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Multichannel Microphone Array Design: Segment Coverage Analysis above and below the Horizontal Reference Plane.

Michael Williams

"Sounds of Scotland", Le Perreux sur Marne, 94170, France. (Soundsscot@aol.com)

ABSTRACT

Individual Segment Coverage for a given Multichannel Microphone System is normally considered (if at all) only in the horizontal reference plane. However, any microphone system has sound pick up throughout the spherical zone surrounding the microphone system. One must therefore know with reasonable precision the operational characteristics of any microphone system in use, at all angles of elevation to the reference plane, before being able to predict the localisation of sound sources outside the reference plane, the distribution of the reverberant field, or the localisation of early reflections within the reproduced sound image. Knowledge of these characteristics can also influence considerably the mechanical design of a variable microphone support system for multichannel microphone arrays.

INTRODUCTION

The basic parameters for Multichannel Microphone Array (MMA) Design were presented at the 107th & 108th AES Conventions in New York and Paris respectively (1)(2). Parameters such as Segment Coverage, Critical Linking, Electronic Time and Intensity Offset, Microphone Position Offset, were defined and their influence on the design of a microphone array discussed. These two papers were followed at the 110th AES Convention in Amsterdam (3) with the description of a large range of different MMA configurations and their surround sound coverage characteristics.

Perforce the discussion in these papers, of Segment Coverage and Critical Linking, was limited to the analysis of the characteristics in the horizontal reference plane. However the restitution of the total sound image must include sound received from all directions. This is particularly important in the restitution of the group of early reflections and even more so for the complex reverberation field surrounding any microphone recording system.

It is unfortunately still not well known that the frequency response characteristics of most high quality directional microphones with small diaphragms (<12mm), remain essentially constant over the audible frequency range up to about 120° off axis and in some cases even further. We are therefore not limited by any means to the traditional reference plane of the microphone system for recording principal sound sources. This also has a considerable impact on our microphone technique as applied to the recording of early reflections and reverberation. Indeed it is the successful integration of these two aspects of the original sound image into the reproduced direct sound image that is the major contributing factor to producing a realistic impression of "space" in a good recording.

In 1991 at the 91st AES Convention in New York the author of this paper presented a paper (4) entitled "Early Reflections and Reverberant Field Distribution in Dual Microphone Stereophonic Sound Recording Systems". It would seem appropriate to refer back to this 1991 paper for some of the basic analysis of the response with elevation for a dual microphone array, before applying the information to the response of a multichannel array.

The first step is to determine the response of a single directive microphone to the position of a sound source defined by the following set of spherical coordinates :

- the angular position of the sound source plane expressed as elevation **(e)** in relation to a horizontal reference plane
- the angular position of the sound source **(θ)** on the elevation plane in relation to a front reference axis
- the orientation of the microphone **(β/2)** in relation to the front reference axis on the horizontal reference plane
- the orientation of the sound source (**α**) with respect to the axis of directivity of the microphone.

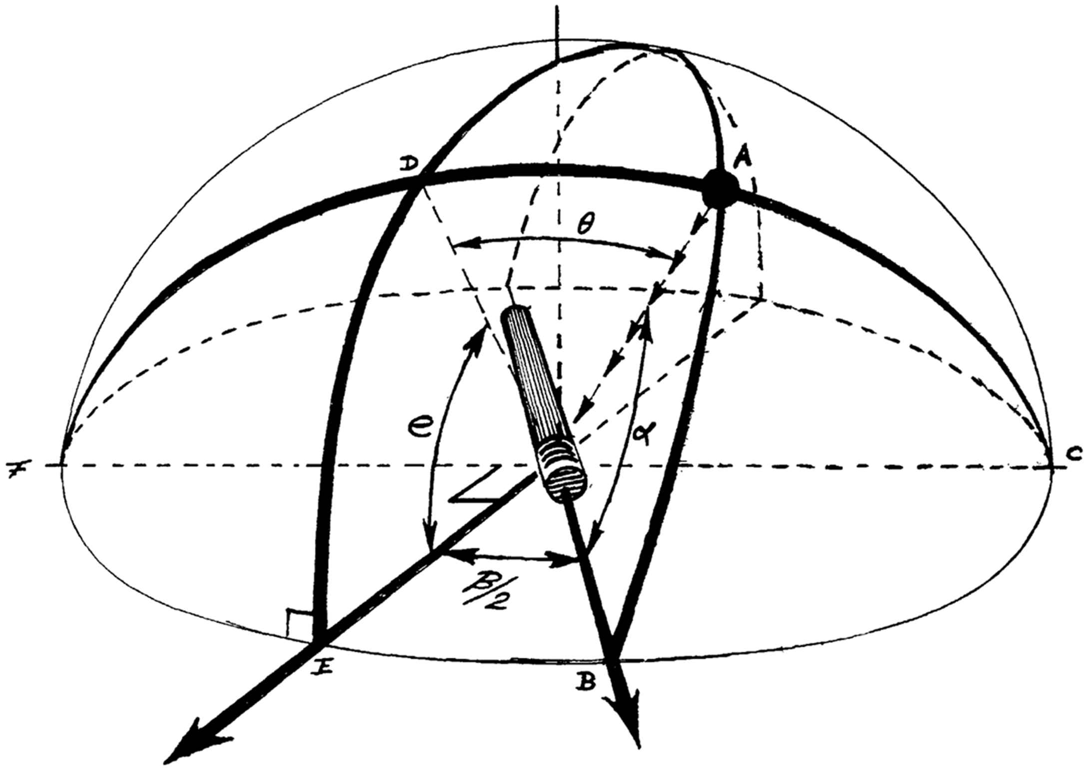

Figure 1 - Spherical Coordinates of the Sound Source "A" (in relation to a single microphone)

Figure 1 is a representation of this rather complicated three dimensional situation.

- The microphone capsule is at the origin **(O)** of the trigonometric sphere.
- The horizontal reference plane passes through **F, O, C, E, & B**.
- The front reference axis is **OE**.
- The orientation of the microphone on the horizontal reference plane in relation to this 'front axis is **Angle EOB (β/2).**
- The elevation plane passes through **F, O, C, D & A.**
- The angle between the elevation plane and the reference plane is **Angle DOE (e).**
- The position of the sound source on the elevation plane is **Angle DOA (θ).**
- The position of the sound source in relation to the axis of directivity of the microphone is **Angle AOB(α).**

Resolution of triangle ABC in Figure 1, using basic spherical trigonometric relationships enable us to express angular position of the sound source **(α)** in relation to the microphone axis as a function of:

- Elevation angle (**e**)
- Angular position of the sound source (**θ**) on the elevation plane
- angle between the microphones (**β**)

$$\mathrm{COS}(\alpha) = \mathrm{COS}(90 - \theta)*\mathrm{COS}(90 - \beta/2) + \mathrm{SIN}(90 - \theta)*\mathrm{SIN}(90 - \beta/2)*\mathrm{COS}(e)$$
$$= \mathrm{SIN}(\theta)*\mathrm{SIN}(\beta/2) + \mathrm{COS}(\theta)*\mathrm{COS}(\beta/2)*\mathrm{COS}(e)$$

The Intensity Response of a microphone, with a specific directivity determined by the coefficient **(cf),** can be expressed with respect to the on axis response as follows :

$$\textbf{Intensity Response} = 20.\mathrm{LOG}_{10}\,[(cf) + (1-cf)*\mathrm{COS}(\alpha)]$$

The Intensity Difference equation now becomes:

$$dI = 20 * LOG_{10}\left[\frac{(cf)+(1-cf).\{SIN(\alpha)*SIN(\beta/2)+COS(\alpha)*COS(\beta/2)*COS(e)\}}{(cf)+(1-cf)*\{SIN(\alpha)*SIN(-\beta/2)+COS(\alpha)*COS(-\beta/2)*COS(e)\}}\right]$$

The angles **- β/2** and **+ β/2** represent the orientation of left and right microphones in relation to the front reference axis **(**OE), the total angle between the microphones being obviously **β**.

The Time Difference relationship is not affected by elevation and is only a function of distance **(d cms)** between the microphone capsules and the position of sound source **(α)** :

$$\text{Time Difference (mS)} = \frac{d * SIN(\alpha)}{34}$$

Using the same procedure as described in reference (5), the intersection between the physical parameters of Intensity Difference and/or Time Difference developed by the microphones and the psycho-acoustical limits of the listening configuration, enable us to determine the Stereophonic Recording Angle at all values of elevation : from 0° (in front of the microphone system on the reference plane) to 180° (behind the microphones).

In determining the best way to represent the results in graphical form, it would seem appropriate to relate the evolution of SRA with elevation, to a specific SRA in the reference plane. The transversal cylindrical projection as shown in Figure 2 shows the variation of SRA with respect to the elevation angle, for five different microphone systems having a SRA in the reference plan of +/-50°.

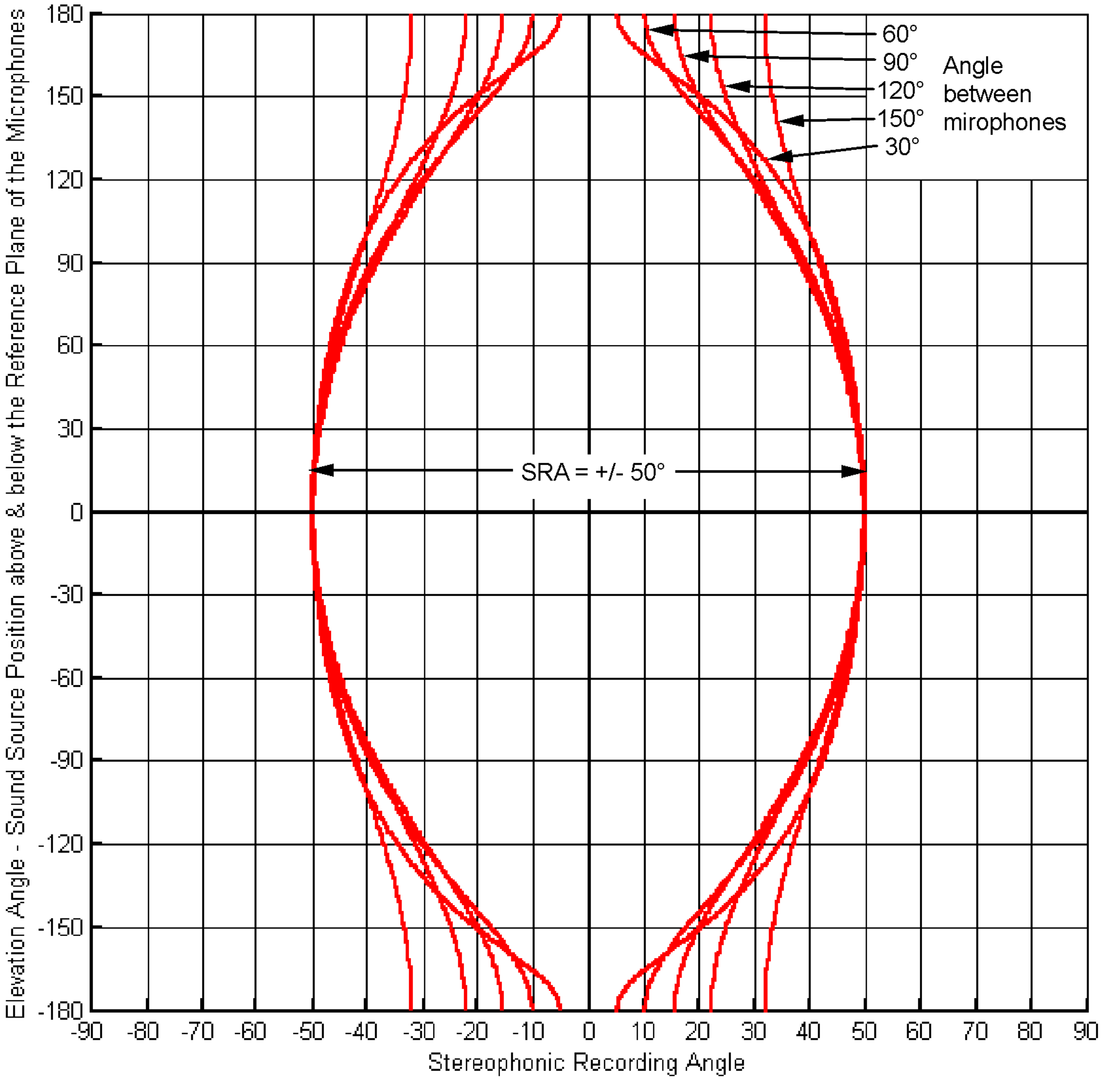

Figure 2 - The Stereophonic Recording Angle as a Function of Sound Source Position (Elevation Angle)

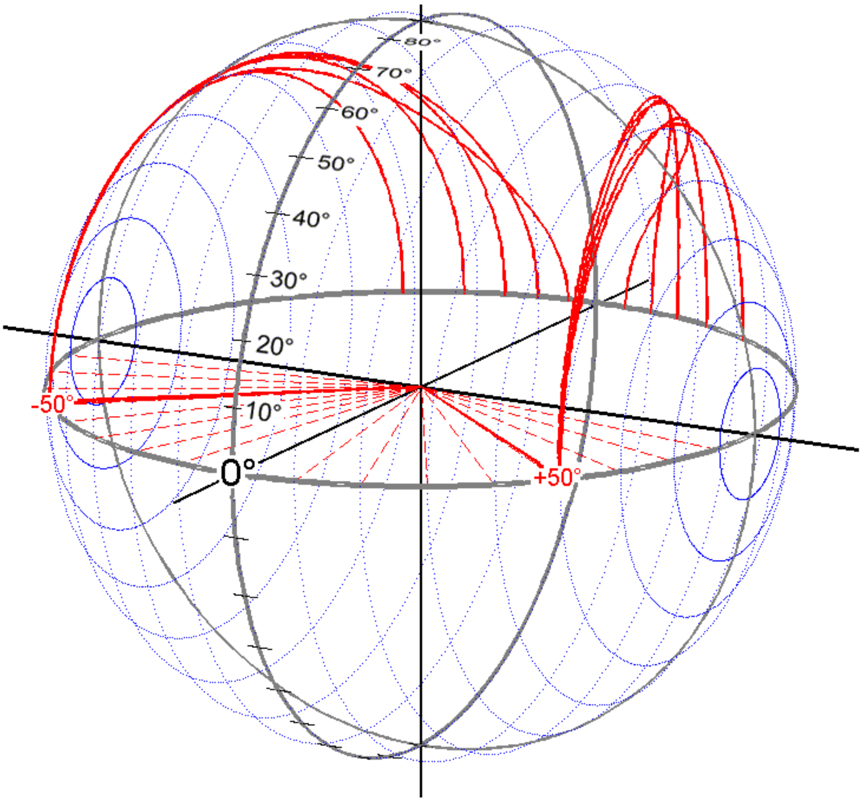

Figure 3 - The Stereophonic Recording Angle as a Function of Sound Source Position or Elevation Angle (this is a three dimensional representation of the same information as in Figure 2, showing only the upper hemisphere - the lower hemisphere is the mirror image of the upper hemisphere)

It should be noted that the theoretical values of directivity pattern do not necessarily correspond with the practical response for angles in excess of about 120°, even for small diameter diaphragm microphones. However the main operational areas of a dual microphone system for stereophonic sound recording as well as multichannel, are usually well outside this doubtful sector.

It can be seen that SRA varies very little in the front hemisphere but can vary considerably in the back hemisphere dependent on the physical angle (**β)** between the microphones.

For the smaller angles between microphones one can see that the SRA in the back hemisphere decreases considerably. However for large angles between microphones there is less variation of SRA, so obviously with an angle of 180° between the axes of the microphones, there would be no variation of SRA with elevation, the SRA remaining constant throughout the spherical zone surrounding the microphone system. In the rare situation where the microphones are parallel, the SRA also remains a constant. Spaced omnidirectional microphones obviously have a constant SRA throughout the spherical zone.

Similar information for different values of SRA in the reference plane tracing the evolution of SRA throughout the spherical zone surrounding the microphones was shown in the preprint ref (4) and will therefore not be reproduced here. This preprint also shows the same type of analysis applied to dual microphone arrays using microphones of any first order directivity pattern.

OPERATIONAL SIGNIFICATION

Once the Sound Recording Engineer has chosen a suitable combination of distance and angle between the microphones for the desired Stereophonic Recording Angle, he should be aware that this SRA is approximately constant over the range of about 60°, both above and below the Reference Plane of the microphone system. Although the SRA diminishes to some extent after this limit, there are however other factors which can modify the sound quality at angles greater than this 60° limit. In particular, the ratio of direct to reverberant sound within the SRA can vary considerably after this limit. This must not be confused with a possible variation of timbral or spectral balance which (again with high quality small diaphragm microphones) will only occur at much higher angles to the microphone directivity axis.

The Stereophonic Recording Angle in the Reference Plane now becomes a cylindrical segment capable of Stereophonic Sound Recording over approximately 60° both above and below the reference plane of the microphone array. In the case of music recording for example, the Sound Recording Engineer can use this characteristic to considerable advantage in determining the position of the microphone system in relation to the orchestra or in the placing of the musicians around the microphone array.

Let us push this possibility to the extreme by placing the microphone array above the musicians but pointing towards the floor. It is then possible to place the musicians on both sides of the microphone system (but of course within the SRA), thereby doubling the usable physical space. In cases where one needs to place the microphone as near as possible to the musicians, this microphone array position is a considerable improvement to using only the front facing segment. It must be borne in mind that the two segments are mirror images of each other when reproduced. As long as the directional radiation pattern of the musical instruments is not in contradiction with this microphone position, some excellent recordings can be obtained by using this technique. Indeed the face to face position of the musicians is often considered as quite an advantage for both visual and auditory communication within a small orchestra.

MULTICHANNEL MICROPHONE ARRAY

Front Triplet Segment Coverage Overlap

We can now apply this type of analysis to a multichannel array. For the purpose of this analysis we will choose a configuration with the Front Triplet Coverage of 60° per segment i.e. the left and centre microphones have a left segment coverage of 60°, and the centre and right microphones have a right segment coverage also of 60°. Using the techniques of segment coverage offset as described in ref (1) & ref (2) we can obtain critical linking of the left and right segments so as to obtain a continuous coverage from -60° to +60°. It is of little importance for this discussion to specify the exact physical position of each microphone as long as the angle between the microphones is either not too large or too small (let us say around 90°).

Figure 3 shows the right hand coverage segment with offset applied so as to cover the sound field from 0° to -60°. Figure 4 shows the left hand segment with offset applied so as to cover the sound field from 0° to 60°. Figure 5 combines these coverage segments to show the complete coverage of the front triplet. It can be seen that although Critical Linking is obtained in the horizontal reference plane, there is considerable overlap of coverage when the position of the sound source moves above this reference plane into the upper hemisphere. The same obviously applies to the hemisphere below the reference plane which, for the sake of clarity, is not shown in these diagrams.

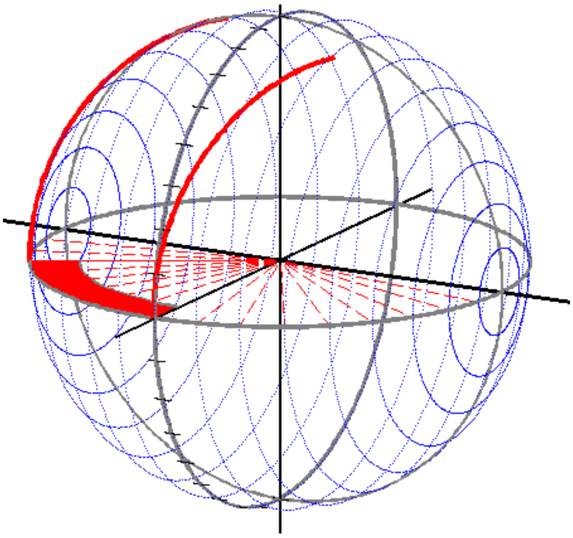

Figure 3 - Right Segment Coverage + Offset

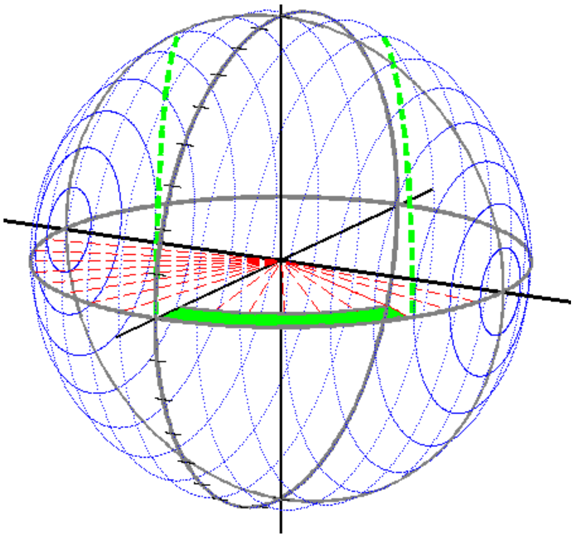

Figure 4 - Left Segment Coverage + Offset

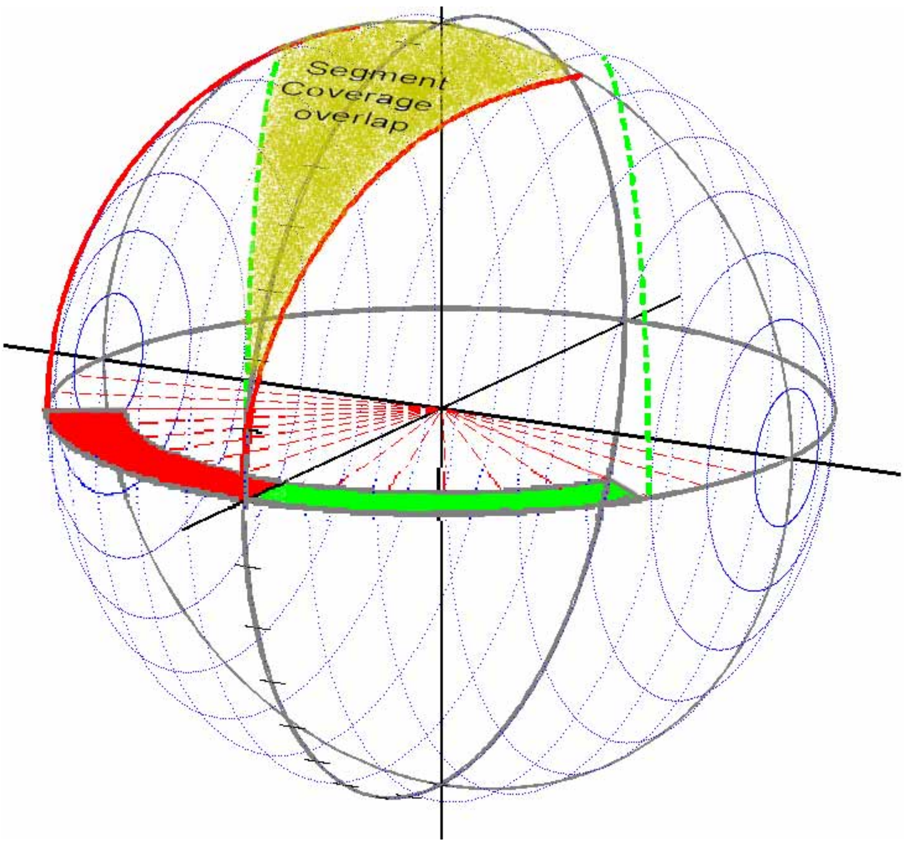

Figure 5 - Front Triplet coverage showing Segment Coverage Overlap in the upper hemisphere

Multichannel Array Segement Overlap

Figure 6 shows three segments of a Multichannel Microphone Array (the Front Triplet Coverage and the Left Lateral Segment), the others have been omitted, again for the sake of clarity. We can see that the Coverage Overlap in the upper (and lower) hemisphere occurs at each junction between segments. Again although Critical Linking has been achieved in the system reference plane, coverage overlap will inevitably occur both above and below the microphone system.

There is little that can be done to change this situation in the design of a specific microphone array, except in the choice of angle between each of the microphone pairs. At the design stage of the array, the angles between the directivity patterns of the microphones should be chosen in such a way as to favour angles somewhere between about 60° to 90°. It is obvious that in this case omnidirectional microphones are to be excluded as they present an almost perfect cylinder of sound coverage, and will therefore have a maximum of coverage overlap.

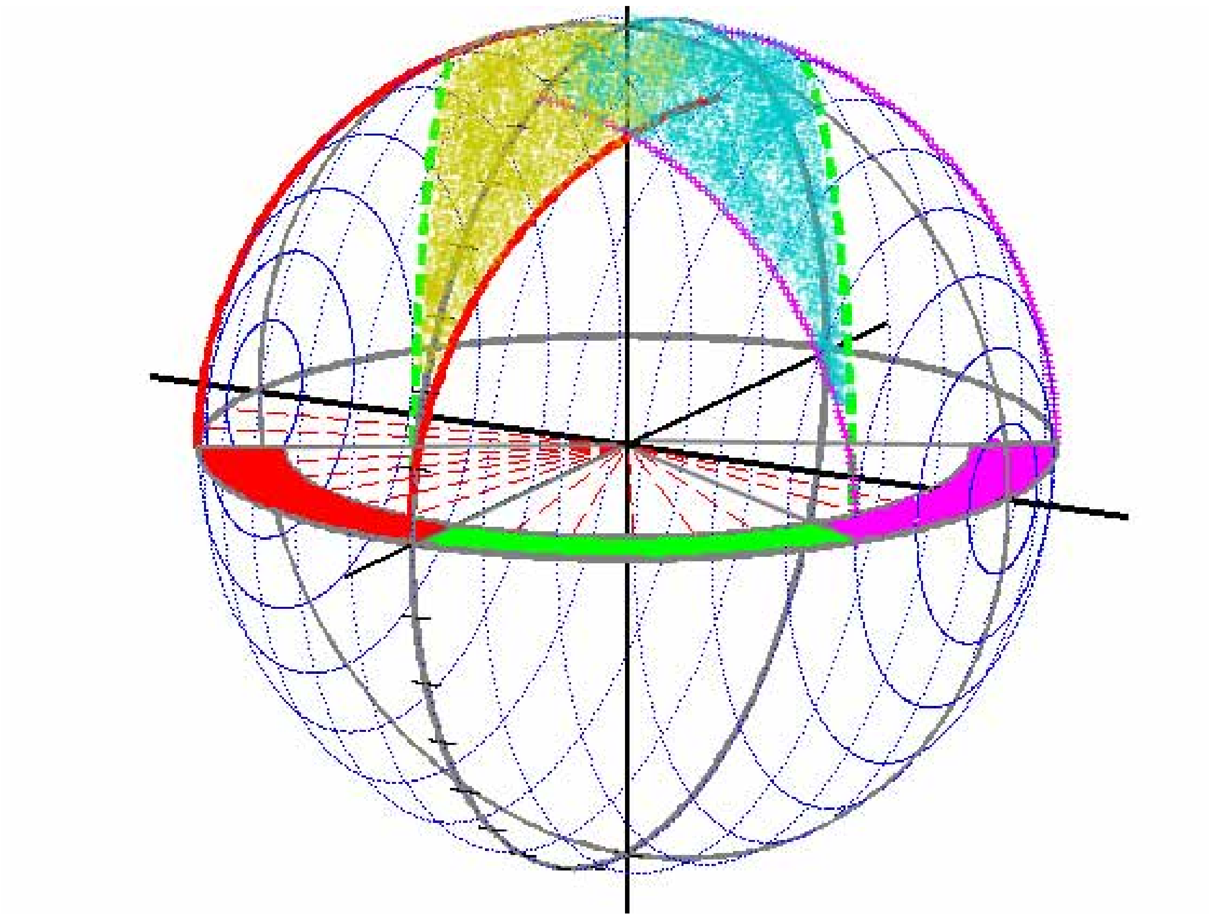

Figure 6 - Front Triplet and One Lateral Segment of a MMA showing Overlap of Segment Coverage in the Upper Hemisphere

THE REPRODUCTION OF SEGMENT OVERLAP

As was described in ref (4) the reproduction of first order reflections and the reverberant field is already rather complex to interpret in the context of stereophony. Any sound originating within the Stereophonic Recording Angle is obviously reproduced between the two loudspeakers. This covers direct sound, early reflections and reverberant field sources - it must not be forgotten that the reverberant field can be considered as a multitude of individual reflections from specific directions. On the other hand all sound that lies outside the SRA will be reproduced at one or other of the loudspeakers, as what one could almost call monophonic sound. The balance between the “weight” of this monophonic sound against the sound reproduced as a stereophonic sound image is a major factor in the success or otherwise of a recording.

In a multichannel system, it would be an error to consider that the coverage overlap will be reproduced by a spread of the sound sources situated in the overlapping zones. Quite the contrary, in a specific overlap zone, the mechanism of sound perception will amalgamate the individual sound cues into one predominant “mass” of sound. This will be perceived as a “condensation” of part of the reverberant sound onto each of the loudspeaker positions. Although this is to some extent inevitable, the sound engineer still has some limited scope to choose a position for the microphone array which will minimise the negative effects produced by this part of the sound field. Fortunately this condensation effect has less impact in the reproduction of a a multichannel recording compared with a stereo recording.

As with the use of dual microphone arrays for stereophonic sound recording, an effort must be made to break the mysticism surrounding the habit of recording only in the (horizontal) reference plane of a dual microphone array or a multichannel microphone array. Any sound engineer, with experience in recording sound effects and even more specially surrounding sound ambiance for stereo reproduction or multichannel, knows that the microphone system has a total spherical sound pick-up even though the eventual reproduction of the sound field is condensed onto the plane of reproduction formed by the loudspeakers.

In multichannel sound recording with a correctly designed microphone array, we are fortunate in being able to reproduce a continuous sound field in and around the main reference plane of the microphone system. However the Multichannel Microphone Array is not yet the miracle sound recording system that will produce the absolutely perfect sound image, but for the time being it's the best we've got!

VERTICAL MICROPHONE ORIENTAION IN RELATION TO THE REFERENCE PLANE

Most of the microphone support systems that are at present under development use either a single transversal bar as the main structural support, or a system of crossed bars somewhat in the form of "La Croix de Lorraine" (a Lorraine Cross).

Due to the Multichannel Microphone Array design procedure developed in previously cited papers(1)(2)(3), the author of this paper has developed a rather more flexible support system which can, under certain circumstances, introduce a vertical angle between the microphones and the reference plane of the system. One is intuitively suspicious of this situation, however a careful analysis of the spherical trigonometry of such a configuration with respect to the basic psychoacoustics of perception of a sound image should put our mind at rest, or at least give us the operational limits to such a support system.

Figure 7 shows a 3D representation of the possible orientation of the microphones introduced by the microphone support system.

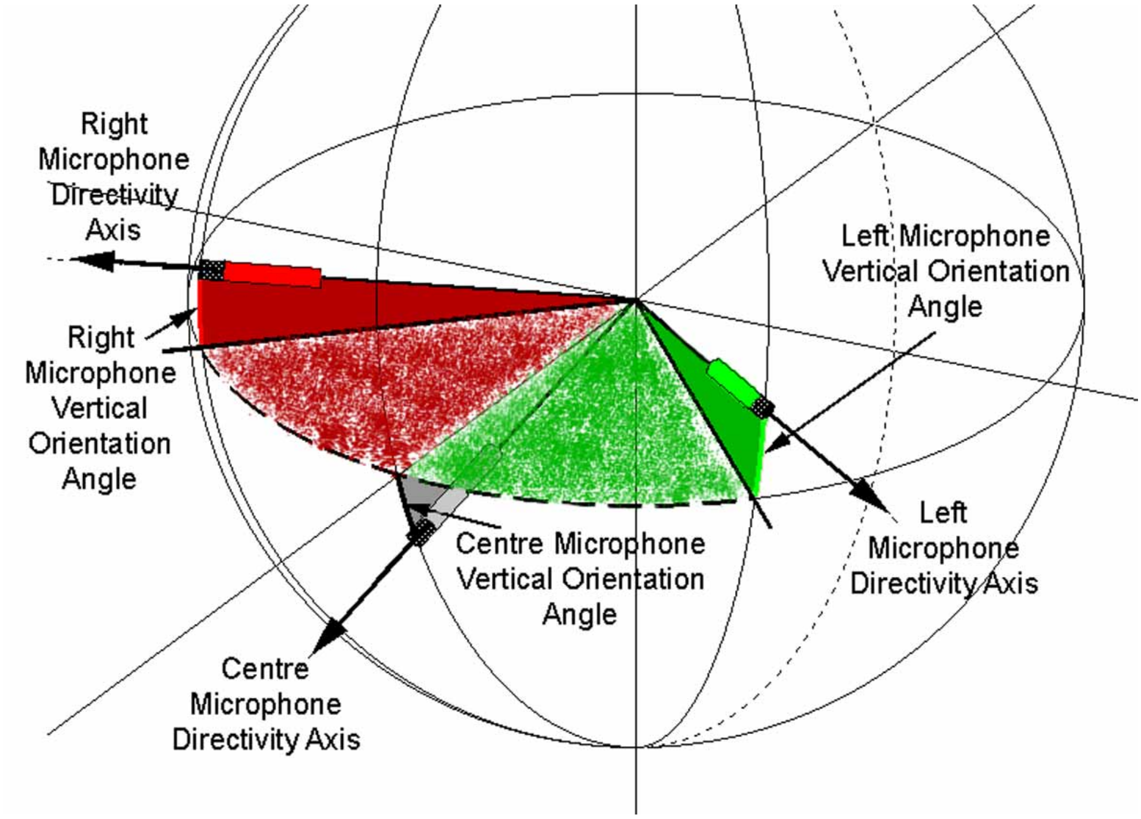

Figure 7 - 3D Representation of Vertical Orientation of the Front Triplet of Microphones

If we analyse this situation with relation to each pair of microphones, we can see that all we need to do is add on an extra term to the Intensity Difference equation which represents the vertical orientation of each microphone. The vertical orientation of each microphone in the stereo pair is represented by (**el**) and (**er**). The Intensity Difference formula then becomes :

$$dI = 20 * LOG_{10} \left[\frac{(cf)+(1-cf).\{SIN(\alpha)*SIN(ß/2)+COS(\alpha)*COS(ß/2)*COS(e+el)\}}{(cf)+(1-cf)*\{SIN(\alpha)*SIN(-ß/2)+COS(\alpha)*COS(-ß/2)*COS(e+er)\}} \right]$$

Figures 8 and 9 show the variation of the Stereophonic Recording Angle as a Function of Sound Source Position for a total of 20° and 40° difference in vertical orientation between the left and right microphones of a stereo pair. We can see that again SRA varies very little in the front hemisphere but varies much more in the back hemisphere. However there is some 'tilting' of the SRA zone due to the opposite vertical orientation of the microphones. In these two figures the curves are shown only for an angle of 90° between the microphones.

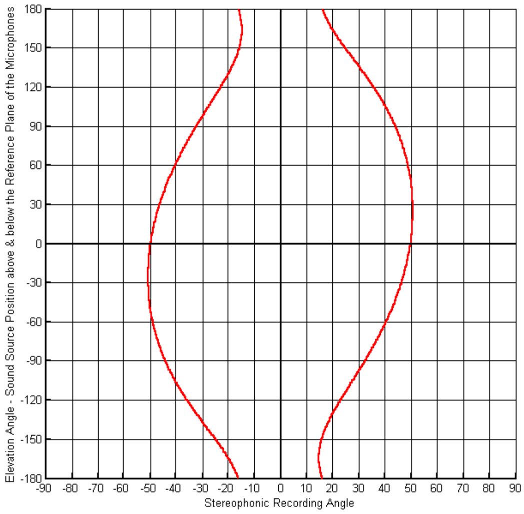

Figure 8 - SRA with Elevation for 20° Difference in Vertical Orientation

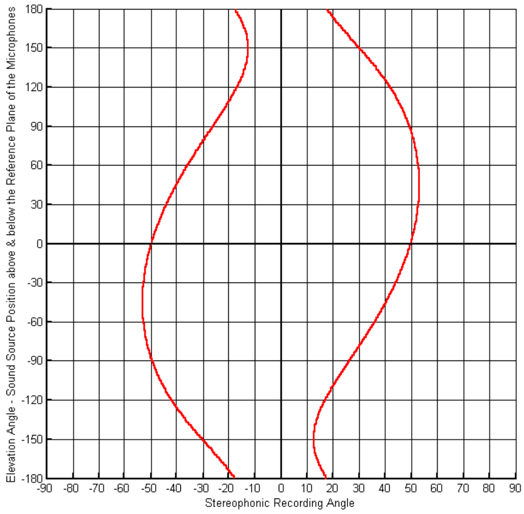

Figure 9 - SRA with Elevation for 40° Difference in Vertical Orientation

If we now consider the introduction of vertical orientation in the Front Triplet of microphones of a Multichannel Microphone Array, so that that the centre microphone is inclined downwards by about 40° with respect to the main reference plane passing through the left and right microphones.

We can see in Figure 10 that, in the upper hemisphere, the tilting of the Left Front Segment and Right Front Segment causes an increase in the Coverage overlapping. However the disadvantage of this overlap is more than compensated by much better Critical Linking in the first 40° in the lower hemisphere.

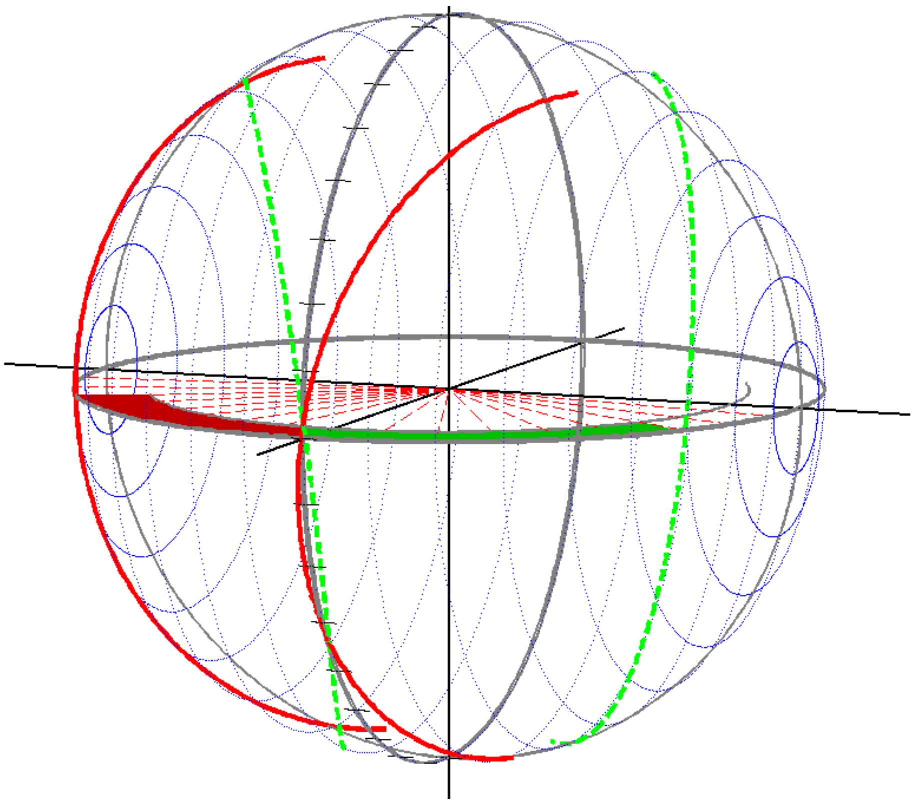

Figure 10 - 3D Representation of the Variation of SRA with Elevation for 40° Difference in Vertical Orientation of Microphones

If we imagine that this system is being used for instance, to record an orchestra in the usual position, as shown in Figure 11, at approximately 1 metre behind the Conductor and about 3 to 4 metres above, then this improvement to Critical Linking is a beneficial result of applying vertical differential orientation.

Even with the "Lorraine Cross" microphone support systems, it would be worth introducing some vertical downwards orientation of the front microphone to obtain good Critical Linking in the first part of the lower hemisphere.

The improvement in the overlap cannot unfortunately be extended to all the segments of the multichannel array, but the Front Triplet of direct sound pick-up is by far the most important.

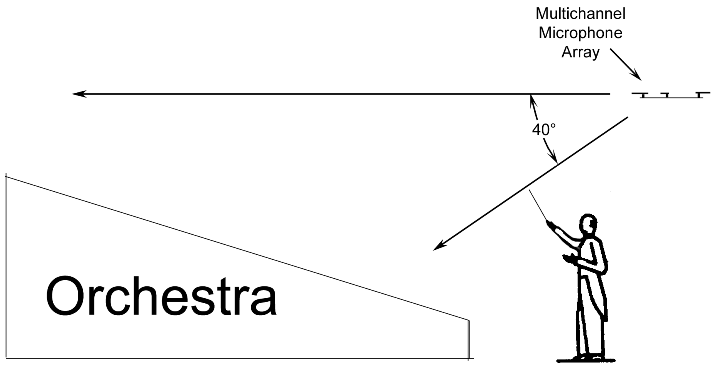

Figure 11 - Multichannel Array and the Orchestra

CONCLUSION

The response of any microphone array system must be considered not only in the 'horizontal' reference plane but at all angles both above and below this reference plane. Considerable advantage can then be drawn from a wise choice of microphone array characteristics which will reproduce a smooth continuous surround sound-field as well as the optimum integration of reflections and reverberation.

The sound recording engineer must at all times bear in mind a visual representation of the characteristics of the microphone array as regards segment coverage angles, and their variation both above and below the microphone system. This coupled with a visual analysis of the position of the direct sound sources and the acoustics of the surrounding reflection surfaces should guide the sound engineer towards achieving the optimum result in the shortest time. This capacity to imagine a 3 Dimensional representation of the microphone array characteristics and the sound recording environment is a vital tool in association with the « Art of the Sound Recording Engineer».

1. 1999 : 107th AES Convention in New York : Preprint 4997 « Microphone Array Analysis for Multichannel Sound Recording » by Michael Williams and Guillaume Le Dû

2. 2000 : 108th AES Convention in Paris : Preprint 5157 « Multichannel Microphone Array Design » by Michael Williams and Guillaume Le Dû

3. 2001 : 110th AES Convention in Amsterdam : Preprint 5336 « The Quick Reference Guide to Multichannel Microphone Arrays Part 1 : using Cardioid Microphones» by Michael Williams and Guillaume Le Dû

4. 1991 : 91st AES Convention in New York - preprint 3155 "Early Reflections and Reverberant Field Distribution in Dual Microphone Stereophonic Sound Recording Systems" by Michael Williams.

5. 1987 : 82nd AES Convention in London : Preprint 2466 « Unified Theory of Microphones Systems for Stereophonic Sound Recording » by Michael Williams