sufficient additional enhancement to far make up for the loss of the questionable reverberant enhancement.

EDUCATIONAL PROGRAMS

Demonstrations of the usefulness of this medium in audio-visual education programs have already disclosed that the third dimensional realism is of considerable assistance in the critical analysis associated with speech classes, band and choir practicing, dramatics, etc. The auditory "liveness" inherent in stereo localization is a major step forward in this field. Several well known choirs and orchestras now use this system as an accepted rehearsal tool.

RESEARCH APPLICATIONS

For the majority of commercial applications, binaural's usefulness lies in the information identifying field where information is normally obscured or masked by a multiple sound background as reproduced by a monaural system. One of the current field uses of the binaural recording system is by a prominent automobile manufacturer, who has standardized experiments with the equipment to assist in judging noise factors in newly designed automobiles. Tape editing allows ready A-B testing, so as to allow judging between automobiles with a critical view toward improvement in design as changes are made.

Considerable research (Reference # 7) has been carried out to improve the "muddy" sounding emphasized bass that results from monaural recordings of engine noises. Deisel engines as well as conventional gasoline automobile engines,both indoors and out-of-doors, were tested yielding the same un-realistic sounding recordings with monaural systems. Road rumble recorded during automotive road testing with a monaural system seemed to come from all directions thus effectively obscuring the test information. Binaural recording overcomes both these effects and through the realism and assignment of sound direction allows evaluation testing to be carried out.

A non-binaural laboratory use of the equipment is dual channel recording of simultaneous information and the recording of separate commentary during a single channel information recording.

CONCLUSION

In the short time since the introduction of the commercial binaural recorder, it has already proven its usefulness. The simplicity of the system developed no doubt has contributed to its wide spread acceptance.

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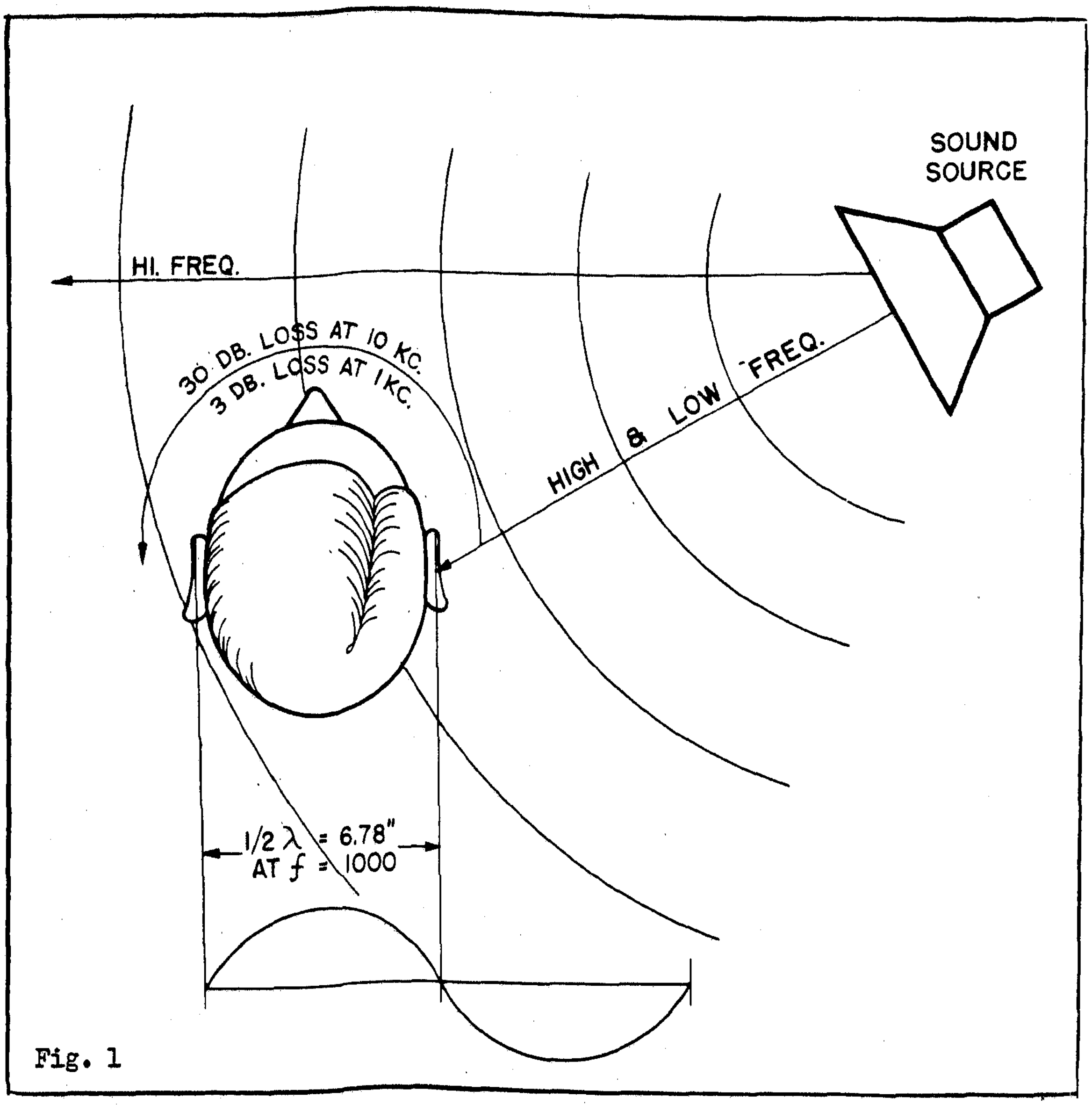

Fig. 1

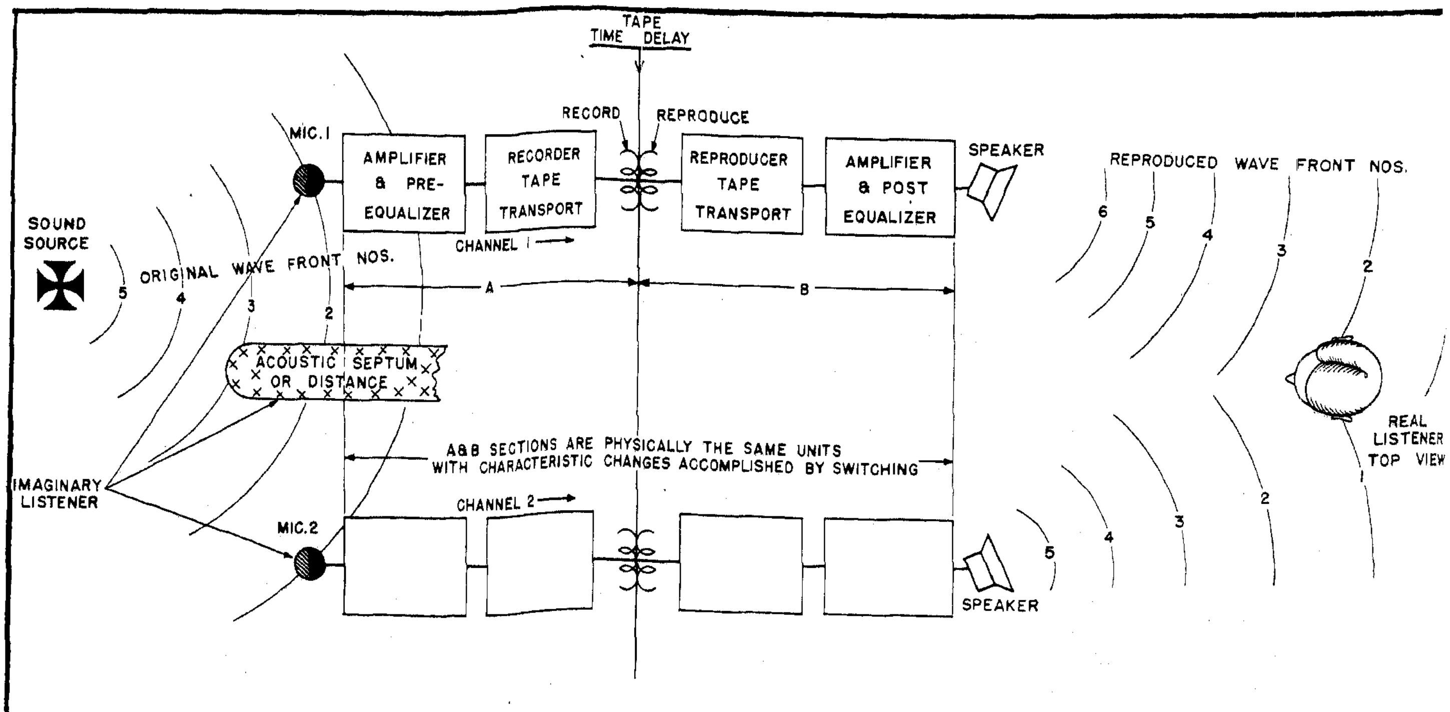

FIGURE 2 NOTE THAT APPROXIMATELY THE SAME SOUND PHASE EXISTS AT THE REAL LISTENERS POSITION AS AT THE IMAGINARY LISTENERS POSITION. THE SLIGHT DIFFERENCE REPRESENTS THE REPRODUCTION ERROR INHERENT IN MICROPHONE & SPEAKER RELATIONSHIPS.