LOUDSPEAKER CONFIGURATION AND CHANNEL CROSSTALK IN MULTICHANNEL MICROPHONE ARRAY DESIGN

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ABSTRACT

In the search for multichannel quality reproduction of music using the recommended 5.1 Multichannel Listening Configuration sound engineers find themselves at a loss to know how to use the centre channel effectively - many opinions being expressed as to the relation between the reproduction of sound with loudspeakers at 30° as in the Multichannel configuration, and the reproduction with 60° between the loudspeakers in the Stereophonic configuration. We can also ask the same question regarding the other segments of the Multichannel configuration, where the angle between the loudspeakers is 80° in the Lateral Segments and 140° at the back. Acoustic Crosstalk is also considered by some to be a limiting factor in the use of multichannel microphone arrays for natural multichannel sound recording and reproduction. This paper will explore some of the misconceptions associated with these two problems and give an overview of the design of Multichannel Microphone Arrays as developed by the authors in recent Audio Engineering Society papers (4997 & 5157).

1 - Angular Distortion of Different Listening Configurations

1.1 Introduction

Some preliminary research[(1)] has shown that the closer the loudspeakers, the better is the Angular Distortion characteristic, but that the overall SRA changes very little. On the other hand increasing the angle between the loudspeakers would seem to produce a marked increase in Angular Distortion, but again the overall SRA remains practically the same. This has certainly been our experience and probably many others, when listening to two channel stereophonic reproduction when placed either too far away from the loudspeakers, or too near to them, with respect to the the standard equilateral triangle configuration.

This means that, in the recommended Standard Configuration for Multichannel Sound, we can expect a much more regular distribution of the sound sources within the main sound stage of the Front Triplet, whilst Angular Distortion should be more predominant within the side segments and even more so within the back segment. This is of little consequence in the reproduction of lateral reflections and reverberation, but becomes more difficult to integrate into realistic total surround sound reproduction, where a more even distribution of loudspeakers would be advantageous. However we would obviously expect our perception of these characteristics to be modified somewhat by the position of each segment with respect to the listener. This will be discussed a little later in this paper.

1.2 The Basic Choice of Microphone Position and the Angular Compression of the Sound Stage

The microphones that are, at present, used for the recording of a sound source are unfortunately unable to reproduce correctly the natural perspective of the original sound source. Therefore one of the initial stages in creating a satisfactory representation of the sound source must be to find a suitable position for the microphone or microphone system that satisfies, as near as possible, our perception of sound perspective within the reproduced sound stage. The variation of distance between the sound source and the microphone will certainly change the level of direct sound reaching the microphone, however this will be perceived as a change in the ratio of direct to reverberant sound. It is this ratio that is responsible almost entirely for our perception of depth or sound perspective within the sound image. Each individual sound engineer will have his own subjective appreciation of the optimum value of this ratio in relation to the type of recording being made. In the case of multiple sound sources, as for instance with an orchestra, one must also take into account the relative acoustic levels of individual instruments or sections of instruments in positioning the microphone, the aim being to obtain a good balance between all the different sections of the orchestra.

In relation to our natural perception of a sound source at a specific position, we normally have to place the microphone array much nearer to the sound source in order to obtain the same perception of distance in the reproduced sound stage. This applies also to the relative distance of individual sound sources and our perception of the reproduced sound perspective. We must therefore choose a microphone array position that will reduce the relative physical distance between sound sources in order to obtain a satisfactory impression of the sound perspective in the reproduced sound image. A typical illustration of this can be seen in Figure 1 where the microphone array « A » is placed in front of the orchestra and the microphone array « B » is placed above the orchestra, the relative distance between the front row and back row of musicians being reduced in position « B ».

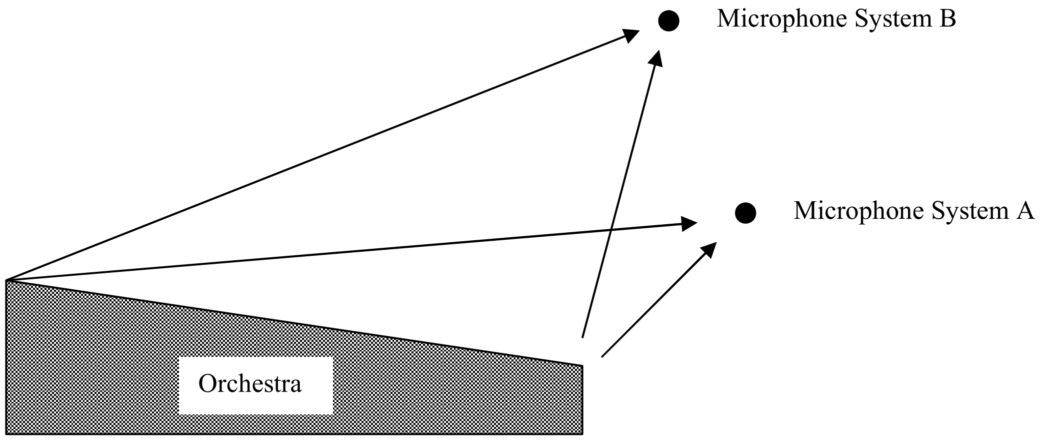


Figure 1 – The effect of Microphone Position on the relative distance between the microphone system and the different sound sources in the orchestra.

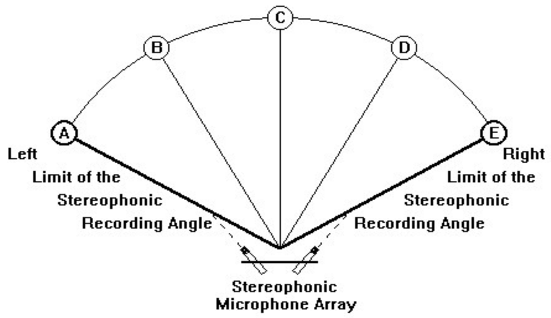
This obviously means that the sound source as seen from the microphone position, occupies an angular segment that is a good deal larger than the 60° sound stage reproduced in the equilateral triangle stereophonic listening configuration. In this case, angular compression of the sound source exists. The opposite situation in which the sound source sector is less than 60°, with expansion of the angular proportions of the reproduced sound image, is hardly ever encountered in practice.

Angular compression (or expansion) however must not be confused with the characteristic of «Angular Distortion » for a given dual microphone system.

1.2 Angular Distortion

A given stereophonic microphone array will also modify to some extent the relative angular position of each individual element of the sound source within the Stereophonic Recording Angle, as reproduced as a virtual source between the loudspeakers. This characteristic is called « Angular Distortion ».

Figure 2 – Position of Sound Sources



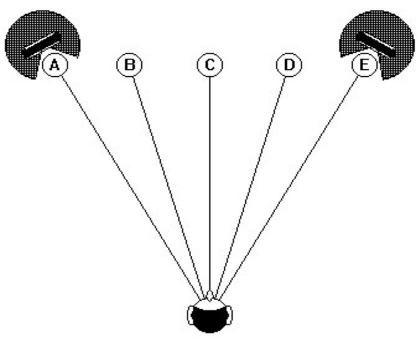


Figure 3 - Reproduction
without Angular Distortion

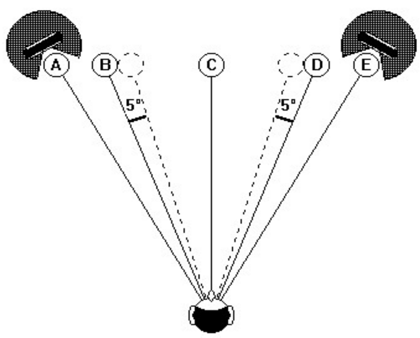


Figure 4 – Reproduction
with 5° of Angular Distortion

In Figure 2, we have sound sources A, B, C, D and E, situated at equal distances along the arc of a circle. If no Angular Distortion exists in reproduction, then the relative positions of A, B, C, D and E will be maintained as illustrated in Figure 3.

- A at the left hand loudspeaker
- B midway between left loudspeaker and centre
- C in the centre
- D midway between right loudspeaker and centre
- E at the right hand loudspeaker

Angular Distortion will modify the reproduced positions of sound sources B and D, they will be shifted towards each loudspeaker, as illustrated in Figure 4, where a shift of 5° of B and D is shown. The sound sources A, C and E will not be affected by this shift and will remain in the same relative position (A and E being by definition the limit of the SRA, C being the centre of the system).

It is this Angular Shift of the sound sources B and D that is used to represent the maximum Angular Distortion of a given system, and depends on the particular combination distance/angle that is chosen for the microphone system[2] as shown in Figure 5. This characteristic of Angular Distortion is perceived as compression or crushing of the extremities of reproduced sound field towards the loudspeakers. These values are in general minimum when a « balanced » combination of distance and angle are chosen (Angular Distortion values of around 4° to 5° for cardioid microphones,). Intensity Difference only systems (coincident microphone systems) show a small increase in Angular Distortion, whilst Time Difference only systems show very much greater Angular Distortion values of 8° to 9°. The actual values of Angular Distortion can be seen from each of the SRA diagrams and of course vary also according to the microphone directivity. However these Angular Distortion values have been determined with precision only for the Stereophonic Listening Configuration (equilateral triangle configuration) based on psychoacoustic measurements made by Simonsen[3].

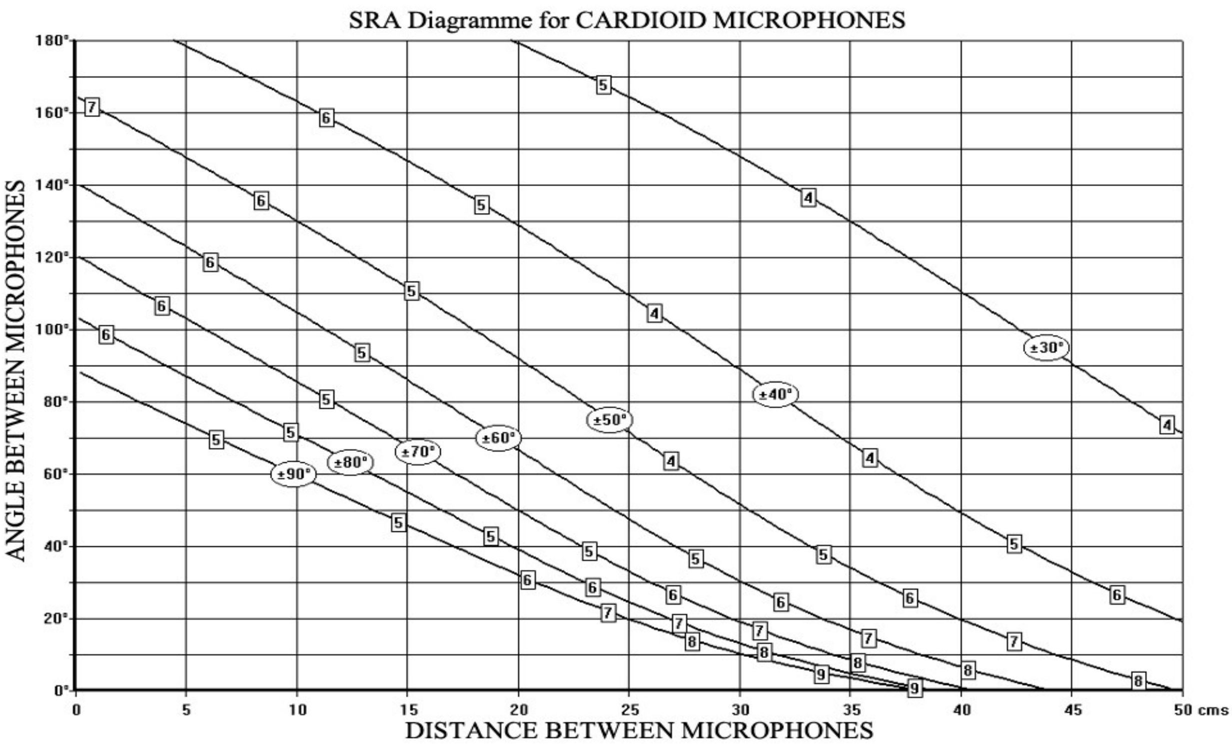


Figure 5 – Stereophonic Recording Angle for Cardioid Microphones

2 - Angular Distortion in the 5.1 Multichannel Configuration

Past experience and some recent preliminary research[1], suggests that there is considerable variation in Angular Distortion as we vary the position of the loudspeaker enclosures in relation to the listener i.e. as we vary the angle between the loudspeaker enclosures as seen by the listener, whilst of course maintaining the loudspeakers directed towards the listener, as shown in Figure 6. It has been shown that reducing the angle to 30° produces almost linear reproduction[1], whilst increasing the angle on the other hand would seem to considerably increase the Angular Distortion. With the larger angles between the loudspeakers it becomes very difficult to determine the exact location of sound sources and therefore the values established for both the Stereophonic Recording Angle and the associated Angular Distortion also tend to be rather approximate. It is also necessary to bear in mind the fact that the specific choice of distance and angle between a pair of microphones can modify considerably the amount of perceived Angular Distortion. Figure 6 is a representation of the overall situation, using specific values for Angular Distortion in the case of 30° and 60° between the loudspeakers, and shows the tendancy for Angular Distortion to increase for angles above 60°. Further psychoacoustic measurements are however necessary to establish more precise values for the Angular Distortion for each loudspeaker placement.

This obviously gives us an indication as to the amount of Angular Distortion that we must expect for each of the segments covered by loudspeakers in 5.1 Multichannel System as recommended by the ITU-R BS.775-1. In this « recommended » Multichannel Listening Configuration, the different segments covered by each respective loudspeaker pair vary from 30° at the front, 80° on the sides, to 140° at the rear. These segments are of course situated at different positions in relation to the listener, so we must therefore expect our perception of the characteristics of each of these segments also to be different. But the variation of perception in each segment basically concerns the quality of resolution associated with the localisation, especially on the side segments. However the Angular Distortion and the fundamental limit to the total « coverage » of each segment remains ostensibly the same, no matter what the relative position of the segment is to the listener.

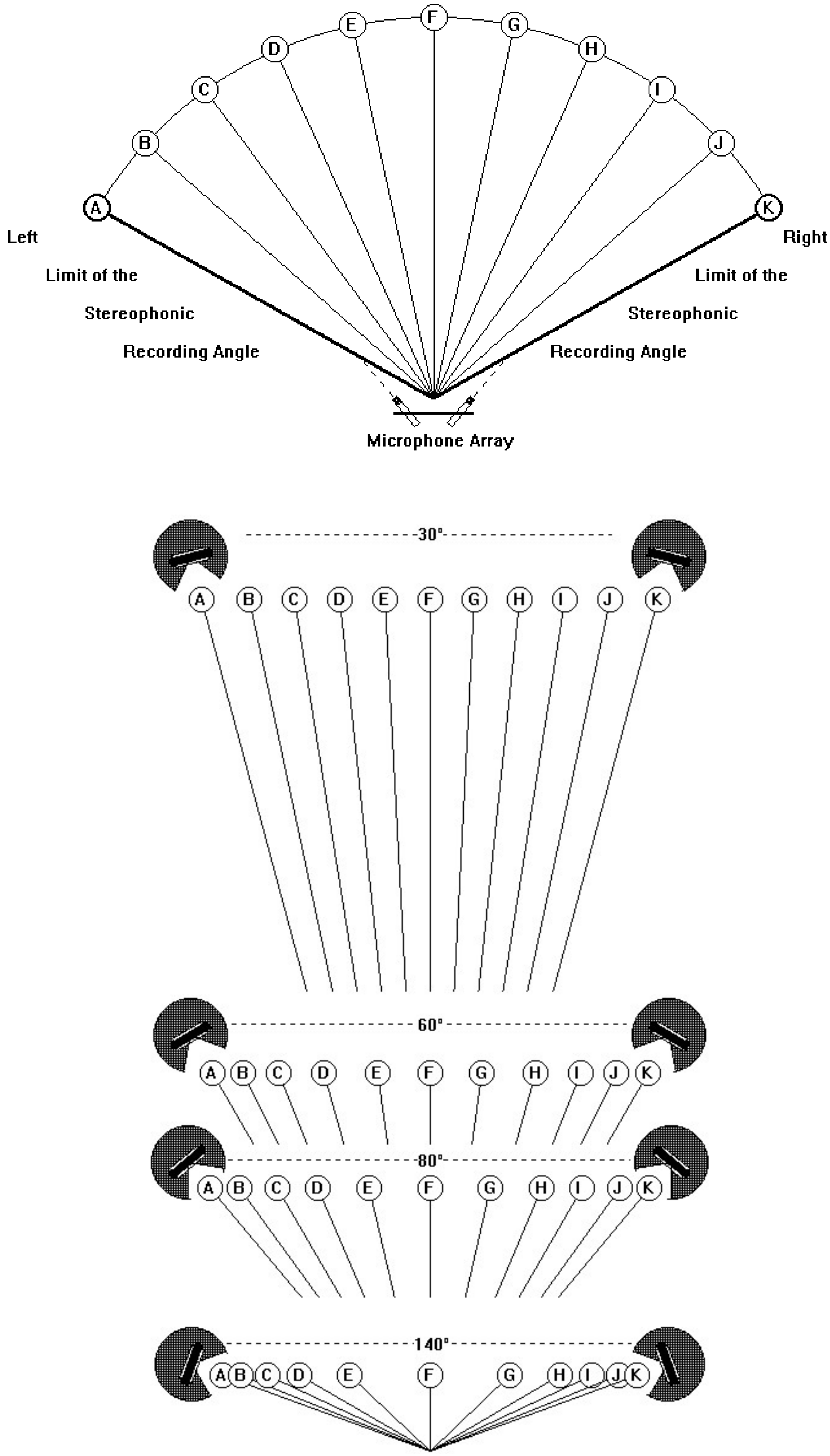


Figure 6 – Angular Distortion relative to Listening Configuration

To resume we can say that:

- the two front segments, each at 30°, show good linear localisation and maximum resolution
- the side segments at 80° show Angular Distortion of approximately the same as with the Stereophonic Listening Configuration, but progressively poor resolution to the sides
- the back segment has very pronounced Angular Distortion, but with reasonably good resolution

This opens up the whole debate concerning the difference between the reproduction system deemed satisfactory for the "Home Cinema" and the specific requirements for good quality music reproduction. In music recording the sound sources are usually situated in front of the microphone array, whilst side and back coverage are responsible for the reproduction of early reflections and reverberation. This is obviously not always the case, and even more so, if we extend the field of our multichannel sound recording to sound effects and the recording of the natural sound environment, where total surround sound must be reproduced.

The purist would argue with some justification that the angle covered by each segment should be equal to the reproduction angle. The "ideal" situation being of course equal segment coverage (72° for each coverage and reproduction) as shown in preprint 3157[4] presented at the 91st AES Convention. An improvement to the 5.1 Multichannel Configuration for music reproduction would be to adopt a wider front loudspeaker spacing in order to decrease the angular coverage of the back segment loudspeakers and thereby improve its relative Angular Distortion. There is however some consolation in the knowledge that changing the position of the loudspeakers will not change the specific coverage of each segment, but only the position of that segment in relation to the listener. Angular Distortion will also vary accordingly. This also explains why in the past the average listener has been reasonably tolerant of loudspeaker placement when listening to stereo.

Some people would also argue that the side coverage characteristics are of little importance due to the poor resolution of our perception on the sides. This is somewhat debatable if we wish to maintain some degree of listener freedom in head displacement. It would also be an mistake to think that resolution is equally poor over the whole of the lateral segments.

3 - Acoustic Crosstalk in the Stereophonic Loudspeaker System

A high level of acoustic crosstalk already exists in the stereophonic listening configuration. Both Intensity Difference and Time Difference values have to be more or less doubled in order to obtain the same results as those produced with binaural reproduction (i.e. with headphones). An Intensity Difference of only 7db will produce a maximum displacement of the virtual sound image towards the left or right headphone, whereas an Intensity Difference of 15db is necessary to produce the same effect with loudspeakers (i.e. displacement of the virtual sound image up to the limit of the loudspeaker position). The same situation also applies to Time Difference information, where about 0.7 mS produce maximum displacement in binaural listening, whilst 1.12 mS is needed with loudspeakers. However despite this high level of crosstalk, stereophonic localisation can be clear and precise, especially with transitory signals. The existence of crosstalk therefore does not necessarily mean dispersion in the localisation of the sound image.

The majority of recordings are made for the standard stereophonic listening configuration with loudspeakers, but there are some examples of recordings made specifically for headphone listening. However there are many people who choose to listen to loudspeaker stereo on headphones, without being aware that the characteristics of each reproduction system are different.

Four combinations of recording/reproduction systems are therefore possible:

1. Loudspeakers used to listen to stereophonic recordings
2. Loudspeakers used to listen to binaural recordings
3. Headphones used to listen to stereophonic recordings
4. Headphones used to listen to binaural recordings

It is obvious that only the 1st and 4th situations will give satisfactory results. In the 2nd situation the sound image will appear too small and will occupy only half of the available reproduction sound stage, whilst in the 3rd situation the sound stage will be too wide – we will only hear satisfactory virtual images over the centre segment of the original sound source. To the initiated this may seem rather elementary, but it is amazing how many people still do not understand this situation.

Although some considerable experimentation has been done with artificial head recordings for binaural reproduction, it is quite remarkable that little has been done to demonstrate the qualities of microphone array recording techniques adapted for binaural listening. It is also impossible for either a given microphone array or acoustic obstacle system to be used as a universal recording system for both binaural and stereophonic recording, without modification to adapt them to each specific reproduction system. On top of this we need considerable flexibility in the choice of coverage of each system used, to take into account the particular conditions of each sound recording situation.

Let us compare the signals received by a specific dual microphone array when recording a sound source, with the information received by each ear when listening either to stereophonic reproduction with loudspeakers or binaural reproduction with headphones. Figure 7 shows both the timing and amplitude of the signals received in each case. It is evident that there is considerable acoustic crosstalk in the signals received by each ear from the left and right channel loudspeakers i.e. the right and left ear receive information from both the left and right loudspeakers with small time and amplitude differences.

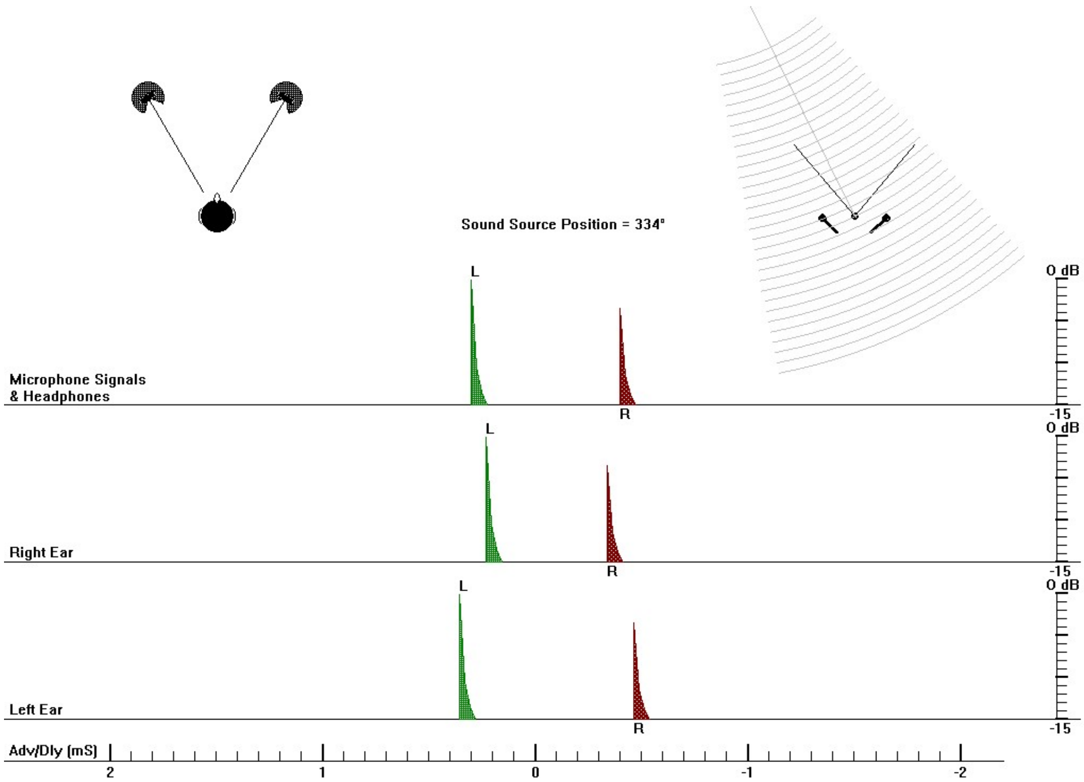


Figure 7 – Crosstalk in Loudspeaker Stereophony compared with the Microphone Signals and Binaural Listening

The cross talk amplitude and arrival time are a function of the Interaural Amplitude and Time Differences. It is not the intention in this paper to analyse the psychoacoustics concerning the perception of localisation in stereophonic reproduction. However it is necessary to point out the structure of the signals received by each ear with loudspeaker stereophony, so that we can attempt to understand the far more complex structure of signals received in a multichannel environment.

It will be shown that in a properly designed multichannel microphone array, crosstalk is not significant within the Front Triplet and Lateral Segments. However it is almost impossible to design the back segment coverage to be free from crosstalk interference whilst maintaining "clean" front and side segments. Also as the back segment reproduction linearity is particularly bad, it would seem that a logical approach would be to sacrifice the performance of the back segment as regards crosstalk (and Angular Distortion) in order to maintain acceptable reproduction characteristics for the front sound stage and the side segment early reflection patterns. Clearly another approach would have to be adopted in the case of a 360° surround sound stage.

4 - Multichannel Acoustic Crosstalk

The microphone array chosen for this analysis has the following specification :

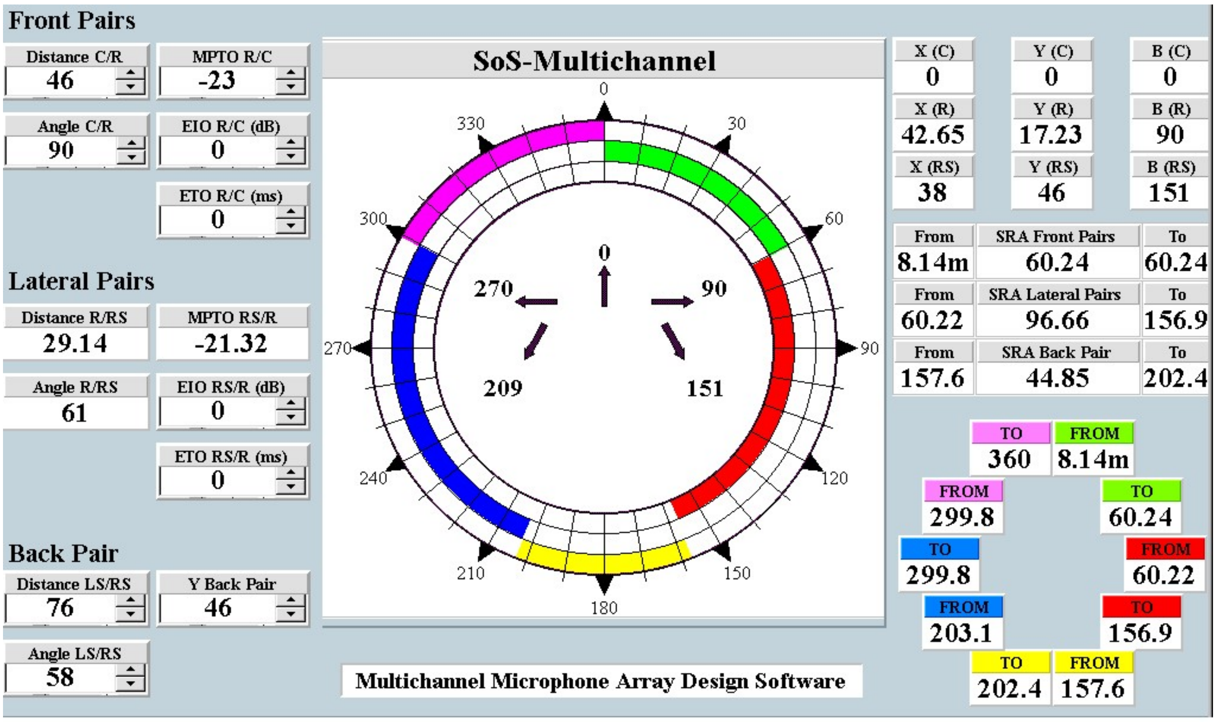
Front Left Segment (FLS) Coverage and Front Right Segment (FRS) Coverage : 60°

Lateral Segment Coverage : 97°

Back Segment Coverage : 45°

	'X' coordinate	'Y' coordinate	Orientation
Centre	0 cms	0 cms	0°
Right	42.6 cms	- 17.2 cms	90°
Left	- 42.6 cms	- 17.2 cms	270°
Right Surround	29.7 cms	- 45.5 cms	151°
Left Surround	- 29.7 cms	- 45.5 cms	209°

The detailed characteristics for this specific array are shown in Figure 8.



Multichannel Microphone Array « 60 / 97 / 45 »

The timing and amplitude of signals generated by this multichannel microphone array with the sound source at 40° to the centre axis, together with the information received at each ear from the complete multichannel loudspeaker configuration array, are shown in Figure 9. Three signal timing / amplitude axes are shown. The first shows the signals transmitted by the loudspeakers, the second and third showing the information received by the right ear and the left ear respectively. Interaural time differences[(5)] are shown with respect to the individual loudspeaker positions in the context of envelope detection of transitory signals. The zero reference for the timing in axes 2 and 3 is taken as the arrival time at the ears for the centre loudspeaker signals.

As well as the arrival time of each signal, the amplitude generated by each microphone is shown w.r.t. a 15 dB scale, but no spectral modification as a result of Interaural Amplitude/Frequency Differences is represented, even though consideration of the IA/FDs should obviously improve the crosstalk characteristics to some extent. Crosstalk is considered as being significative only when the interfering signal starts to overlap the signals received from the main microphone pair, either in the left or right ear. Before this overlapping occurs the “precedence effect” will dominate the perception of localisation over the major part of the segment (except for the back segment).

Figure 9 shows the sound source situated in the segment covered by the centre and right microphones, the localisation being derived for the right and left ears from the two envelopes shown in dotted line boxes. If an interfering crosstalk signal were present, it would have been shown by a third dotted box. However in this figure no interfering signal is present, and the localisation is the same as with a stereo system, except that the head is turned towards the centre loudspeaker.

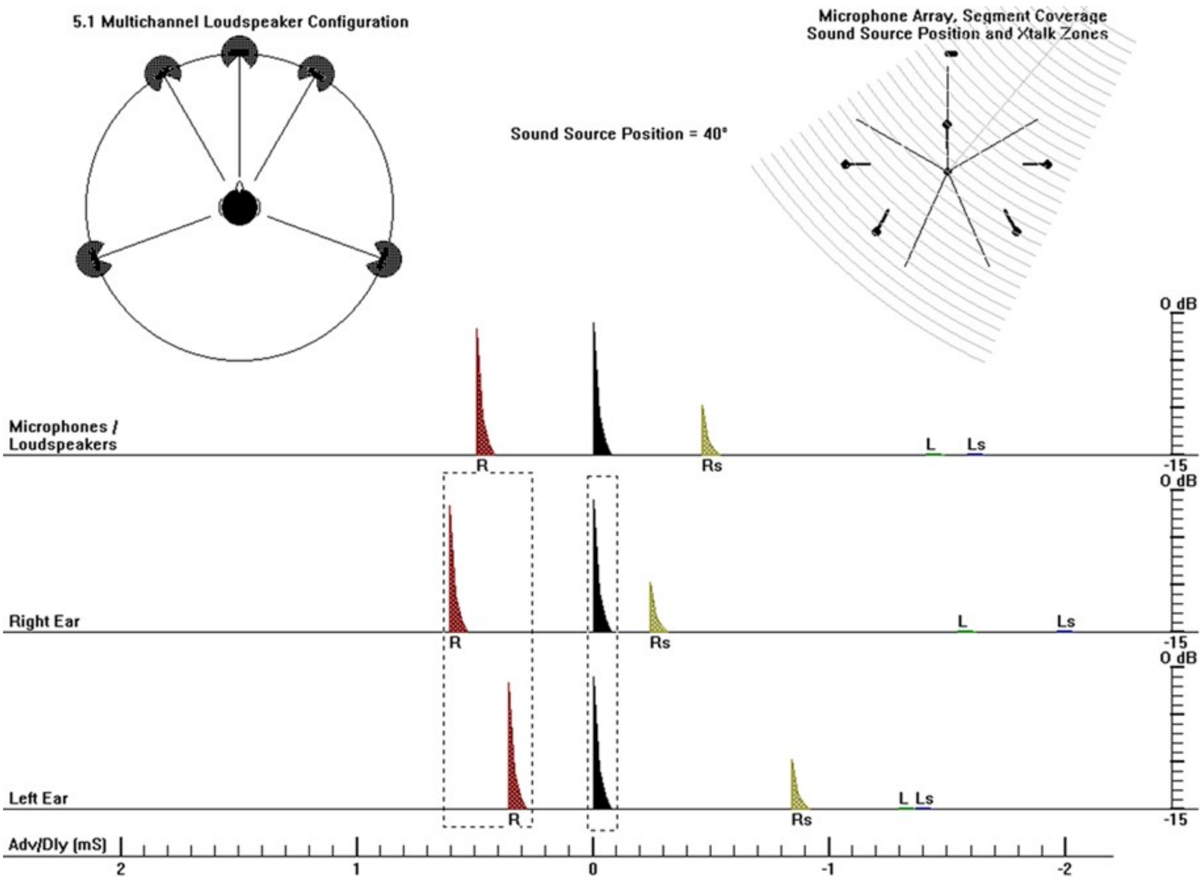


Figure 9 – Sound Source at 40° - no significant crosstalk

The absence of significant crosstalk is also evident in Figure 10 for a sound source situated at 100°, the localisation being perceived this time in the right lateral segment.

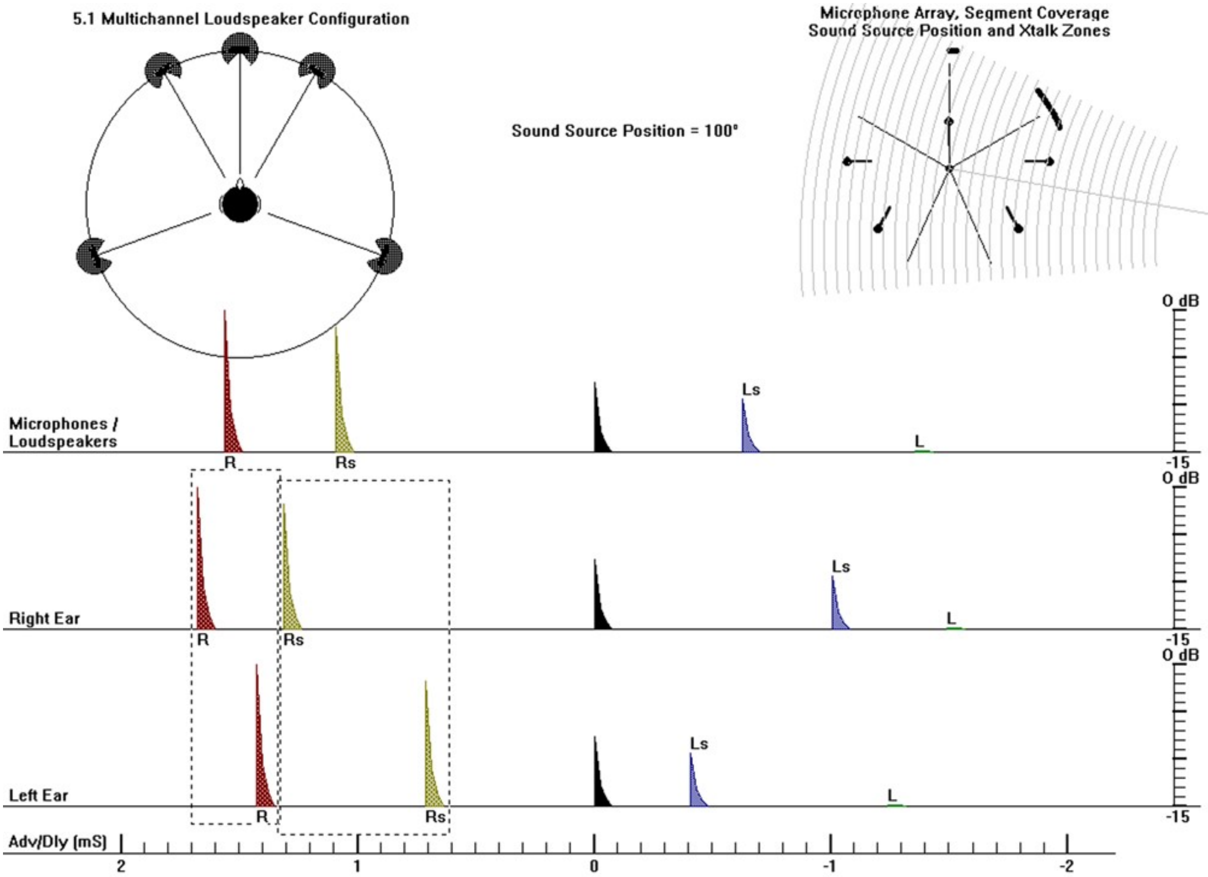


Figure 10 – Sound Source at 100° - no significant crosstalk

Figure 11 on the other hand shows how the major part of the back segment is troubled with interference signal information either from the left or right front microphones. In the specific case shown in Figure 11, the sound source is situated at 165°, and the interference generated by the signal from the right microphone in the Front Triplet is all too apparent. The fact that the right microphone is attenuated by about 4dBs will fortunately lessen the impact of this crosstalk interference signal. Whether this cross talk will create a dispersion in the localisation of the sound image, or whether it will simply produce a change in the localisation transfer function remains to be seen. On top of this the back segment already suffers from a high degree of Angular Distortion so we cannot expect the sound image in the back segment to be stable or clearly defined.

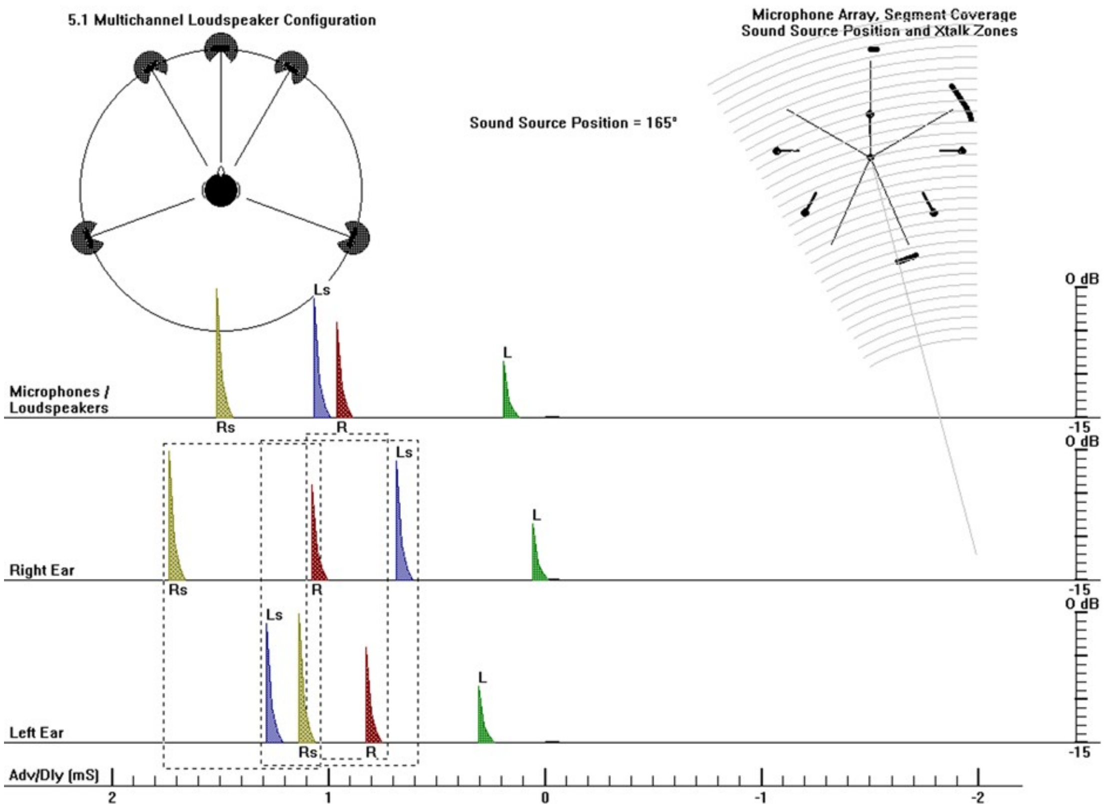


Figure 11 – Sound Source at 165° - considerable crosstalk present from the right Front Triplet microphone

Each time significant crosstalk is generated in a segment, it is represented by an arc of a circle in the microphone array diagram situated in the top right hand part of each figure. If we examine the diagram after the sound source has scanned a total of 360°, as in Figure 12, we can situate clearly the segments where the crosstalk could interfer with the normal localisation of the sound image.

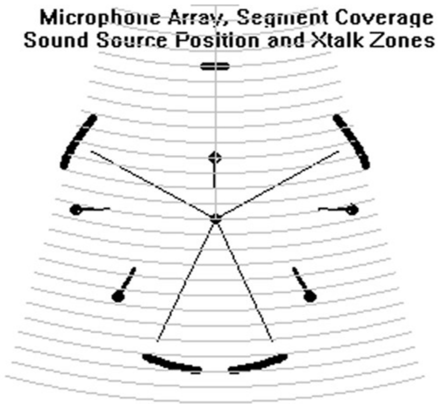


Figure 12 – Segments of the Microphone Array where Crosstalk could interfer with localisation

During the transition across adjacent segments there will obviously be a situation where the two microphones on each side of the transition are sending information of equivalent significance. However the first stage of listening tests seem to suggest that the microphone nearest the transition zone is predominant and therefore stabilises the image.

Further research has to be undertaken to analyse in detail the interference of a crosstalk signal on the main sound image localisation, whether this be with a single interference source or more than one. This information should enable us to more closely define the size of the doubtful segments and know the influence of this interference on the character of the localised sound image.

5 - The Basic Techniques of Multichannel Microphone Design

Extracts from AES preprint 4997[(6)] **:** In the design of multichannel microphone arrays we must have complete control over the angular offset of the reproduced segments of the sound field in relation to the axis of symmetry of the microphone pair covering each specific segment. In the design of the front facing triplet of microphones covering the left and right front segments, we must be able to offset the reproduced sound field segments so that the side limits of the left and right sound fields correspond to the axis of the front facing centre microphone. For the lateral segments however we need to be able to rotate freely the coverage of the side segments, without any coincidence between the physical axis of the microphones and the limits of each of the sound field segments. And finally, for the back segment we return to the simple symmetrical segment as used in stereophony.

5.1 Offset and Linking

The application of Offset is illustrated in Figures 13 to 18.

- Figure 13 shows the standard Stereophonic Recording Angle (SRA) for a microphone pair where the SRA is less than the physical angle between the microphones.
- Figures 14 & 15 show how this sound field coverage can be rotated in an anti-clockwise direction by using a negative angular offset.
- Figure 16 shows an SRA that is larger than the angle between the microphones.
- Figures 17 & 18 show the same principle of offset, but using, this time, clockwise rotation or positive angular offset.

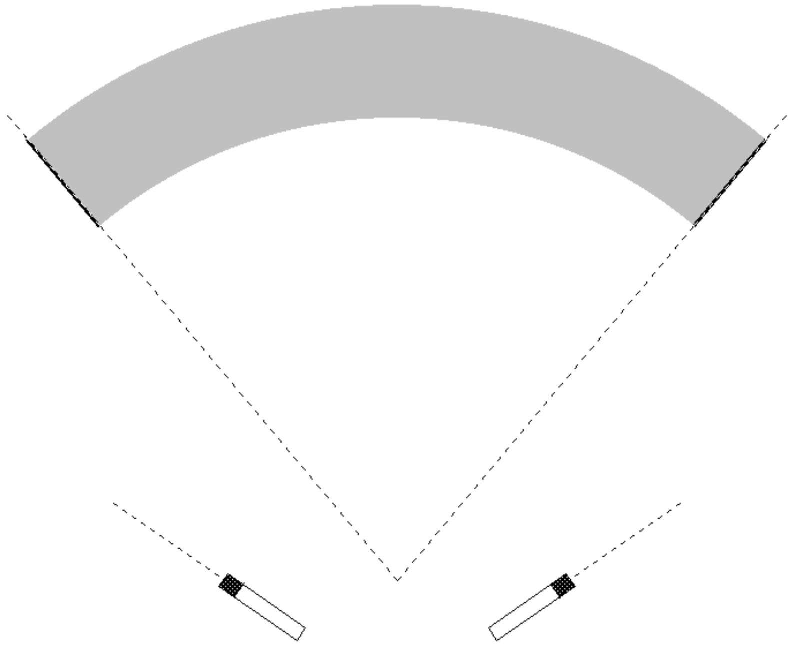


Figure 13 : Stereophonic Recording Angle (SRA) less than Angle between Microphones

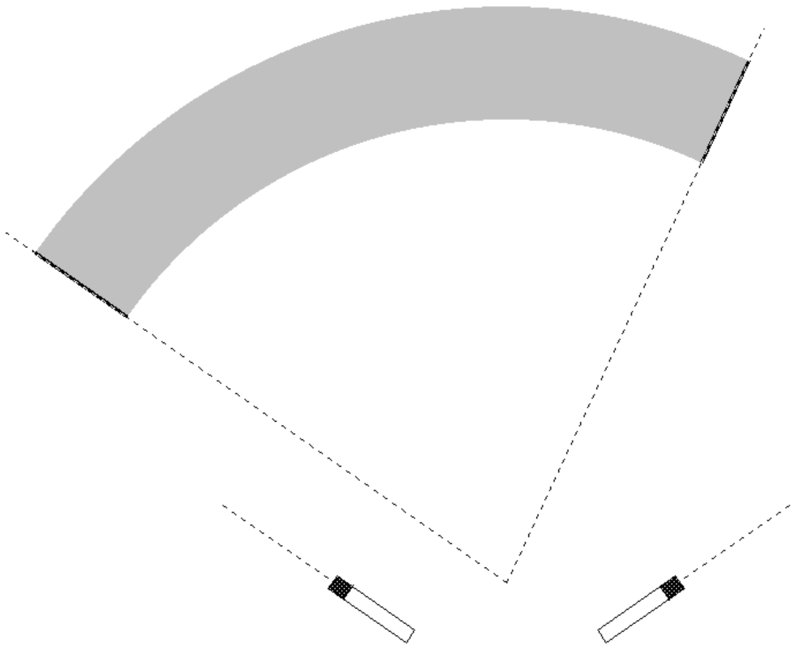


Figure 14 : Negative Offset of -15° (Left Limit of SRA aligned with Microphone Axis)

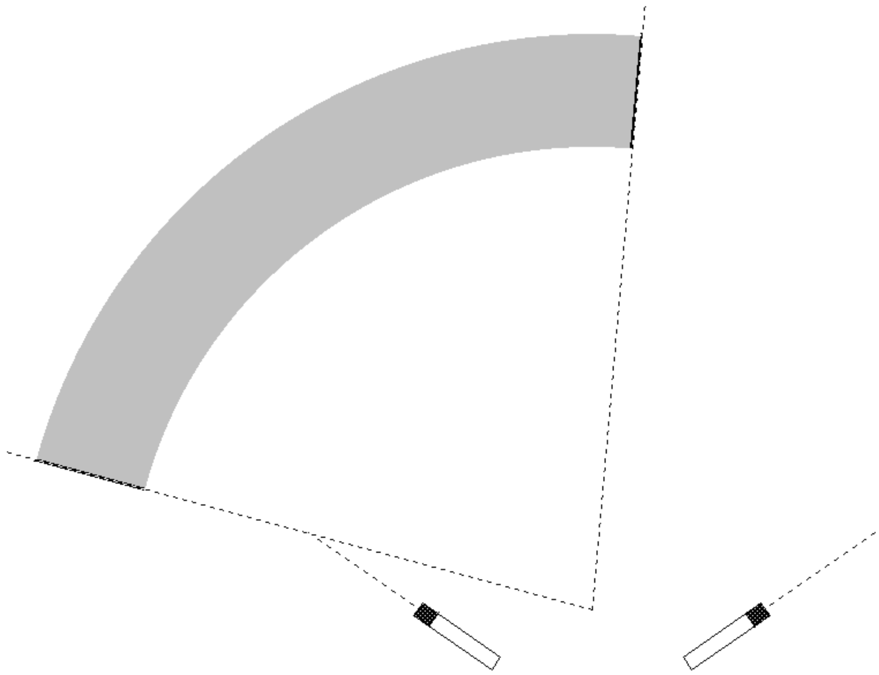


Figure 15 : Negative Offset of -35° : Axis left microphone now within the SRA

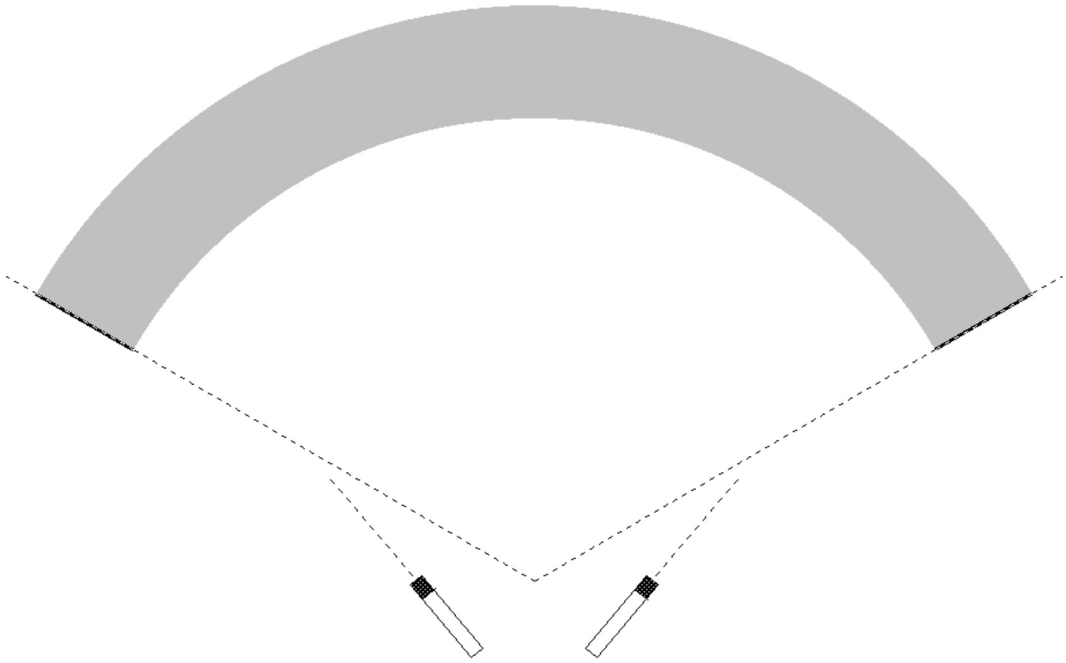


Figure 16 : Stereophonic Recording Angle is Greater than Angle between Microphones

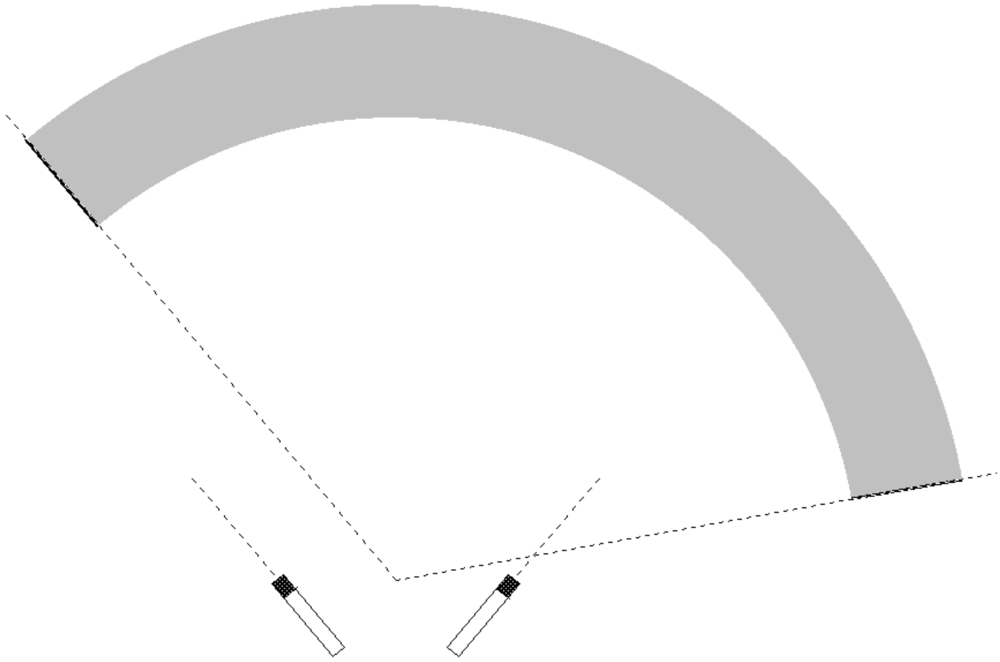


Figure 17 : Positive Offset of 15° (Left Limit of SRA aligned with Microphone Axis)

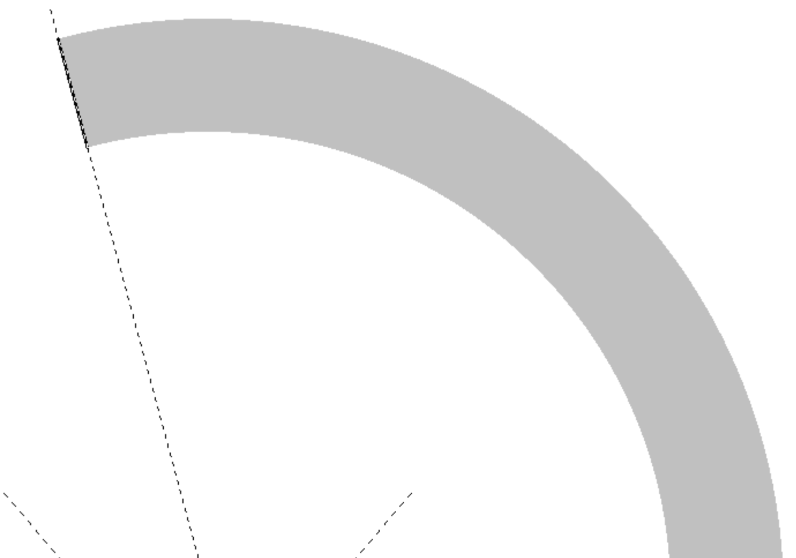


Figure 18 : Orientation of SRA with Positive Angular Offset of 40°

In these figures the Stereophonic Recording Angle has been drawn with its true origin on a line between the two microphone capsules. In Figure 14 and Figure 17 we see that the left limits to the SRA are aligned (or parallel) with the axis of the left microphone. The process of linking is represented in Figures 19 to 22. As the sound source is relatively far away compared with the distance between the microphones, it is an acceptable approximation to draw the graphical origin of the SRA coverage at the intersection between the microphone axes. This enables us in Figures 20 & 21, and thereafter, to illustrate more clearly the process of linking that is an essential characteristic in the design of a multichannel microphone array for smooth and continuous coverage.

- Figure 19 shows the front triplet of a Multichannel Microphone Array. We can see that we have microphones facing both towards the left-hand side and right-hand side, forming left facing and right facing pairs by sharing the centre microphone.

- In Figures 20 & 21 we show how to link the SRAs of each pair to produce continuous coverage of the front sound stage. Figure 20 uses the link between two SRAs that are each smaller than the physical angle between the microphones that make up their respective pairs. We need to use Positive Angular Offset on the left segment and Negative Angular Offset on the right segment to « critically link » the two segments. However in Figure 21 the link is between the two SRAs that are larger than the angle between the microphones, we therefore use Negative Angular Offset on the left segment and Positive Angular Offset on the right segment for correct linking. By this process we can create a front triplet with any desired coverage angle, thereby giving more flexibility to the sound recording engineer in setting up the coverage of the main front sound stage.

- Figure 22 shows how this process of linking is applied for the complete Multichannel Microphone Array. Only the front facing centre microphone is aligned with the linking of two segments i.e. the link between the Front Left Segment (FLS) and the Front Right Segment (FRS). The Back Segment (BS) is usually symmetrical with respect to the back axis of the system.

5.2 Intensity and Time Offset Generation

The method used to produce this offset technique is in fact remarkably simple, both in theory and practice. The difficulty comes in the choice of specific offsets so that « critical linking » is obtained, and smooth and continuous sound field reproduction is achieved. Basically there are four different types of offset that we can apply :

- Electronic Intensity Offset – addition of a constant Intensity Difference to the Intensity/Time Difference function between two microphones
- Electronic Time Offset – addition of a constant Time Difference to the Intensity/Time Difference function between two microphones
- Microphone Position Intensity Offset
- Microphone Position Time Offset

These last two offsets are one and the same, as it is just a question of one type of offset relative to the other. By creating a Microphone Position Intensity Offset in one direction, it is equivalent to creating a Microphone Position Time Offset in the other direction.

There is however a subtle difference between « Electronic Offset » and « Microphone Position Offset ».

- Electronic Offset is simply the addition of a constant value of Intensity Difference or Time Difference to the Intensity/Time function of a pair of microphones covering a particular segment.
- Microphone Position Offset is created by changing the physical position of the microphones forming the pair, thereby creating an angular difference between the Intensity and Time axes.

Let us be clear on the convention that has been adopted for Positive and Negative Offsets :

POSITIVE OFFSET IS DEFINED AS THAT OFFSET WHICH PRODUCES A ROTATION OF THE COVERAGE ANGLE IN A CLOCKWISE DIRECTION.

- This is obtained in the case of a Positive Electronic Time Offset by introducing a delay in the right hand microphone in relation to the left hand microphone.
- Similarly with Positive Electronic Intensity Offset the right hand microphone is attenuated in relation to the left.
- With Positive Microphone Position Time Offset the right hand microphone is rotated clockwise (i.e. backwards) using the centre of the left microphone diaphragm as the centre of rotation whilst maintaining the same distance between the microphones and angle between the axes of the microphones.

Each of these different positive offsets will produce a shift in their respective Intensity/Time function graphs either <u>to the left</u> for Positive Time Offsets, or <u>downwards</u> for Positive Intensity Offsets. This can be a little disconcerting at first, however the sound position coordinates show the relative position of the Coverage Angle and this leaves no room for ambiguity. The values of the Sound Position Coordinates are shown in ellipses superimposed on the Intensity/Time Difference function in each graph. The following table will help in following the analysis and practical implementation of each type of Offset.

Angular Offset	Coverage Angle Rotation	dI/dT shift	Right-hand Microphone
Positive Electronic Intensity Offset	Clockwise (Positive Rotation)	Downwards (- 'y' db)	attenuated
Positive Electronic Time Offset	Clockwise (Positive Rotation)	to the left (- 'x' mS)	electronic delay
Positive Microphone Position Time Offset	Clockwise (Positive Rotation)	to the left (+ angle°)	delayed (by physical position)
			Left-hand Microphone
Negative Electronic Intensity Offset	Anticlockwise (Negative Rotation)	Upwards (+ 'y' db)	attenuated
Negative Electronic Time Offset	Anticlockwise (Negative Rotation)	to the right (+ 'x' mS)	electronic delay
Negative Microphone Position Time Offset	Anticlockwise (Negative Rotation)	to the right (- angle°)	delayed (by physical position)

5.3 Offset Functions with Coverage Angle > Physical Angle between Microphones

5.3.1 Electronic Offset

Figure 23 shows the Intensity/Time Difference Function for a pair of microphones at 25cm/70° between the microphones without any Offset of any sort.

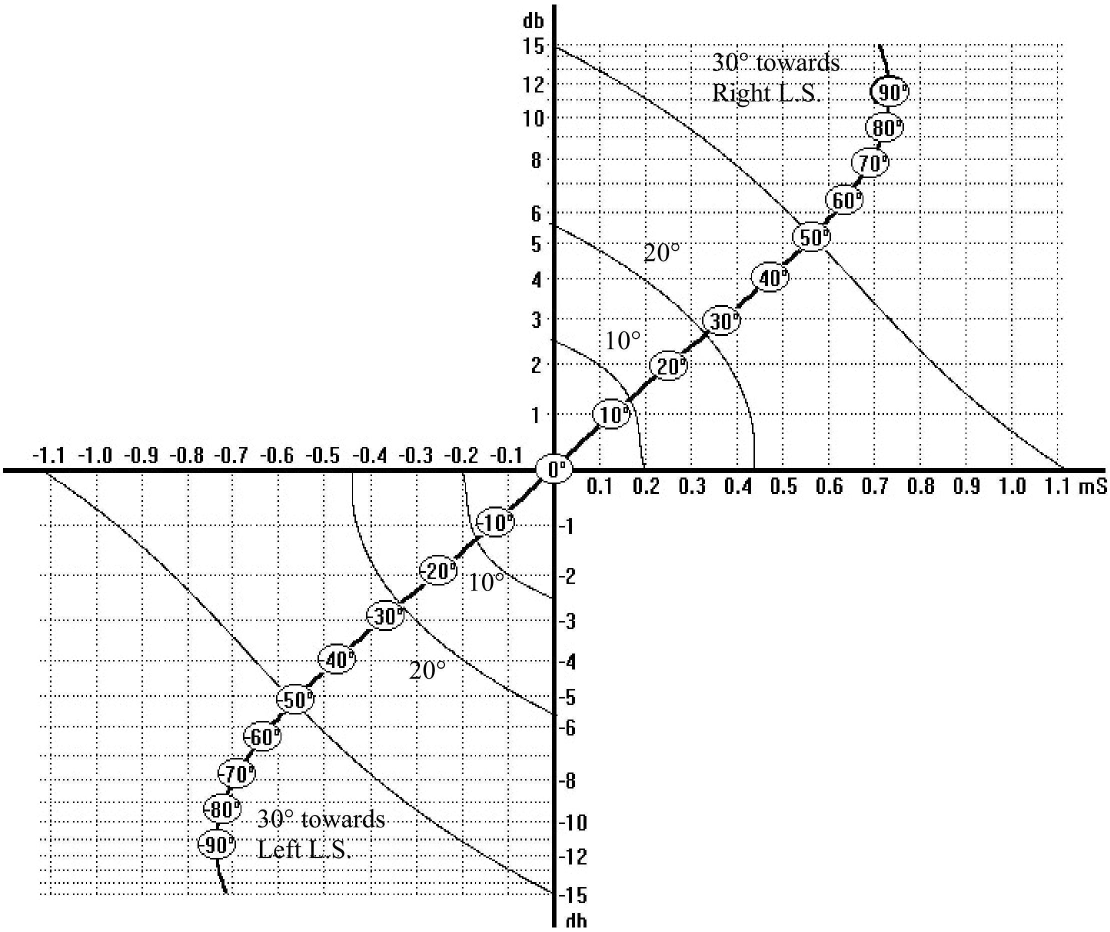


Figure 23 : Intensity / Time Difference Function without Offset

Figure 24 however has a « Positive Electronic Time Offset » of -0.28 mS (the right hand microphone has been delayed in relation to the left), i.e. the whole of the Intensity/Time

Difference function has been displaced towards the left by 0.28 mS, we can see that the origin (0°) of sound source position in this diagram is also at –0.28 mS.

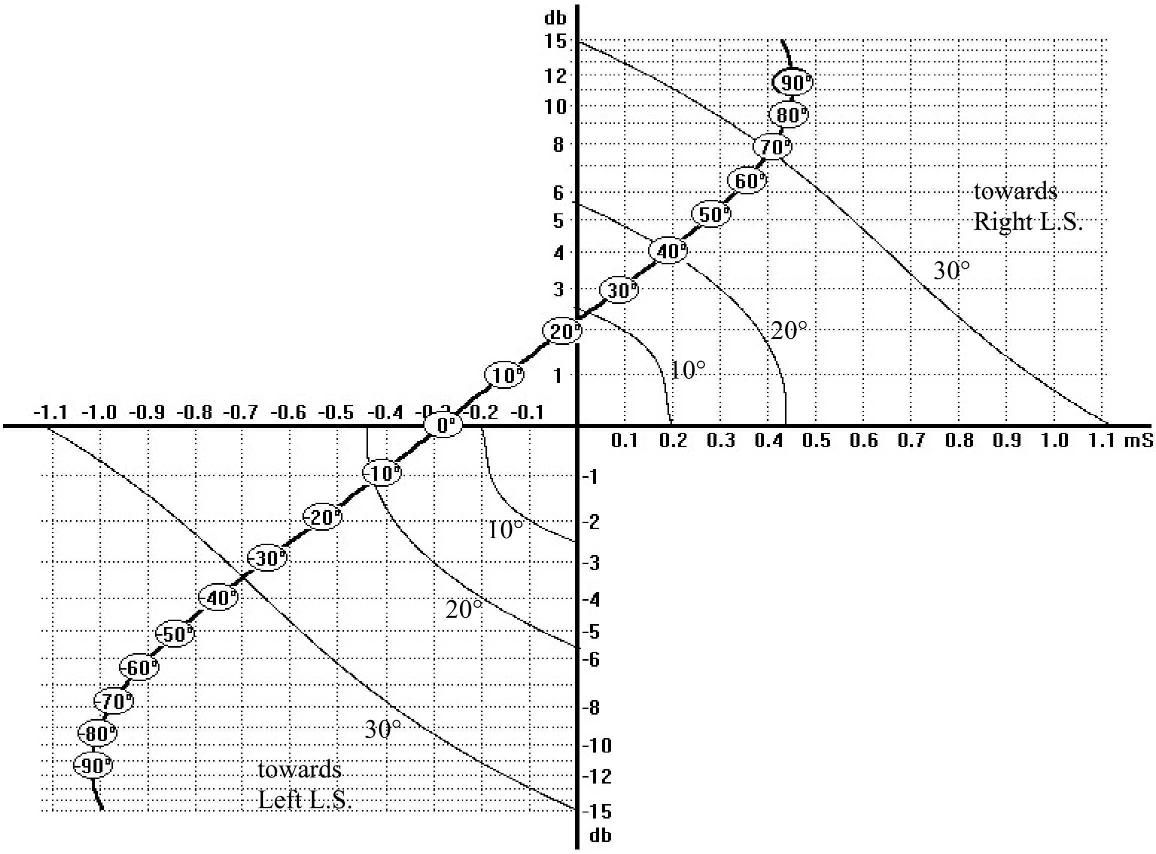


Figure 24 : Intensity/Time Difference Function
with Positive Electronic Time Offset of −0.28 mS

In Figure 25, « Positive Electronic Intensity Offset » of -2.5 db has been applied (the right hand microphone has been attenuated in relation to the left). In relation to Figure 23, the Intensity/Time Difference function has been translated downwards by 2.5 db. Again the origin of the sound source position has followed suit, and is at –2.5 db on the Intensity Difference axis.

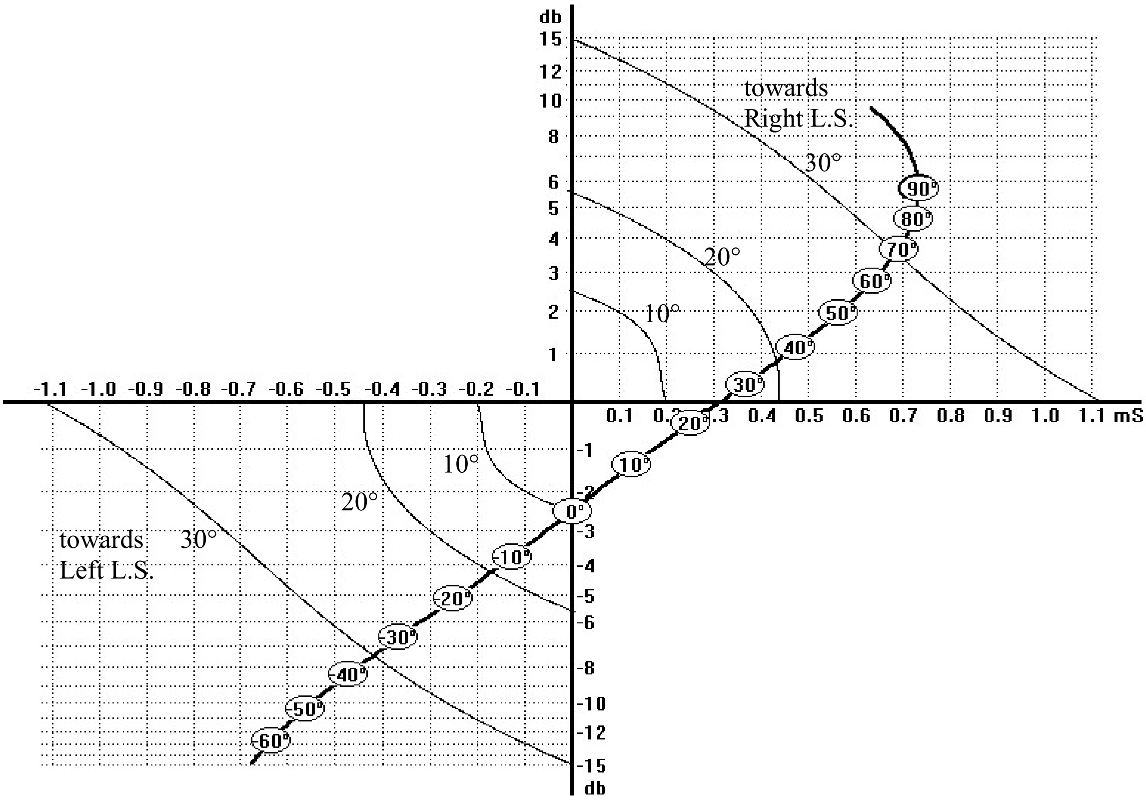


Figure 25 : Intensity/Time Difference Function
with Positive Electronic Intensity Offset of -2.5 db

It can be clearly seen in these examples the influence of the two types of offset on the Stereophonic Recording Angle. In Figure 23 the SRA is about +/- 50° (a total angle or Coverage Angle of 100°). Whereas in Figure 24 the offset has created a SRA with an overall coverage of about 103°, but now with an asymmetrical coverage from –35° (to the left) to +68° (to the right). In Figure 25 the Intensity Offset is –2.5 db covering about 105° in all, but with an asymmetrical coverage from –35° (to the left) to +70° (to the right). It is to be noted that the use of offset can modify slightly the total coverage angle of the system in relation to the SRA without offset. This will have to be taken into account in the final design of the complete microphone array.

It is easy to see how we can adjust both positive and negative intensity and time offsets to obtain almost any position of the coverage, within reason. A word of warning however, excessive values of offset will produce some unexpected effects :

- There must be intersection between the Intensity/Time Difference function and the Psychoacoustic curves for +/- 30° otherwise we will not be able to produce correct linking.

- Angular Distortion is normally just a function of intersection of the Intensity/Time Difference function with the psychoacoustic curves (at 10°, 20° & 30°) representing the reproduced position of the various sound sources as virtual images between the loudspeakers. As can be seen in Figures 24 & 25, with excessive values of offset, the non-linearity of the Intensity/Time Difference function can perceptibly increase the Angular Distortion.

- We must also be careful not to introduce too much Electronic Intensity Offset, as this will cause an imbalance in the general energy distribution around the system. Unfortunately there is at present too little published information concerning the psychoacoustics of energy perception when in the presence of complex summation of Intensity/Time Difference signals.

In Figure 26 we can see that it is also possible to apply a combination of Electronic Intensity and Time Offset so that the Intensity/Time Difference function passes through the Intensity/Time origin (0 db / 0 mS). This has no magical significance as it is perfectly possible to exploit the two other sectors of Intensity/Time Difference graph, especially if we are concerned only by values reasonably close to the Intensity/Time origin. Some preliminary research(1) has been done to be sure that there are no surprises when the Intensity/Time function passes close to the origin, however it would seem that there is some dispersion of localisation of the virtual image when crossing these sectors. It would be interesting to have a complete mapping of this area ; this is yet another area where more psychoacoustic research is necessary.

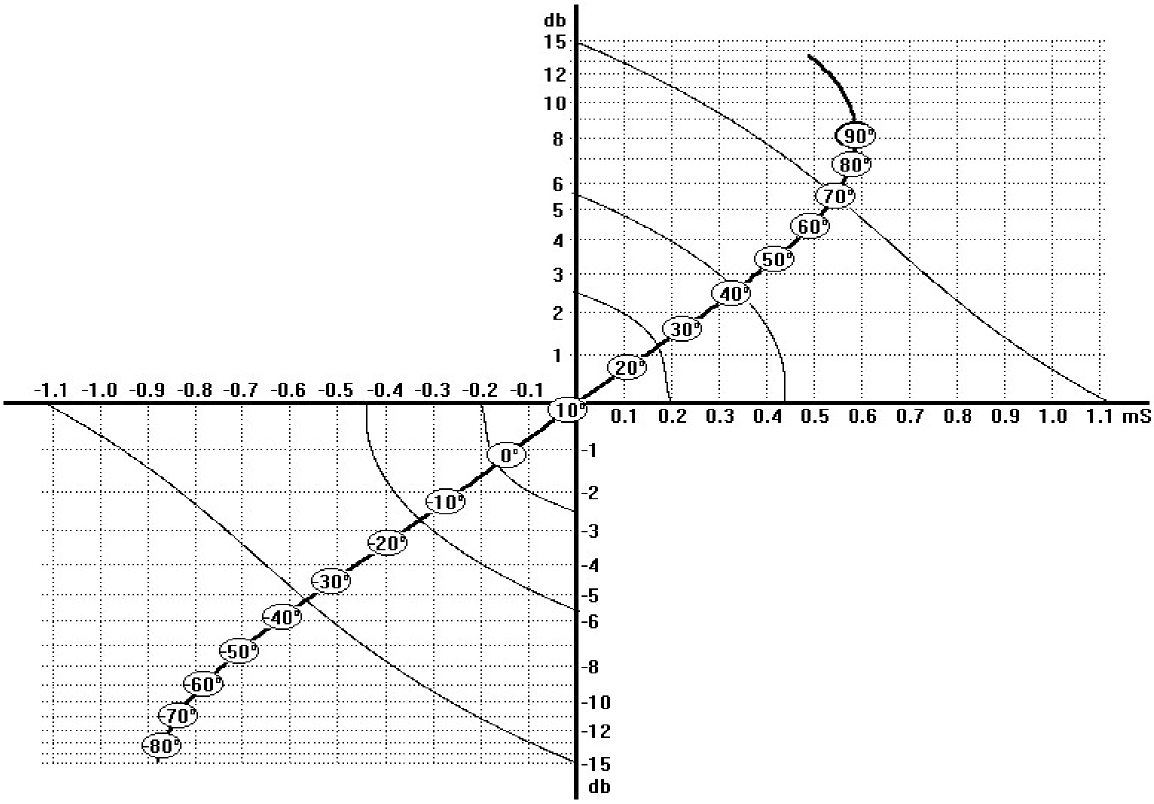


Figure 26 : Intensity/Time Difference Function :
Positive Electronic Intensity Offset of –1.15 db and Positive Electronic Time Offset of -0.145 mS

5.3.2 Microphone Position Offset

Figure 27 shows the effect of Microphone Position Time Offset using an angular rotation of +37° (37° of clockwise rotation of the right microphone, the centre of the diaphragm of the left microphone is the centre of rotation and the same angle is maintained between the microphone axes).

5.3.3 Combined Offsets

In Figure 28 the same Coverage Angle Offset is obtained with a combination of both Microphone Position Offset and Electronic Intensity Offset, i.e. a combination of +13° Microphone Position Offset and –1.3 db Electronic Intensity Offset. This produces a Coverage Angle Offset of +15° (compared with Figure 23 where no Offset is applied) and is explained in detail in the next paragraph.

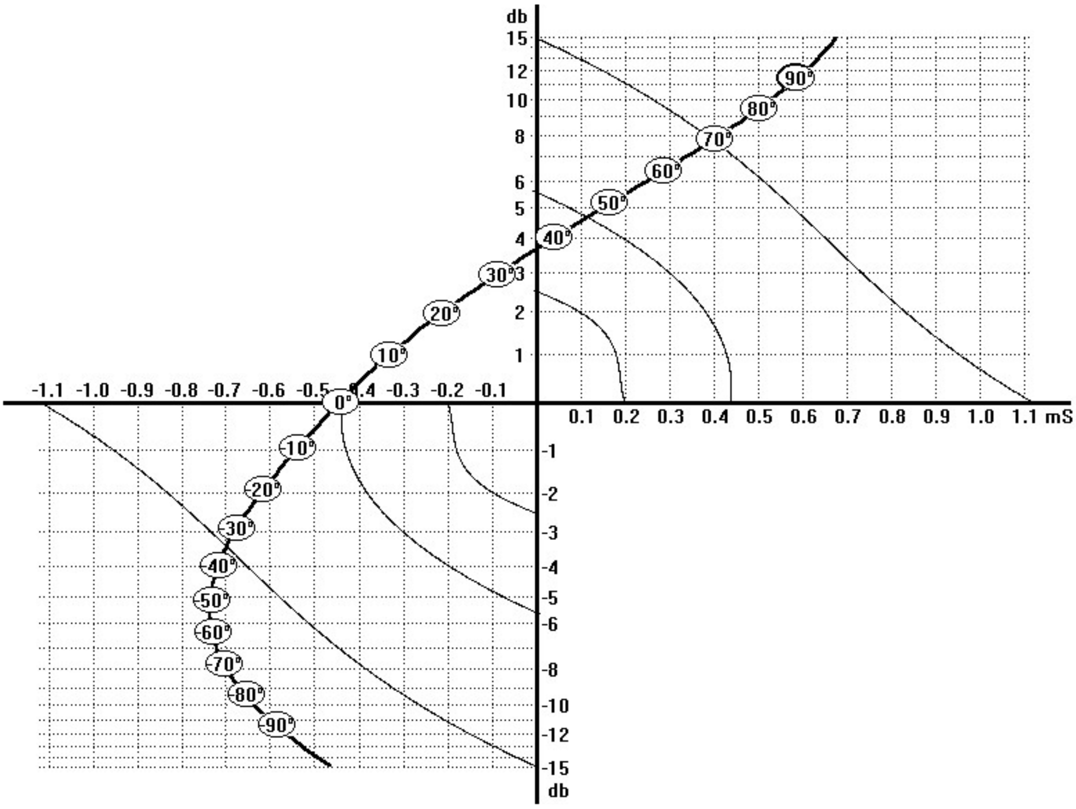


Figure 27 : Intensity/Time Difference Function
with Positive Microphone Position Time Offset of +37°

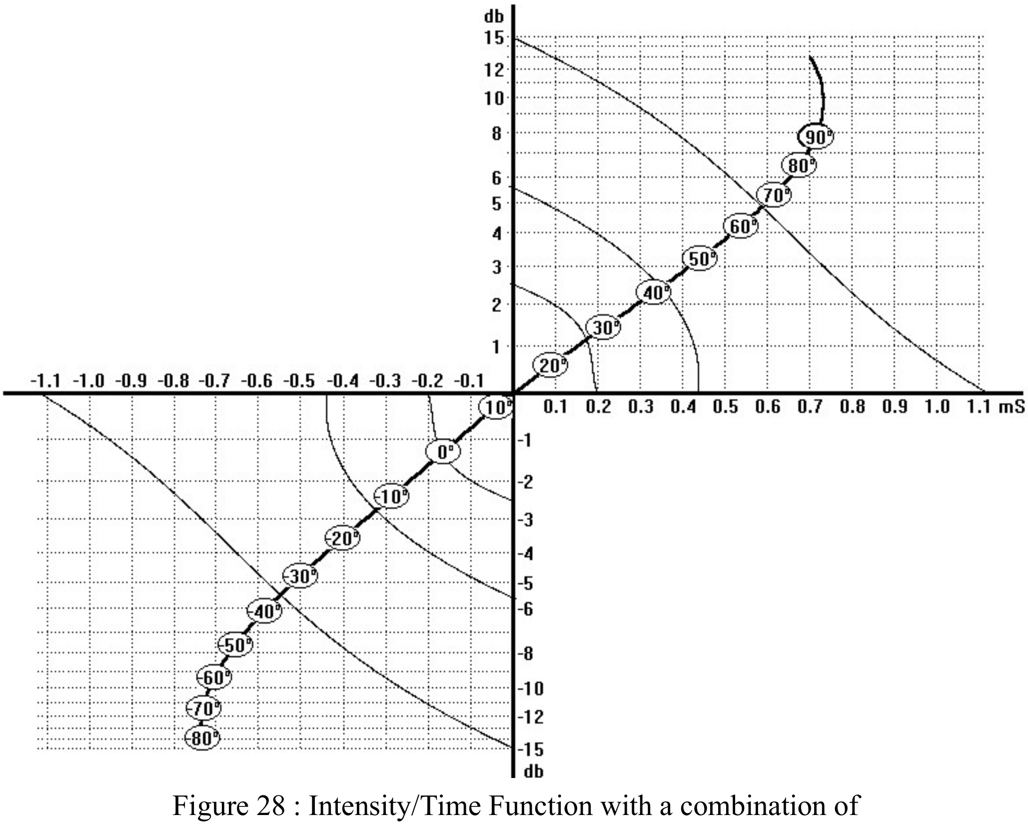


Figure 28 : Intensity/Time Function with a combination of
Positive Microphone Position Offset of +13° and Positive Electronic Intensity Offset of −1.3 db

5.3.4 Critical Linking of the Front Triplet

In Figure 29, the Front Facing Triplet is represented with 25cm/70° between the microphones, the SRA is +/- 50°.

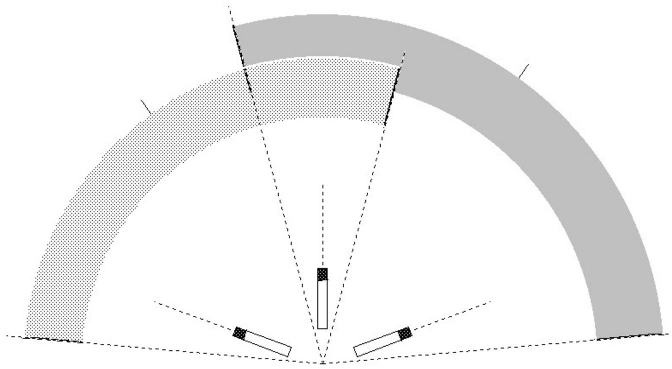


Figure 29 : Front Triplet 25cm/70° - Coverage Angle 100° for each Segment – No Offset

The angle between the microphones is 70°, the Coverage Angle is 100°, so we need 15° of Angular Offset to align the edge of the Coverage Angle with the axis of one of the microphones. Instead of a symmetrical coverage of +/- 50° we are looking for coverage from –65° to +35° or –35° to +65° according to whether we have to apply Negative Angular Offset to the Left Front Segment or Positive Angular Offset to the Right Front Segment, in order to obtain critical linking as shown in Figure 30.

Critical Linking

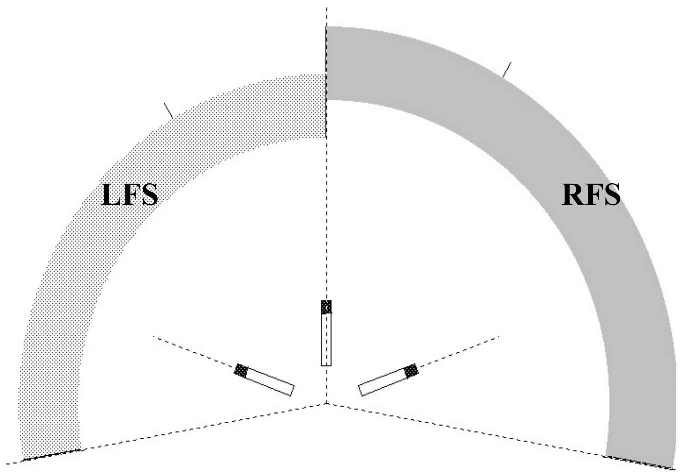


Figure 30 : Front Triplet 25cm/70° - Coverage Angle 100° for each Segment
with Negative Offset of –15° on Left Front Segment
and Positive Offset of +15° on Right Front Segment

The examples in Figures 24, 25,26, 27&28 have been chosen to illustrate the application of offset in the design of the Front Facing Triplet. In each of these examples, each pair of microphones making up the Front Triplet has an angle of 70° between the axis of the microphones and 25cm between the centre of the microphone diaphragms. From these examples we now have a disconcerting choice of methods to use, in order to obtain a desired offset with the edge of the Coverage angle of each segment aligned with the centre microphone axis.

- Figure 24 : Positive Electronic Time Offset of –0.28 mS (right hand microphone is delayed in relation to the left).
- Figure 25 : Positive Electronic Intensity Offset of –2.5 db (right hand microphone is attenuated in relation to the left).
- Figure 26 : Combined Positive Electronic Time and Intensity Offsets of –1.15 db and 0.145 mS respectively.
- Figure 27 : Microphone Position Time Offset of +37° .
- Figure 28 : Combination of Microphone Position Offset of +13° and Positive Electronic Intentensity Offset of –1.3 db;

5.4 Offset Functions with Coverage Angle < Physical Angle between Microphones

The coverage angle used for Figures 24 to 28 is wider than the physical angle between the microphones. To have the complete picture of the application of this offset technique for linking in the final Multichannel Microphone Array, we must also look at the opposite situation, i.e. when the Coverage Angle of a pair of microphones is less than the angle between the microphones.

It should not be necessary here to make a detailed analysis of Figures 31 to 35, suffice it to say that, in each of these illustrations, Negative Offset has been applied to rotate the Coverage Angle anticlockwise, which is the case when the pair is being used to cover the Right Facing Segment of the Front Triplet (the opposite offset is applied when the pair covers the Left Segment of the Front Facing Triplet). Further details concerning a detailed analysis of these figures will be found in AES Preprint 4997.

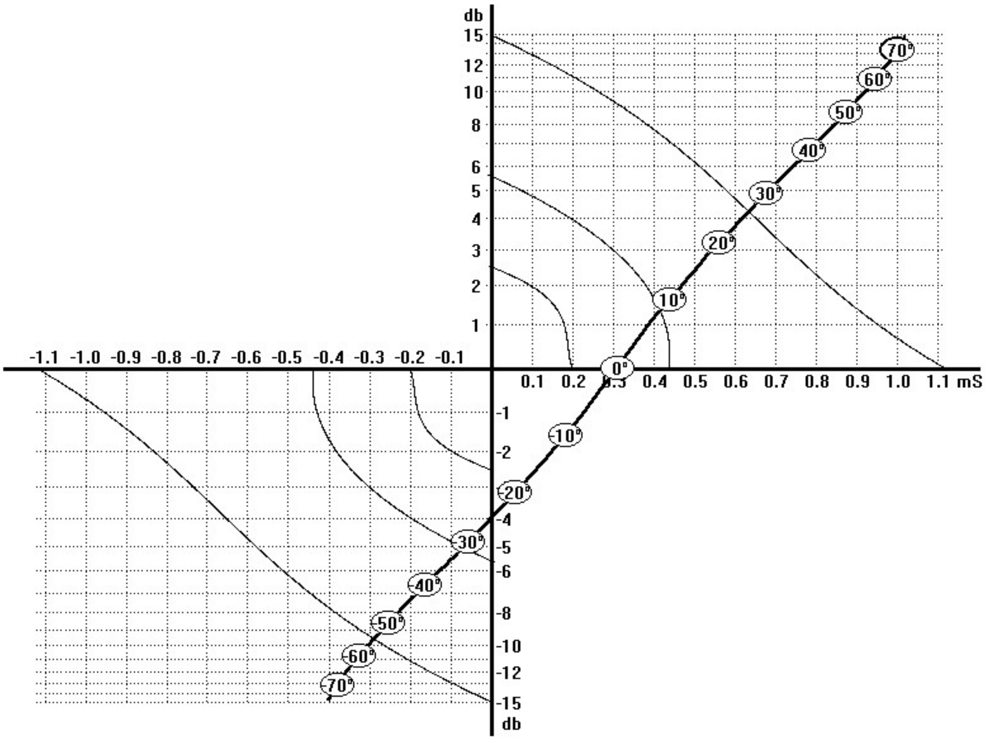


Figure 31 : Intensity/Time Difference Function
with Negative Electronic Time Offset of 0.31 mS

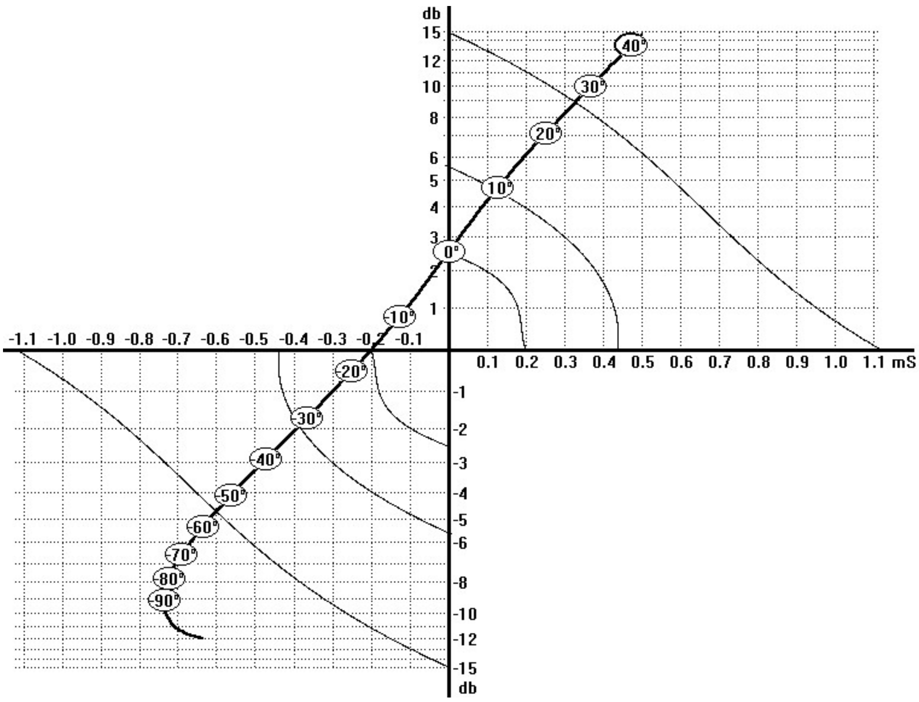


Figure 32 : Intensity/Time Difference Function
with Negative Electronic Intensity Offset of 2.5 db

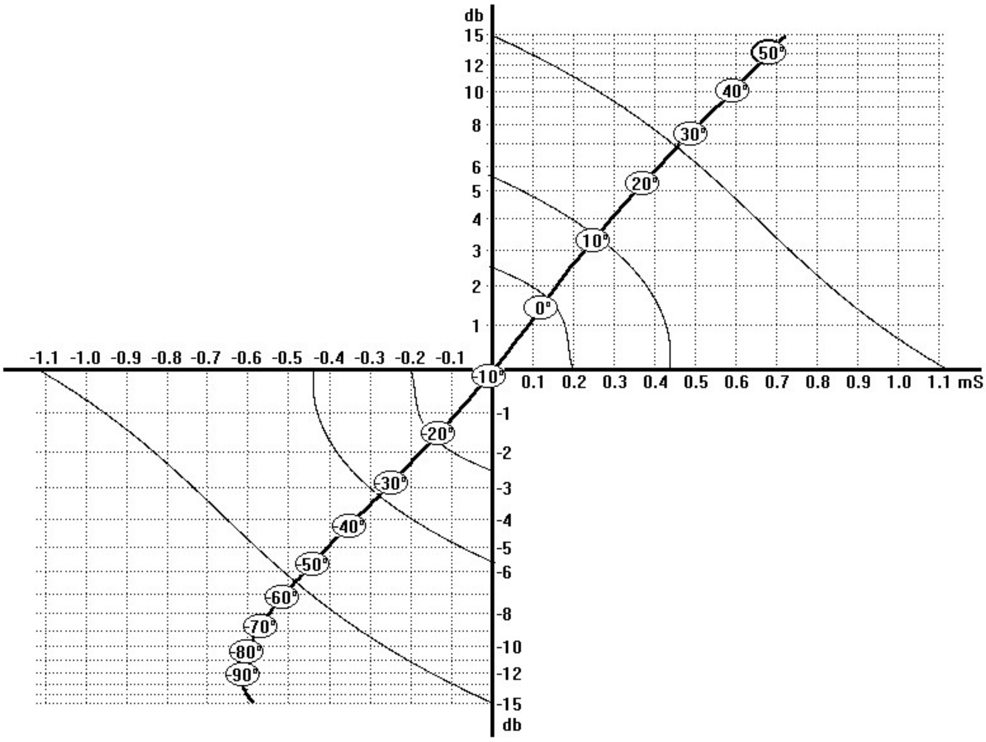


Figure 33 : Intensity/Time Difference Function
with Negative Electronic Intensity Offset of 1.38 db
and Negative Electronic Time Offset of 0.12 mS

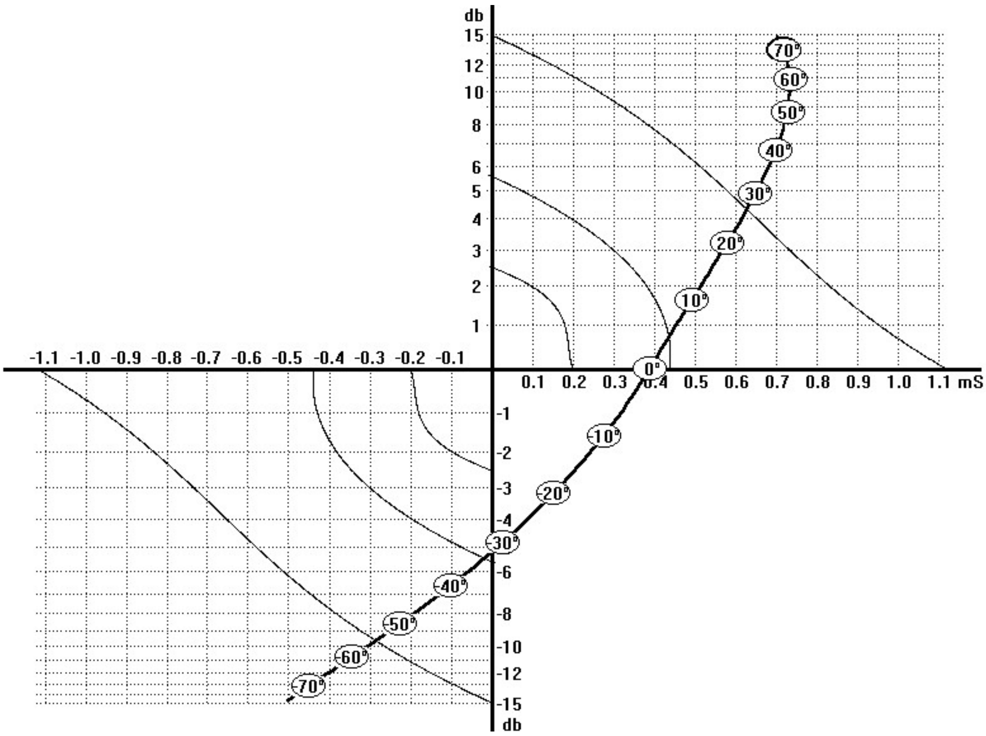


Figure 34 : Intensity/Time Difference Function
with Negative Microphone Position Time Offset of –32°

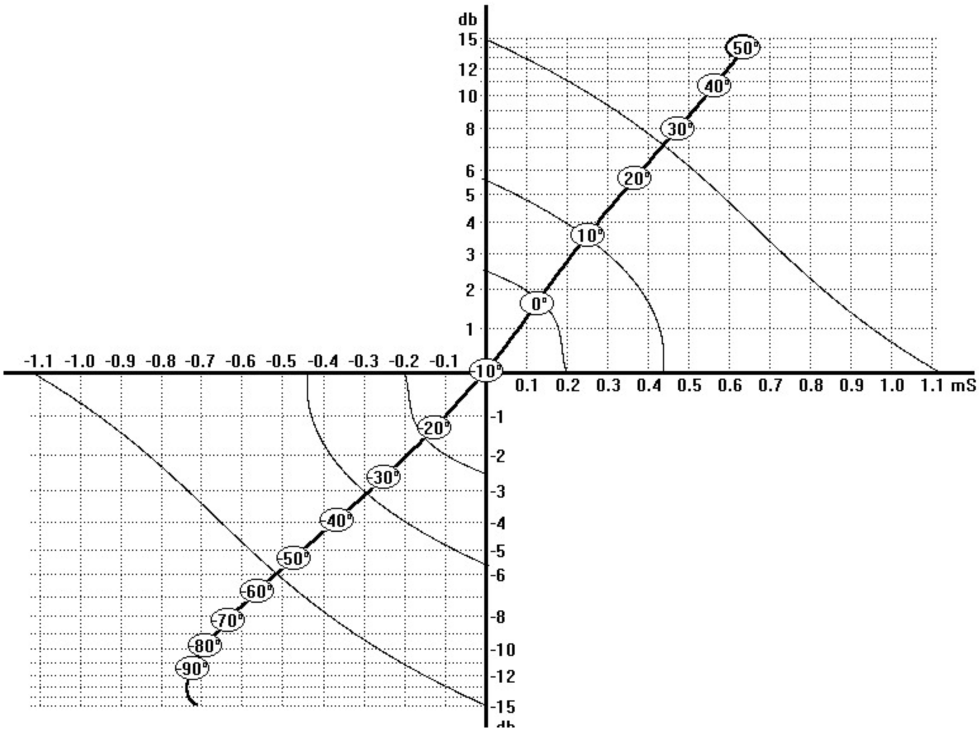


Figure 35 : Intensity/Time Difference Function with a combination of
Negative Microphone Position Time Offset of –10°
and Negative Electronic Intensity Offset of 1.6 db

☞ WARNING - Any use of Electronic Intensity Offset must be done with caution, as this may effect the smooth energy distribution around the system. However in the case of Negative Electronic Intensity Offset we are in fact decreasing the relative level of the centre microphone of the triplet and there are a few people who consider this already to be necessary in a multichannel system to achieve a balance in energy distribution around the system!

5.5 Segment Design of a Multichannel Microphone Array (MMA)

There are three distinct stages in the design of the complete MMA :

1) Design of the Front Facing Triplet
2) Choice of the Back Segment Coverage
3) Coverage and Critical Linking of the Lateral Segments

5.5.1 Front Facing Triplet

The Coverage Angle (CA) of the Front Facing Triplet (FFT) is probably the most important parameter that must be determined right from the start of the process of design of the MMA. The physical position of the microphone system i.e. its distance from the sound source, will obviously determine the angular size of the sound source as 'seen' by the MMA. On the other hand the choice of Coverage Angle will determine the reproduced angular 'size' of the sound source. A large CA will reduce the reproduced sound image – a small CA will, on the contrary, widen the reproduced sound image, even to the extent of overlapping into the Left and Right Lateral Segments.

This is part of the personal choice of the sound engineer in the effect that he wishes to produce. The main sound stage formed by the front three loudspeakers is responsible for the reproduction of the FFT. Overlap into the Lateral Segments will envelop the listener in a wider sound stage, but one should not expect to have precise localisation over the total width of these Lateral Segments, as our natural perception shows a gradual loss towards the sides. However this is not a reason for rejecting totally the possibility of overlap, and do not forget that we must have the freedom to turn the head during listening, which in itself changes our perception of the different segments of sound reproduction.

With the reproduction of a wide sound source such as a Symphony Orchestra, the overlap can be a definite advantage. The stereophonic recording of this type of sound source has always been a compromise between the spread of the centre of the orchestra and the cut-off on the sides of the sound surface of violins on the left, and cellos and double-basses on the right. With MMA a new field of experimentation is opened up into the amount of overlapping into the Lateral Segments that is considered desirable.

5.5.2 Back Segment

The combination chosen for the back segment covering generally the reverberant field is relatively arbitrary. It has been our experience that too heavy a sound field in the back segment can be disturbing. However as the spacing of the back segment loudspeakers is 140°, there is considerable Angular Distortion associated with this segment, and therefore the reproduced sound field has a tendancy to widely spread in the centre part of the field. The choice of a reasonably small SRA would also tend to accentuate this effect.

5.5.3 Lateral Segments

Having determined the coverage required for the Front Triplet (FT) and the Back Pair (BP), we must vary the distance between these two components (FT & BP) so that the coverage angle of the Lateral Pairs (LP) corresponds to the angle of coverage needed for the Lateral Segments (LS). For the time being this is not necessarily correctly orientated. Each of the pairs covering the lateral segments will have an inherent time offset due to the physical position of the back facing microphones in relation to the side facing microphones of the pairs. This must be compensated by simple Intensity Difference Offset so that the segment orientation critically links with its front & back facing neighbours.

In order to determine the value of this Electronic Offset we have to map out the specific coordinates and orientation of each microphone. The position of the Front Triplet and its distance from the Back Pair determines the distance separating the microphones in each of the Lateral Pairs. This distance enables us to determine the coordinates of each microphone forming the lateral microphone pairs, and thus to be able to calculate the inherent Microphone Position Time Offset created by their position. It is then just a question of determining the amount of Electronic Intensity offset needed to obtain Critical Linking with the neighbour segments.

6 - Conclusion

Multichannel Microphone Array Design using the concept of different types of « Offset » is a major tool in improving the performance of multichannel microphone array systems. It will enable us to design a multitude of microphone configurations that will satisfy the different conditions experienced in multichannel sound recording. Critical Linking becomes a reality, and the resultant smooth continuous reproduction of the sound field maintains the original structure of the sound source and its acoustic environment.

This paper has tried to show the general structure of signals arriving at the ears in a multichannel listening environment and the influence of acoustic crosstalk on the localisation of the sound source around the microphone array. It has been shown that the major part of the front and lateral segments are exempt from any significant interference from crosstalk information resulting in good localisation over the major part of the usual sound stage. However this result is based on a common-sense approach to the design of the Front Triplet characteristics which will do much to improve the eventual magnitude of crosstalk.

7 - Vocabulary and Abbreviations

« Multichannel Microphone Array (MMA) » is any group of microphones forming a coherent sound recording microphone system.

« Sound Field Segmentation » – The sound field is divided into angular segments or sectors, covered by a specific microphone pair. Each segment is analysed in relation to the characteristics of the relative microphone pair and with respect to the corresponding loudspeaker positions.

« Coverage Angle (CA) » is the total angle covered by a dual microphone system, which will be reproduced as a virtual sound field in the reproduction configuration. The Coverage Angle is equivalent to the total Stereophonic Recording Angle (SRA) of a single pair of microphones. The SRA is usually specified with the prefix +/- (for example +/- 50° is a Coverage Angle of 100°).

« Angular Offset or Offset » is the angular rotation of the Coverage Angle.

« Positive or Negative Offset » is used to refer to the direction of rotation of the Coverage Angle, (positive - clockwise, negative – anticlockwise), when some form of offset is applied.

« Critical Linking or Linking » is the use of angular offset on two neighbouring Coverage Angles, so that the side limits of each Coverage Angle link up with each other, without overlapping or leaving an uncovered space.

« Electronic Intensity Offset » is the addition of a constant Intensity Difference to the Intensity/Time Difference function.

« Electronic Time Offset » is the addition of a constant Time Difference to the Intensity/Time Difference function between two microphones.

« Positive Microphone Position Time Offset » is applied when the right hand microphone is rotated clockwise (i.e. backwards) using the centre of the left microphone diaphragm as the centre of rotation whilst maintaining the same distance between the microphones and angle between the axes of the microphones.

« Negative Microphone Position Time Offset » is applied when the right hand microphone is rotated anticlockwise (i.e. forwards) using the centre of the left microphone diaphragm as the centre of rotation whilst maintaining the same distance between the microphones and angle between the axes of the microphones.

« Front Facing Triplet (FFT) » is the group of three microphones covering the main sound stage.

« Front Left Segment (FLS) » is the segment of the sound field covered by the left pair (centre microphone + left side microphone) of the Front Facing Triplet.

« Front Right Segment (FRS) » is the segment of the sound field covered by the right pair (centre microphone + right side microphone) of the Front Facing Triplet.

« Left Lateral Segment (LLS) » is the segment of the sound field covered by the left side pair (left side microphone + left back microphone) of the microphone array.

« Right Lateral Segment (RLS) » is the segment of the sound field covered by the right side pair (right side microphone + right back microphone) of the microphone array.

« Back Segment (BS) » is the segment of the sound field covered by the pair of microphones facing the back of the microphone array.

8 - References :

(1) 1999 : Memoire de Recherche de l'Ecole Nationale Supérieure Louis Lumière « Conception de systèmes de prise de son multicanaux » by Guillaume Le Dû.

(2) 1987 ; 82nd AES Convention in London – preprint 2466 (H6) « Unified Theory of Microphone Systems for Stereophonic Sound Recording » by Michael Williams.

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

(4) 1991 : 91st AES Convention in New York – preprint 3157
« Microphone Arrays for Natural Multiphony » by Michael Williams.

(5) G.F.Kuhn, « Model for the Interaural Time Differences in the azimuthal plane »,
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(6) 1999 : 107th AES Convention in New York - preprint 4997
« Microphone Array Analysis for Multichannel Sound Recording »
by Michael Williams and Guillaume Le Dû