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Unified theory of microphone systems for stereophonic sound recording

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UNIFIED THEORY OF MICROPHONE SYSTEMS
for
STEREOPHONIC SOUND RECORDING

Abstract:
None of the present microphone systems used for stereophonic sound recording (X/Y, A/B-ORTF-NOS, etc) can be considered as universal or rarely even optimum. This paper shows how these different systems are in fact part of a much larger continuous field, where "recording angle" (in the horizontal plane and for various elevations) and "geometric distortion" of the sound field are related to angle and distance between microphones. The limits of our choice in this continuous field are shown to be determined by an unacceptable ratio of direct to reverberant sound.

Introduction:
In the field of monophonic sound recording, the sound engineer has considerable freedom to choose the microphone position according to the sound quality desired. The relationship between the distance of the microphone from the sound source, its frequency response curve, and the amount of "presence" required is easily appreciated; and the different microphone directional characteristics available, enable the ratio of direct to indirect sound to be easily optimized.

This unfortunately is not the case in stereophonic sound recording. The number of different microphone systems available for stereophonic sound recording is very limited and almost without exception these systems have fixed characteristics. Each system has been developed to be "optimum" in a given set of circumstances; however, as recording conditions are infinitely variable, this optimum is rarely achieved. Microphone position is generally a compromise between a good coherent stereophonic image and the required ratio of direct to reverberant sound. Many attempts have been made to compare different stereophonic microphone systems in a given recording situation, however, the fact that each system has a unique combination of characteristics renders this operation almost futile.

My aim in presenting this paper is to try and clarify the different characteristics of a given microphone system and show how these characteristics vary from one system to another. It will then become clear that there is an infinitely larger choice of systems available, forming in fact a continuous field of choice. It is therefore possible for the sound engineer to choose within this field the characteristics unique to his particular recording situation.

(I) Derivation of Recording Angle(1):

In 1966, H. Mertens(2) published information giving the relationship between Intensity Difference(dI) and/or Time Difference(dt) for an apparent reproduction angle of 30° in the normal listening configuration (Fig. 1) - that is the minimum values of dI and/or dt necessary to give the impression that the reproduced sound is coming from one loudspeaker or the other. Mertens used an artificially generated sound source to produce this information.

In October 1984, G. Simonsen(3) published a new set of psycho-acoustic data using natural sound sources (voice and maracas), Intensity Difference and/or Time Difference information was given for the apparent angles of reproduction of 10°, 20° and 30°. The results obtained by Mertens and by Simonsen are given in Fig. 2. To help in computer analysis of these results, I have used a convenient polynome to interpolate between the data established by Simonsen. The graphical representation shows an apparent statistical spread of psychoacoustical information, but this is symbolic only. No detailed statistical analysis is at present available for a large number of subjects. The data for dI/dt at 30° reproduction angle established by Simonsen differs slightly from that obtained by Mertens probably due to the use of natural sound sources.

The intensity and time difference for a spaced pair of high quality cardioid microphones can be calculated as a function of sound source position and various distances and angles between the microphones. This purely physical information, together with the psychoacoustic limits of the stereophonic listening situation, enables a usable angle for coherent stereophonic recording (Recording Angle) to be determined.

The relationship between Intensity Difference, sound source position, and angle between microphones for a coincident pair of cardioid microphones is given in Figure 3. The psycho-acoustic limits of the listening situation (15db Intensity Difference for 30° - data established by Simonsen) are also indicated on Figure 3. We can use this information to determine the Recording Angle of any given coincident pair. We must look for the intersection between the variation of Intensity Difference for different sound source positions and the 15 db Intensity Difference necessary to produce an apparent angle of reproduction of 30°. For example, if we consider a coincident pair of cardioid microphones with 120° between the microphones, we obtain intersection when the sound source is at about 70°. The limit to the Recording Angle is therefore at 70° on the right side of the axis of the pair and 70° on the left side - the total Recording Angle is therefore 140°. For an angle of 90° between the microphones the half recording angle is about 90° (the total Recording Angle being 180°).

Using a spaced pair of omnidirectional microphones the relationship between time difference and sound source position can also be determined as a function of different spacing between the microphones (Fig. 4). The Recording Angle can also be determined from the intersection between the physical and the psychoacoustical information (the same way as in Fig 3). For example, with 50cms between omnis the total Recording Angle is about 100°.

Combining these two functions for a spaced pair of cardioid microphones one obtains a whole series of curves, with Intensity Difference and Time Difference as a function of sound source position, spacing, and angle between microphones. A few examples using different microphone spacings (12cm, 17cm, 22cm and 30cm) are illustrated in Figs. 5,6,7 and 8. This time, both Intensity Differences and/or Time Differences are indicated for apparent angles of reproduction.

Figs. 5 to 8 are used to determine the Recording Angle of a spaced pair of cardioid microphones for different distances and angles between microphones (using the data established by Simonsen for the apparent angle of reproduction of 30°). For instance, in Fig. 6 one can see that with spacing of 17cm and an angle of 110° between the microphones, the half recording angle is about 50° (total recording angle of 100°). However, the same recording angle can obtained with 12cm 130°(Fig. 5), 22cm 90°(Fig. 7), 30cm 55°(Fig. 8) etc.

A series of equivalents can be established for other recording angles and the various values of spacing and angle between microphones produce the graphical representation shown in Fig. 9. **A whole series of combinations of distance and angle are possible for a given recording angle.** For instance, for a total recording angle of 80°, the following combinations are possible : 12cm 160°, 17cm 145°, 22cm 125°, 30cm 90° (NOS), 40cm 50° and 50cm 20°. For adjacent "equivalents" the difference in subjective quality is quite difficult to determine. However, if extreme equivalents (17cm 135° as against 40cm 50°) are compared, the listener can begin to feel the subjective contribution of Time Difference as against Intensity Difference. The final choice of a particular equivalent is of course a personal one and long may it remain so!

One can deduce from Fig.9 that the Recording Angle can be varied by keeping one of the axes constant and varying the other, or by gradually varying both. This situation is somewhat similar to the zoom lens of a television or film camera. For instance, starting with 10cm 60° and gradually changing to 50cm 180°, one "zooms" from a total recording angle of 180° (wide angle lens) to a Recording Angle of 40° (narrow angle lens).

It is common practice in recording a symphony orchestra to place an additional stereophonic pair well behind the main recording microphone pair in order to "open up the sound". It is obvious that the Recording Angle of this additional pair must be carefully determined so as not to mix up the main stereophonic image or create a double image. For instance if a 17cm 110° pair is used (total recording angle of 100°) in its normal position in front of the orchestra and another pair is placed 8 metres further away, it must cover a Recording Angle of only 60° (from Fig. 9 the values of spacing and mic angle can be determined for a Recording Angle of 60°), i.e. 35cm 130°, 40cm 110° or 45cm 90°.

Conclusion : In a given situation, the microphone pair can be placed at the optimum distance from the sound source to produce the desired ratio of direct to indirect sound. The values of spacing and mic angle can then be chosen to reproduce the best stereophonic image possible. We must now look at the angular distortion produced by different combinations of angle and distance between the microphones.

(II) Angular Distortion
Each combination of angle and of distance between microphones introduces a certain amount of angular distortion. Already recording angles of more than 60° produce expansion of the sound image whilst recording angles less than 60° produce compression of the sound image. Added to this, angular distribution within this recording angle is in itself non linear.

If we take as an example the "NOS" (30cm 90°-Fig 8), we can see from the intersections between the physical and the psycho-acoustical information that:

i) the curve representing an apparent angle of reproduction of 10°intersects with the 30cm 90° curve at dt=0.16mS and dl=0.14. These values are produced when the sound source position is 11° in relation to the axis of the microphone pair.

ii) for an apparent angle of reproduction of 20°, the intersection with the 30cm 90° curve is at dt=0.32mS and dl=0.26. The sound source position is 22° in relation to the axis of the pair.

iii)for an apparent angle of reproduction of 30°, we obtain dt=0.56mS and dl=0.45. The sound source position is 39° in relation to the axis of the microphone pair (39° is, of course, the half recording angle).

(These values are represented graphically in Fig. 10).

If one considers a sound source at halfway between the centre axis of the pair and the extreme limit of the Recording Angle (i.e. at 50%), this can be taken as about the maximum "deviation" from a linear reproduction that will be produced by a given microphone pair. I propose to take this value of "deviation" as characteristic of the geometrical distortion produced by a given microphone pair and to call it **"Standard Deviation"**. In the example illustrated above ("N.O.S."), the 50% position is at about 20° to the axis of the pair. With linear reproduction, this sound source should normally be reproduced at 15° to the centre of the standard listening situation. However "Standard Deviation" is about 4° so the sound source in question will be reproduced at a position of about 19° to the listening axis, as seen in Fig.10. This value of deviation is near to the minimum that is posible for any combination of distance and angle between microphones. Values of "Standard Deviation" for other combinations of angle and distance are given in Fig.11.

It is interesting to note that systems using a balanced combination of Intensity Difference and of Time Difference in general produce less angular distortion than systems using a predominance of one or the other - a predominance of Time Difference being most prone to angular distortion (up to 10° Standard Deviation)

(III) Directivity Patterns and Frequency Response.

Although I have used microphones with cardioid directivity patterns to produce Intensity Difference information to illustrate the first and second sections of this paper, it is obvious that equally valid results can be obtained using almost any directivity pattern.

However, each directivity pattern has its own associated difficulties with respect to the "on axis" frequency response of the microphone and the regularity of the directivity pattern throughout the frequency range.

i) Theoretically perfect omnidirectional microphones (i.e. small diaphragms) can of course only be used on the time axis with associated high value of angular distortion (Standard Deviation being about 10°). However, if we are prepared to use only 2/3 of the available reproduction base for the main sound sources, the angular distortion is not quite as high. The excellent frequency response of omnis at low frequencies is an obvious attraction in using this system.

ii) Hypocardioid (wide angle cardioid) microphones offer an interesting compromise between low frequency response and reasonable angular distortion. Using combinations of time and Intensity Difference, we can see that values of Standard Deviation at various Recording Angles (Fig. 12), are considerably lower than with Time Difference only systems. Low frequency response is much better than with cardioid mics even though not as good as with omnis. It is unfortunate that no small diapragm hypocardioid microphones are at present commercially available.

iii) The directivity patterns of small diaphragm cardioid microphones are very near to the theoretical value up until about 120° to the main axis,and within the major part of the frequency spectrum (200Hz - 8kHz). It is worth noting that the majority of microphone systems for stereophonic sound recording use cardioid directivity patterns (X/Y, A/B - ORTF, NOS, etc.) However, low frequency response is not very satisfactory and this has led many recording engineers to look for other systems with better low frequency response. Larger diaphragms can of course improve somewhat the response in the low frequencies, at the expense unfortunately, of good cardioid directivity at the higher frequencies.

iv) Hypercardioid directivity can produce totally adequate stereophonic response with very low angular distortion (Fig.13). Unfortunately, hypercardioid directivity patterns are rarely well maintained on the side of the microphones and even less so behind . Low frequency response is of course even worse than with cardioids.

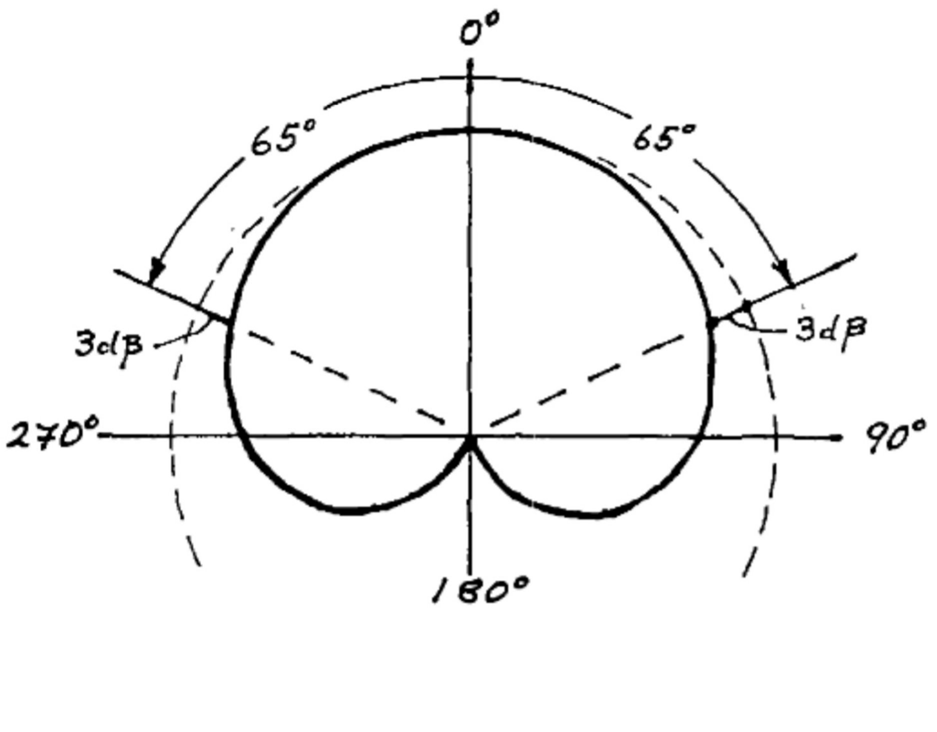
v) Coincident bi-directional microphones at 90° have been used for some time (since the Blumlein patent in 1934) for stereophonic recording. However, **spaced** bi-directional microphones at various angles between microphones can produce some very useful results (Fig. 14). It must be noted that Intensity Difference information is in opposition to *Time Difference information* behind the microphone pair. This zone of more or less compensated stereo can in fact be used to produce some interesting effects (as with any other directivity patterns working in compensation).

Angular distortion is very low, Standard Deviation even becoming negative; corresponding to squeezing of the sound image in the middle of the sound base.

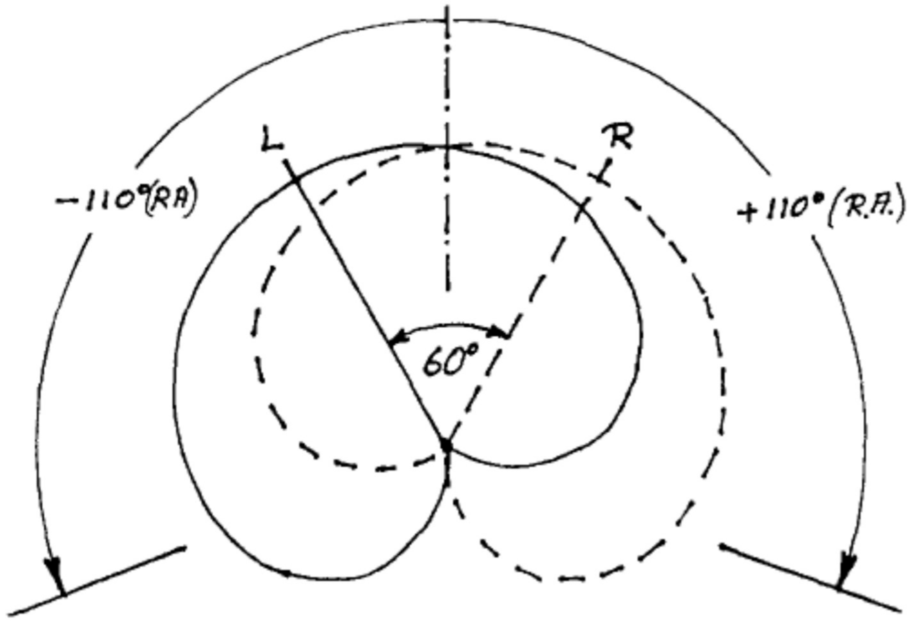
(IV) Ratio of Direct to Reverberant Sound

The ratio of direct to reverberant sound can vary within a given recording situation and become a limiting factor in using certain combinations of distance and angle between microphones.

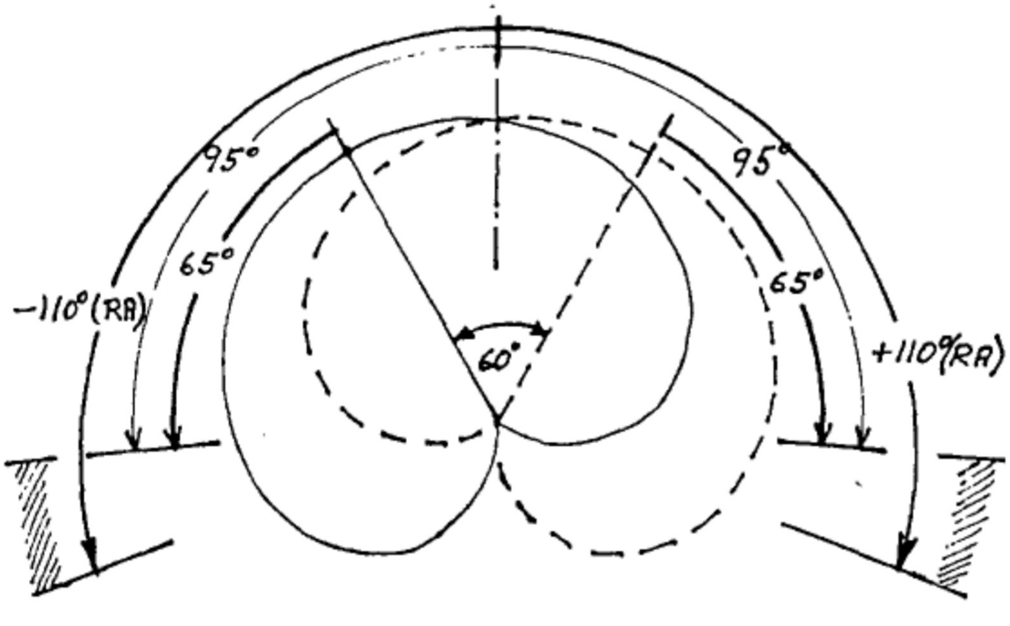
When one listens to a sound souce at an angle greater than about 65° to the axis of a single cardioid microphone, it is posible to detect a decrease *in direct sound with relation to the fixed level of* reverberant sound. This limit of 65° is of course subjective and small variations will be found with different subjects. (The response of the cardioid at 65° is about -3db)



This same limit of 65° can also be applied to a microphone pair. If we consider a pair of coincident microphones with, for example, an angle of 60° between the axis of the cardioids, we should normally obtain a Recording Angle of about +/- 110°.



However, if we consider the direct to reverberant sound limit at 65° to the cardioid axis, we have a usable Recording Angle of only 95°.



Therefore, from 95° to 110° we will begin to hear a decrease in the ratio of direct to reverberant sound and therefore have the impression the the sound source is receding.

In order to avoid this difficulty we must choose combinations of distance and angle so that :-

$$\text{Recording Angle} < \frac{\text{angle between mics}}{2} + 65^\circ$$

For a coincident pair of microphones, this relationship is fulfilled when the angle between the microphones(B) is about 80 degrees.

B/2 = 40, B/2 + 65° = 105°
Recording Angle for B= 80° is about +/- 100 degrees.

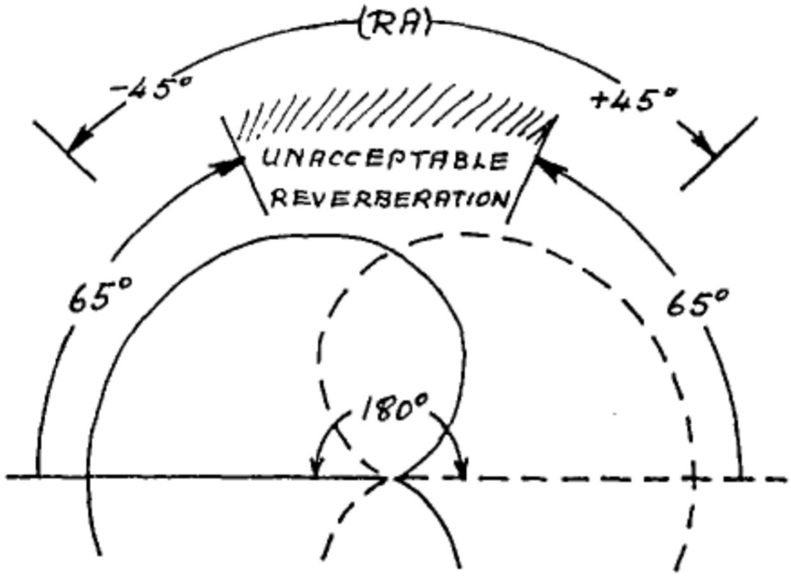
The ratio of direct to reverberant sound becomes unacceptable after we have passed this Recording Angle limit. This same relationship also applies to spaced pairs, no matter what the distance is between microphones:

$$\text{Recording Angle} < \frac{\text{Angle between mics}}{2} + 65^\circ$$

We can plot this relationship across the bottom of Fig. 11 to obtain the lower limits of distance and angle for various microphone pairs.

The same situation occurs, but in reverse, when the angle between the microphone pair is greater than a certain limit.

Suppose we have 180° angle between microphones :



For a coincident pair of cardioid microphones, the Recording Angle is about +/- 45° in relation to axis of the pair. Therefore,an unacceptable ratio of direct to reverberant sound occurs in the centre of the sound base and covers the majority of the Recording Angle.

To avoid this problem one has to accept that the angle between the microphones must not be more than 130 degrees (2x65 degrees), no matter what distance there is between microphones. This "no go" area is also indicated by shading above an angle of 130°in Fig.11.

The same analysis can be applied to Hypocardioids, Hypercardioids and Figure of Eight microphones. The critical point is still -3db and we can see in figs.12, 13 and 14 the resulting shaded areas that limit our choice of distance and angle between microphones.

Conclusion: In choosing a combination of distance and angle for a given Recording Angle, we must in general observe two conditions:

(i) choose a combination of distance and angle with a reasonable minimum angular distortion.

(ii) avoid the shaded areas where reverberation "creeps" into the recording angle.

However, angular distortion can have some useful applications. It is also possible to use the "reverberation effect" in special circumstances (increase in reverberation giving an impression of the source receding).

(IV) Variation of Recording Angle with Elevation.

We now have a reasonably complete picture of the characteristics of various microphone systems in the horizontal plane. It is of course usual to place the sound source(s) as near as possible to this horizontal plane.

However, in certain circumstances it is sometimes necessary to record sound sources well away from this horizontal plane. When recording sound effects and environmental sound, the sounds may come from almost any direction, and of course reverberation almost completely surrounds the microphone pair.

It is therefore necessary to have a good idea of how the characteristics of a given microphone pair vary at various elevations and perhaps to choose certain combinations of distance and angle to control to a certain extent what happens above, below and behind the microphones. However, it is beyond the scope of this paper to study every aspect of these variations.

The Recording Angle is, of course, the first stereophonic characteristic that is of interest to us. Figs.15, 16, 17 and 18 show the variation of Recording Angle using cadioid microphones for various values of elevation, Recording Angle in the horizontal plane being kept constant, whilst various combinations of angle and distance are tried. The amount of information to be shown on this type of graph is very difficult to represent without loosing sight of the wood for the trees! So I have kept the number of steps in the changing parameters to a minimum.

What deductions can we make from these elevation characteristics?

Our appreciation of the ratio of direct to reverberant sound now becomes a little more difficult to describe. We can now distinguish between two types of reproduction of indiret sound or reverberation. As with direct sound sources, we have both coherent and non coherent reproduction, i.e. the coherent reproduction produces a virtual image of the original sound source within the reproducing sound base (between the two loudspeakers), whilst non coherent reproduction is concentrated at the extremities of the sound base (on the left and/or the right loudspeaker).

Therefore, depending on the variation of recording angle with elevation, we can have more or less coherent reverberation, i.e. more or less reverberation reproduced between the loudspeakers. We can say in general that if the quantity and quality of reverberation is acceptable, then it can be reproduced between the loudspeakers (coherent) to good advantage. This means that we must choose a system with as much angle between the microphones as possible. However, the more it becomes a negative factor, the more we must try to "push it to each side" to leave the main sound sources as free as possible. In this case the system must have an angle between the microphones as small as possible.

Our appreciation of the ratio of direct to reverberant sound now becomes the appreciation of the ratio of

$$\frac{\text{direct}}{\text{coherent indirect}} \text{ plus } \frac{\text{direct}}{\text{non coherent indirect}}$$

We are now completely within the individual choice of the sound engineer. It is his subjective decision which will determine the choice of direct to coherent and non coherent indirect sound and therefore the distance and angle for a given recording angle.

However the situation is slightly different if we are concerned by a specific event in environmental sound, or sound sources distributed over a large surface in relation to the microphones. We must remain within the front sector of elevation as here the recording angle varies very much less than behind the microphones. This means that a change in the direction of the microphone pair in the vertical plane has very little effect on the reproduced sound image. A good example of this is in recording an opera using only one pair of microphones, where the position adopted is above the orchestra and directed towards the stage. The recording angle presented to the orchestra will be approximately the same as that covering the stage. As to the desirability of one microphone pair for orchestra and stage, that is another matter and again depends on one's personal preference.

(V) Pratical application to stereophonic sound recording.

The sound recording engineer now has control over the majority of the characteristics of a microphone pair. The order in which he chooses to consider each characteristic in a specific recording situation is again a matter of personnel preference. However I would like to suggest a possible approach.

(i) Microphone position:
Choice of directivity is perhaps the most important factor in the whole process. Frequency response in the bass frequencies is almost completly dependent on this choice. Once microphone directivity has been determined, the desired ratio of direct to reverberant sound will dictate the position of the microphone. Little attention to Recording Angle is necessary at this stage, however nothing prevents adjustment of the recording angle at the same time

(ii) Recording Angle:
The position of the microphone obviously determines the Recording Angle - it is simply a matter of measuring the angle presented by the sound sources plus any margin one wishes to leave on each side.

(iii) Standard Deviation:
We now have to decide within certain limits on the amount of angular distortion that we can accept. In most cases we are looking for a minimum of standard deviation. In which case, reference to the appropriate graph (appropriate to the directivity used) will give us the <u>unique</u> combination of distance and angle between the microphones.

(iv) Distribution of Reverberation:
The ratio of coherent to non coherent reverberation is of course predetermined by the preceeding considerations.

(v) Compromise, Preferences, or Preconceived Ideas:
The next stage is one of compromise. Modification of just one of these characteristics will produce a corresponding shift in the others. Also, any preferences or preconceived ideas can dictate the choice of one of these characteristics to the detriment of the others, or simply change the order of priority.

(VI) Notes on the comparison of Stereophonic Microphone Systems.

Here are the characteristics of the fixed systems at present used for stereophonic sound recording:

X/Y - Coincident cardioids at 90 degrees.
- ---- Recording Angle is +/- 90 degrees (180 degrees in all)
- ---- Standard Deviation is about 6 degrees
- ---- Recording Angle constant (+/-90°) up to 90° elevation, gradually reducing to +/- 20° at 180° elevation.

Coincident Figure of Eights at 90 degrees.
- ---- Recording Angle is +/- 45 degrees (90 degrees in all)
- ---- Standard Deviation is about 5 degrees
- ---- Four equal sectors of stereo pick up

A/B (ORTF)- Cardioids at 17cms and 110 degrees.
- --- Recording Angle is +/- 50 degrees (100 degrees in all)
- --- Standard Deviation is about 5 degrees
- --- Recording Angle diminishing gradually to +/- 20° at the back of the pair (180° elevation).

A/B (NOS) - Cardioids at 30cms and 90 degrees.
- --- Recording Angle is +/- 40 degrees (80 degrees in all)
- --- Standard Deviation is less than 4 degrees
- --- Recording Angle diminishing gradually to +/- 15° at the back of the pair.

Omnis at 50cms (for example)
- --- Recording Angle is +/- 50 degrees (100 degrees in all)
- --- Standard Deviation is about 8 degrees
- --- Recording Angle is constant at all elevations

I think the differences between these individual systems speak for themselves without even considering the different frequency reponses. There are so many characteristics that are different from one system to another that no useful information can be determined by direct comparaison.

However, it is now possible to construct an experiment to study the contribution of Time Difference and Intensity Difference to the subjective quality of a stereophonic sound recording.

It is obvious that directivity and Recording Angle must be the same in any comparison between microphone pairs, so that microphone position and the total quantity of reverberation do not change from one to the other. Combinations of distance and angle can also be chosen so that standard deviation remains constant.

For example, a coincident pair of cardioid microphones at an angle of 90 degrees can be compared to a pair of spaced cardioids at 20cms and an angle of 30 degrees. The recording angle is +/- 90 degrees, Standard Deviation is 6 degreees and the limit to acceptable reverberation is just at the limit of Recording Angle. Evolution of Recording Angle with elevation is very similar for both pairs.

If smaller recording angles are desired then 10cms/130 degrees can be compared with 37cms/30 degrees. R.A. is +/- 50 degrees and Standard Deviation is about 5.7 degrees, however variation of Recording Angle with elevation is not quite the same.

I have chosen extreme values to give the maximum chance of hearing something! IF you have been able to detect a difference with these extreme values, less extreme values are much easier to set up.

However, I think the best chance of understanding this highly complex subject will come from collaboration between sound recording engineers and psychoacoustical experts working in the universities. There are three aspects of this work that I think important and need to be studied.

i) The work done by Simonsen needs to be expanded in a number of respects. Intensity Difference and Time Difference information were studied only in the positive sector. This information needs to be developed in the compensated sectors were Intensity Difference information is in opposition to Time Difference information. It would also be interesting to have intermediate values of apparent angles of reproduction at say 5° intervals. It is also important to confirm these results with detailed statistical analysis of a large number of subjects. I would like to stress two important aspects of Simonsen's work. One is the use of natural sound sources. The other is the way in which the standard stereophonic sound recording system was used for all measurements.

ii) Anybody who has worked in this field knows that perception of Intensity Difference information is different to perception of Time Difference information. It would be interesting to know if these psychoacoustical characteristics vary throughout the frequency range. This might solve some of the problems concerning dispersion of the sound image.

iii) The function of group propogation time as against purely phase effects still cause considerable confusion. In the stereophonic system in use is there any contradiction between these two factors? This also could explain certain dispersion problems or instability in the sound image.

Postscript

The calculation of all these characteristics would be absolutely impossible without the help of a computer. If you wish to reproduce the theoretical basis of this work or continue its development in the light of new measurements, I have included at the end of this paper, the programme I used to calculate the main characteristics. I am a sound recording engineer not a computer programmer, so I ask you to make allowances for what is neither the neatest nor the most efficient of programmes. For this reason any suggestions that might improve its performance or presentation would be welcome.

This paper presents the theoretical basis on which the unified theory of microphone systems for stereophonic sound recording was developed. The calculation of the purely physical characteristics of a microphone pair would be of little interest, if it were not for the interaction with psychoacoustical measurements carried out at the Acoustical Laboratory, Lyngby in Denmark. Experimental verification and "in the field" recording has been carried out not only by myself as a sound engineer, but also by my colleagues and students at the INSTITUT NATIONAL D'AUDIOVISUEL, the ECOLE NATIONALE de PHOTO et CINEMA (ECOLE LOUIS LUMIERE) in Paris, and at RADIO MONTECARLO in Monaco.

References:

(1) Section 1 of this paper (Derivation of the Recording Angle in the horizontal plane) is an update of the paper I presented to the A.E.S. in March 1984 in Paris entitled "The Stereophonic Zoom".

(2) H.Mertens, Revue du Son, 1966.

(3) G.Simonsen, Master's Thesis, October 1984, Lyngby, Denmark.

Michael Williams
January 1987

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#                                                                               #
#                   UNIFIED THEORY OF MICROPHONE SYSTEMS                        #
#                     FOR STEREOPHONIC SOUND RECORDING                          #
#                          by Michael Williams                                  #
#                          (A.E.S.   March 87)                                  #
#                                                                               #
#################################################################################
#                                                                               #
#                 RECORDING ANGLE AND ANGULAR NON-LINEARITY                     #
#                 IN THE HORIZONTAL PLANE AND IN ELEVATION.                     #
#                                                                               #
#           Developed on an ATARI 1040 using GFA Basic (no 110196)              #
#                                                                               #
#################################################################################
##  MAINPROGRAM # MAINPROGRAM # MAINPROGRAM # MAINPROGRAM # MAINPROGRAM  ##
#################################################################################
 Gosub Initialization
iosub Directivitycode
'itlew 2," RECORDING ANGLE AND STANDARD DEVIATION IN THE HORIZONTAL PLANE "
iosub Horizontal.recording.angle
'itlew 2," VARIATION OF RECORDING ANGLE AS A FUNCTION OF ELEVATION "
iosub Elevation.recording.angle
:nd
#################################################################################
# subroutines ## subroutines ## subroutines ## subroutines ## subroutines #
#################################################################################
'rocedure Directivitycode
  Fullw 2
  Clearw 2
  Deftext 1,0,0,13
  Print "              - COEFICIENTS FOR MICROPHONE DIRECTIVITY -"
  Print
  Print "              - Hypocardioid microphones ----- 2"
  Print "              - Cardioid microphones --------- 1"
  Print "              - Hypercardioid microphones --- 0.5"
  Print "              - Figure of eight microphones -- 0"
  Print
  Print "              You can modify these coeficients if you "
  Print "              require intermediate directivity patterns."
  Print
  Print "              What is the directivity coeficient of"
  Input "              the microphones you wish to use ?  --> ",F
  Clearw 2
Return
```

```
' ################################################################
Procedure Horizontal.recording.angle
  ' **************************************************************
  ' *                                                            *
  ' *        VARIATION OF RECORDING ANGLE AND ANGULAR NON-LINEARITY    *
  ' *                    IN THE HORIZONTAL PLANE                     *
  ' *                                                            *
  ' **************************************************************
  ' *                                                            *
  ' *          ------------------ First Step ---------------------    *
  ' *            Calculation of distance between microphones given     *
  ' *          the recording angle and the angle between microphones   *
  ' *            "RA" = Recording Angle                              *
  ' *             "B" = Angle between microphones                    *
  ' *             "D" = Distance between microphones                 *
  ' *             "W" = Indice for apparent angle of reproduction    *
  ' *                                                            *
  ' **************************************************************
  Gosub Axes1
  For Ra%=90 To 20 Step -10
    X2=0
    B%=0
    For B%=0 To 180
      X1=X2 ! ****************************************    Preceeding graph
      Y1=Y2 ! ************************************** coordinates memorized
      A=Ra%
      E%=0  ! ********************************************* Horizontal plane
      Gosub Intensity
      W=30  ! *********** Selection code for 30 degree psychoacoustical curve
      Gosub Psychotime
      Gosub Distance
      X2=D        ! ******************************************** New graph
      Y2=B%       ! ******************************************* coordinates
      If D>50 Or D<0 Then!"D"is outside the upper or lower limit of the Xaxis
        Goto Jump1        ! so avoid return scan by going to next coordinate
      Endif
      If Y1=180 Then ! ******** Avoid return scan by going to next coordinate
        Goto Jump1
      Endif
      ' ************************************************************
      ' *                                                          *
      ' *          ---------------- Second Step ---------------------  *
      ' *           Calculation of non-linearity of microphone pair and   *
      ' *                 determination of "standard deviation"          *
      ' *                                                          *
      ' ************************************************************
      W=20   ! ********** Selection code for 20 degree psuchoacoustical curve
      Gosub Intercept
      Ac2a=Ac2b ! *************************** Previous value of Ac2 memorized
      Ac2b=A-(Ra%*0.6666) ! *********** Difference w.r.t. linear reproduction
      W=10   ! ********** Selection code for 10 degree psychoacoustical curve
      Gosub Intercept
      Ac1a=Ac1b ! *************************** Previous value of Ac1 memorized
      Ac1b=A-(Ra%*0.3333) ! *********** Difference w.r.t. linear reproduction
      Gosub Interpolation
      Gosub Standard.deviation
      Jump1:
    Next B%
  Next Ra%
  Hardcopy
  Clearw 2
Return
```

```
' ################################################################################
Procedure Elevation.recording.angle
  ' ****************************************************************************
  ' *                                                                          *
  ' *        VARIATION OF RECORDING ANGLE AS A FONCTION OF ELEVATION           *
  ' *                                                                          *
  ' ****************************************************************************
  ' *                                                                          *
  ' *          Calculation of distance between microphones given               *
  ' *        the recording angle and the angle between microphones             *
  ' *          "RA" = Recording Angle                                          *
  ' *           "B" = Angle between microphones                                *
  ' *           "D" = Distance between microphones                             *
  ' *           "W" = Indice for apparent angle of reproduction                *
  ' *                                                                          *
  ' ****************************************************************************
  For Ra%=90 To 30 Step -15
    Gosub Axes2
    X2=0
    For B%=20 To 180 Step 20
      A=Ra%
      E%=0
      Gosub Intensity
      W=30
      Gosub Psychotime
      Gosub Distance
      If D>50 Or D<0 Then!"D"is outside the upper or lower limit of the Xaxis
        Goto Jump3
      Endif
      Gosub Elevation ! *************** This is where the real work is done !
      Jump3:
    Next B%
    Hardcopy ! *************************************** Copy screen to printer
    Clearw 2
  Next Ra%
Return
' ################################################################################
' ################################################################################
Procedure Intensity
  ' ****************************************************************************
  ' *                                                                          *
  ' *      Calculation of Intensity Difference between two microphones        *
  ' *         -  "A" = sound source position                                   *
  ' *         -  "B" = angle between the axis of the microphones               *
  ' *         -  "E" = elevation angleof sound source                          *
  ' *         -  "F" = directivity indice (see initial input conditions)       *
  ' *                                                                          *
  ' ****************************************************************************
  Local L,R,X,Y,Z
  V=Pi/180
  X=A*V
  Y=(B%/2)*V
  Z=E%*V
  L=F+Sin(X)*Sin(Y)+Cos(X)*Cos(Y)*Cos(Z)
  R=F+Sin(X)*Sin(-Y)+Cos(X)*Cos(-Y)*Cos(Z)
  Di=1-(R/L)
Return
```

```
' ##########################################################################################
Procedure Psychotime
  ' ****************************************************************************************
  ' *                                                                                      *
  ' *   -----------------  Psychoacoustical curves  ----------------------                 *
  ' *                                                                                      *
  ' *   - Time Difference expressed as a function of Intensity Difference -               *
  ' *   ---------- for various apparent angles of reproduction -----------                 *
  ' *                                                                                      *
  ' *   "W" is identification code to select the 10, 20 or 30 degree curve                *
  ' *                                                                                      *
  ' ****************************************************************************************
  If W=30 Then
    Dt=-1.79*Di^3+1.913*Di^2-1.726*Di+1.12
  Endif
  If W=20 Then
    Dt=-1.079*Di^3-1.65*Di^2+0.101*Di+0.439
    Goto Finish
  Endif
  If W=10 Then
    Dt=-22.856*Di^3+3.857*Di^2-0.336*Di+0.2
    Goto Finish
  Endif
  Finish:
Return
' ##########################################################################################
Procedure Time
  ' ****************************************************************************************
  ' *                                                                                      *
  ' *        Calculation of time difference between two microphones                       *
  ' *                 "D" = distance between microphones                                   *
  ' *                 "A" = sound source position                                          *
  ' *                                                                                      *
  ' ****************************************************************************************
  T=(D*Sin(A*0.0174533))/34
Return
' ##########################################################################################
Procedure Distance
  ' ****************************************************************************************
  ' *                                                                                      *
  ' *        Calculation of distance between two microphones given                         *
  ' *        the value of time difference and sound source position                        *
  ' *                                                                                      *
  ' ****************************************************************************************
  D=(34*Dt)/Sin(A*0.0174533)
Return
```

```
' ##########################################################################
Procedure Intercept
  ' ************************************************************************
  ' *                                                                      *
  ' *       Calculation of the intersection between the psychoacoustical  *
  ' *       curve for 30 degrees apparent angle of reproduction and the    *
  ' *       physical curve (intensity and time difference) for the given   *
  ' *       angle and the calculated distance between the microphones      *
  ' *                    "K" = precision of loop                           *
  ' *                                                                      *
  ' ************************************************************************
  A=0
  K=5 ! ************************************************************ Test step
  Do
    Add A,K
    Gosub Intensity
    Gosub Psychotime
    Gosub Time
    Exit If Int(Dt*10000+0.5)=Int(T*10000+0.5)
    K=(((-1.12*A)/((Dt-T)-1.12))-A)*0.5 ! **** Calculation of automatic step
  Loop
Return
' ##########################################################################
Procedure Interpolation
  ' ************************************************************************
  ' *                                                                      *
  ' *             Calculation of curve passing through origin, intercept   *
  ' *             values A10 and A20, and R.A., to within one degree.      *
  ' *                  "K" = amplitude of sinus function                   *
  ' *                  "L" = assymetrie of sinus function                  *
  ' *                  "G" = precision of determination in loop            *
  ' *                                                                      *
  ' ************************************************************************
  If Sgn(Ac1b)<>Sgn(Ac2b) Then
    Dev=0
  Endif
  L=1.1547*Atn(1.732*(Ac1b-Ac2b)/(Ac1b+Ac2b))
  K=Ac1b/(Ra%*Sin(1.047+0.866*L))
Return
' ##########################################################################
Procedure Standard.deviation
  ' ************************************************************************
  ' *                                                                      *
  ' *        -------- CALCULATION OF "STANDARD DEVIATION" --------         *
  ' *        ---- Deviation of an assymetrical sinus function ----         *
  ' *        --------- from a linear function (k=0, l=0) ---------         *
  ' *        i.e. Value of the deviation from linear reproduction          *
  ' *        of a sound source situated at half the recording angle        *
  ' *                    from the axis of the pair                         *
  ' *                                                                      *
  ' ************************************************************************
  Q=0
  G=1
  Beginning3:
  Zl=0.5-(Q/Pi)
  Zc=K*Sin(Q+L*Sin(Q))
  If Int(Zl*1000)=Int(Zc*1000) Then
    Goto Jump4
  Endif
```

```
  If Sgn(Zl-Zc)=+1 Then
    Add Q,G
    Goto Beginning3
  Endif
  Sub Q,G
  Div G,10
  Goto Beginning3
  Jump4:
  Dev=((Q-1.571)*180/Pi)/6
  Dev1=Dev2 ! ****************************** Previous value of "Dev" memorized
  Dev2=Dev  ! ******************************************** New value of "Dev"
  Gosub Plot
  If Y1=0 Or Y2=180 Then
    Goto Jump6           ! ************** Otherwise a false deviation will be
  Endif                  ! ************** plotted on the return scan
  If Int(Dev1)=Int(Dev2) Then ! *********************  do not print deviation
    Goto Jump6
  Endif
  If Int(Dev1)<Int(Dev2) Then ! ************  the deviation is now increasing
    U=48+Int(Dev2)
    Goto Jump5
  Endif
  U=48+Int(Dev1) ! *********** "U" is ASCII value of deviation (whole number)
  Jump5:
  Deftext 1,1,0,6   ! **************** Size of print for "standard Deviation"
  Text Xof+X1*Xcf-2,Yof-Y1*Ycf+2,1,Chr$(U)  ! **** Print "Standard Deviation"
  Jump6:
Return
' ###########################################################################
Procedure Elevation
  ' *************************************************************************
  ' *                                                                       *
  ' *     Angle and Distance having been determined for a given             *
  ' *     Recording Angle in the Horizontal Plane, the variation            *
  ' *     of Recording Angle can be determined as a fonction of             *
  ' *     Elevation (Angle and Distance remaining constant)                 *
  ' *           "E" = angle of elevation of sound source                    *
  ' *                                                                       *
  ' *************************************************************************
  E=0
  For E%=0 To 180 Step 1
    X1=X2 ! ******************************************    Preceeding graph
    Y1=Y2 ! ***************************************  coordinates memorized
    If X1<0 Then ! do not try analysing compensated stereo
      Goto Jump2
    Endif
    W=30
    Gosub Intercept
    X2=A  ! *********************************  "A" is new Recording Angle
    Y2=E%  ! ********************************     at Elevation "E"
    If X1=0 Or Y1=180 Then ! supress return scan
      Goto Jump2
    Endif
    Gosub Plot
    Jump2:
  Next E%
Return
```

```
' ##############################################################################
Procedure Axes1
  Xof=55           !******************** X AXIS OFFSET in pixels
  Xcf=11.3         !******************** X CONVERSION FACTOR (degrees to pixels)
  Yof=325          !******************** Y AXIS OFFSET in pixels
  Ycf=1.75         !******************** Y CONVERSION FACTOR (degrees to pixels)
  Gosub Xaxis1
  Gosub Xscale1
  Gosub Yaxis1
  Gosub Yscale1
Return
' ------------------------------------------------------------------------------
Procedure Axes2
  Xof=55           !******************** X AXIS OFFSET in pixels
  Xcf=6.3            !******************** X CONVERSION FACTOR (degrees to pixels)
  Yof=325          !******************** Y AXIS OFFSET in pixels
  Ycf=1.7         !******************** Y CONVERSION FACTOR (degrees to pixels)
  Gosub Xaxis2
  Gosub Xscale2
  Gosub Yaxis2
  Gosub Yscale2
Return
' ------------------------------------------------------------------------------
Procedure Xaxis1
  For X=0 To 50 Step 5
    Line Xof+X*Xcf,Yof+5,Xof+X*Xcf,Yof-180*Ycf
  Next X
  Line Xof-1,Yof-1,Xof-1,Yof-180*Ycf
Return
' ------------------------------------------------------------------------------
Procedure Xaxis2
  For X=0 To 90 Step 10
    Line Xof+X*Xcf,Yof+5,Xof+X*Xcf,Yof-180*Ycf
  Next X
  Line Xof-1,Yof-1,Xof-1,Yof-180*Ycf
Return
' ------------------------------------------------------------------------------
Procedure Xscale1
  Deftext 1,16,0,8
  Text Xof-4,Yof+18,-67,"0 5"
  Text Xof+102,Yof+18,-477,"10 15 20 25 30 35 40 45 50"
  Text Xof,358,-550,"--- DISTANCE BETWEEN MICROPHONES (cms)---"
Return
' ------------------------------------------------------------------------------
Procedure Xscale2
  Deftext 1,16,0,8
  Text Xof-4,Yof+18,-16,"0"
  Text Xof+10*Xcf-12,Yof+18,-(80*Xcf+24),"10 20 30 40 50 60 70 80 90"
  Text Xof+30,358,-500,"-------- HALF RECORDING ANGLE --------"
Return
```

```
' -----------------------------------------------------------------------
Procedure Yaxis1
  For Y=0 To 180 Step 10
    Line Xof-5,Yof-Y*Ycf,Xof+50*Xcf,Yof-Y*Ycf
  Next Y
  Line Xof-1,Yof-1,Xof+50*Xcf,Yof-1
Return
' -----------------------------------------------------------------------
Procedure Yaxis2
  For Y=0 To 180 Step 10
    Line Xof-5,Yof-Y*Ycf,Xof+90*Xcf,Yof-Y*Ycf
  Next Y
  Line Xof-1,Yof-1,Xof+90*Xcf,Yof-1
Return
' -----------------------------------------------------------------------
Procedure Yscale1
  Deftext 1,16,0,13
  Text Xof-23,Yof+5,19,"0x"
  Text Xof-30,Yof-20*Ycf+5,27,"20x"
  Text Xof-30,Yof-40*Ycf+5,27,"40x"
  Text Xof-30,Yof-60*Ycf+5,27,"60x"
  Text Xof-30,Yof-80*Ycf+5,27,"80x"
  Text Xof-38,Yof-100*Ycf+5,35,"100x"
  Text Xof-38,Yof-120*Ycf+5,35,"120x"
  Text Xof-38,Yof-140*Ycf+5,35,"140x"
  Text Xof-38,Yof-160*Ycf+5,35,"160x"
  Text Xof-38,Yof-180*Ycf+5,35,"180x"
  Deftext 1,16,900,8
  Text 10,Yof,325,"- ANGLE BETWEEN MICROPHONES -"
Return
' -----------------------------------------------------------------------
Procedure Yscale2
  Deftext 1,16,0,13
  Text Xof-23,Yof+5,19,"0x"
  Text Xof-30,Yof-20*Ycf+5,27,"20x"
  Text Xof-30,Yof-40*Ycf+5,27,"40x"
  Text Xof-30,Yof-60*Ycf+5,27,"60x"
  Text Xof-30,Yof-80*Ycf+5,27,"80x"
  Text Xof-38,Yof-100*Ycf+5,35,"100x"
  Text Xof-38,Yof-120*Ycf+5,35,"120x"
  Text Xof-38,Yof-140*Ycf+5,35,"140x"
  Text Xof-38,Yof-160*Ycf+5,35,"160x"
  Text Xof-38,Yof-180*Ycf+5,35,"180x"
  Deftext 1,16,900,8
  Text 10,Yof,310,"--- ELEVATION ANGLE ---"
Return
' ######################################################################
Procedure Plot ! ******
  Line Xof+X1*Xcf,Yof-Y1*Ycf,Xof+X2*Xcf,Yof-Y2*Ycf
  Line Xof+X1*Xcf,Yof-Y1*Ycf-1,Xof+X2*Xcf,Yof-Y2*Ycf-1
Return
' ######################################################################
```

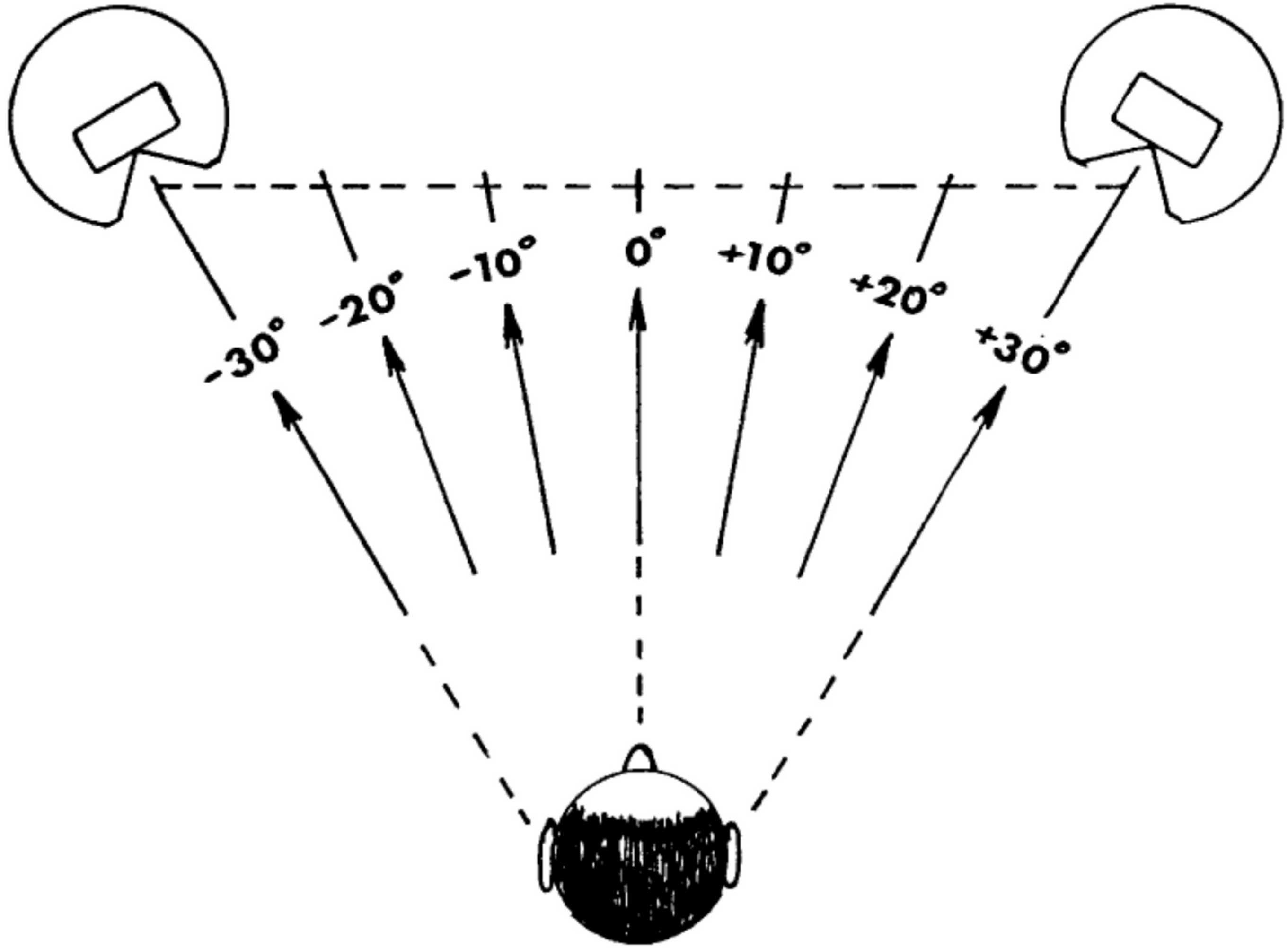


FIG.1

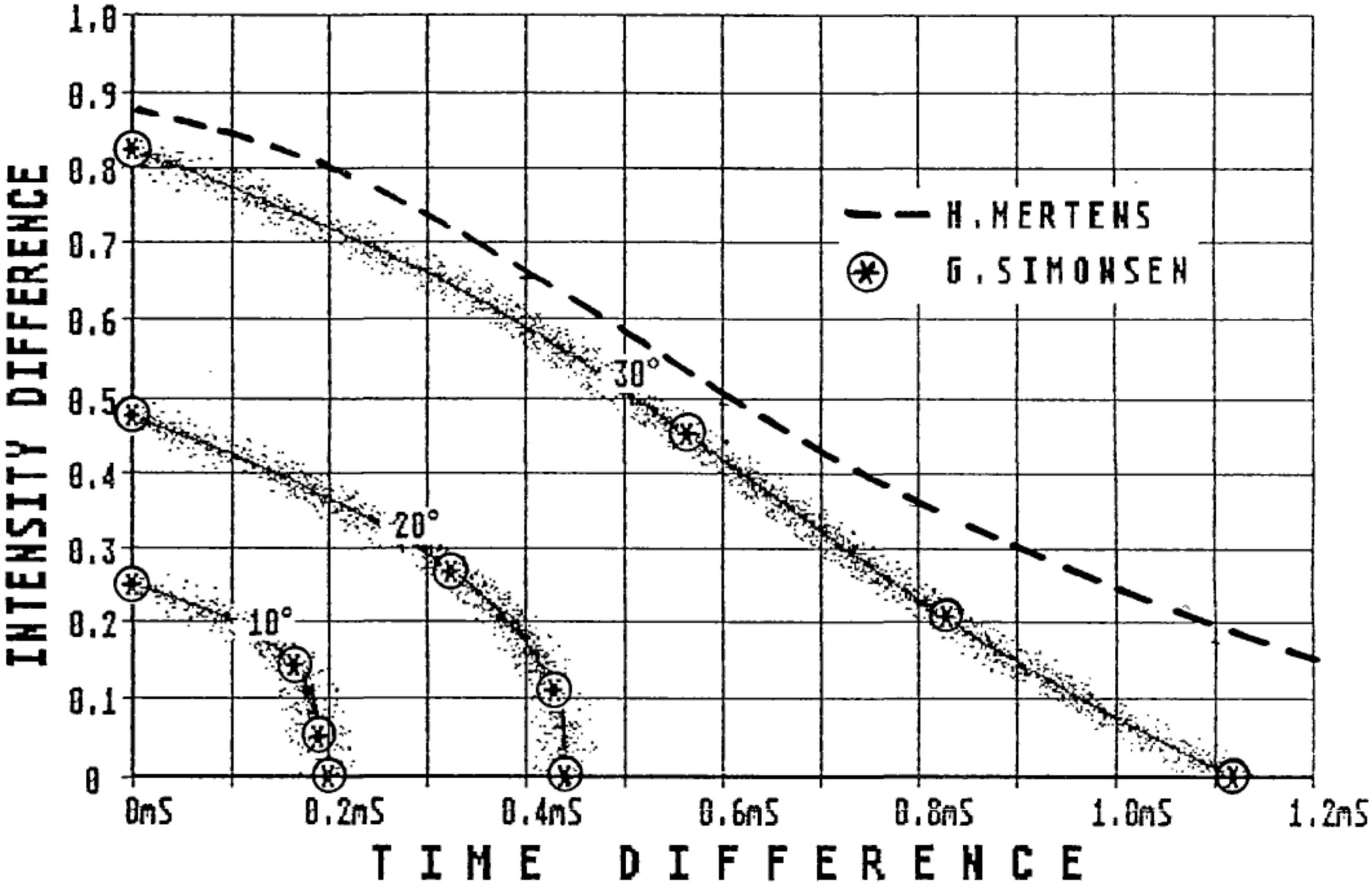
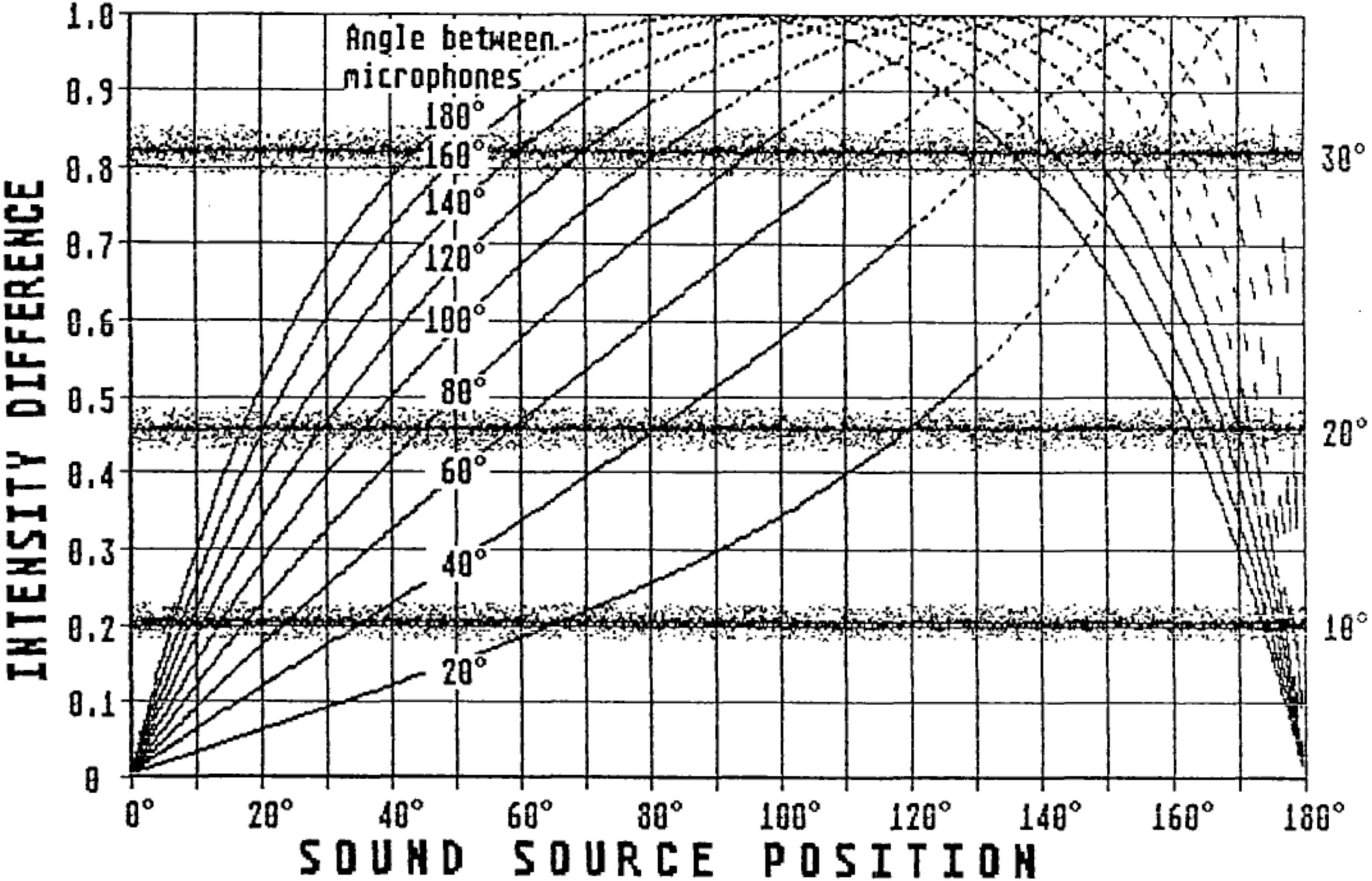

INTENSITY DIFFERENCE
1,0
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
0mS
0,2mS
0,4mS
0,6mS
0,8mS
1,0mS
1,2mS
TIME DIFFERENCE
H.MERTENS
G.SIMONSEN
10°
20°
30°

FIG. 2



INTENSITY DIFFERENCE
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Angle between microphones
180°
160°
140°
120°
100°
80°
60°
40°
20°
30°
20°
10°
0°
20°
40°
60°
80°
100°
120°
140°
160°
180°
SOUND SOURCE POSITION

FIG. 3

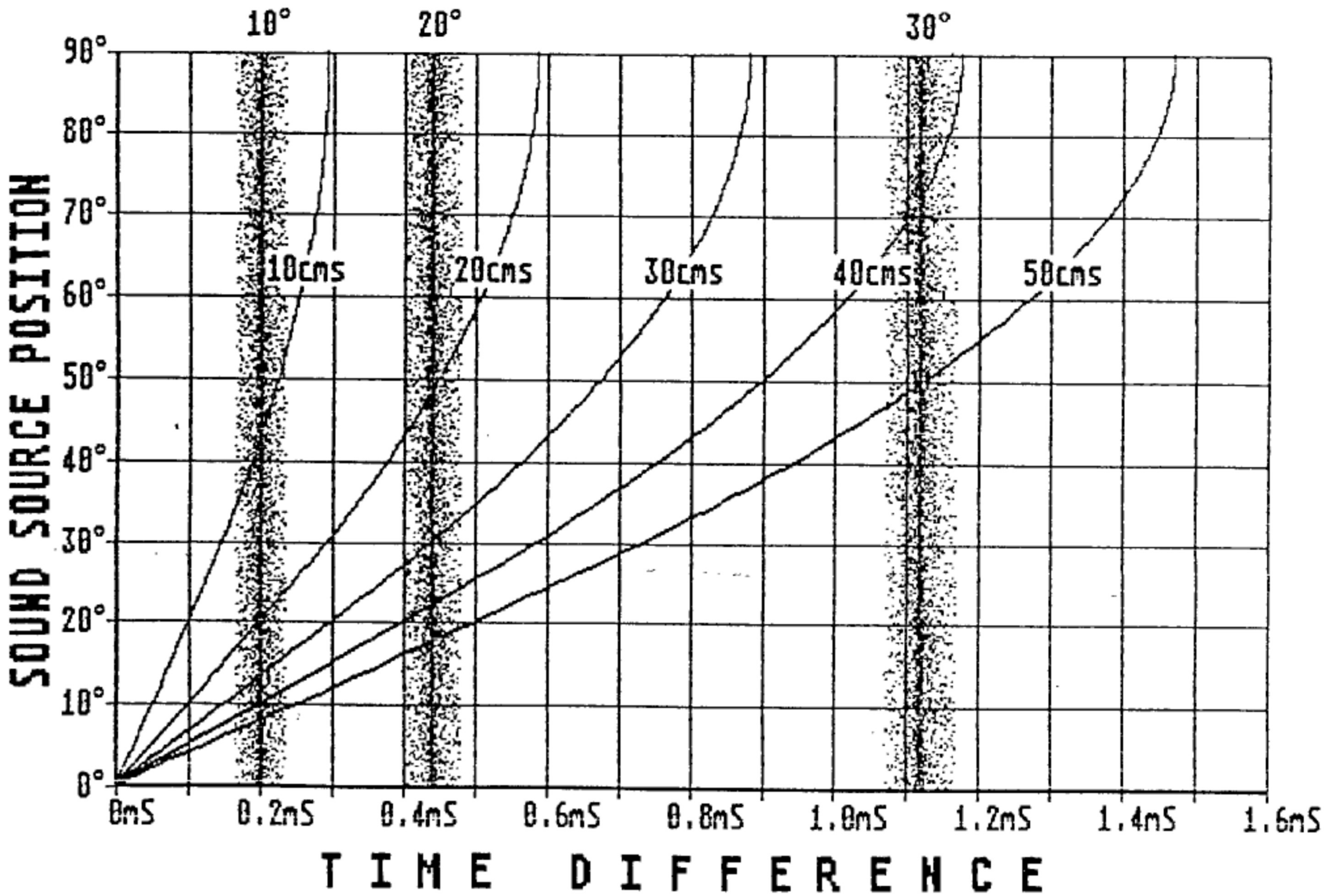
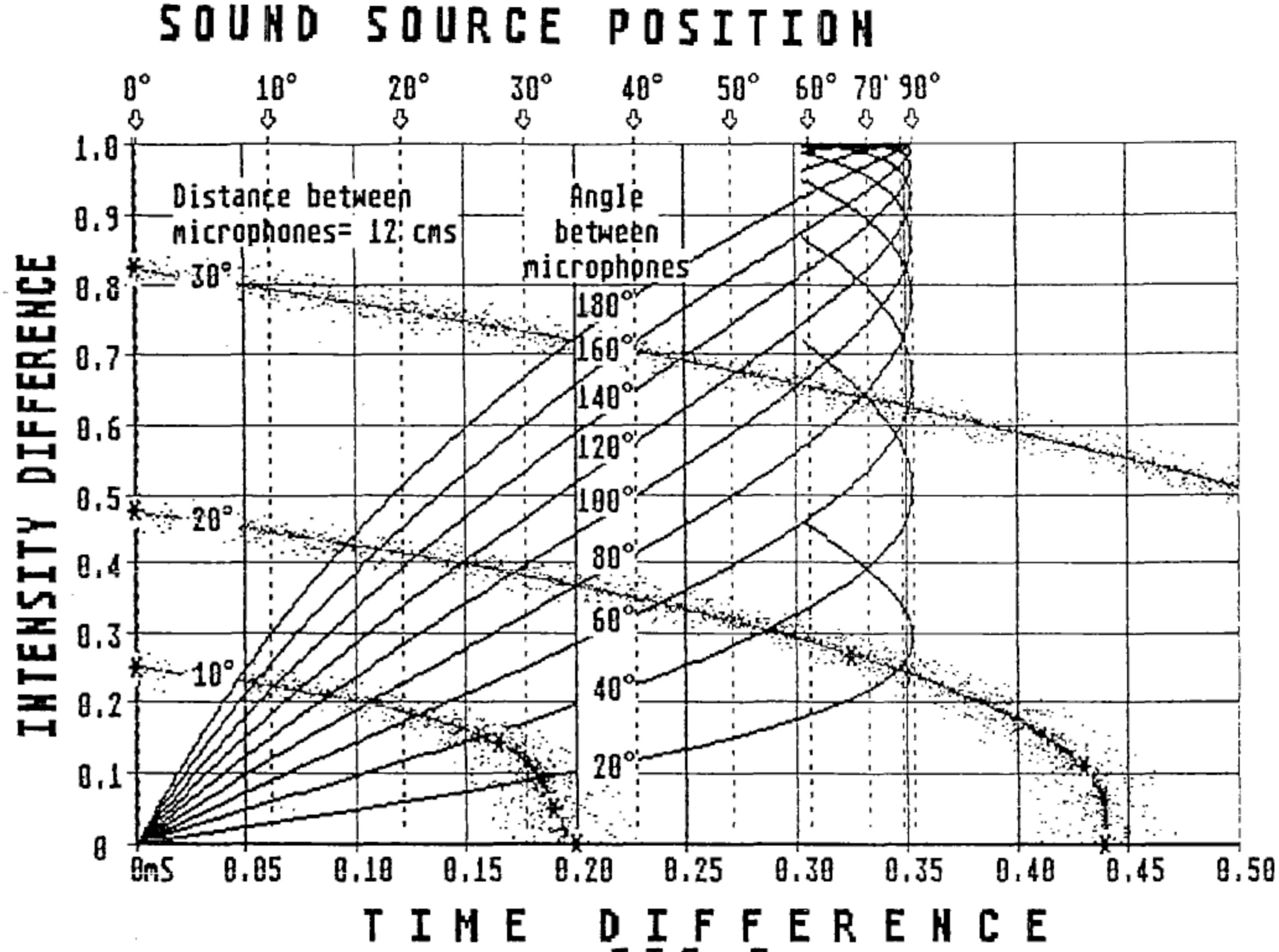

10°
20°
30°
90°
80°
70°
60°
50°
40°
30°
20°
10°
0°
SOUND SOURCE POSITION
10cms
20cms
30cms
40cms
50cms
0mS
0.2mS
0.4mS
0.6mS
0.8mS
1.0mS
1.2mS
1.4mS
1.6mS
TIME DIFFERENCE

FIG. 4



SOUND SOURCE POSITION
0°
10°
20°
30°
40°
50°
60°
70°
90°
Distance between microphones= 12 cms
Angle between microphones
180°
160°
140°
120°
100°
80°
60°
40°
20°
30°
20°
10°
INTENSITY DIFFERENCE
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0mS
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
TIME DIFFERENCE

FIG.5

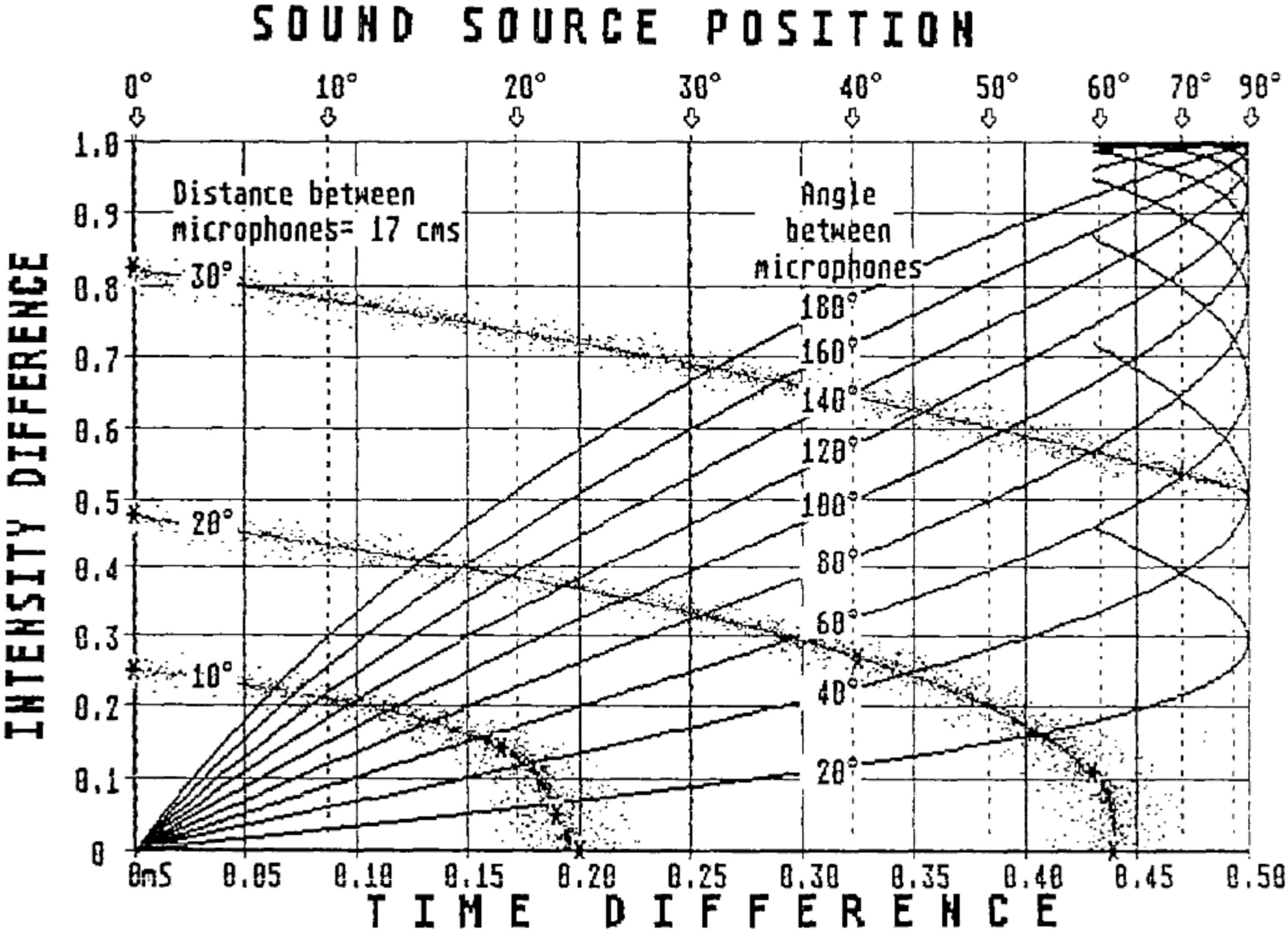

SOUND SOURCE POSITION
0° 10° 20° 30° 40° 50° 60° 70° 90°
INTENSITY DIFFERENCE
1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0
Distance between microphones= 17 cms
30°
20°
10°
Angle between microphones
180° 160° 140° 120° 100° 80° 60° 40° 20°
0mS 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50
TIME DIFFERENCE

FIG. 6

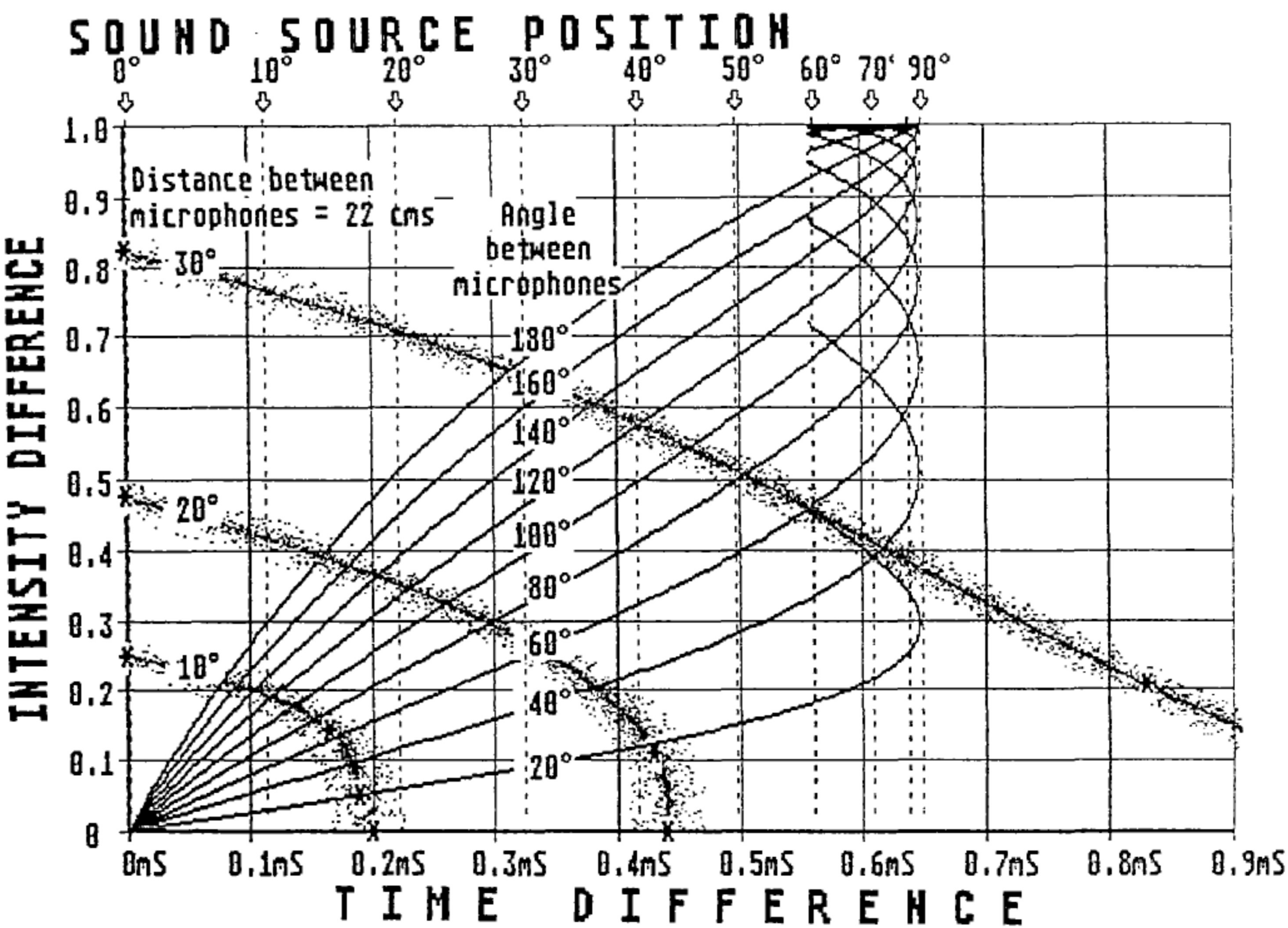

SOUND SOURCE POSITION
0°
10°
20°
30°
40°
50°
60°
70°
90°
INTENSITY DIFFERENCE
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Distance between microphones = 22 cms
Angle between microphones
180°
160°
140°
120°
100°
80°
60°
40°
20°
30°
20°
10°
0mS
0.1mS
0.2mS
0.3mS
0.4mS
0.5mS
0.6mS
0.7mS
0.8mS
0.9mS
TIME DIFFERENCE

FIG.7

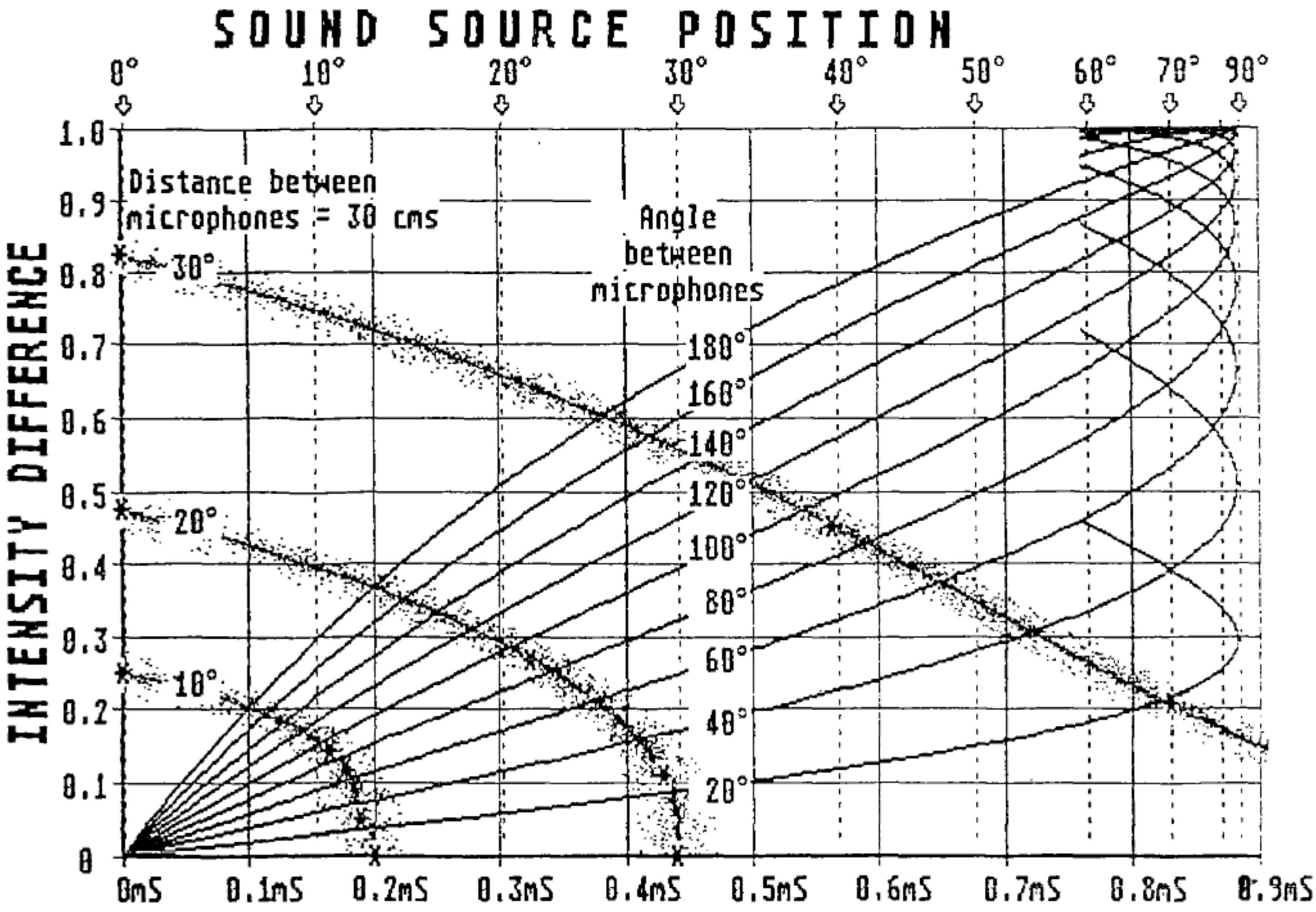

SOUND SOURCE POSITION
0°
10°
20°
30°
40°
50°
60°
70°
90°
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Distance between
microphones = 30 cms
Angle
between
microphones
180°
160°
140°
120°
100°
80°
60°
40°
20°
30°
20°
10°
INTENSITY DIFFERENCE
0mS
0.1mS
0.2mS
0.3mS
0.4mS
0.5mS
0.6mS
0.7mS
0.8mS
0.9mS
TIME DIFFERENCE

FIG.8

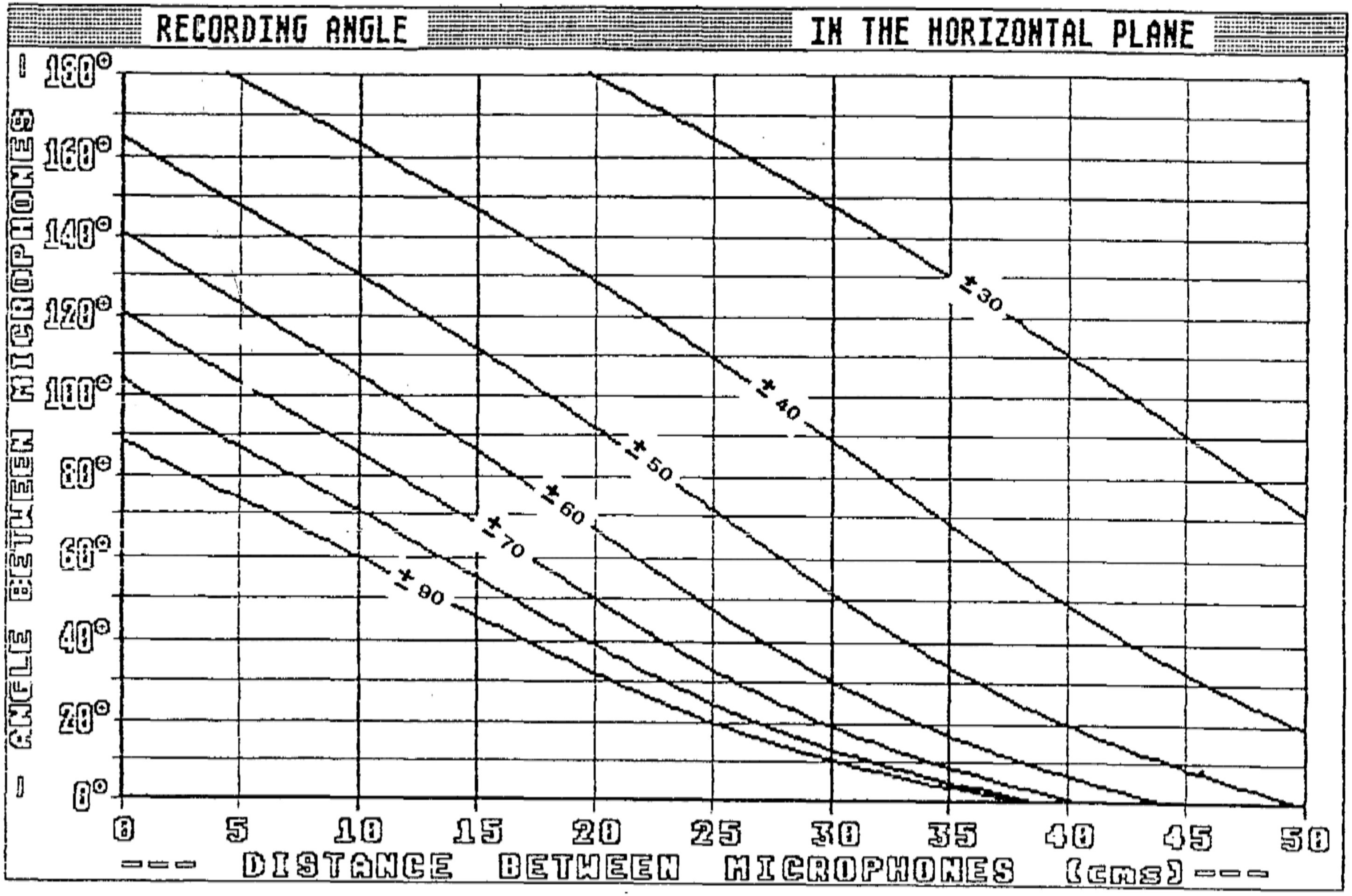

RECORDING ANGLE
IN THE HORIZONTAL PLANE
180°
160°
140°
120°
100°
80°
60°
40°
20°
0°
— ANGLE BETWEEN MICROPHONES —
±30
±40
±50
±60
±70
±80
0
5
10
15
20
25
30
35
40
45
50
--- DISTANCE BETWEEN MICROPHONES (cms) ---

FIG. 9

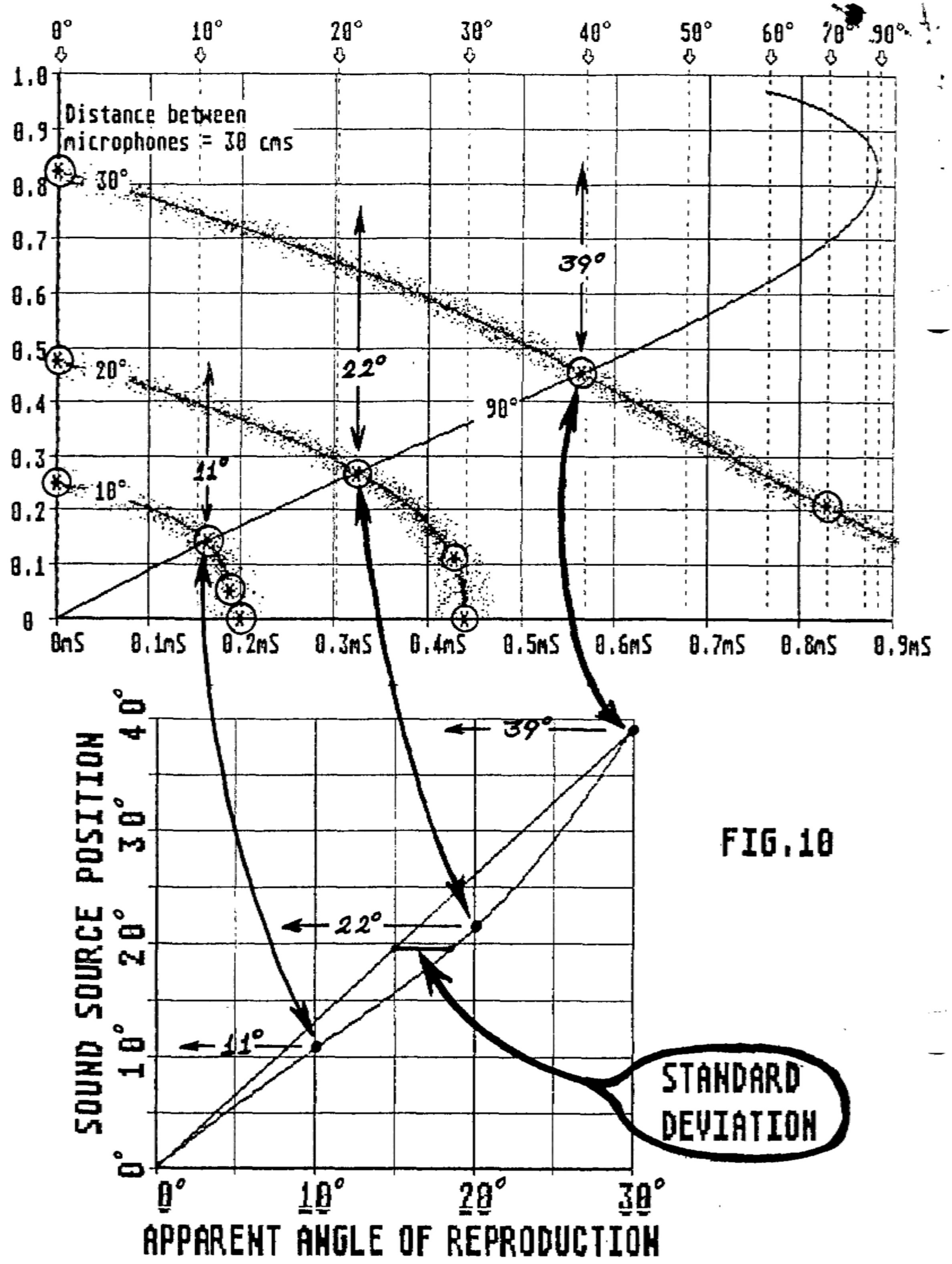
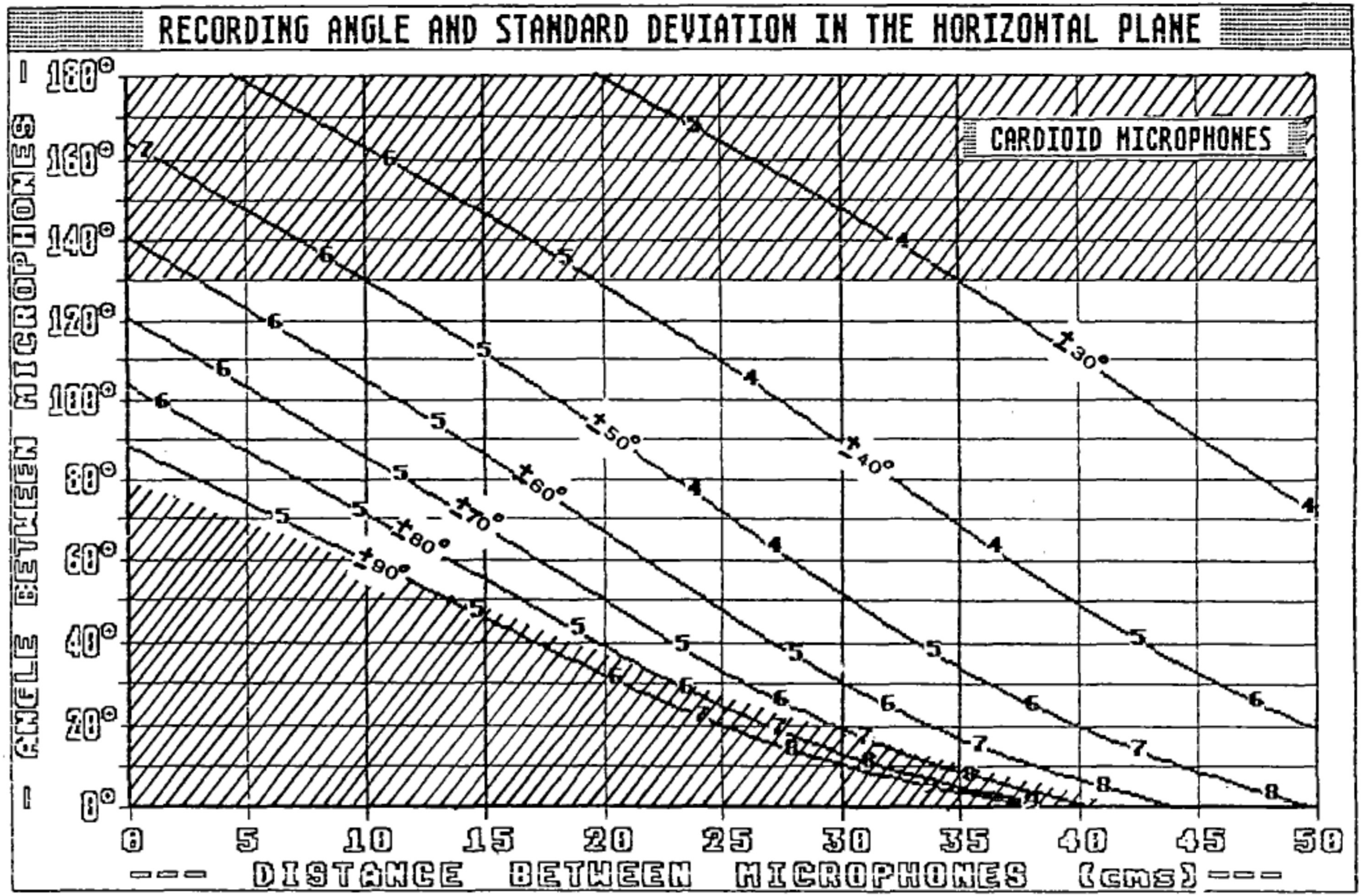
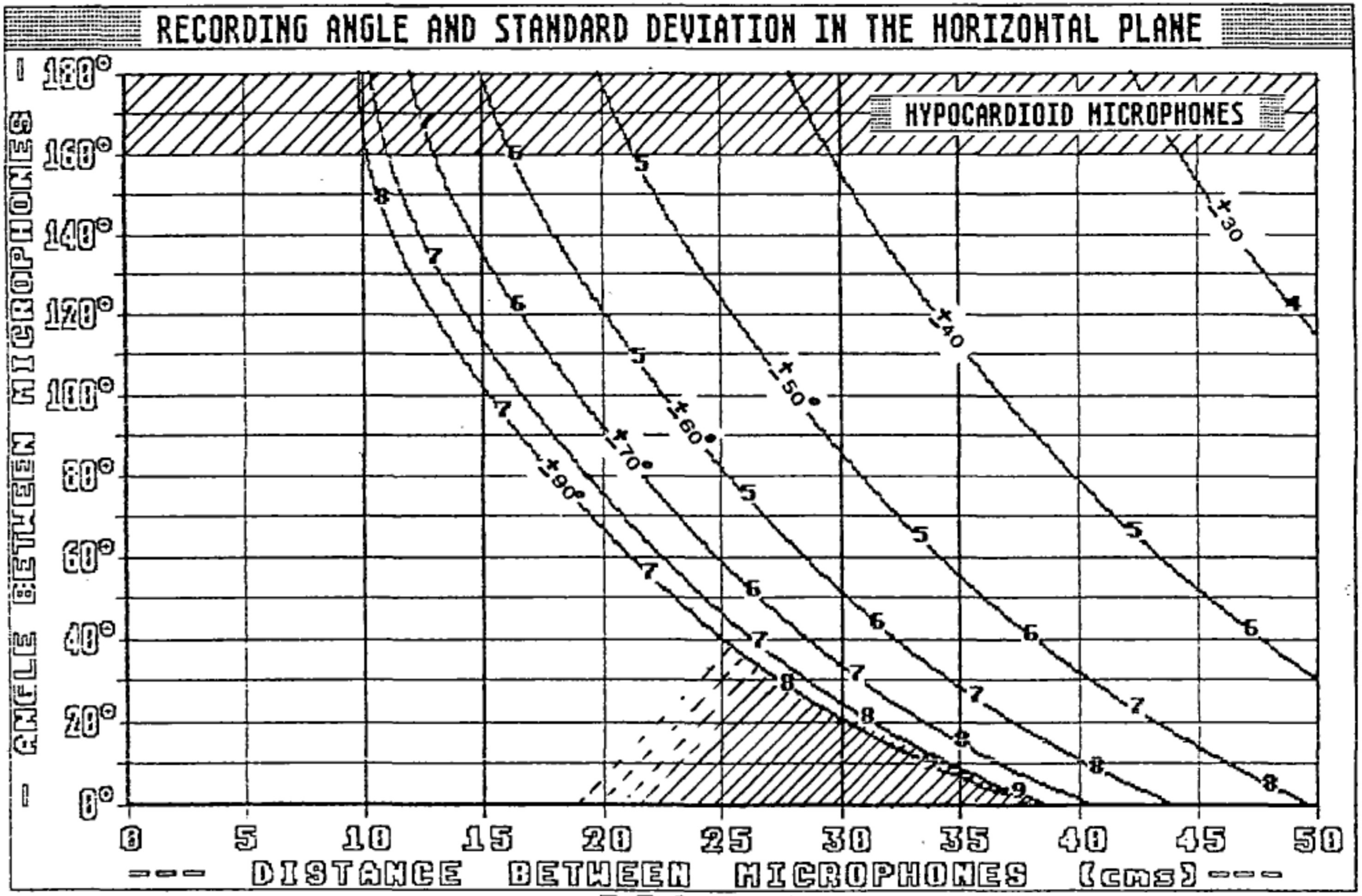

Distance between microphones = 30 cms
0° 10° 20° 30° 40° 50° 60° 70° 90°
1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0
0mS 0.1mS 0.2mS 0.3mS 0.4mS 0.5mS 0.6mS 0.7mS 0.8mS 0.9mS
30°
20°
10°
90°
39°
22°
11°
SOUND SOURCE POSITION
0° 10° 20° 30° 40°
APPARENT ANGLE OF REPRODUCTION
0° 10° 20° 30°
STANDARD DEVIATION

FIG.10



RECORDING ANGLE AND STANDARD DEVIATION IN THE HORIZONTAL PLANE
CARDIOID MICROPHONES
ANGLE BETWEEN MICROPHONES
180°
160°
140°
120°
100°
80°
60°
40°
20°
0°
±30°
±40°
±50°
±60°
±70°
±80°
±90°
0
5
10
15
20
25
30
35
40
45
50
--- DISTANCE BETWEEN MICROPHONES (cms) ---

FIG. 11



RECORDING ANGLE AND STANDARD DEVIATION IN THE HORIZONTAL PLANE
HYPOCARDIOID MICROPHONES
ANGLE BETWEEN MICROPHONES
180°
160°
140°
120°
100°
80°
60°
40°
20°
0°
0
5
10
15
20
25
30
35
40
45
50
DISTANCE BETWEEN MICROPHONES (cms)
±30
±40
±50°
±60°
±70°
±90°

FIG. 12

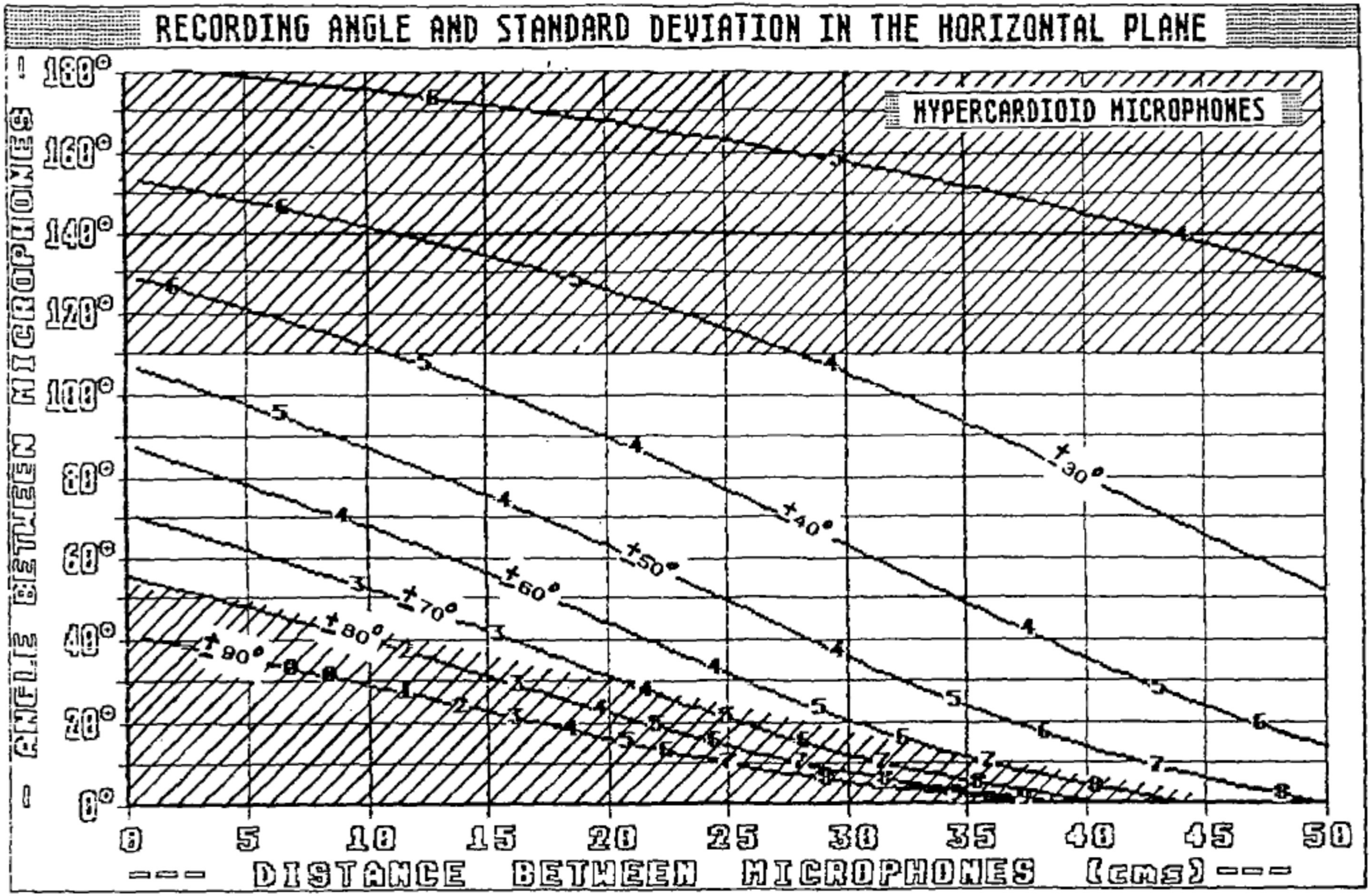

RECORDING ANGLE AND STANDARD DEVIATION IN THE HORIZONTAL PLANE
HYPERCARDIOID MICROPHONES
ANGLE BETWEEN MICROPHONES
180°
160°
140°
120°
100°
80°
60°
40°
20°
0°
±30°
±40°
±50°
±60°
±70°
±80°
±90°
0
5
10
15
20
25
30
35
40
45
50
DISTANCE BETWEEN MICROPHONES (cms)

FIG. 13

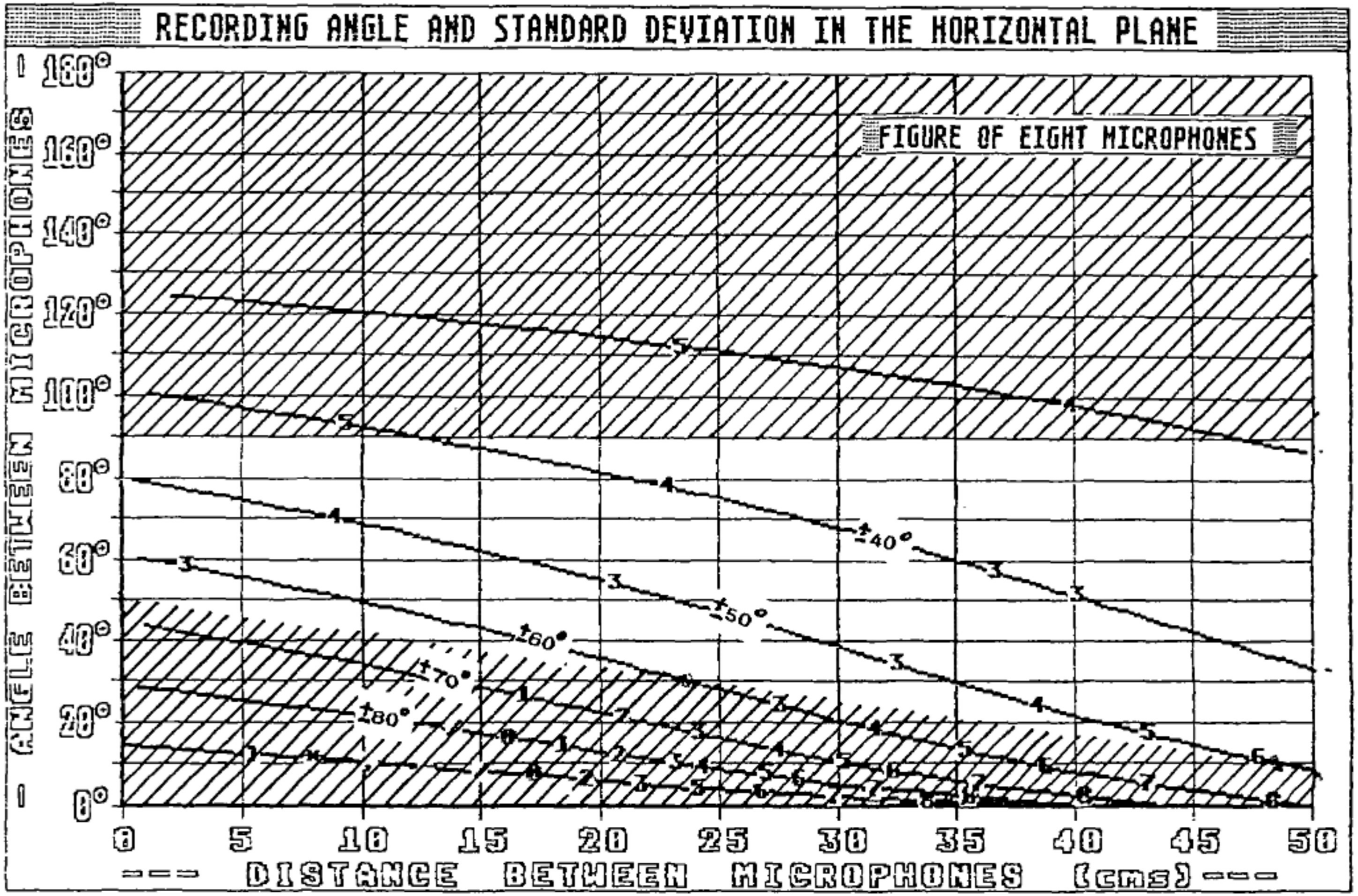

RECORDING ANGLE AND STANDARD DEVIATION IN THE HORIZONTAL PLANE
FIGURE OF EIGHT MICROPHONES
ANGLE BETWEEN MICROPHONES
180°
160°
140°
120°
100°
80°
60°
40°
20°
0°
±40°
±50°
±60°
±70°
±80°
0
5
10
15
20
25
30
35
40
45
50
DISTANCE BETWEEN MICROPHONES (cms)

FIG. 14

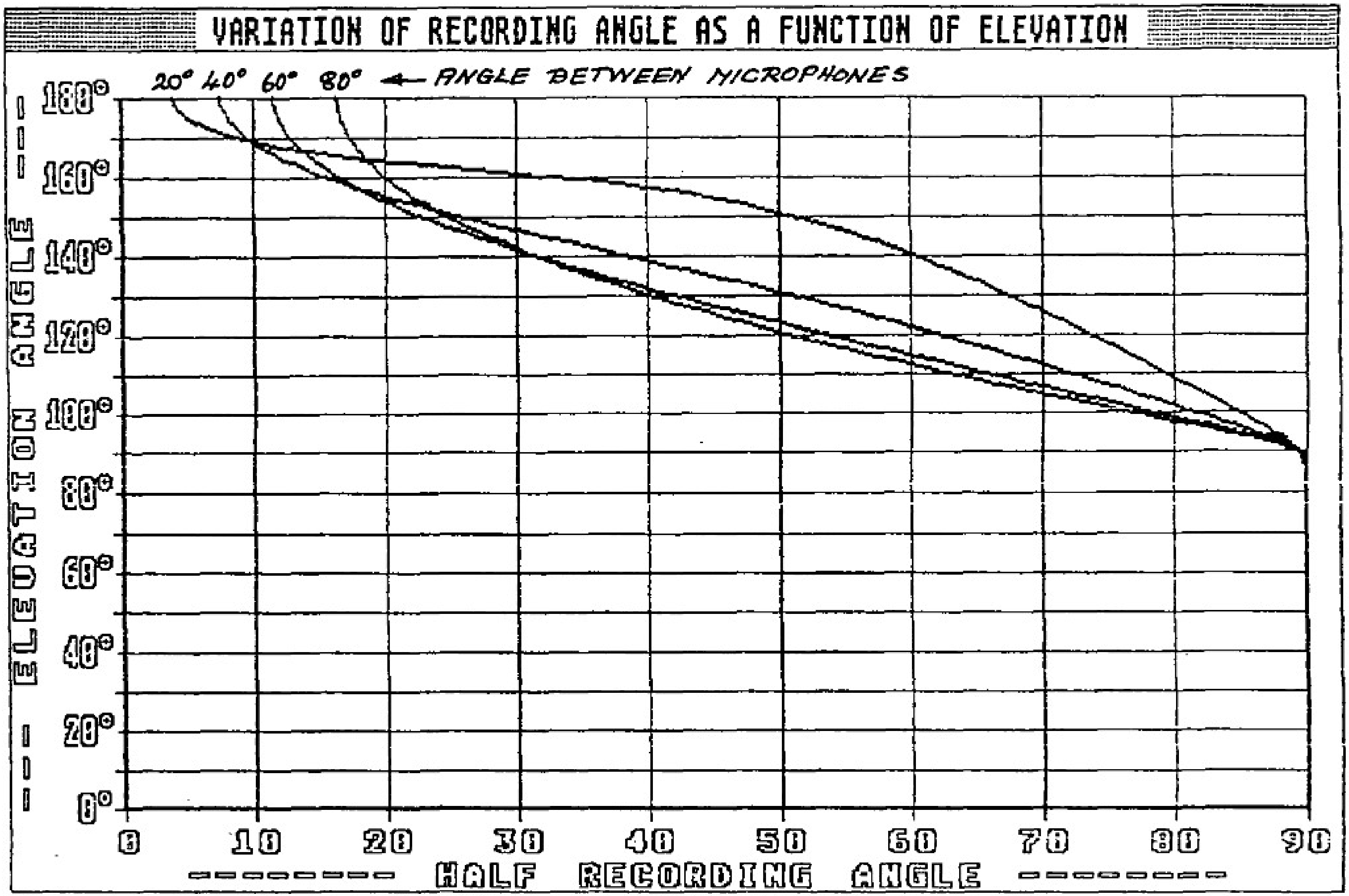

VARIATION OF RECORDING ANGLE AS A FUNCTION OF ELEVATION
20° 40° 60° 80° ← ANGLE BETWEEN MICROPHONES
180°
160°
140°
120°
100°
80°
60°
40°
20°
0°
ELEVATION ANGLE
0
10
20
30
40
50
60
70
80
90
HALF RECORDING ANGLE

FIG. 15

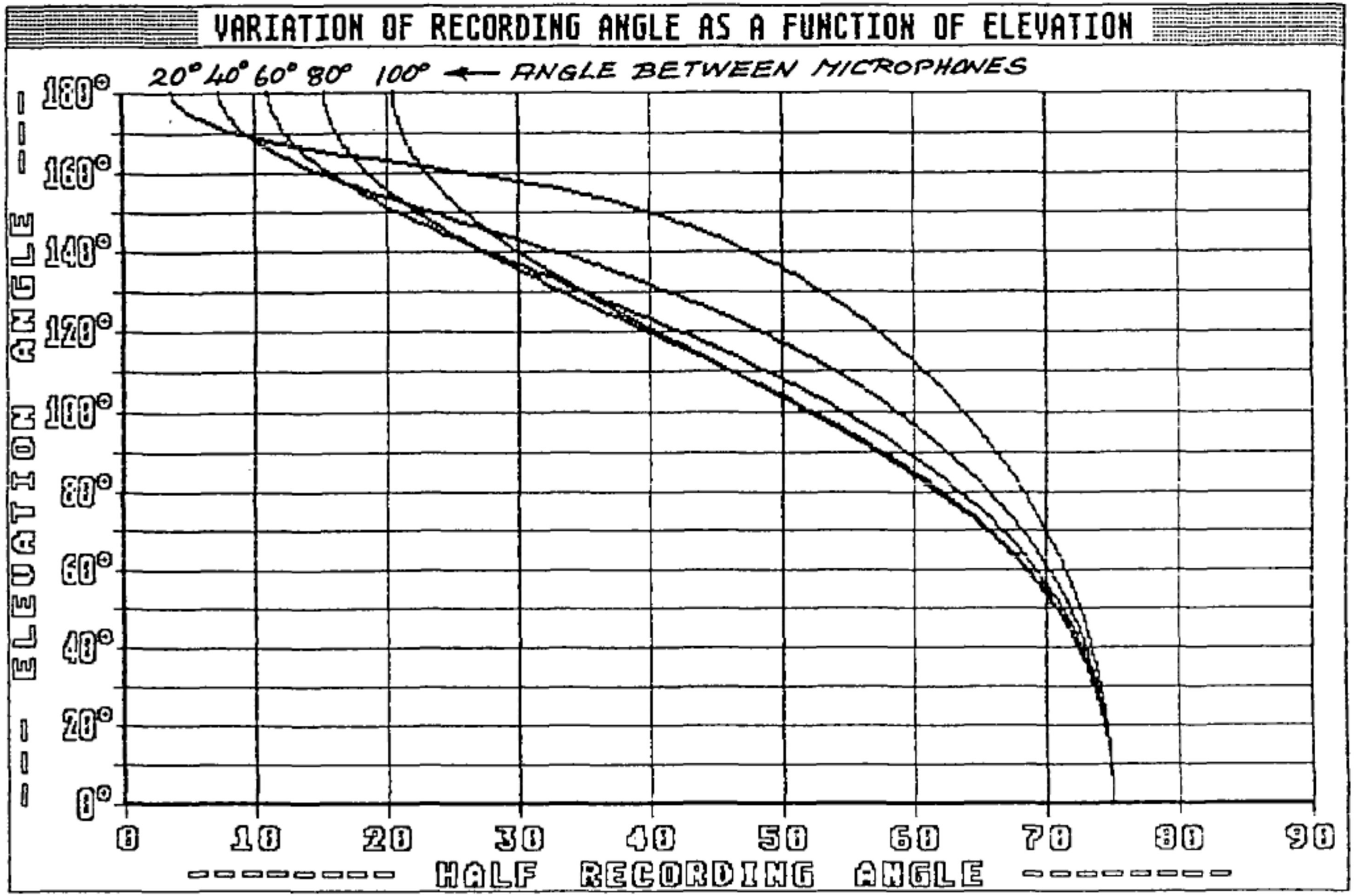

VARIATION OF RECORDING ANGLE AS A FUNCTION OF ELEVATION
20° 40° 60° 80° 100° ← ANGLE BETWEEN MICROPHONES
180°
160°
140°
120°
100°
80°
60°
40°
20°
0°
ELEVATION ANGLE
0
10
20
30
40
50
60
70
80
90
HALF RECORDING ANGLE

FIG. 16

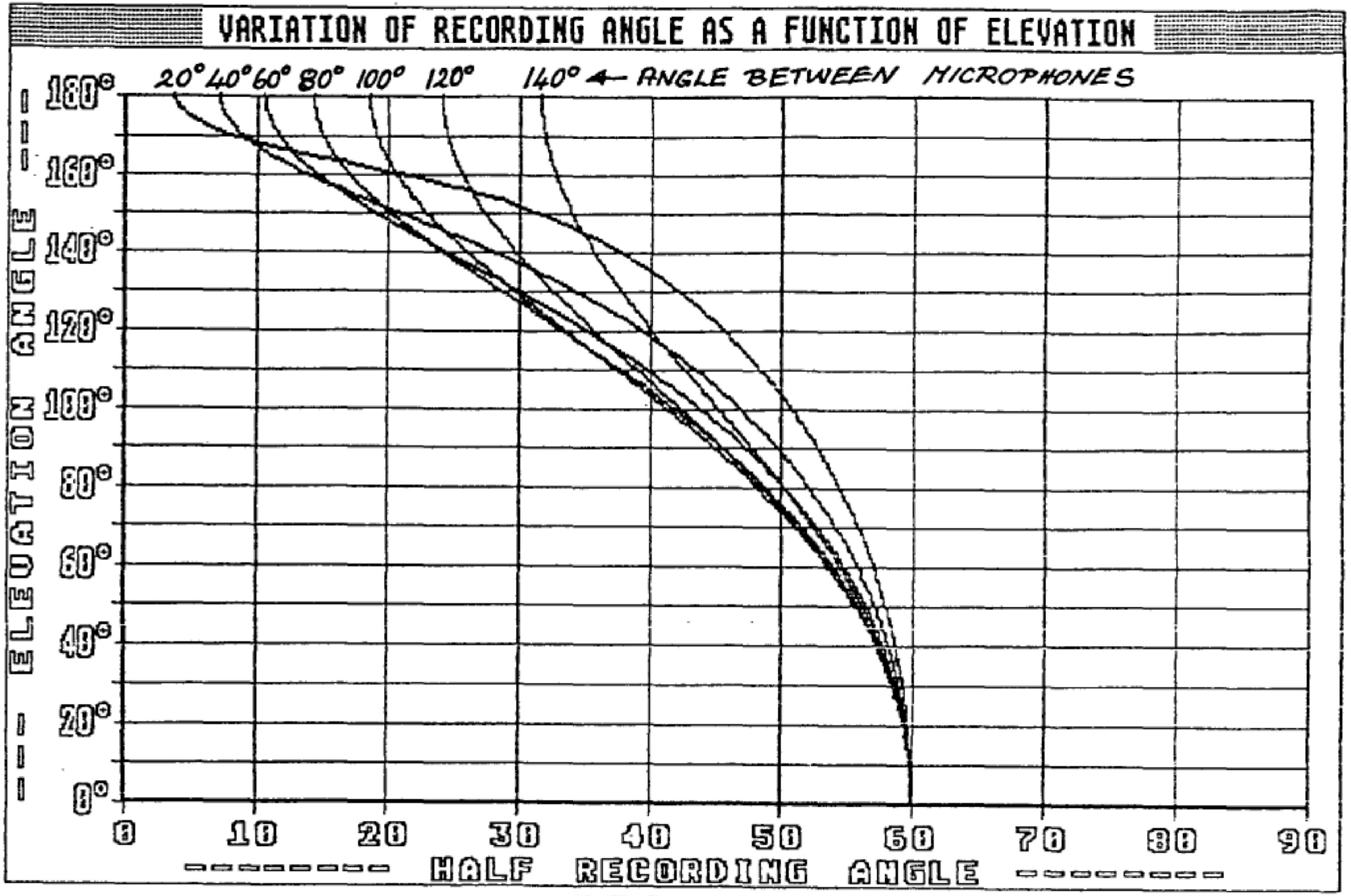

VARIATION OF RECORDING ANGLE AS A FUNCTION OF ELEVATION
20° 40° 60° 80° 100° 120° 140° ← ANGLE BETWEEN MICROPHONES
180° 160° 140° 120° 100° 80° 60° 40° 20° 0°
ELEVATION ANGLE
0 10 20 30 40 50 60 70 80 90
HALF RECORDING ANGLE

FIG. 17

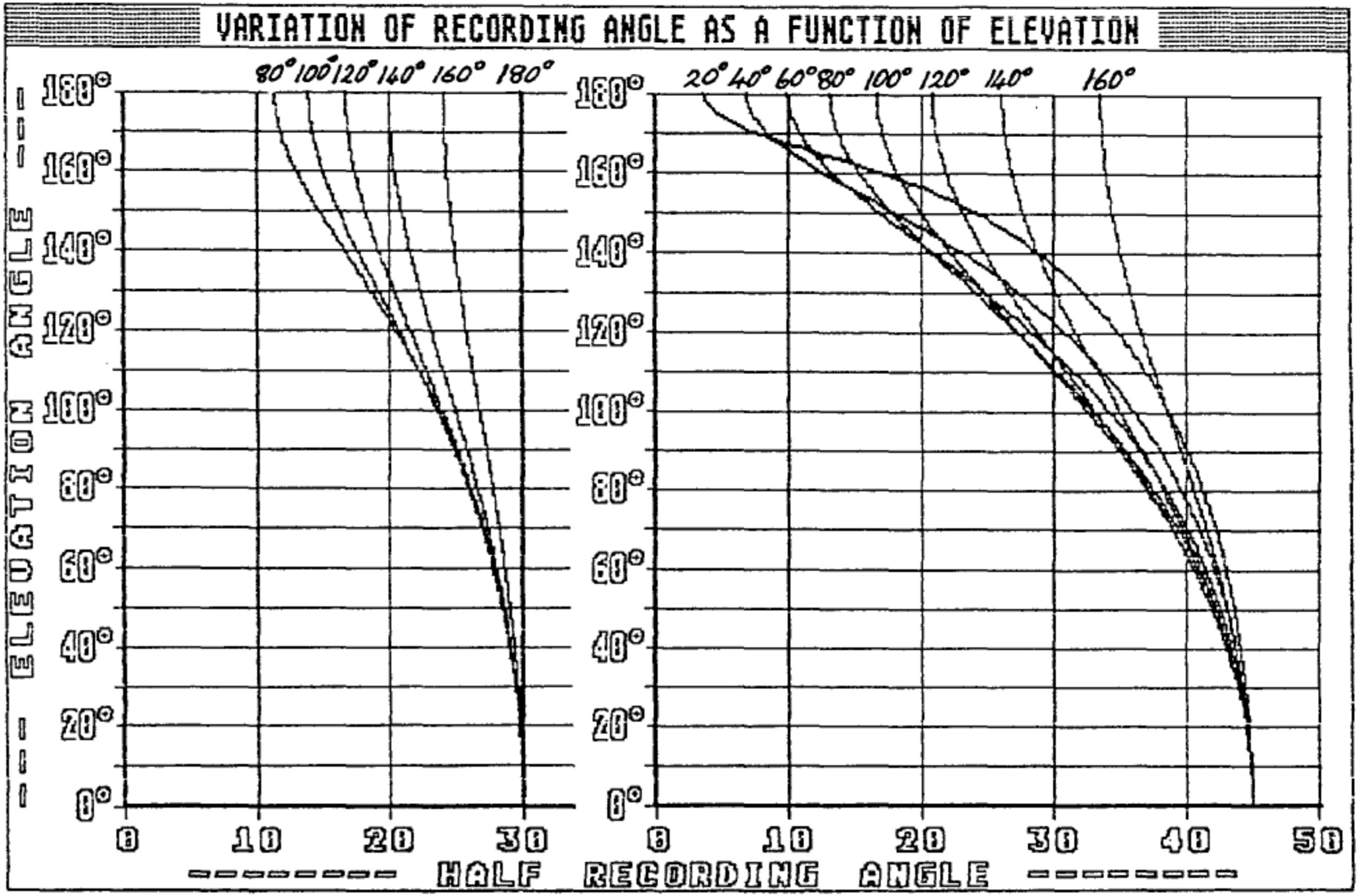

VARIATION OF RECORDING ANGLE AS A FUNCTION OF ELEVATION
80° 100° 120° 140° 160° 180°
20° 40° 60° 80° 100° 120° 140° 160°
180° 160° 140° 120° 100° 80° 60° 40° 20° 0°
0 10 20 30
0 10 20 30 40 50
ELEVATION ANGLE
HALF RECORDING ANGLE

FIG. 18