Proceedings of the Institute of Acoustics

STEREO IN THE ROOM

Gareth Millward & Richard Lee

Wharfedale Loudspeakers Ltd.

ABSTRACT

Two simple measures of stereo performance are proposed and the results of a computer simulation of zero and first order sources in a room are presented. The room is shown to have considerable impact on stereo performance.

INTRODUCTION

Remarkably few loudspeaker designers can give a concise and accurate description of what stereo is trying to achieve and suggest possible ways of achieving this. One example of the many fallacies about good stereo loudspeakers is the requirement for a 'wide dispersion' (whatever that means).

Good descriptions have actually been around a long time. (1) & (2). We would like to summarize some important points from these two documents here.

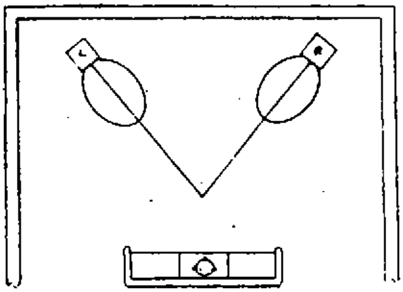
> The operation of the ears in determining direction is not yet fully known but the main factors are probably the phase differences and intensity differences between the sounds reaching the two ears.
>
> Stereo is a method of recording and reproducing sound such as to recreate a semblence of these differences AT THE EARS of the listener.
>
> This is done by feeding two matched loudspeakers arranged as in Fig 1, with signals DIFFERING ONLY IN AMPLITUDE according to the direction of the source.
>
> It relies on the fact that the sounds produced by these speakers combine AT THE EARS to give similar phase and intensity differences to that of a real source.
>
> If the listener is off the centre-line between the loudspeakers, the interchannel time differences are modified which lead to further interaural time differences and the position of the image is different and less sharply defined than for a central listener.

(1) British Patent 394,325 granted 1933 to Alan Dower Blumlein

(2) BBC Training Instruction P4 Feb 1966

STEREO IN THE ROOM

FIG 1



We have emphasized two points.

Firstly, that positional information is coded only by amplitude differences between the two loudspeaker signals. This is equivalent to the signals derived from a coincident pair of directional microphones as proposed by Blumlein (1) or that from a studio pan-pot. We are of the opinion that microphone techniques involving spaced microphones, while capable of pleasing results are incapable of encoding direction sensibly; a short explanation of this appearing in Appendix A.

Secondly, that it is the resulting signals AT THE EARS which are of importance rather than secondary concerns like the amount of crosstalk between channels.

WHERE'S THE LEAD SINGER ?

There is a body of opinion that stereo is about left and right. However, in most musical events, the really interesting stuff is actually in the centre. Hence how a reproducing system deals with central images is probably of greater importance than how it deals with left and right images.

An extreme left or right signal is very simple. If one loudspeaker is more than about 20 dB (2) louder than the other, the sound will appear to come from the direction of that loudspeaker. Practically all stereo loudspeaker arrangements get this case right.

The next simplest case is when the sound is supposed to come from the centre and this is done by feeding identical, (in both amplitude and phase) signals to both loudspeakers. (ie MONO) We suggest that stereo loudspeaker systems should at least try to get this right as well. There is more to stereo than left, right and centre; but if you can't even reconstruct these, you haven't much chance of getting anything else right !

If the listener is facing forward directly between identical loudspeakers as in Fig 1, he will perceive a sharply defined image directly in front of him. If he were to sit slightly left of centre, it is likely that this centre image is replaced by a large hazy area somewhat to the left of centre. If he were to move further to the left (and this might only be one seat postion away from centre) the sound is likely to have collapsed into the nearer speaker. Fig 2

STEREO IN THE ROOM

Two effects are operating to cause this. The listener is closer to the left speaker and hence it sounds louder. Also its proximity means signals from the other speaker reach him after those from the nearer speaker.

Some may argue that they always listen only in the centre position. However, with many loudspeakers, the effect is observed even if the CENTRE listener swivels his head slightly. This is most unpleasant and with these loudspeakers, certain certain listeners are unable to listen sitting directly in the centre because of it.

Quite a few investigations on this have been published. We steal Fig 2 from Jordan (3) as we like the description and his rather refreshing viewpoint.

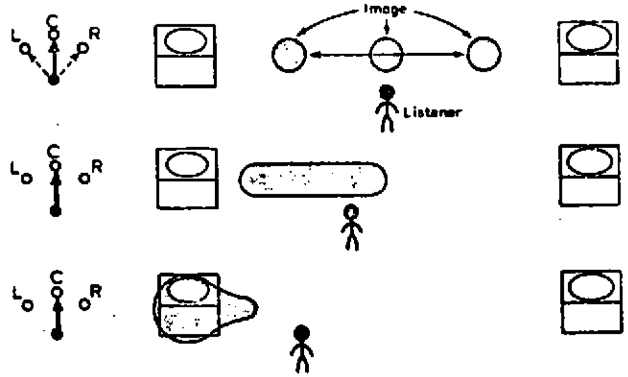


FIG 2

Poor central images for off-centre listeners

A CENTRAL DIRECTION

If we could in some way make the nearer loudspeaker sound softer as we move closer to it, we might be able to make this offset the postional change caused by the signal arriving sooner than that from the other speaker.

This is done by tailoring the directivity characteristics of the loudspeakers and again much work has been published. See below.

(3) E J Jordan 'Loudspeaker Stereo Techniques' Wireless World Feb 1971

(4) J Crabbe 'Broadening the Stereo Seat' HFN & RR Jun/July/Sept 1979

(5) J Enock 'Loudspeakers for Stereo' HFN Jan 1964

(6) D M Leakey 'Stereophonic Sound System' Wireless World Apr/May 1960

(7) J Kates 'Optimum Loudspeaker Directional Patterns' JAES Nov 1980

STEREO IN THE ROOM

The gist of these articles is to have a pair of directional speakers and place them so that their axes cross in front of the listening area. If you sit in the centre, you hear equal signals from the two speakers for mono and hence perceive a central image. A move to the right will put you into the region where the left speaker is stronger and this compensates for the fact that you are nearer the right speaker; pushing the image back towards the centre.

A problem with these 'solutions' is that it is very difficult to control the directivity of a loudspeaker over a wide frequency range; especially to the strange patterns suggested by these authors.

WELL, NEARLY CENTRAL

We decided to turn the question round and ask ourselves what type of results we could get with easily obtainable directivity patterns.

A computer model was set up to model the extent of the stereo seat for loudspeakers of various directivity patterns. It explores two theories current about our directional perception.

THE THEORETICAL MODEL

Both of these assume that the listener will turn his head such that he appears to face the source. This will happen when each ear receives equal 'quantities' of whatever factor is important for localization and this is the approach taken by Makita (8) and Gerzon (9).

The simpler model is an 'energy' model and suggests the listener will turn his head to minimize the intensity differences between the sound received by the two ears. It is thought to be appropriate for frequencies from about 400 Hz to 5 kHz. This is also thought to be a sort of 'default' mode used when other localization faculties give confusing results with multiple speakers.

Appendix B describes this as applied to off-centre listening with two stereo loudspeakers of arbitary directivity pattern and is an extension to Gerzon's methods (9).

When we first started this work, we assumed that room reflections were not all that important and were expecting results similar to de Boer who achieved good results with dipoles. However some initial experiments with band limited noise and dipoles suggested that this was too simplistic a view. In particular, the areas of good stereo did not really coincide with the predicted results.

(8) Y Makita '.the Directional Localization of Sound in the Stereophonic Sound Field' EBU Review part A no 73 1962 pg 102 - 108

(9) M Gerzon 'Surround Sound Psychoacoustics' Wireless World Dec 1974

The model was enhanced to include the effect of first the back wall and then side walls and it was only then when we found reasonable correlation with the experimental results.

The method used (Appendix C) was to modify the Energy Directional Patterns over the required frequency range to take into account the first order reflections in the side and back walls and substitute the new Directivity Patterns in the Appendix B equations.

At low frequencies, the head presents only a small shadow to sound and the intensity at both ears is about the same. The most significant information available to the ears then is the 'Phase' difference between the two ear sounds. This is probably appropriate to about 500 Hz beyond which the distance between the ears results in the phase cycling and hence complicating the information which must be processed to determine direction.

Because the phase must be preserved, the mathematics is considerably more complicated and the simple techniques used in Appendix B & C cannot be used.

Our approach is an enhancement of Kate's (7) :

correcting the assumption that space & time differences were small
adding the contribution of the first order, back & side reflections
averaging over a range of frequencies.

This 'Phase' model can be shown to be equivalent to the localisation considered by Makita (8), Leakey (10) and Bernfeld (11) for central listeners.

THE DRAGON PROGRAM

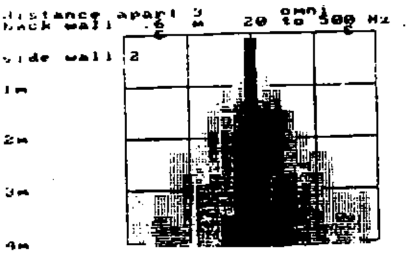
The computer program displays a grid 4 m. square. Speaker positions are indicated by 'S'. The directional pattern and angle of orientation of the speaker can be specified as well as the position of the back and side walls.

At 0.2 m intervals, the output received from each speaker is determined and compared with the output which should have been received if the image was to have remained in the centre. A block is then plotted on the screen in a colour depending on the fit. In this paper, a black block says that the ratio of right speaker output to left speaker output is within 1 dB of the ideal, followed by progressively lighter shades of grey for each extra dB difference.

(10) D Leakey 'Some Measurements on the Effect of Interchannel Intensity and Time Differences in Two-Channel Sound Systems' JASA Vol 31 1959

(11) B Bernfeld 'Attempts for Better Understanding of the Directional Stereophonic Listening Mechanism' AES 44th Conv. Rotterdam Feb 1973

FIG 3 Omnidirectional Source



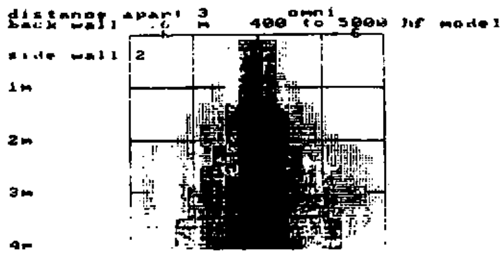
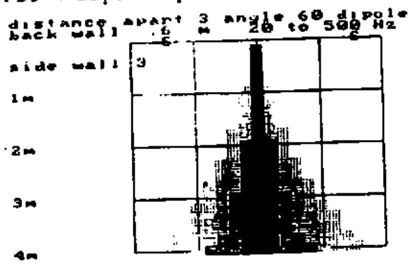
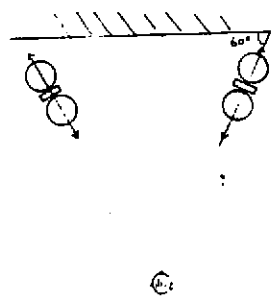


Fig 3 shows some results for an omnidirectional (ie of Zero Order directivity) speaker. They show that the stereo seat is not very wide even at 4 m. listening distance. This is not surprising since such a speaker provides no compensation for distance or precedence. This does not mean that an 'omni' speaker cannot reproduce stereo; only that there is a relatively small area where you can observe this.

It is actually possible to construct dipoles which mantain their directivity characteristics over quite a large frequency range. Bauer (12) and de Boer have suggested dipoles for stereo over a larger area. However, it is important to place dipoles properly to get an improvement. Fig 4 shows how dipoles are often placed facing the listener in the centre and how this results in a very small listening area indeed. This is experienced by owners of most of the electro-static and flat-panel loudspeakers on the market today.

FIG 4 Dipoles placed conventionally



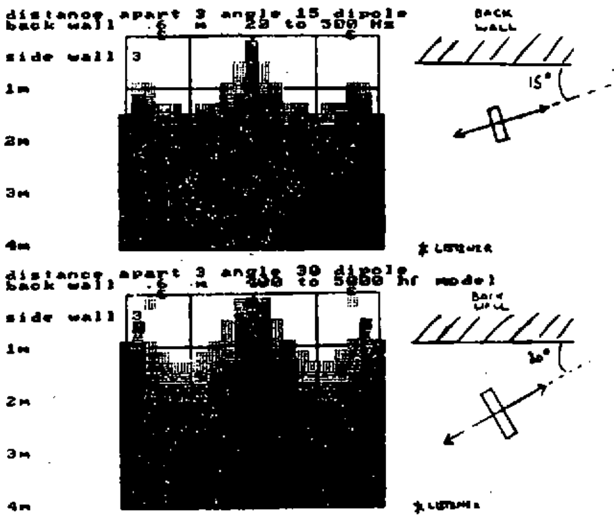


If the dipoles are further toed in, we get a remarkable increase in the good stereo area as in Fig 5. It was the large 'wings' which extend to well beyond the extreme speaker positions gave rise to the 'Dragon' name for this computer program.

(12) B Bauer 'Broadening the Area of Stereophonic Perception' JAES Apr 1960

STEREO IN THE ROOM

FIG 5 Dipoles toed well in



DIPOLES

Dipoles have other advantages as well. In particular, if they are placed at odd fractions along a wall dimension and firing along it, the resonant modes due to the speaker and its reflections in the orthogonal walls are interlaced with the room modes along that dimension.

A dipole speaker designed to take advantage of this as well as the benefits for stereo is best placed at one third intervals along the long wall of a rectangular room. It then divides the room into 3 parts; the area outside the speakers and that inside.

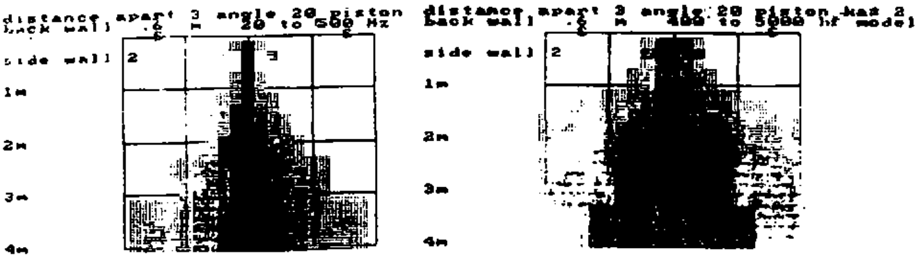
Outside the speakers, the impression is that the speakers define a large door within which some musical event is taking place. It is quite disconcerting to move up along the 'wings of the dragon' right up to behind one of the dipoles and still hear what appears to be happening between the speakers although you are obviously receiving a large amount of sound from the back of the dipole.

As one moves across the boundary defined by one of the speakers, a most peculiar effect takes place (probably because you are moving through the null). Once into the listening area, the impression is not that you have moved in front of a large open door, but that you have moved into the room, as suddenly, the sound stage has widened to beyond the speakers.

OTHER TYPES OF SPEAKER

It is possible to do the same exercise with other types of polar pattern and Fig 6 shows how some broadening of the stereo seat is possible with a large diameter piston on a wide baffle. In general, however, a conventional box speaker is no better than an omni in this respect and may even be worse unless attention is paid to ensuring that the polar pattern is as CONSISTENT as possible especially through the crossover frequencies.

FIG 6



SUMMARY

In fact, this last point is probably the most important one to have emerged from our experiments. We don't use any single auditory clue to determine direction and if most of these suggest the same thing, we have good sound. If several important clues disagree, we have listening fatigue.

That is not to say we cannot modify these clues to suggest different things as long as what is suggested is not dis-similar to what happens in real life. Hence it is possible to move the sound stage with the dipole speaker described above backwards or forwards by adjusting the angle which the mid and treble units make compared to the bass unit. Both the frequency balance as well as the ratio of pressure to velocity information change in a manner consistent with this.

Hence 'wide directivity pattern for stereo' is actually a fallacy. In fact directional loudspeakers come closer to the ideal and the important factor is to mantain this directivity consistent over a large frequency range. Also it would appear that one requires more directiviy at low frequencies which is off course quite difficult to achieve.

Lastly, where you place and the angle which one toes in loudspeakers is critical and probably the worse case is that which has both speakers firing down the room.

INACCURACIES AND FURTHER WORK

The present model assumes perfect rectangular reflecting boundaries.

Allowing the specification of other than zero absorbtion coefficient would allow investigation into the performance of local 'arbsorbers to improve stereo'. This paper supports previous work that suggests early reflections are extremely important for good stereo. (eg Stereo is very poor in an anechoic chamber but is considerably improved if a solid floor is laid down.)

It only adds the first order reflections from the back and side walls. However, in a 5 x 4 m. room, the reflections from the wall behind the listener and the second order reflections would be heard more than 20 msec after the first arrivals and would tend to be heard as seperate echoes if they were heard at all (being more than 10 dB down).

More important might be the simulation of floor and ceiling reflections but we are unsure of the theoretical framework on which to extend the present two dimensional model to three.

Perhaps the most suspect substitution is the derived Directivity Functions (from Appendix C) for the arbitary Directivity Functions in the Energy and Phase Models for directional perception. We plan to cut out the directivity function stage and apply the phase and energy models directly to the simulated sources to check this.

However, the proof of any theoretical model must be whether it makes useful predictions and the present model certainly does this. In particular, the correlation between its results and experimental data for dipoles is quite remarkable and suggests that large advances in the standard of realism available with stereo are still possible if we learn to control directivity simply in domestic loudspeakers.

ACKNOWLEDGEMENTS

We would like to acknowledge the work of Michael Gerzon whose work on Ambisonics suggested to us that it is possible to develop tractable mathematical tools to describe the listening process and hence help design better loudspeakers !

APPENDIX.A : DIRECTIONAL CODING OF COINCIDENT AND SPACED MICROPHONES

Fig A.1 shows the equi-coded contours of the sound stage from a coincident fig-8 pair of microphones at 90 degrees. Note that although there is a front back ambiguity, each DIRECTION IS UNIQUELY coded very simply by the amplitude difference between the two microphone channels.

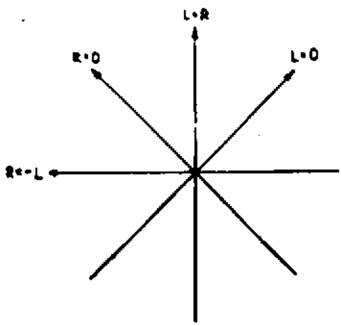


FIG A1 : EQUI-CODED POSNS. FIG 8 PAIR

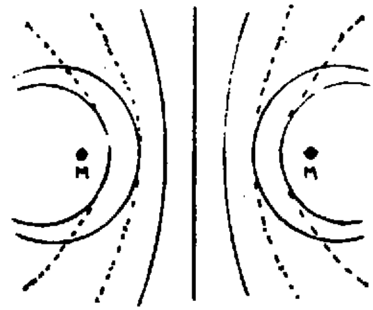


FIG A2 : SPACED OMNIS AT M — EQU.AMP DIFF
--- EQU.TIME DIFF

In contrast, Fig A.2 shows the equi-coded contours for a pair of spaced omni microphones for equal amplitude difference as well as equal time difference between the channels. Note that the lines of equal amplitude differences are NOT THE SAME as the lines of equal interchannel time differences.

Hence any sound source position will have different amplitude as well as time coding and there is no simple relation between these or the

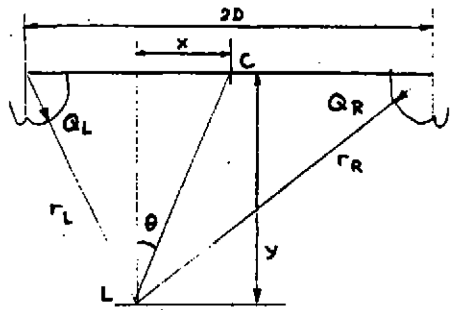
POSITION WHICH IS SENSIBLY ALLOCATED TO THEM IN THE REPRODUCED SOUND STAGE.

One anamoly is that the locii of equal amplitude differences are quite tight circles. Where should these positions of identical coding appear on the reproduced sound stage ? If they appear at a particular position between the speakers than the recording/reproduction process has distorted circles into straight lines ! (Time difference coding is even more complex in this case and the information coded conflicts with the amplitude difference coding.)

We also see from this that if spaced omnis are used, why they should not be too far apart. If they are, the circles are very tightly curved near the sound sources and the distortion is emphasized.

'Stereo Microphone Techniques: Are the Purists Wrong ?' by S Lipshitz, JAES Sep 1986 is a VERY detailed, accurate and readable treatment of this topic.

APPENDIX B : ENERGY MODEL



Q_L & Q_R : Arbitary directivity Functions r_L & r_R : Distances from L

Then 'Energy' from these two sources are

$$P_L^{\,2} = Q_L^{\,2} \qquad \& \qquad P_R^{\,2} = Q_R^{\,2} \qquad \text{Eqn B1 \& 2}$$

Using Gerzon's ( ) nomenclature, we form the following, 'resolving Energy' in the X & Y directions relative to the listener L.

$$W_E' = P_L^{\,2} + P_R^{\,2} \qquad \text{Eqn B3}$$

$$X_E' = \frac{-(D - x)}{r_L} P_L^{\,2} + \frac{(D + x)}{r_R} P_R^{\,2} \qquad \text{Eqn B4}$$

$$Y_E' = \frac{y}{r_L} P_L^{\,2} + \frac{y}{r_R} P_R^{\,2} \qquad \text{Eqn B5}$$

Then X_E'/W_E' & Y_E'/W_E' are Direction Cosines for this 'Energy' mode of directional perception and for the image to appear from centre C,

$$X_E' \,/\, Y_E' = \operatorname{Tan}\theta = x \,/\, y \qquad \text{Eqn B6}$$

ie

$$\frac{-(D - x)\, r_R P_L^{\,2} + (D + x)\, r_L P_R^{\,2}}{y(r_R P_L^{\,2} + r_L P_R^{\,2})} = \frac{x}{y}$$

$$D(r_L P_R^{\,2} - r_R P_L^{\,2}) = 0$$

$$\frac{P_R^{\,2}}{P_L^{\,2}} = \frac{r_R}{r_L}$$

Substituting B.1 & 2

$$\frac{Q_L^{\,2}}{Q_R^{\,2}} = \frac{r_L^{\,3}}{r_R^{\,3}} \qquad \text{Eqn B7}$$

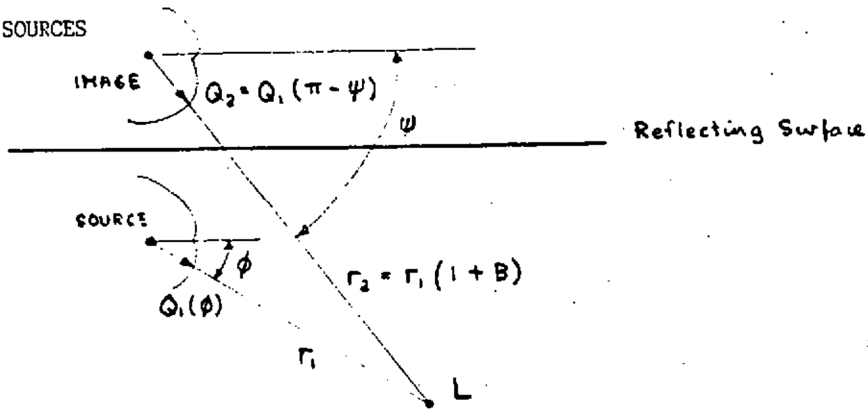
which is the distribution characteristic for stable central images.

STEREO IN THE ROOM

APPENDIX C : DIRECTIVITY OF SOURCE WITH REFLECTIONS

This treatment of the directivity pattern Q of simple sources near reflecting surfaces is an extension to Waterhouse ( ) but modified to mantain accuracy for the near field as would pertain in domestic rooms.

2 SOURCES



We consider a source with directivity pattern $Q_1(\phi)$ near a large reflecting surface. It will have an image with directivity pattern $Q_2(\psi) = Q_1(\pi - \psi)$.

For listener L at distances r_1 & r_2 from source & image as in Fig C1, we have for freqency w, the signal received is :

$$P = A\, e^{jwt} \left[\frac{Q_1}{r_1} e^{-jwr_1} + \frac{Q_2}{r_2} e^{-jwr_2} \right] \qquad \text{Eqn C1}$$

where A : arbitary constant
$k = w / c$ c : Speed of Sound.

This give a directivity pattern dependent on r_1 & factor B where $r_2 = r_1(1 + B)$

$$Q(\phi) = \text{sqr} \left[Q_1^{2} + \frac{Q_2^{2}}{(1+B)^2} + \frac{2Q_1Q_2}{(1+B)} \text{Cos } kBr_1 \right] \qquad \text{Eqn C2}$$

For B much greater than rl ie very far away, this reduces to :

$$Q(\phi) = \text{sqr} \quad Q_1^{2} + Q_2^{2} + 2Q_1Q_2\text{Cos}(2kl\text{Sin}\,\phi) \qquad \text{Eqn C3}$$

which is Waterhouse's (14) Eqn 9

(14) Output of a Sound Source in a Reverberation Chamber and Other Reflecting Environments. R V Waterhouse JASA Jan 1958

STEREO IN THE ROOM

If the square of Eqn C2 is integrated for frequencies from 0 to w rad/s, we have

$$\text{Mean Energy Directivity Pattern} = \frac{1}{w}\int_0^w Q^2(\phi)$$

$$= Q_1^2 + \frac{Q_2^2}{(1+B)^2} + \frac{2Q_1Q_2}{(1+B)}\,\frac{\mathrm{Sin}(wBr_1/c)}{(wBr_1/c)} \qquad \text{Eqn C4}$$

MULTIPLE SOURCES

Multiple sources (reflections) are dealt with by extending Eqn C2 which gives for n sources :

$$Q(\phi) = \mathrm{sqr}\left[\sum_{r=1}^{n}\sum_{s=1}^{n}\frac{A_rA_s}{(1+B_r)(1+B_s)}\,\mathrm{Cos}\;k(B_r-B_s)R_1\right] \qquad \text{Eqn C5}$$

where the distances of the sources are R_1 to R_n and :

$R_r = R_1\ (1+B_r)$ $\qquad$ $R_s = R_1\ (1+B_s)$

$B_1 = 0$ $\qquad$ ie the original source

The Mean Energy Directivity Pattern is derived by integrating Eqn C5 in the same way that Eqn C4 is derived from Eqn C2.