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## **Magic Arrays - Multichannel Microphone Array Design applied to Multi-format Compatibility.**

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### **ABSTRACT**

This paper describes the principles and design procedure of Multi-format-compatible Microphone Arrays for a range of different segment coverage angles and for Omnidirectional, Hypocardioid, Cardioid and Supercardioid microphones. At present the only practical solution available for the main microphone array for a multiple format recording is to use different microphone arrays for each of the required formats. This paper shows how this jungle of main microphone arrays can be replaced by a single 5 channel microphone array that will supply signals that are directly compatible with 5 standard formats : mono, two and three channel "stereo", four channel "quadraphony", and "multichannel" with the full 5 channels. The specific reproduction format can be chosen either during the production process as a function of the desired support media, or by the consumer from a multichannel media product according to their own particular listening configuration.

### **INTRODUCTION**

The objective of the microphone array design process is to create a range of microphone recording systems that will give the impression of reproducing as faithfully as possible the natural dimensions of the sound source and its acoustic environment, including the early reflection distribution and the surrounding reverberant field - this approach is a fundamental aesthetical choice in the process of producing satisfactory sound recording and reproduction.

No microphone system can be considered as perfect and microphones are in no way capable of

intelligent listening. The art of the sound recording engineer is therefore to use his mastery of the available techniques to translate the live musical experience into a satisfactory recording and reproduction experience. The microphone array should be the optimum choice for the particular environment, but the imperfections of the main microphone array recording system may still have to be smoothed out by many an artifice. How far one needs to go in the smoothing process will depend on a multitude of acoustical and musical factors, but the choice of the optimum central recording system is of prime importance either as the complete and final result, or simply as the starting point in a more elaborate recording and reproduction system.

## 1. MULTIFORMAT RECORDING

Multiple format recording of almost any production project is now becoming a basic requirement in most media – the 2 channel stereo and multichannel release formats of the same title being almost a commercial necessity. Whether we use the main microphone array as a single unique recording system or whether it is only part of a more complex microphone recording system is a basic aesthetic choice to be made by the recording engineer at the beginning of a recording session. However the eventual production and diffusion formats can often require that a number of different recording formats be recorded at the same time - the minimum standard requirement at present being to produce separate stereo and multichannel recordings either as individual system tracks at the time of recording or as mixdown at a future post production stage.

However who knows what will be the requirements at any future remix situation. Three channel stereo provides a much more linear localisation and more stable reproduction compared to the present two channel stereo configuration but it is not considered a priority product for the consumer at present. Quadraphony as such would seem to have had its day, but it is becoming an interesting format within the five channel multichannel reproduction format for certain aspects of mixing music and reproducing sound effects and environmental surround sound. Perhaps we should even be thinking of a 6 or 7 channel format as being a basic requirement at least as a reference archive recording. However for the time being this paper will consider multiformat compatibility as applied to the 5 channel or 'multichannel' format.

### 1.1 MMAD FOR MULTIFORMAT COMPATIBILITY

The normal multichannel microphone array design procedure may be divided into 3 stages :

- the design of the front segment(s) coverage
- the determination of the back pair coverage
- the configuration of the lateral pair coverage

In designing for array compatibility we must pay particular attention to the configuration of the front coverage segment or segments, whereas the side

and back coverage microphone configurations correspond to the normal design procedure. Image folding of the side and back segments into the front coverage in two or three channel reproduction, called in a previous paper<sup>1</sup> "Twisted Quad Matrixing", is of course optional.

We must adopt a very different strategy for compatibility in the design of the front coverage segments, compared to the relatively simple design procedure for the lateral and back segment coverage. The multi-format-compatible array design process is directly applicable to two specific situations :

- Front Sound Stage Coverage with 3 microphone channels – either two or three channel compatible reproduction being possible
- Surround Sound Coverage with a 5 microphone array – equally compatible with 4, 3 or 2 channel reproduction, or even mono reproduction

### 1.2 THE FRONT SEGMENT COVERAGE DESIGN FORMULA

For multiformat microphone array compatibility the two segment front coverage system of a triplet array of microphones must obey the simple but fundamental coverage formula:

**the Left Front Segment Coverage angle (LFSC)**  
*formed by the left and centre microphones*

PLUS

**the Right Front Segment Coverage angle (RFSC)**

*formed by the centre and right microphones*

MUST BE EQUAL TO

**the Left and Right Pair Coverage angle (LRPC)**  
*formed by the left and right microphones*

**LFSC + RFSC = LRPC**

*(as shown in Figure 1)*

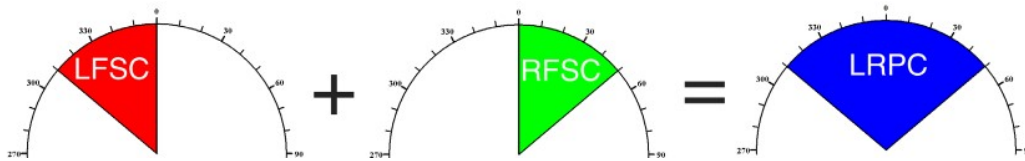


FIGURE 1 - THE FRONT SEGMENT COVERAGE DESIGN FORMULA

This would seem to be absolutely self evident, but only a clear understanding of the function of the centre microphone in the design of the left and right segment coverage will enable the correct design to be achieved.

The ever recurring mythology concerning the function of the centre microphone of a front triplet array is a major source of confusion in the mind of the sound engineer in the complex process of optimisation of the microphone array. It must be clearly understood that the adjunct of the centre microphone is not a banal addition of a centre source, but the creation of two distinct and theoretically separate segments: the left front and the right front segments. This design process in no way implies that the left front-coverage segment together with the right front-coverage segment are superimposed on the front coverage segment, determined by the left and right microphone pair.

The precedence effect will assure that we perceive only these two segments in hybrid or spaced microphone arrays. As described in a previous AES paper presented at the 118<sup>th</sup> AES Convention in Barcelona<sup>1</sup>, the "precedence effect" will limit our perception of a triplet microphone array to the coverage by the left and right front segments, whereas the stereo pair created by the left and right microphones will ONLY be perceived in the context of two channel stereo reproduction using just the left and right microphones as the stereo pair. When the precedence effect is operative this double perception of segment coverage in a triangle of microphones as superimposed segments is a pure figment of intellectual imagination and has no foundation in psychoacoustic analysis.

The precedence effect is one of the major advantages in reproduction using the hybrid (level and time difference) microphone array recording systems over the many coincident microphone array systems. It almost goes without saying that any attempt at coincident microphone array design will not be able to make use of the advantages of the precedence effect, simply because there is no time difference function to help the ear differentiate between localisation information developed by each combined pair of microphones. In this level-difference-only context it is more than probable that segment coverage superimposition will modify considerably the overall distribution of the sound image.

It is nevertheless necessary to design the microphone configuration so that good critical linking is achieved between the two segments, thereby achieving the impression of a smooth and continuous sound field coverage.

### 1.3 THE FRONT SEGMENT CONFIGURATION - DESIGN PROCEDURE

The starting point for the design of the front segment configuration is to determine the segment coverage of the stereo pair (formed by the left and right microphones), and each segment coverage of the triplet array (left front segment coverage and right front segment coverage).

From Figure 2 we can see that a combination of 100° between the microphone axes and 18cm between the centre of the microphone diaphragms will produce a stereo pair with a Stereophonic Recording Angle (SRA) of +/- 50° (a total coverage of 100°) for a pair of cardioid microphones.

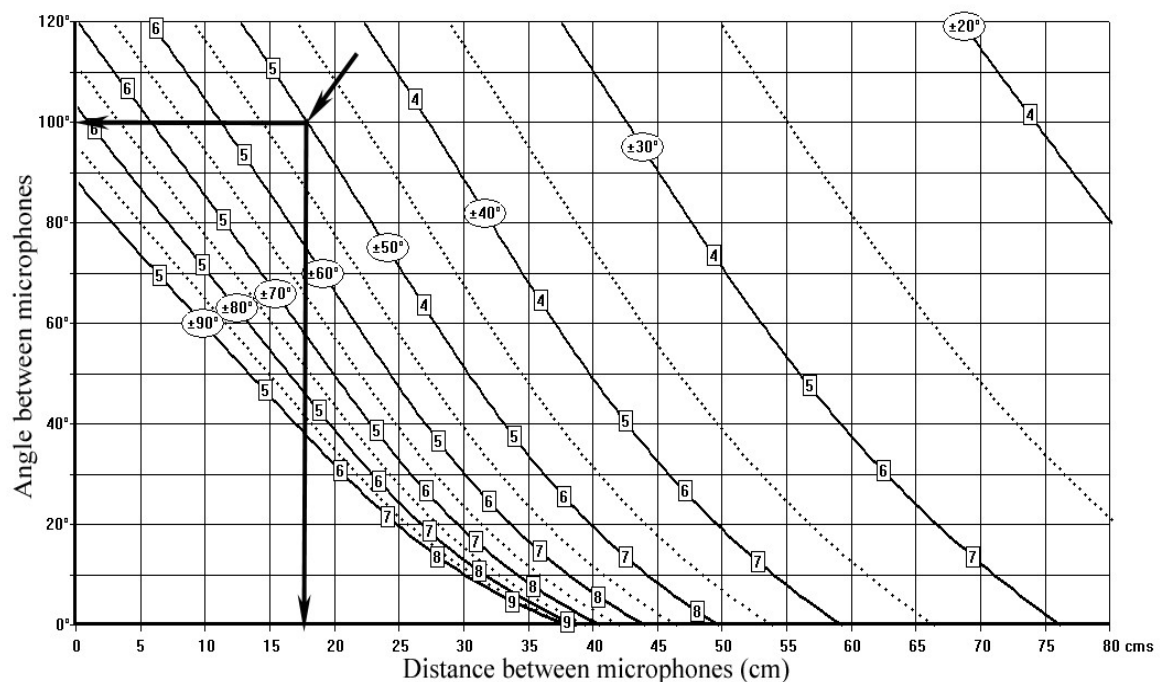


FIGURE 2 – SRA DIAGRAM SHOWING THE STEREO PAIR ARRAY COMBINATION 100° / 18CM - SRA OF +/- 50° FOR CARDIOID MICROPHONES

The  $dl/dt$  function and the psychoacoustic localisation curves for 10°, 20° and 30° are shown in Figure 3. The intersection between the psychoacoustic localization curves for 30° left and 30° right, and the  $dl/dt$  curve show clearly the limits to the SRA to be +/-50°.

The centre microphone of the triplet array will obviously be forward facing at 0°. The angle between the left microphone (orientation 310°) and the centre microphone (at 0°) is 50°, the angle between the centre microphone (at 0°) and the right microphone (orientation 50°) is also 50°.

As it would seem from Figure 4, to obtain a segment coverage of 50° (corresponding to an SRA of +/- 25° i.e. a total of 50°), with 50° between the microphones, we must use a spacing between the microphones of about 69cm.

If we now add the centre front facing microphone we can create a triplet 'root' array with two coverage segments – the left front

segment formed by the left and centre microphones, the right front segment formed by the centre and right microphone. As the stereo-pair originally had a segment coverage of 100°, then each triplet coverage segment must obviously be 50°, at least for the front segment-coverage formula to be valid.

The 'Root Array' will always be used for microphone arrays where the orientation of the microphones also corresponds to the limits of the respective coverage angles. In order to simplify the presentation of arrays in this paper only 'Root Arrays' will be described.

The term 'Root' Array is one specific type of array selected from the large number of critically linked microphone arrays that can be designed using MMAD and the various segment steering techniques that are available (Microphone Position Offset – MPO, Electronic Time Offset – ETO and Electronic Intensity Offset - EIO).

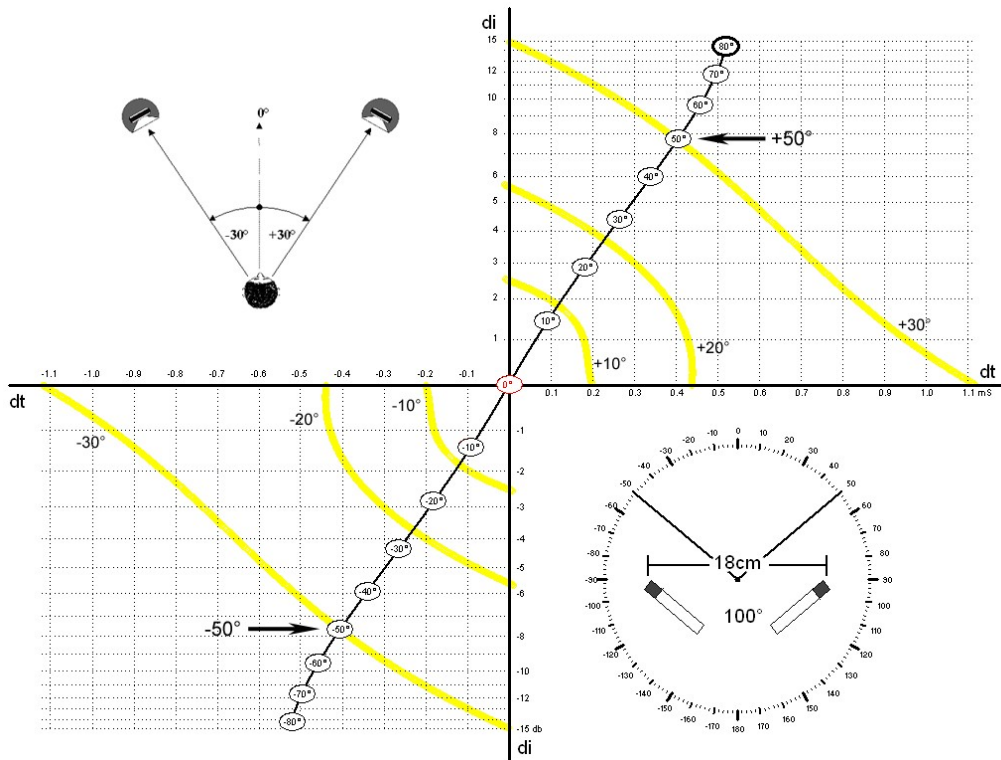


FIGURE 3 - DL / DT FUNCTION AND PSYCHOACOUSTICS LOCALISATION CURVES FOR THE STEREO PAIR  $100^\circ / 18\text{cm}$

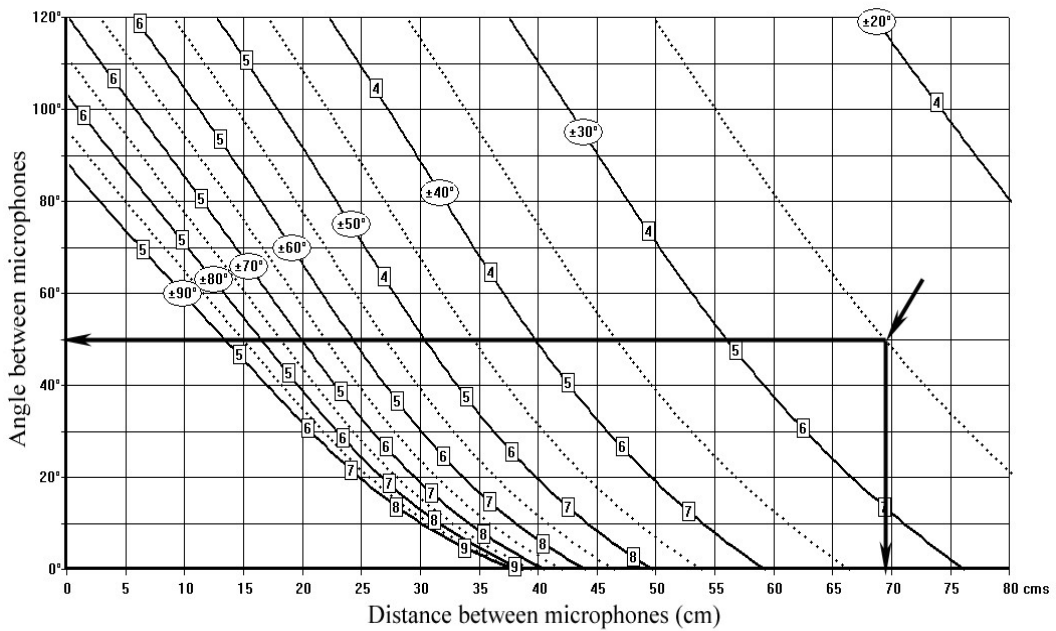


FIGURE 4 – SRA DIAGRAM SHOWING STEREO PAIR COMBINATION: SRA  $\pm 25^\circ$  ( $50^\circ / 69\text{cm}$ )

The front triplet can be constructed as two side-by-side pairs of 50° / 69cm sharing the centre microphone as shown in Figure 5.

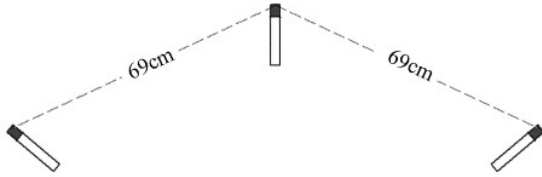


FIGURE 5 – FRONT TRIPLET MADE UP FROM TWO PAIRS AT 50° / 69CM

The coverage of each pair is 50° and the angle between the microphones is also 50° - the coverage segments from each part of the front triplet will naturally be critically linked – i.e. no underlap or overlap. The dl/dt characteristic for the left hand side of this array is shown in Figure 6, the coverage of the left front segment will be from 310° to 0° and symmetrically the right front

segment from 0° to 50°. The left coverage segment angle is therefore critically linked with the right segment coverage angle.

However in designing for compatibility the left and right microphones must also form the left-right stereo pair - this would seem to be almost impossible to achieve in relation to the left-right stereo pair of 100° / 18cm as shown in Figure 3. However if we consider that the 'stereo pair' is placed at about 69cm behind the centre microphone, we obtain the same pair characteristics for each component pair.

The fundamental difference now being that the front triplet pair now has a Microphone Position Offset (MPO) of about 57.5° as shown in Figure 7. The concept of different types of offset and in particular MPO was developed in a previous AES paper presented at the 107<sup>th</sup> AES Convention in New York<sup>2</sup>.

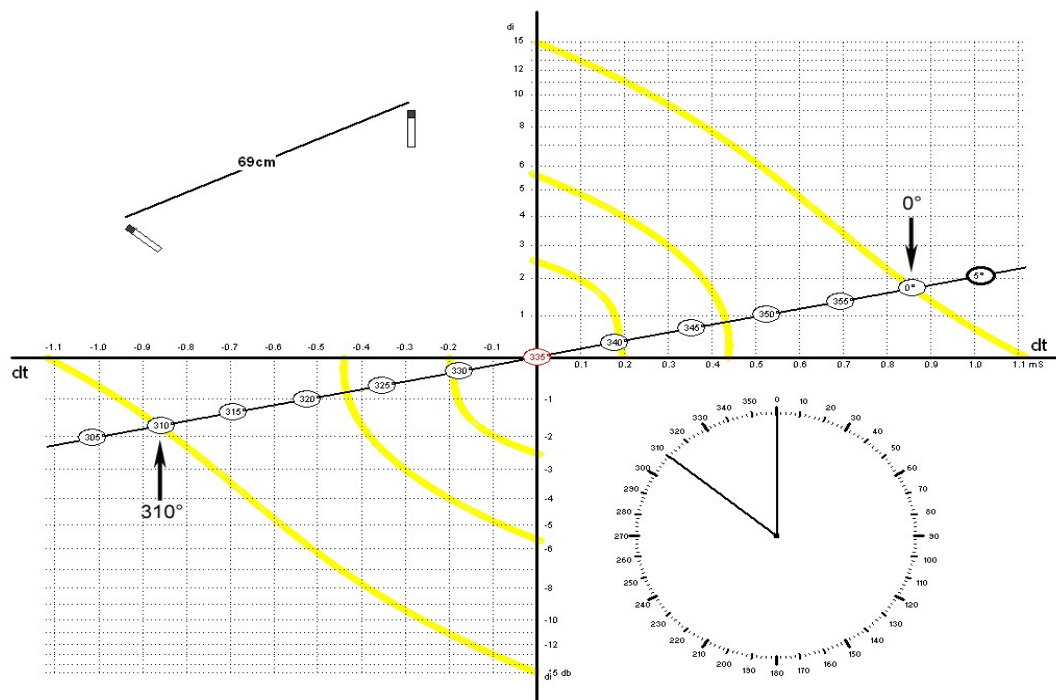


FIGURE 6 – DT / DL FUNCTION FOR A STEREO PAIR 50° / 69CM

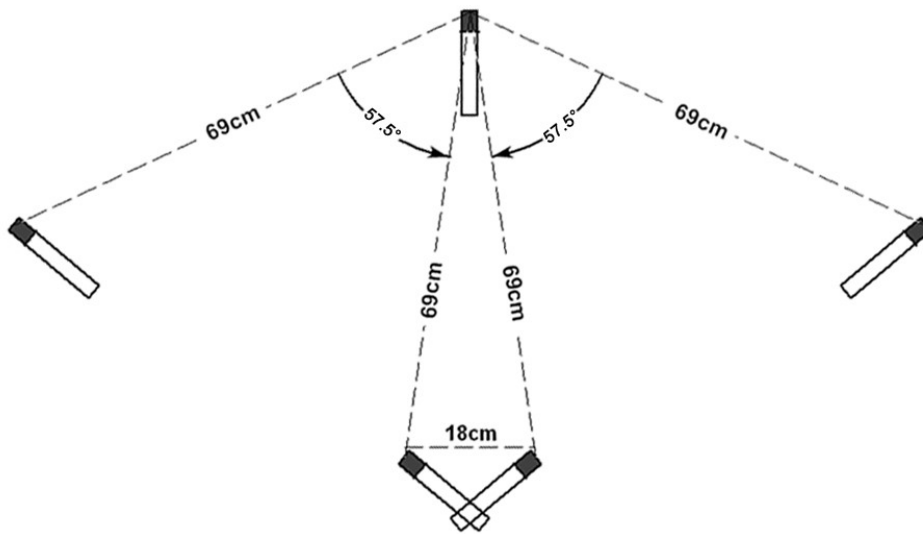


FIGURE 7 – FRONT TRIPLET WITH MPO OF 57.5° ON LEFT AND RIGHT MICROPHONES

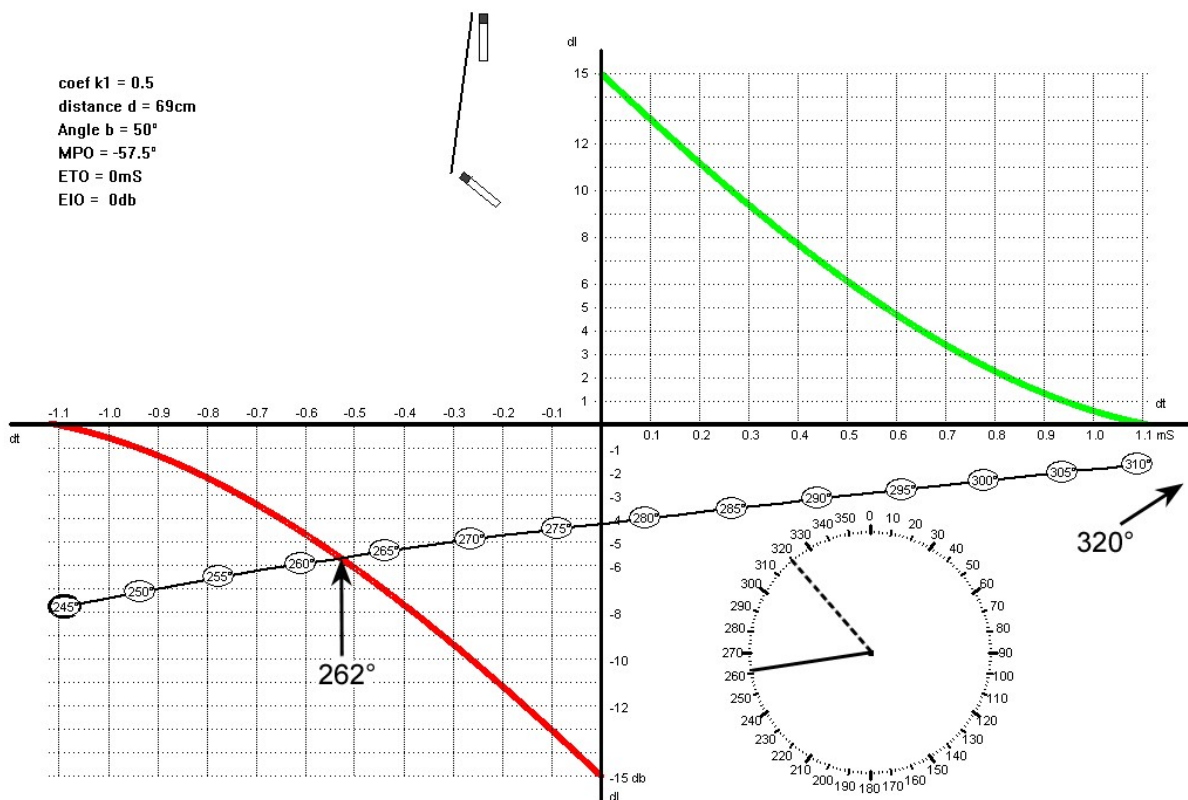


FIGURE 8 – DL / DT FOR LEFT FRONT SEGMENT WITH MPO OF 57.5°

Figure 8 shows the left front segment dl/dt characteristics. The segment coverage is from 262° to about 320° (by extrapolation). The symmetrical coverage of the right front segment will therefore be from approximately 40° to 98°.

For perfect Critical Linking between the left and right segments, about -1.15mS of Electronic Time Offset (ETO) will be needed to steer the two segments so that they will link at 0° as shown in Figure 9.

Due to the non linearity of the physical and psychoacoustic curves, some considerable adjustment to the distance between the centre microphone and the left/right

microphones is necessary (a change from 69cm to 139cm) in order to maintain a Coverage Angle of 50°. An increase in ETO is also necessary from -1.15mS to -3.25mS, as shown in Figure 10.

Initial design of offset will tend towards a dl/dt function that passes through the zero-dl / zero-dt point in the dl/dt function diagram. However other ratios of dl and dt are possible - it is not necessary for the dl/dt transfer function to always pass through the zero point in the dl/dt function diagram. However a wide offset away from the zero point should be avoided – otherwise localisation can be somewhat problematic.

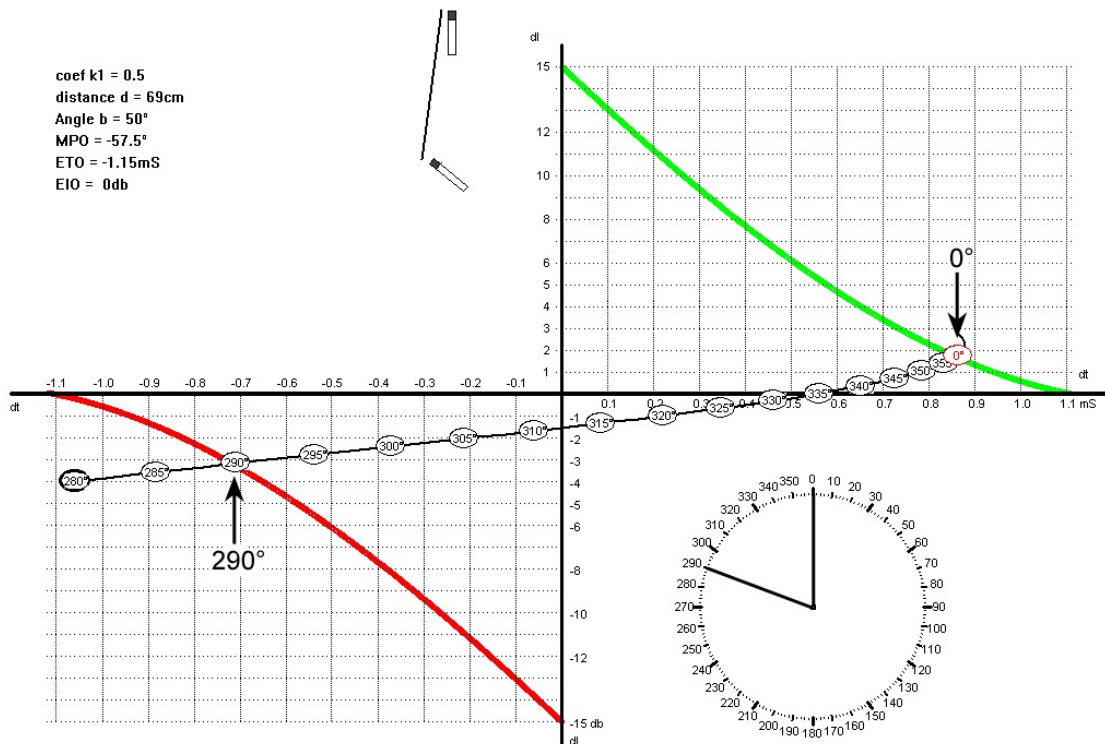


FIGURE 9 – DL / DT FOR THE LEFT FRONT SEGMENT WITH AN MPO OF 57.5° AND ETO OF -1.15 mS



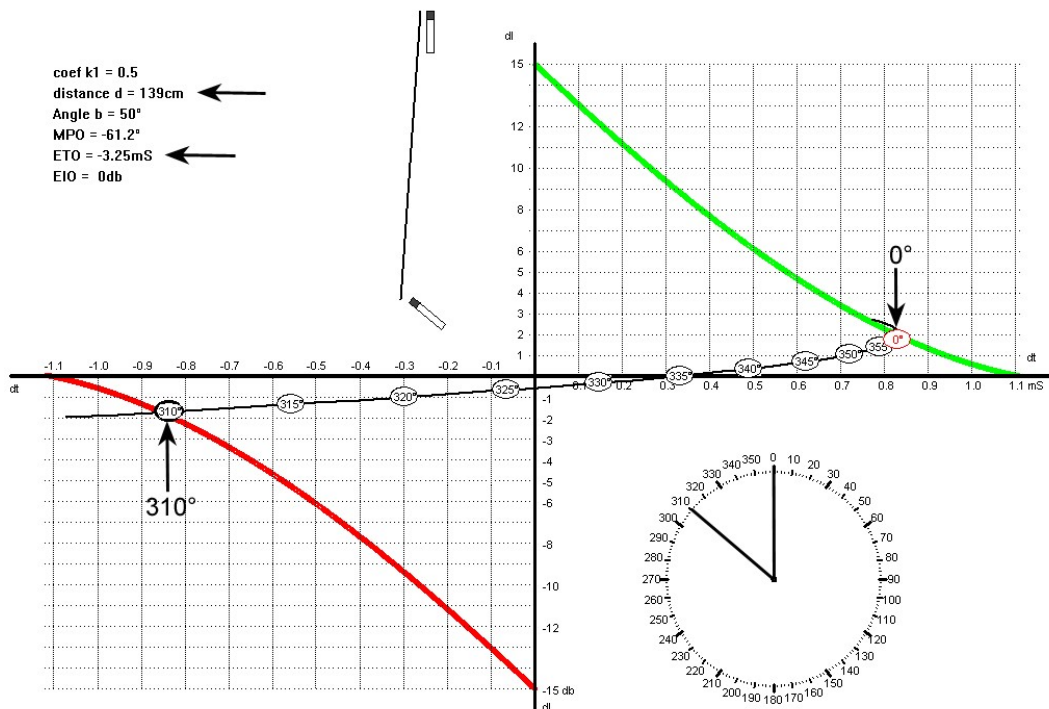


FIGURE 10 – DL / DT FOR LEFT FRONT SEGMENT WITH AN MPO OF 57.5° AND ETO OF –3.25mS  
DISTANCE BETWEEN THE CENTRE AND THE LEFT/RIGHT MICROPHONES IS 139CM

**1.4 THE SIDE AND BACK COVERAGE SEGMENTS**

A simple solution for back coverage coupled with this compatible triplet array design is to use the same stereo pair configuration, as formed by the left and right microphones, but placed facing to the rear. The back pair therefore has a coverage of 100° (or +/-50° for a stereo pair).

The next stage is to determine the distance between the front triplet and the back pair. The coverage angle remaining on each side is half the difference between 360° and the sum of the front triplet coverage plus the back pair coverage (as shown in Figure 11).

Font Triplet coverage = 50° +50°  
Back Pair Coverage = 100°

The Left and Right Front Coverage Segments (LFSC & RFSC) are 50°. The Back Pair Coverage (BPCS) is 100°. Therefore the left and right lateral coverage segments are each 80° (or +/- 40° on the SRA Diagram). In a Root array

the angle between the lateral segment microphones is also 80° - therefore from Figure 12 we can see that the lateral segment microphone distance must be about 32cm.

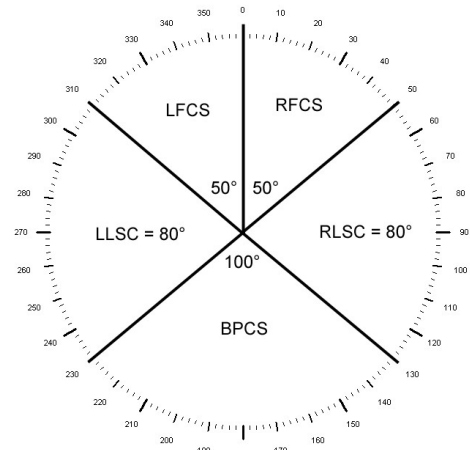


FIGURE 11 – SEGMENT COVERAGE DISTRIBUTION

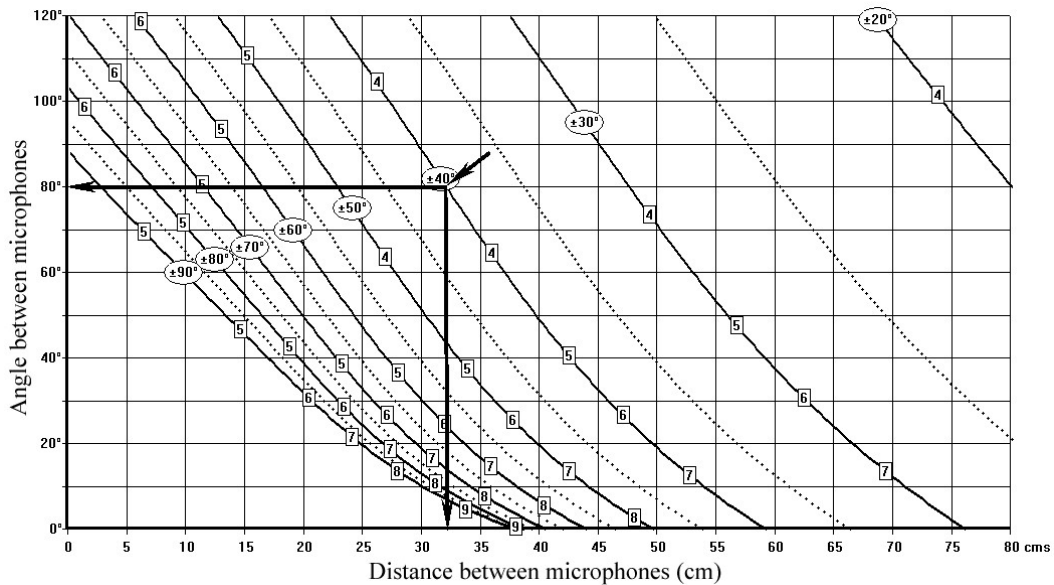


FIGURE 12 – SRA DIAGRAM SHOWING STEREO PAIR COMBINATION 80° / 32CM - SRA +/- 40°

**1.5 THE COMPLETE ARRAY DESIGN**

The final design for this particular array is shown in Figure 13.

From a Master 5 Channel recording using this array, reproduction can be chosen

- as the standard 5 Channel Multichannel using all five channels as in the left hand side of Figure 14
- or 4 Channel Quadraphony using only the L, R, Ls and Rs channels (the centre channel is disconnected) as shown in Figure 15
- or 3 Channels for front sound stage coverage only (the Ls and Rs channels are disconnected) as shown in Figure 16
- or simply the standard Stereo Pair (only the L and R channels are active) as shown in Figure 17
- or even 1 Channel Mono (if this still exists!) with just the centre channel active.

The reproduction format can be chosen at the production end or by the consumer according to their own particular listening configuration.

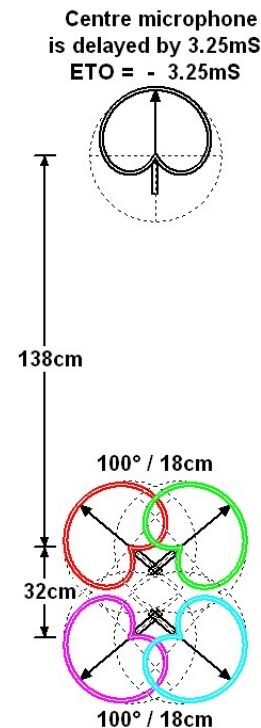


FIGURE 13 - A MULTI-FORMAT-COMPATIBLE ROOT ARRAY DESIGN USING CARDIOID MICROPHONES

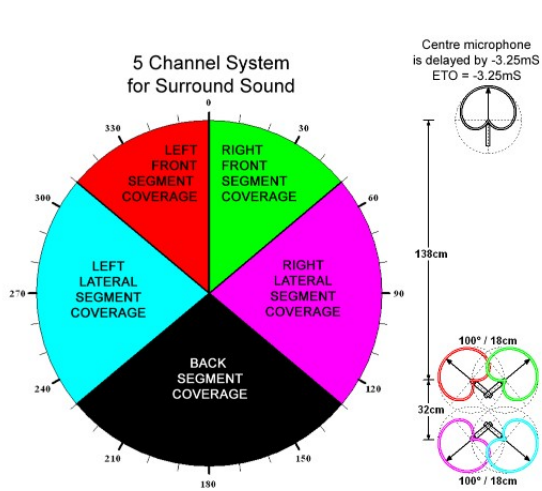


FIGURE 14 - 5 CHANNEL SYSTEM USING ALL 5 CHANNELS

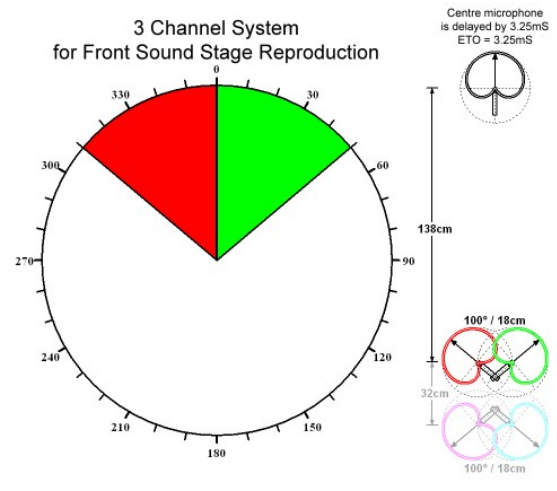


FIGURE 16 – 3 CHANNEL SYSTEM USING ONLY THE FRONT TRIPLET CHANNELS FOR REPRODUCTION

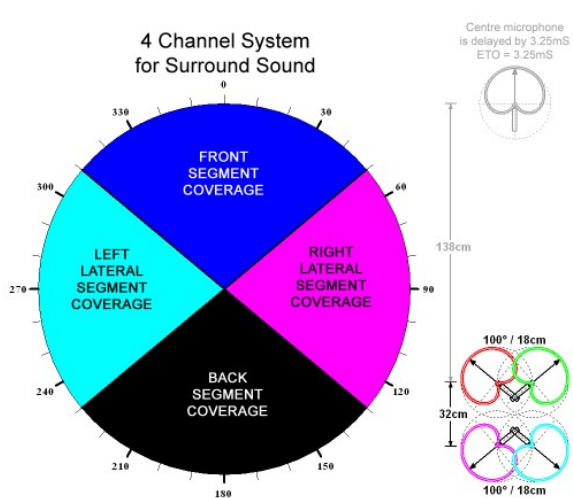


FIGURE 15 - 4 CHANNEL SYSTEM USING LEFT, RIGHT, LEFT SURROUND AND RIGHT SURROUND CHANNELS FOR REPRODUCTION

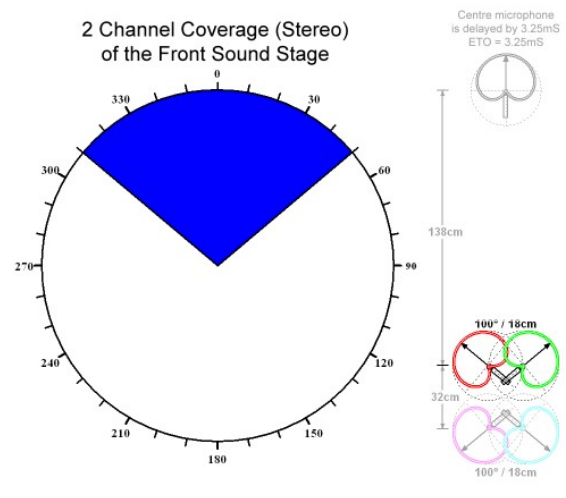


FIGURE 17 – 2 CHANNEL SYSTEM USING ONLY THE LEFT AND RIGHT HAND MICROPHONE PAIR FOR REPRODUCTION

## 2 THE OPTION OF TWISTED QUAD MIXING

It is also possible to add on the additional option of Twisted Quad Mixing (TQM) which folds the side and back segments into the stereo pair reproduction as described at the 118<sup>th</sup> AES Convention in Barcelona in 2005<sup>1</sup>. This is an addition to the main compatibility design, but can improve considerably the spatial attributes of the 2 and 3 Channel reproduction formats derived from the basic 5 channel array.

The major advantage of the Twisted Quad mixdown is that early reflections picked up from the sides of the array together with the reverberation field in these segments is redeployed within the stereo front sound stage. The same applies to a three channel stereo recording where three loudspeakers are used to reproduce the front triplet of microphones. Twisted Quad Mixdown in this case folds the lateral early reflections only into the left and right channels. The back reverberation field will also automatically be folded back into the main sound stage, the left/right directionality being inverted to right/left.

As usual with a surround sound array, care must be taken to adjust the position of the microphone array so that the direct to reverberant level ratio is acceptable. When using TQM no adjustment of the level of the back microphones should be attempted as this will upset the critical linking between the front and side segments. Level adjustment is equivalent to applying a certain amount of Electronic Intensity Offset (EIO) to the side segments – this could of course be compensated to some extent by the requisite amount of opposite time offset (ETO).

The addition of Twisted Quad Mixing to the basic 5 channel compatible array creates the possibility of 7 reproduction formats:

- Standard multichannel format using the five univalent channels
- Four channel reproduction using the left, right, left-surround and right-surround channels only
- Three channel reproduction using the left, centre and right channels

- Three channel reproduction using the left, centre and right channels, plus twisted quad mixing, which will fold the lateral and back segments sound images from the left-surround and right-surround into the stereo pair reproduction
- Two channel stereo from the left and right channel
- Two channel stereo with twisted quad mixing folding the lateral and back segments into the stereo pair
- One channel or mono using the centre channel only

## 3 AN OPERATIONAL RANGE OF MULTIFORMAT COMPATIBLE ARRAYS

The above illustration using cardioid microphones (Figure 13), is of course, only one amongst many possible multi-format compatible designs. It is possible to vary almost any parameter of this design process within certain limits, and obtain satisfactory compatible array designs. The following examples are illustrations of a limited number of possible variants, chosen to cover the most frequently encountered operational sound recording situations as regards sound recording coverage angles (stereo coverage of +/- 45°, +/- 50° and +/- 55°), and of course for the usual microphone directivity patterns (Omnidirectional, Hypocardioid, Cardioid and Supercardioid). The amount of offset (Electronic Intensity Offset or Electronic Time offset) required for each design is an inevitable function of the layout of the microphones and cannot be chosen independently of this layout. The illustrations have been chosen so as to give the sound recording engineer the maximum latitude in choosing an optimum array design for a given sound recording environment. A much larger range of designs will be published at a later date at [www.soundsscot.com](http://www.soundsscot.com).

A Stereophonic Recording Angle (SRA) of +/- 50° (a total of 100°) is perhaps the most frequently encountered stereophonic recording angle in common usage for the recording of the front sound stage. The Front Triplet Coverage will therefore be 50° (on the left of centre) and 50° (on

the right of centre) for the Front Segment-Coverage Design Formula to be valid. As in the first illustration shown in this paper, the back pair coverage will be chosen simply to be the same as the coverage angle of the stereo pair. This is by no means an obligation but chosen in order to simplify the design procedure. The same reproduction format possibilities as shown in Figure 18 are valid for all the arrays shown in this paper.

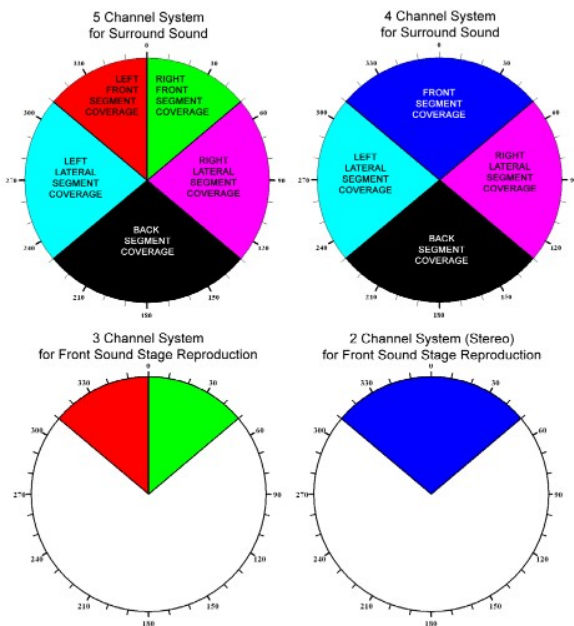


FIGURE 18 - REPRODUCTION FORMATS FOR ARRAYS SHOWN IN PARAGRAPH 3 (I.E. FOR FIGURES 20 TO 31)

Figure 19 shows a table of configurations for a range of Stereophonic Recording Angles for the Stereo Pair, and the corresponding values for the configuration of the Front Triplet and Lateral segments. For those who do not wish to return to the drawing board, a plan representation for each of these configurations is given in Figures 20 to 31.

Figures 20 to 22 show multiformat-compatible arrays using omnidirectional microphones. For small diaphragm microphones (<12mm) the orientation of the microphone is almost immaterial, but it is shown in order to give an indication of the limit to the coverage angle of each segment of the array. However 1<sup>st</sup> order directional microphones are used in the arrays shown in Figures 23 to 31, so the orientation of the microphone is critical.

Figures 23 to 31 show arrays using Omnidirectional, Hypocardioid, Cardioid and Supercardioid directivities with a front stereo/triplet coverage of +/- 45°, +/- 50° and +/- 55°. The back pair coverage is always the same as the front stereo coverage, and the lateral segment coverage is just the 360° complement to the Coverage Angles of the Front Triplet and the Back Pair.

All these arrays are ROOT arrays – the orientation of the microphones therefore corresponds to the limits of each of the respective coverage segments.

Directivity	SRA	Stereo & Back	Front Triplet	Lateral	ETO	Figure
Omni	+/- 45°	90° / 53cm	45° / 188cm	90° / 53cm	-4.8mS	20
	+/- 50°	100° / 50cm	50° / 150cm	80° / 59cm	-3.3mS	21
	+/- 55°	110° / 46.5cm	55° / 126cm	70° / 66cm	-2.55mS	22
Hypocardioid	+/- 45°	90° / 33cm	45° / 180cm	90° / 33cm	-4.33mS	23
	+/- 50°	100° / 28cm	50° / 143cm	80° / 39cm	-3.28mS	24
	+/- 55°	110° / 23cm	55° / 118cm	70° / 48cm	-2.54mS	25
Cardioid	+/- 45°	90° / 24.5cm	45° / 175cm	90° / 24.5cm	-4.2mS	26
	+/- 50°	100° / 18cm	50° / 139cm	80° / 32cm	-3.25mS	27
	+/- 55°	110° / 12cm	55° / 117cm	70° / 42cm	-2.65cm	28
Supercardioid	+/- 45°	90° / 16.5cm	45° / 172cm	90° / 16.5cm	-4.2mS	29
	+/- 50°	100° / 7.5cm	50° / 142cm	80° / 26cm	-3.38mS	30
	+/- 55°	110° / 0cm	55° / 119cm	70° / 36cm	-2.75mS	31

FIGURE 19 – TABLE OF SRA, FRONT TRIPLET AND LATERAL SEGMENT CONFIGURATIONS FOR SRA COVERAGE OF +/-45°, +/-50° AND +/-55°

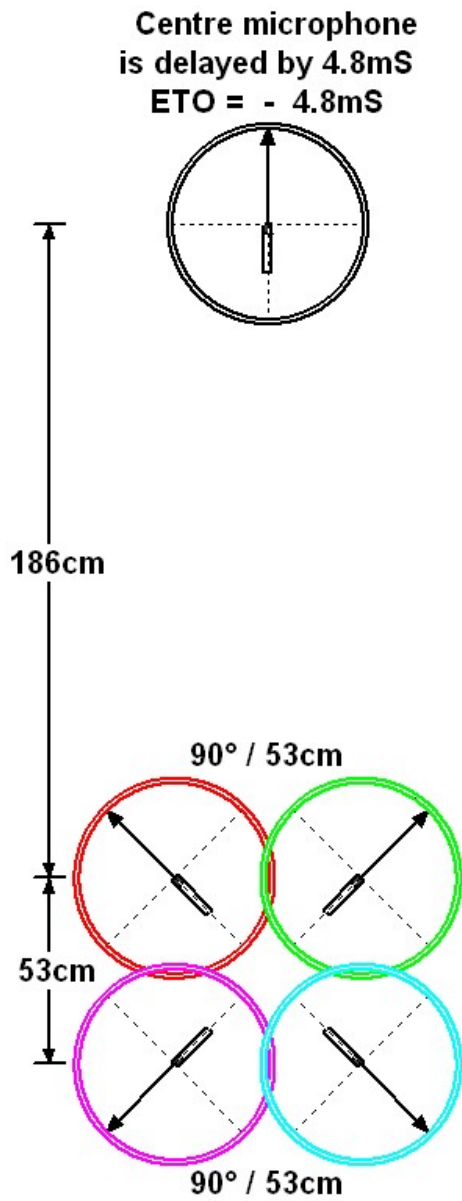


FIGURE 20 – MULTIFORMAT- COMPATIBLE ARRAY  
USING OMNIDIRECTIONAL MICROPHONES  
FRONT STEREO COVERAGE OF +/- 45°

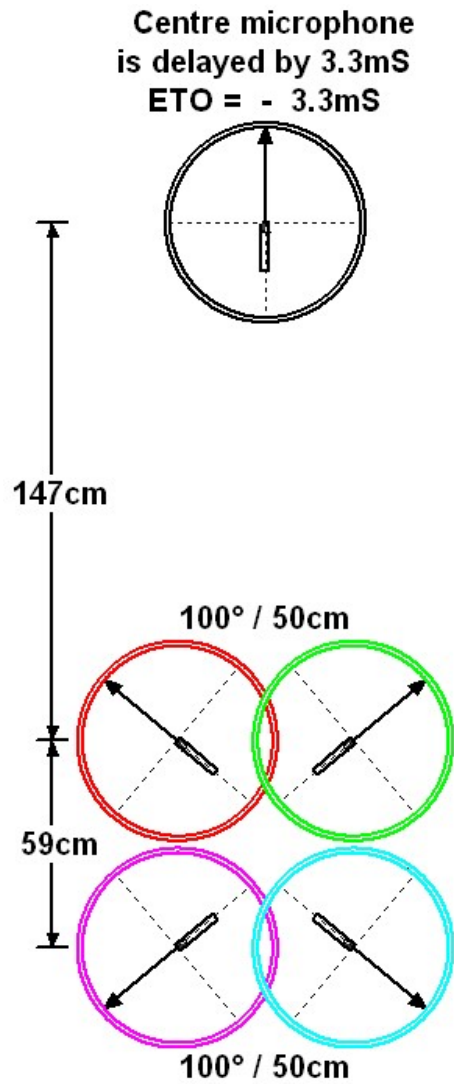


FIGURE 21 – MULTIFORMAT- COMPATIBLE ARRAY  
USING OMNIDIRECTIONAL MICROPHONES  
FRONT STEREO COVERAGE OF +/- 50°

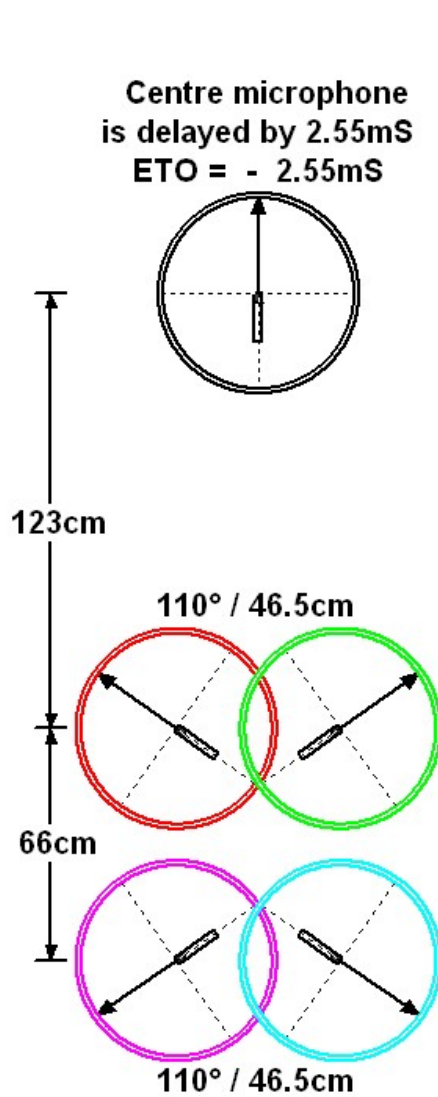


FIGURE 22 – MULTIFORMAT- COMPATIBLE ARRAY  
USING OMNIDIRECTIONAL MICROPHONES  
FRONT STEREO COVERAGE OF +/- 55°

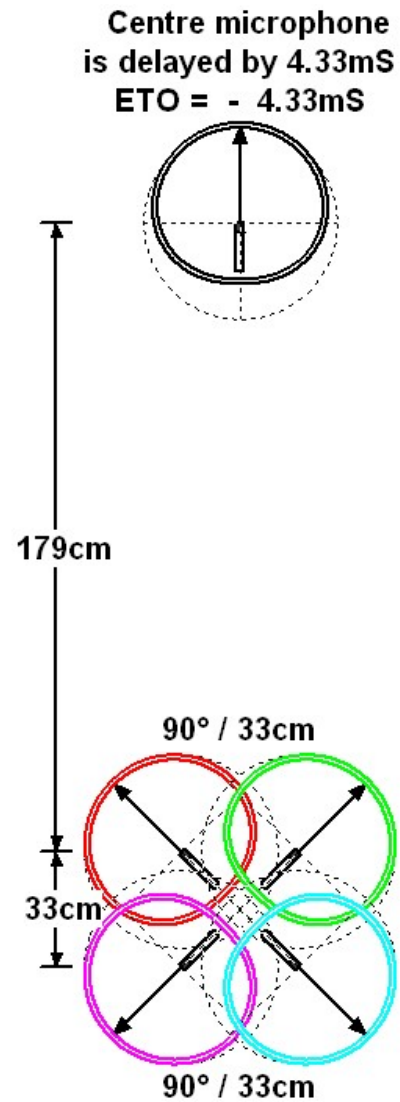


FIGURE 23 – MULTIFORMAT- COMPATIBLE ARRAY  
USING HYPOCARDIOID MICROPHONES  
FRONT STEREO COVERAGE OF +/- 45°

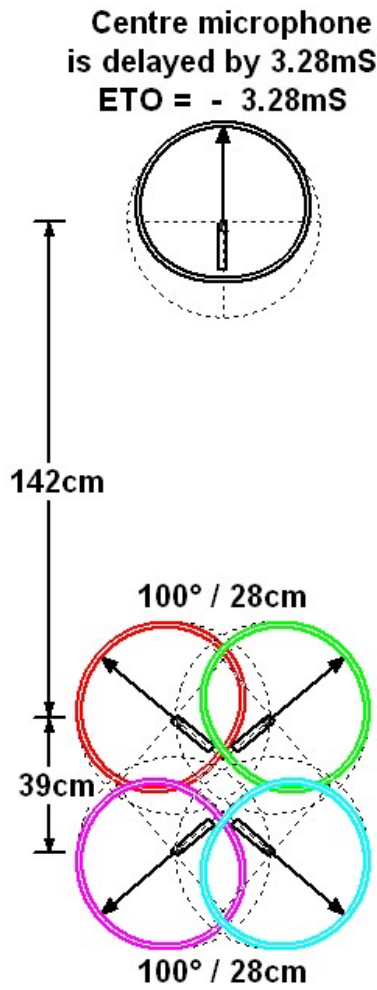


FIGURE 24 – MULTIFORMAT- COMPATIBLE ARRAY  
USING HYPOCARDIOID MICROPHONES  
FRONT STEREO COVERAGE OF +/- 50°

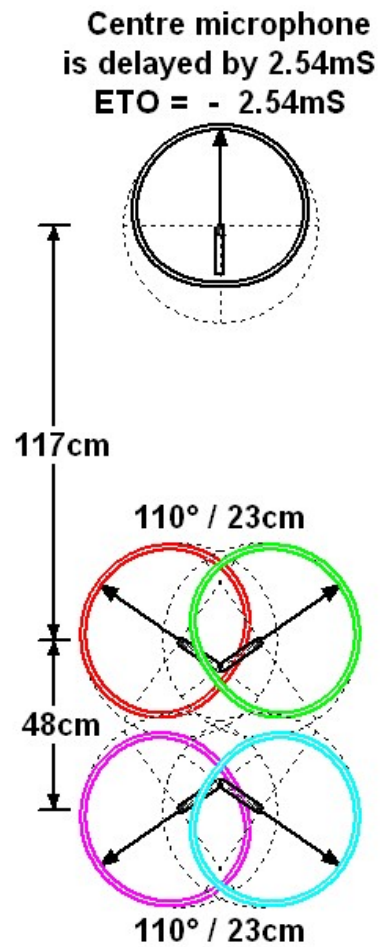


FIGURE 25 – MULTIFORMAT- COMPATIBLE ARRAY  
USING HYPOCARDIOID MICROPHONES  
FRONT STEREO COVERAGE OF +/- 55°



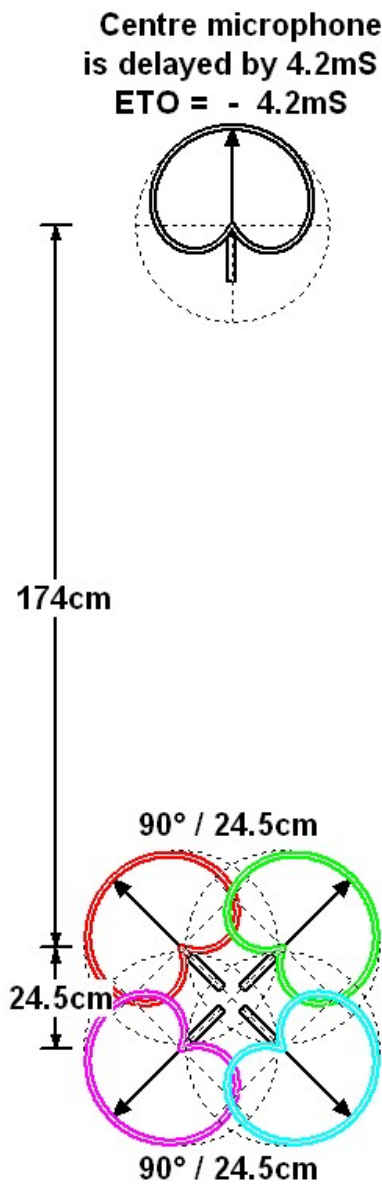


FIGURE 26 – MULTIFORMAT- COMPATIBLE ARRAY  
USING CARDIOID MICROPHONES  
FRONT STEREO COVERAGE OF +/- 45°

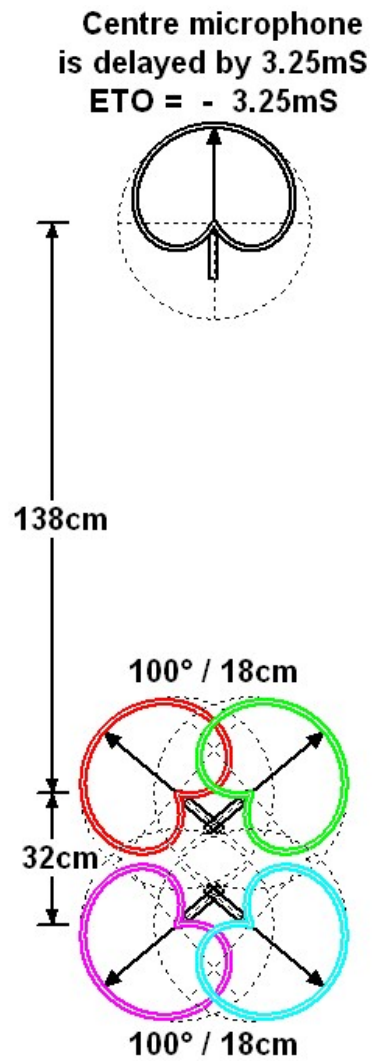


FIGURE 27 – MULTIFORMAT- COMPATIBLE ARRAY  
USING CARDIOID MICROPHONES  
FRONT STEREO COVERAGE OF +/- 50°

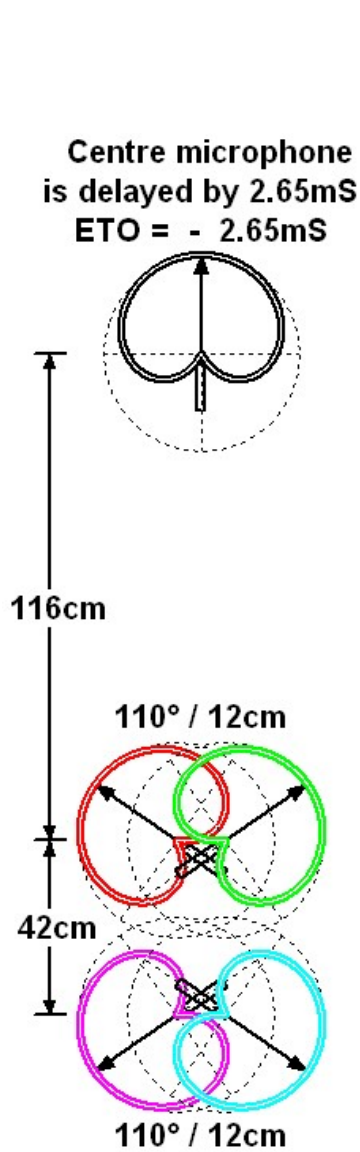


FIGURE 28 – MULTIFORMAT- COMPATIBLE ARRAY  
USING CARDIROID MICROPHONES  
FRONT STEREO COVERAGE OF +/- 55°

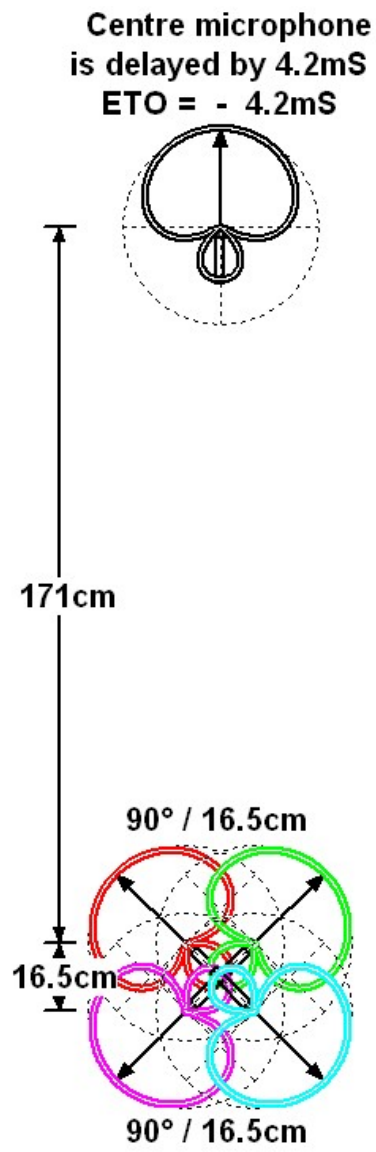


FIGURE 29 – MULTIFORMAT- COMPATIBLE ARRAY  
USING SUPERCARDIROID MICROPHONES  
FRONT STEREO COVERAGE OF +/- 45°

Centre microphone  
is delayed by 3.38mS  
ETO = - 3.38mS

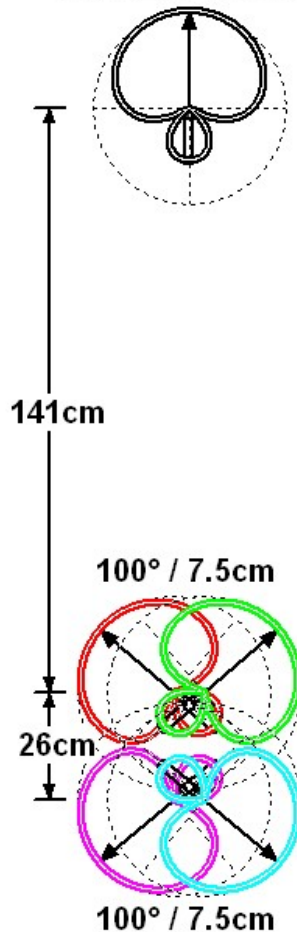


FIGURE 30 – MULTIFORMAT- COMPATIBLE ARRAY  
USING SUPERCARDIOID MICROPHONES  
FRONT STEREO COVERAGE OF +/- 50

Centre microphone  
is delayed by 2.75mS  
ETO = - 2.75mS

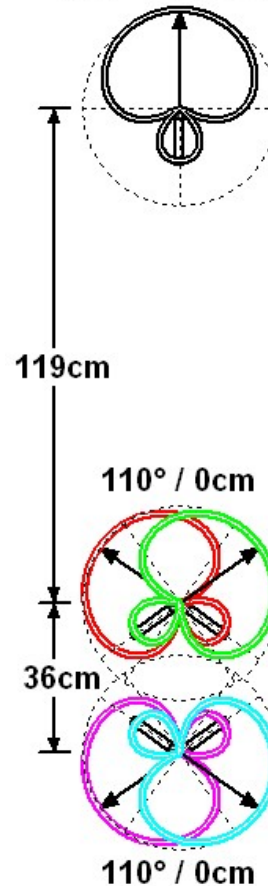


FIGURE 31 – MULTIFORMAT- COMPATIBLE ARRAY  
USING SUPERCARDIOID MICROPHONES  
FRONT STEREO COVERAGE OF +/- 55°

#### REFERENCES

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