Proceedings of the Institute of Acoustics

THE LOUDSPEAKER - ROOM INTERFACE SOME NEW PERSPECTIVES

Peter Mapp Peter Mapp Associates, Colchester, Essex, C03 4JZ,

1 INTRODUCTION

Although the Loudspeaker - Room interface has been extensively researched and reported eg [1-6], measurement and assessment techniques are continually developing and can provide new insights into this critical subject. Loudspeaker technology is also currently going through a new phase of development with the recent introduction of the Distributed Mode Loudspeaker (DML) [7-9]. Reports suggest that such devices interact with their acoustic environment in a significantly different manner to conventional cone or pistonically based devices. It has previously been shown for example that the sound field may be less variable and that there is considerably less destructive interference with local boundaries [10,11]. Early Psychoacoustic studies of DML devices indicate that parameters such as the perception of loudness and auditory imaging within the listening environment are also affected in a different manner to conventional loudspeakers [12,13].
This paper sets out not only to introduce a number of new measurement techniques such as Cross-Correlation Function analysis and Reflection Intensity Mapping to shed some new light onto the Loudspeaker - Room interface in general, but also to compare the in-room characteristics of conventional cone and Distributed Mode loudspeakers.

2 LISTENING ROOM & TEST SET UP

The in-room measurements reported in this paper were carried out in a typically sized small listening room located at PMA, measuring 5.2m (L) x 3.1m (W) x 2.5m (H) [see figure 1]. The room is acoustically treated to provide a well damped response and exhibits an essentially flat reverberation time characteristic of 0.3 seconds over the range 250 Hz to 4 kHz, dropping slightly to 0.25 seconds at 8 kHz. As can be seen from the figure, the room is rectangular though not quite symmetrical laterally, with the RHS wall surface being broken up by two, 2 metre, 300 mm deep recesses.

The results reported here are restricted to single loudspeaker operation. The test loudspeakers were placed centrally in the room and approximately 1.2 - 1.3 m from the front wall. The loudspeakers were mounted such that the centre of their typical axial radiation was at 1.2 m enabling the measuring microphone to be located at seated listener ear height. Test measurements were made both on and off axis as indicated in figure 1. The size of the room allowed measurements over the range 0.5 to 3.5 metres to be made, enabling the near and reverberant far field to be investigated.

Five different models of loudspeaker were employed to provide a range of source directivities and radiation characteristics. These were a 2.5 inch cone in small infinite baffle cabinet to provide a wide dispersion point source with single driver. A JBL 'Control 1', 2-way, small commercial loudspeaker was employed as the other conventional source. Three very different forms of DM Loudspeaker sources were employed and comprised a small open back DML panel type PRD1 (230 x 260 mm) larger open back experimental PA1 panel (350 x 500 mm) and a closed back panel, CB1, (600 x 430 mm). The DML sources apart from offering diversity in physical size, also differed in terms of their structural composition with materials ranging from glass fibre on Polycarbonate core, glass fibre on Rohacell core, and paper on PU foam core panels. The radiation characteristics were also very different with the two open back panels operating as diffuse dipoles, with essentially equal radiation from front and rear whilst the closed back panel operated as a diffuse monopole.

3 LOUDSPEAKER RADIATION CHARACTERISTICS

The polar radiation characteristics of the loudspeakers were measured under anechoic conditions. As would be expected, the 2.5 inch cone and the small 'control 1', 2-way loudspeaker, provide wide dispersion characteristics, though still narrowing down at high frequencies as per conventional pistonic theory. Interestingly, the Control 1 polar becomes slightly skewed due to the off-centre position of the tweeter. The 2.5 inch unit provides wider dispersion at 2 kHz than the JBL and is fractionally wider at 4 kHz. The differences enabling useful and interesting comparisons to be made.

In contrast, the PRD1 and the PA1 Panel exhibit very wide dipolar dispersion as shown in figure 2. The PRD1, provides a very well controlled dipolar characteristic throughout the range of interest, whereas the PA1 panel offers an apparently surprisingly wide dispersion for an acoustic object of its size. Again, the dipolar nature is maintained throughout the range, although at 4 kHz the on axis level drops slightly and a small side lobe develops at around 75 degrees. There is also a slight asymmetry front to back at high frequencies due to the presence of the exciter mechanisms on the rear panel.

The Closed Back DM Panel, CB1, exhibits quite a different radiation characteristic to the other two DM panels as can be seen immediately from inspection of figure 3. Again at high frequencies, the panel exhibits wide dispersion (again surprisingly wide for an object of this size) that quite unconventionally does not collapse to a narrow beam. At lower frequencies, the panel acts more as a conventional monopole source of quite large physical dimension commensurate with the wavelengths involved.

Clearly, the various sources will interact quite differently with the room and its associated boundaries.

4 TRADITIONAL SOUNDFIELD MEASUREMENTS

4.1 Sound Level Fall Off with Distance

This most basic of measures still provides a very useful insight into the developing sound field. Under anechoic conditions the cones and the two open back DM Loudspeaker panels were shown to almost exactly follow the inverse square law.

In the test listening room, the small DM panel (PRD1) and the 2.5 inch were found to almost exactly mimic the classic enclosed space inverse square law - reverberant level curve. The initial spl in the nearfield of the panel however, was approximately 3 dB lower for the same resultant far field level. The larger PA1 panel exhibited a greater difference, being some 9 dB lower in level at 100 mm in comparison to the cone. The fall off with distance curve is also distorted, exhibiting a slight peak between approximately 1.2 and 2.3 metres.

4.2 Direct to Reflected Sound Ratios

A series of direct to reflected sound ratio measurements at various room positions was carried out. Figure 4 compares the D/R ratios at 2 metres from the source for all five loudspeaker models. Here a clear pattern emerges with the cone devices showing positive values and all three DML panels exhibiting negative indices. This is an important and possibly surprising finding, though not unique to the particular room - loudspeaker combination under review.

The ratios were also examined over the range 0.5 to 3.5 metres. Figure 5 compares the results for the 2.5 inch cone and the PA1 panel. The curves track one another very closely, with the PA1 panel ratios exhibiting an almost constant negative offset. The above results, however, are again based on broadband measurements. Examining the ratios at 2 metres from the source, but on an octave band frequency basis, supports a very different trend. Figure 6 shows the frequency dependency of the two cone devices. As would be expected from simple piston theory, the 2.5 inch cone exhibits a marginally lower ratio but importantly both speakers follow exactly the same trend. With the exception of the 1KHz measurement, the two open back DM panels approximately track each other, with the closed back panel being more akin to the cone devices. It generally tracks between them but with a 5 to 6 dB negative offset - except at 250 Hz where it would appear to be exciting the low frequency room modal structure in a different manner.

4.3 Speech Transmission Index (STI)

The Complex Modulation Transfer Functions for all 5 loudspeakers were measured and the Speech Transmission Indices (STI) computed. The results were almost identical at 0.829 to 0.830 for the DM loudspeakers and 2.5 inch cone and 0.847 for the JBL. There was therefore no significant difference between the devices under the given test conditions.

4.4 Lateral Energy Fraction

The lateral energy fraction (LEF) for each of the devices was measured for the 2 metre test position at 500 Hz and 2 kHz. The results are presented in figure 7. These results show that at 2 kHz, the two Dipolar DM loudspeakers produce significantly higher ratios (i.e. higher level of lateral reflected energy) than the cone devices, with the PA1 Panel being exactly double the JBL Control 1. The LEF for the closed back panel is similar to the 2.5 inch cone - although not an entirely unsurprising result, considering the polar radiation characteristics of the two devices, one that is counterintuitive based on the physical size of the objects and their expected acoustic radiation behaviour. At 500 Hz the PA1 Panel again exhibits the greatest LEF but this time the Control One, 2.5 inch and PRD1 are effectively the same with the closed back giving the lowest value. The results would appear to be consistent with the devices' polar radiation characteristics and indicate that the DM loudspeakers and the dipolar types in particular, will produce a greater degree of laterally reflected sound compared to conventional loudspeakers. It would not seem unreasonable to assume that such an effect would be of some psychoacoustic significance and may affect both image and loudness perception.

5 CROSS CORRELATION MEASUREMENTS & EFFECTS

Whereas strong, early reflections associated with conventional loudspeakers generally lead to undesirable coloration and interference effects, this does not appear to be the case with DML devices. The diffuse nature of the DML suggests that its output should not be highly correlated. This for example is demonstrated by the significantly reduced boundary interaction interference effects as previously shown by Azima & Mapp [12]. In this respect, a new technique for assessing the correlation characteristics of a source's output with respect to angular variation has recently been developed by Guntcharov [16]. This gives rise to a 'Polar Cross Correlation' (PCC) measure, whereby the acoustic radiation at any given angle can be cross correlated with the 'on axis' output.

The Polar Cross Correlation diagrams for the PA1 panel, PRD1 and the small 2-way loudspeaker are presented in figure 8. It can immediately be seen that the two Distributed Mode Loudspeakers exhibit very different correlation characteristics to the conventional 2-way device. Whilst the PCC for the two DMLs decreases rapidly for off axis radiation, the PCC value for the conventional cone device is essentially maintained with off-axis angle. This result readily explains and reinforces the reduced boundary interaction previously observed [12]. Transposing the PCC characteristic of the DM type loudspeakers into a room environment with local reflecting boundaries, indicates that the majority of any side wall, ceiling, floor (or lateral early reflections) will not be correlated with the direct on-axis sound. Indeed it is only those reflections caused by forward radiation over a 30-40 degree total included angle, that will correlate. This point is well illustrated by reference to figure 9, the plan view of the test listening room. By superimposing the PCC angle onto a DM loudspeaker's radiation pattern, it can be seen that few side wall reflections should be correlated to the on axis sound, leaving primarily the rear wall reflections that potentially correlate. The same is also true in the vertical plane for the floor and ceiling reflections. Such a result will clearly have significant implications from a pyschoacoustic point of view – particularly in normal listening rooms. This effect may be considered in two ways. Firstly, the lower PCC in the vertical plane reduces the effect of the reflections from the floor and the ceiling, which are notably responsible for the added "mono" sound by acoustic mixing of the left and right channels. The effect from the ceiling is usually the most destructive, as normally there is little or no sound absorption employed on this surface in domestic listening rooms. Secondly, is the reduced degree of correlated energy received from the boundaries near the respective Left & Right channels, helping to preserve the integrity of the direct sound and therefore enhancing the stereo effect and reducing coloration.

That the majority of room reflections from a DML will be uncorrelated has further interesting implications, not least in terms of the Direct to Reflected Sound ratio measures. From the D/R ratios reported in section 4.2, an immediate inference is that the majority of the sound arriving at a listener will be uncorrelated. This hypothesis was tested by carrying out a series of cross correlation function measurements at each of the 7 previous test positions for each of the five loudspeakers. Correlations were primarily carried out between the 0.5 metre position and the remaining six positions but were also supplemented by inter-test position cross correlations.

Figure 10 presents the in-room correlation data for the PA1 and PRD1 panels. The data is in the form of surface plots with the distance from the source along the X axis, time along the Z axis and the correlation on the Y axis. The plot for the PA1 panel shows the correlation to decrease both with distance from the source and also rapidly with time. The correlation reduces to a residual of around 0.25, in less than 50 milliseconds in the centre of the room. Positions closer to the source have higher correlation than those elsewhere. The graph shows the reflected sound to be highly decorrelated. The

Correlation surface plot for the PRD1 shows the same general trend but with a slower rate of decrease in correlation, both spatially and temporally. Overall, the correlation values are slightly higher as compared to the PA1 panel with the residual correlation being around 0.4.

Figure 11 shows the surface correlation plots for the Closed Back DML and JBL Control 1 loudspeakers. An immediate contrast is apparent here. The cross correlation value for the CB1 panel decreases rather faster than the PRD1 both spatially and temporally. The JBL Control 1 by comparison exhibits a very different characteristic. Not only are the correlation values generally higher than for the DM loudspeakers but are highly position dependent. Ridges of higher correlation are present at the 2.0 and 3.0 metres positions and more interestingly are shown to be time independent. The surface correlation graph for the 2.5 inch loudspeaker showed a similar trend. Again the overall correlation values are generally higher than for the DMLs accompanied by a slower rate of decay. Distinct correlation ridges were again present, but interestingly these occurred at different test positions to the JBL (1.5m and 2.5m). The significance of this is currently undergoing further investigation.

6 REFLECTION ARRIVAL & DIRECTION ANALYSIS

The difference in polar radiation characteristics of the Distributed Mode Loudspeakers to traditional cone based devices, suggests that the reflection patterns generated within a room are also likely to be significantly different. This aspect was therefore investigated for each of the five devices. The results reported are based on a detailed analysis of the 500 Hz and 2 kHz octave band reflection patterns at the 2 metre on-axis test position. Conventional impulse response (ETC) reflectograms were measured and in addition, the directions of arrival and the intensity of the reflections were also analysed to produce polar reflectographs.

Figure 12 presents a horizontal Reflection Intensity Polar plot for the 500 Hz and 2 kHz bands for the JBL Control 1. The centre of the diagram represents the listening (measurement) position and so the figure describes the direction and relative intensity of the reflections arriving at a given listening position. The reflections shown are windowed so that only those occurring within 25 dB of the direct sound and within an arrival time window of 80 mS are plotted.

The 2 kHz plot shows the direct sound to be arriving at 0° followed by a strong reflection from the left and by two reflections from the right. The diagram is time blind, allowing at this stage of the technique's development purely the reflection directions and intensities in the horizontal plane to be analysed. Rear reflections can be seen in the left quadrant but surprisingly none were found to be arriving from the rear right section of the room within the selected time / intensity window.

The 500 Hz reflection intensity polargraph indicates a different pattern of behaviour to be occurring. It is clear that not only is there a greater density of reflections in this lower frequency band but also that their directions of arrival are better distributed. One point to note however, is that the direct sound appears to be coming from slightly to the right of the nominal loudspeaker position due to a slight measurement / positioning bias error. The floor / ceiling reflection coming from the same planar direction as the loudspeaker is clearly visible. The greater number of reflections occurring at 500 Hz as compared to 2 kHz can be explained by the reduced directivity of the source at lower frequencies. This is particularly highlighted in figure 13 which is an analysis of the reflections arriving in the vertical plane. From a brief inspection of the diagrams, it can be clearly seen that not only do far fewer reflections occur at 2 kHz than at 500 Hz but that at 2 kHz, all the reflections bar one, originate from above the loudspeaker - i.e. from the ceiling or upper wall areas. The single floor reflection is clearly visible in the lower quadrant of the diagram. At 500 Hz a better distribution is seen, although still with a bias to the ceiling. This new reflection intensity tracking technique is clearly a powerful tool and allows a further novel perspective into the loudspeaker - room acoustic interface. (A slight modification to the procedure, currently being examined, will enable the front-rear reflections to be distinguished and charted).

Figure 14 presents the reflection polargraphs for the PA1 Panel. These contrast sharply with the 2-way Control 1 loudspeaker with the 500 Hz and 2 kHz reflection trends effectively being reversed. The 2 kHz polar plot shows there to be a much denser reflection pattern, arriving effectively from all directions. The 500 Hz graph shows a lower density pattern with fewer, discrete reflections occurring. Figure 15, the vertical plane arrivals, shows the 500 Hz pattern to be fairly well distributed whereas at 2 kHz there are rather more reflections from the ceiling / upper wall areas, consistent with the greater absorption afforded by the carpeted floor. Based on the PCC measurements, it is almost certain that the early reflections from the front of the room will exhibit low correlation with the direct sound, whereas the slightly later arriving initial rear wall reflections are likely to be highly correlated, a point not immediately obvious from the polargraphs.

7 CONCLUSIONS

The results from a number of different measurement techniques show that Distributed Mode Loudspeakers behave very differently in small rooms / spaces to conventional cone / piston-type devices. This has been identified not only by virtue of their reflection correlation, but also in terms of the density and spatial distribution of such reflections. Measures of Direct to Reflected Sound ratios and Lateral Energy Fractions suggest that perceived loudness, imaging, and spaciousness / envelopment may differ from conventional devices and suggest a raft of new psychoacoustic factors that require further investigation.

The reflected sound field has been shown to dominate when DM loudspeakers are employed and may require a different approach to room acoustics and sound system design to be developed. The dominant reflected sound field also helps explain previously noted subjective impressions relating to evenness of coverage and spatial equality of perceived loudness. The Reflection Intensity Polar (RIP) measurements are shown to provide new perspective on the sound field generated within a listening space and provide a powerful new acoustics measurement technique.

The cross correlation polar measurements provide new insights into the way in which loudspeakers radiate and also helps to explain previous findings relating to reduced local boundary interactions. The cross correlation measurements showed that DM loudspeakers not only produced significantly lower residual in room correlations to conventional devices but also exhibited a more even spatial distribution. This contrasts to conventional devices which produced significant peaks in the spatial cross correlation function. The gradients of the in-room cross correlation versus time graphs also indicate that DM devices decorrelated significantly faster than conventional devices. This provides further evidence to suggest that the associated off-axis, early reflections from DM devices are decorrelated with respect to the forward axial sound. The lower in-room cross correlations of the DM Loudspeakers also helps explain why such devices can achieve greater gain before feedback margins due to the decorrelated nature of the resultant early and reverberant sound fields as compared to traditional coherent sources.

8 ACKNOWLEDGEMENTS

The author would like to acknowledge the assistance provided by Vladimir Gontcharov in producing the cross correlation polar measurements and cross correlation function data analysis.

9 FUTURE RESEARCH

The findings reported above raise a number of interesting issues that require pursuing. It is planned to further study the in-room acoustic soundfield using the new correlation methods and investigate any potential frequency dependencies. Such techniques will also be used to investigate larger and more reflective spaces. Extending the technique to provide a measure of inter-aural cross correlation (IACC) should also be undertaken. A number of psychoacoustic studies to look at the associated effects of non-correlated reflections may enable this parameter to be optimised from a subjective point of view in both small and large spaces. Further work to optimise the non-correlated energy distribution in live sound systems would enable further advances in feedback gain margin to be made and result in potentially improved systems. The Reflection Polar techniques can also be further developed to enable the practical utilisation of directional and time of arrival information in acoustic device/room system design.

REFERENCES

[1] R Allison, The Influence of Room Boundaries on Loudspeaker Output. JAES vol 22 1974.

[2] P Mapp, The Loudspeaker-Room Interface. Hifi News and Record Review Vol. 20 No. 8, 1981.

[3] J Salma & A Weckstrom, Listening Room Influence on Loudspeaker Sound Quality and Ways of Minimising It. AES 71st Convention, 1982.

[4] F Toole, Loudspeakers and Rooms for Stereophonic Sound Reproduction. AES 8th International Conference, Washington DC (May) 1990.

[5] S Bech, The Influence of the Room and of Loudspeaker Position on the Timbre of Reproduced Sound in Domestic Rooms. AES 12th International Conference, Copenhagen (June) 1993.

[6] P Schuck et al., Perception on Perceived Sound in Rooms: Some Results of the Athena Project. AES 12th International Conference, Copenhagen (June) 1993.

[7] N Harris & M Hawksford, The Distributed-mode loudspeaker (DML) as a broad-band acoustic radiator. AES 103rd Convention, New York (September) 1997.

[8] G Bank & N Harris, The Distributed Mode Loudspeaker- Theory and Practice. AES UK Conference, London (March) 1998.

[9] M Colloms & C Ellis, Diffuse Field Planar Loudspeakers in Multimedia and Home Theatre. AES 103rd Convention, New York (September) 1997.

[10] H Azima & N Harris, Boundary Interaction of Diffuse Field Distributed Mode Loudspeakers. AES 103rd Convention, New York (September) 1997.

[11] H Azima & P Mapp, Diffuse Field Distributed-Mode Radiators and Their Associated Early Reflections. AES 104th Convention, Amsterdam (May) 1998.

[12] N Harris, S Flanagan & M Hawksford, Stereophonic Localisation in Rooms Comparing Conventional and Distributed-Mode Loudspeakers. AES 105th Convention, San Francisco (September) 1998.

[13] S Flanagan & V Taylor, Investigation into the Relationship between Subjective Loudness and Auditory Distance Perception. AES 107th Convention, New York (September) 1999

[14] P Mapp & C Ellis, Improvements in Acoustic Feedback Margin in Sound Reinforcement Systems. AES 106th Convention, Munich (May) 1999.

[15] P Mapp, A Novel Design Approach to Sound Distribution in a Reflective Environment. AES 107th Convention, New York (September) 1999.

[16] V Gontcharov, N Hill, Paper to be presented at AES 108th Convention, Paris (February) 2000

[17] R Guy & A Abdou Sound Intensity and its Use in Assessing the Sound Quality in a Space, Proc IOA Vol 16 : pt 4 1994.

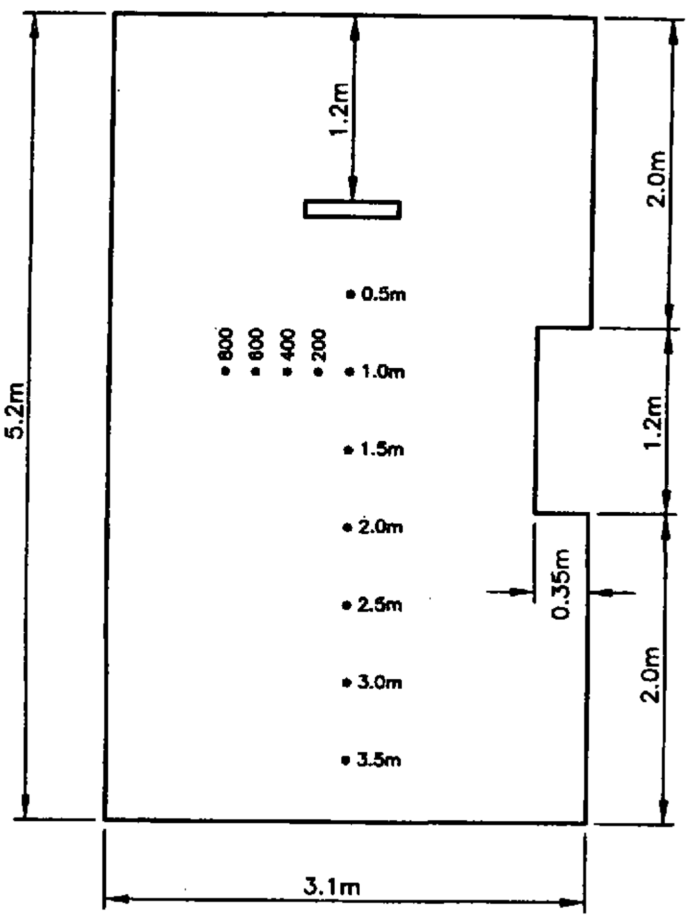
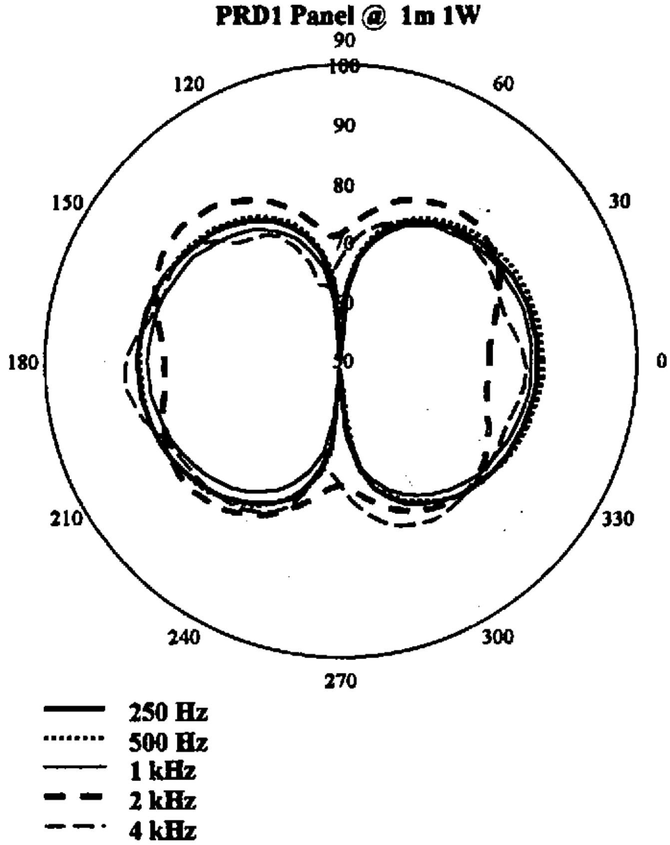


FIGURE 1 TEST ROOM SET UP



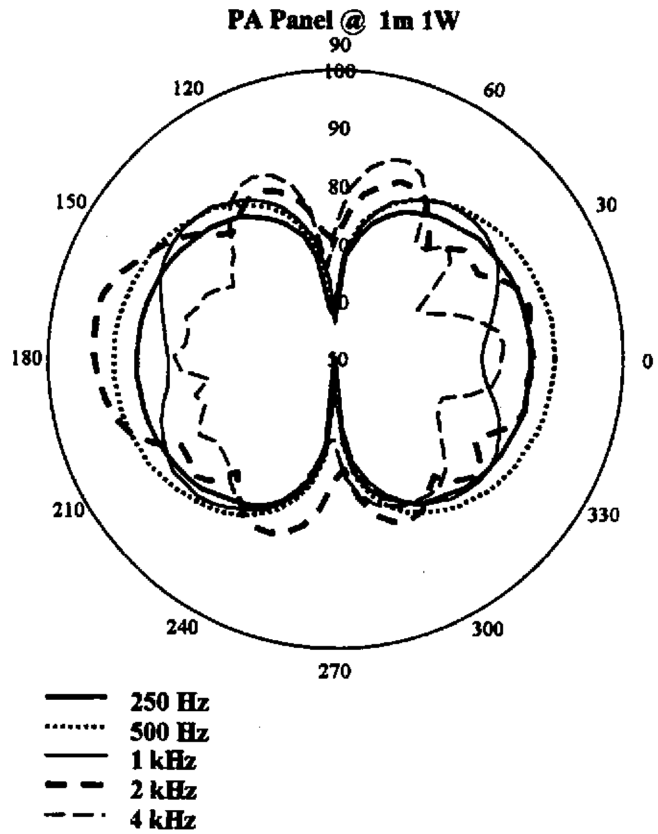


FIGURE 2 POLAR DIAGRAMS FOR PRD1 AND PA1 DM LOUDSPEAKERS

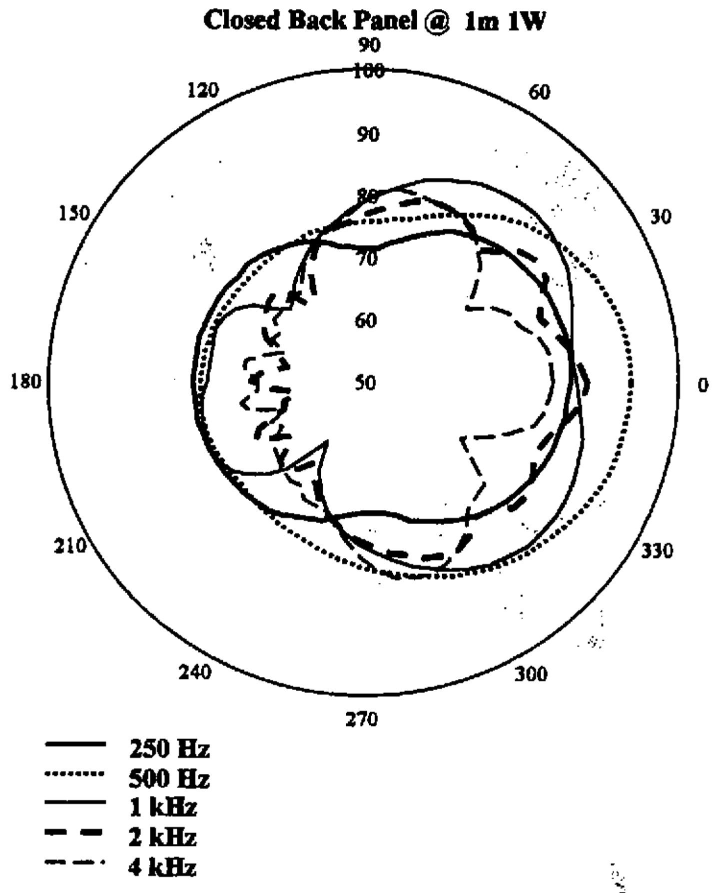


FIGURE 3 POLAR DIAGRAM FOR CLOSED BACK DM LOUDSPEAKER

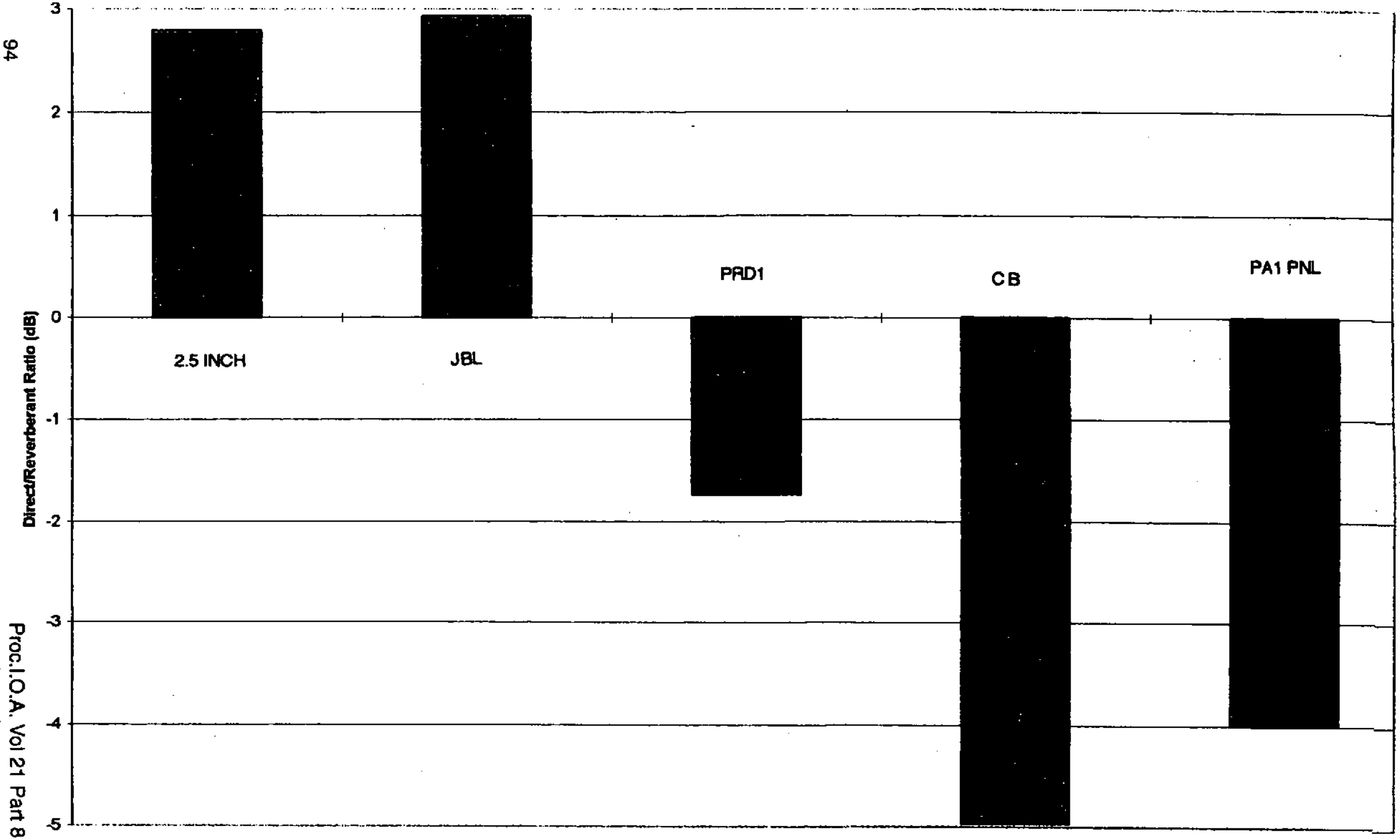


FIGURE 4 DIRECT TO REFLECTED SOUND RATIOS FOR CONE AND DM LOUDSPEAKERS

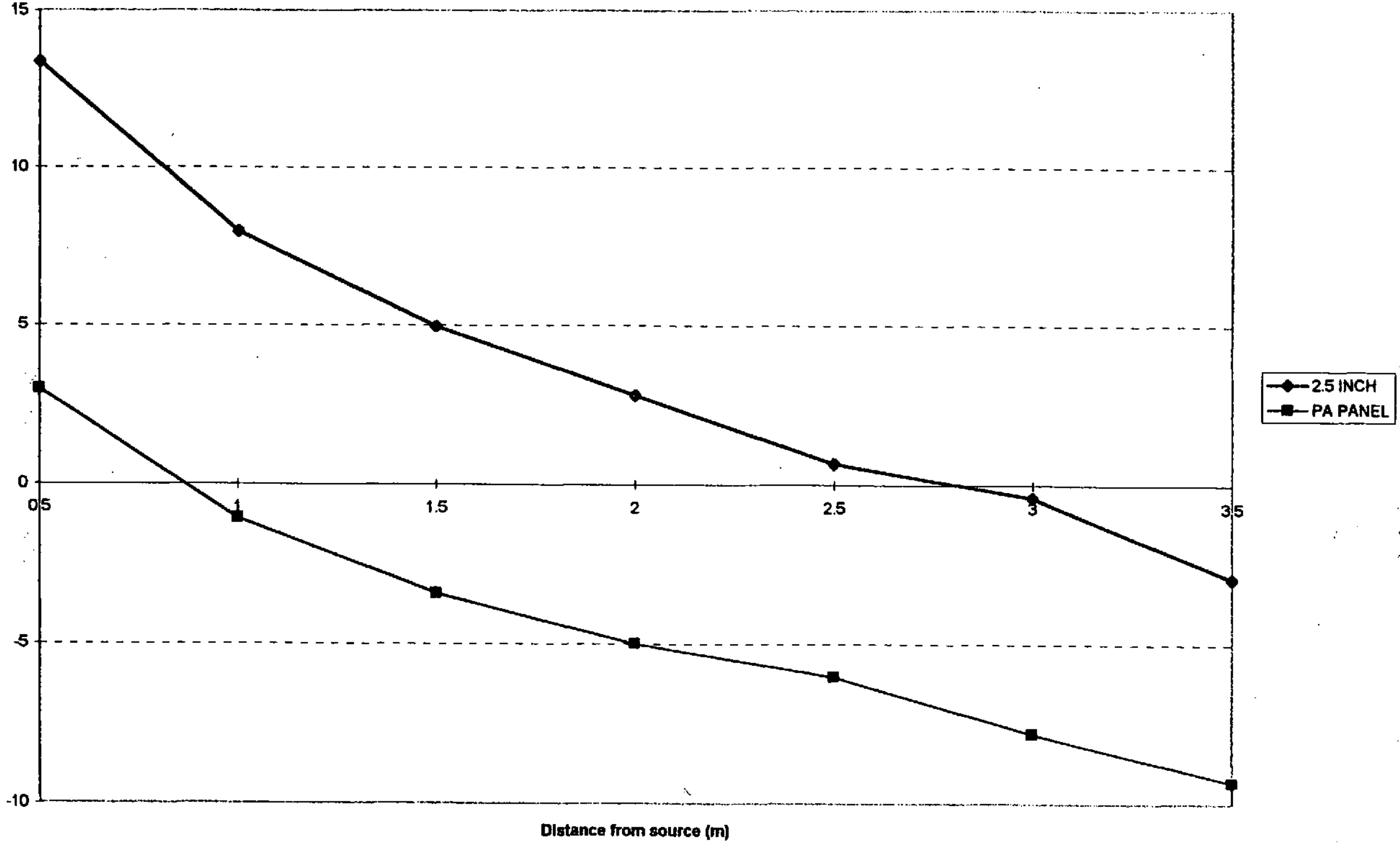


FIGURE 5 DIRECT TO REFLECTED SOUND RATIOS AS A FUNCTION OF DISTANCE 2.5 INCH + DML

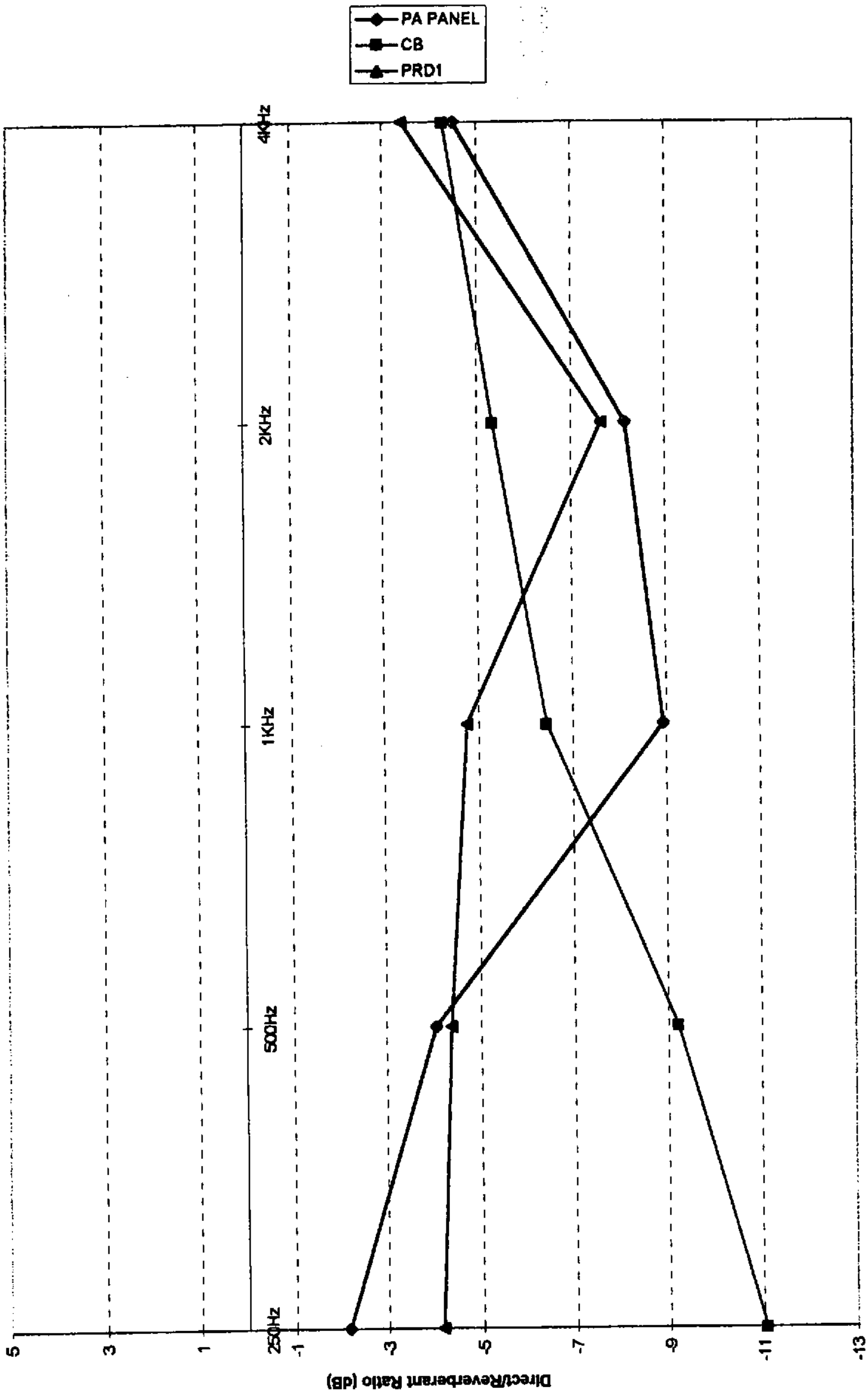


FIGURE 6 DIRECT TO REFLECTED SOUND RATIOS AS A FUNCTION OF FREQUENCY FOR DM DEVICES

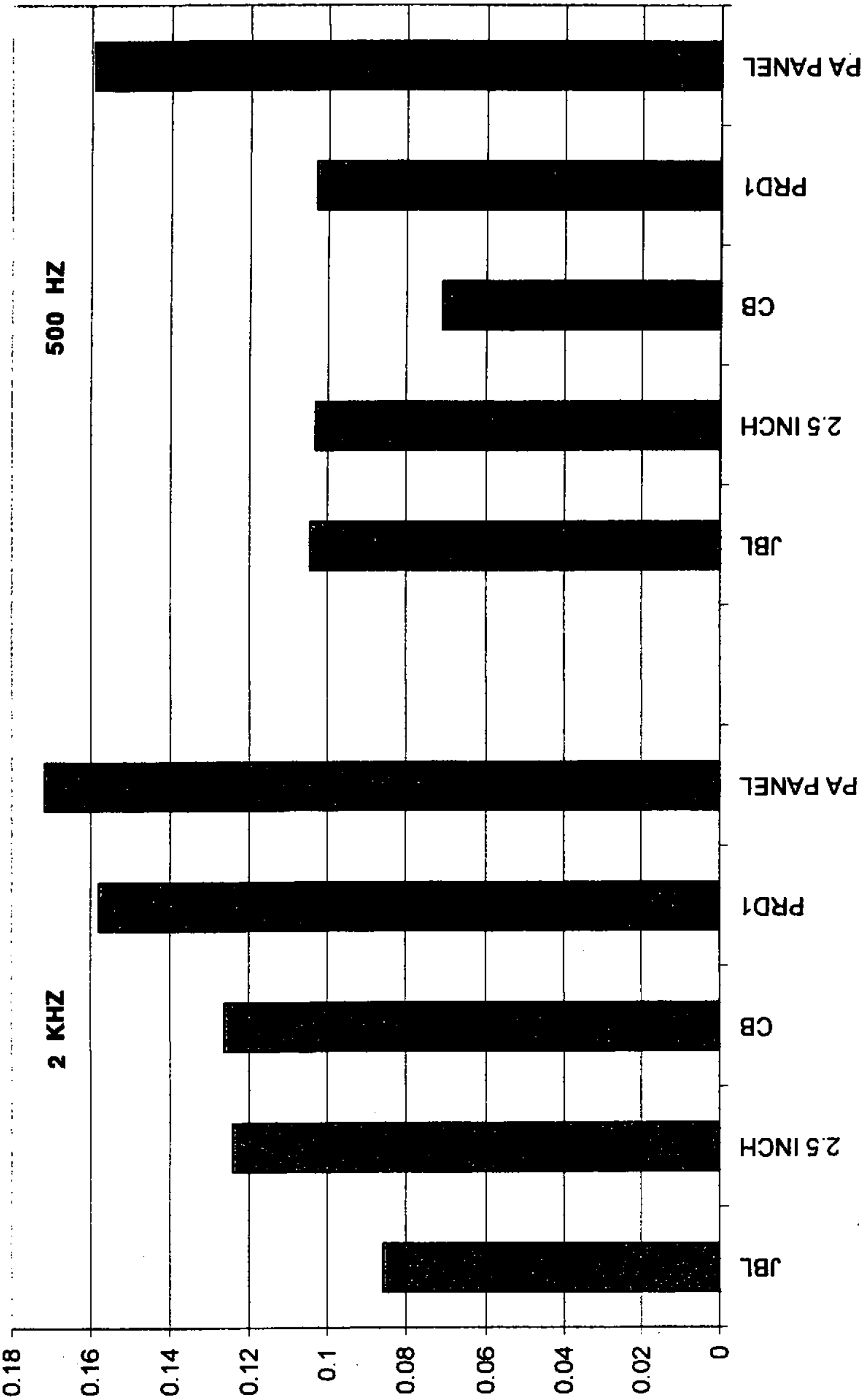


FIGURE 7 LATERAL ENERGY FRACTION MEASUREMENTS AT 2 METRES

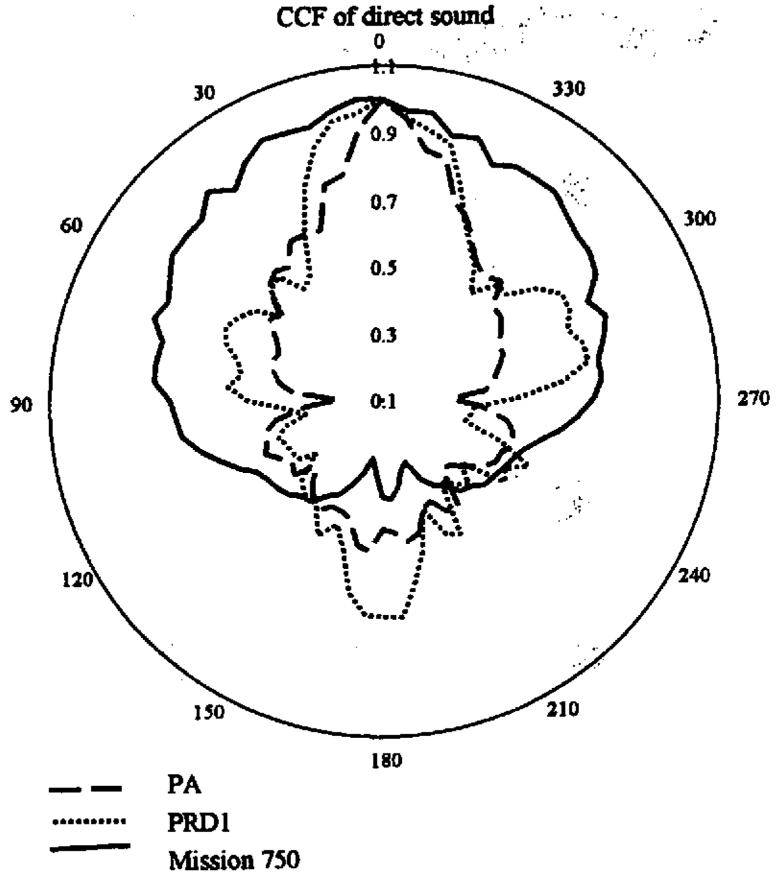


FIGURE 8 CROSS CORRELATION FUNCTION POLAR DIAGRAM (CCP) FOR DML & 2 WAY CONE LOUDSPEAKER

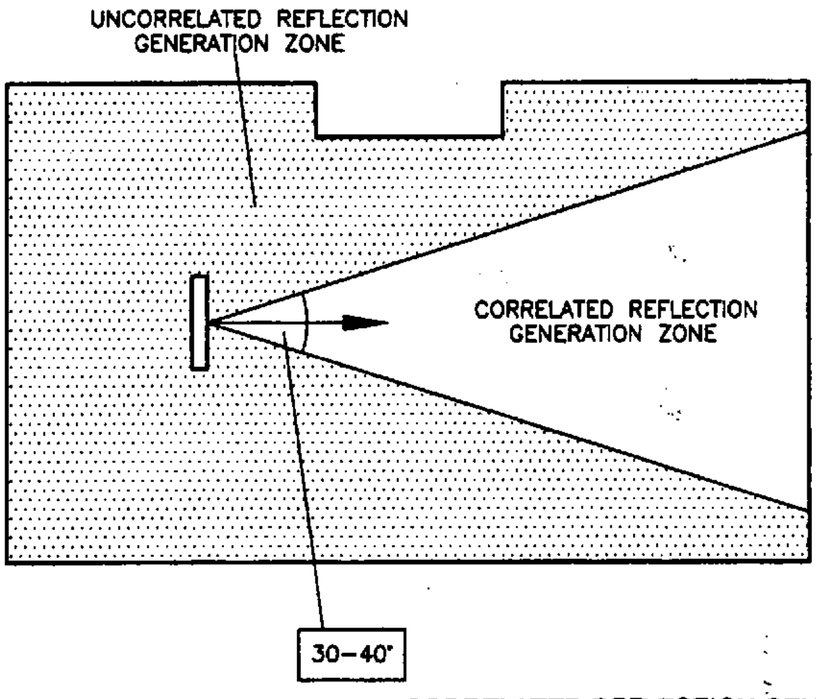
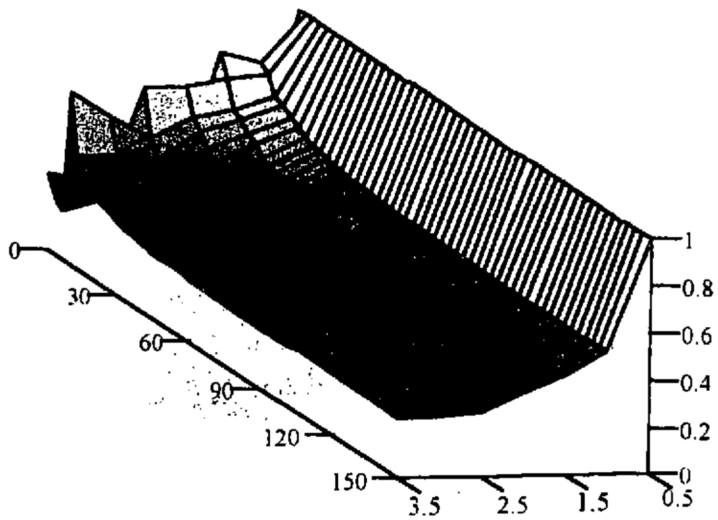


FIGURE 9 TEST ROOM CORRELATED AND UNCORRELATED REFLECTION GENERATION ZONES

PA panel



PRD1 panel

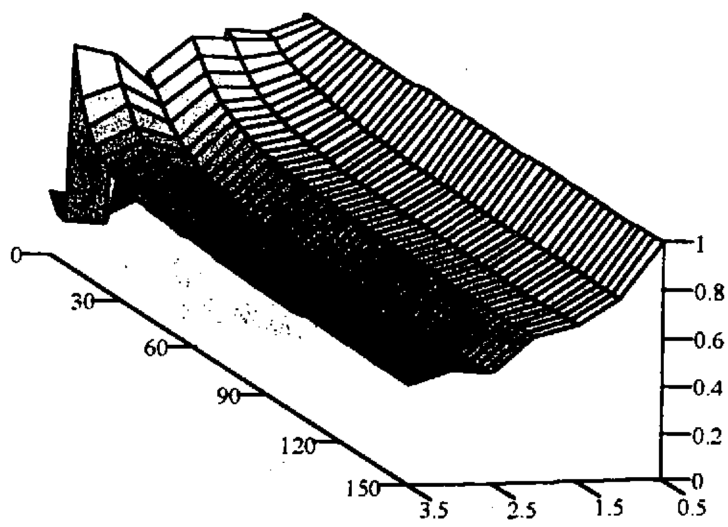
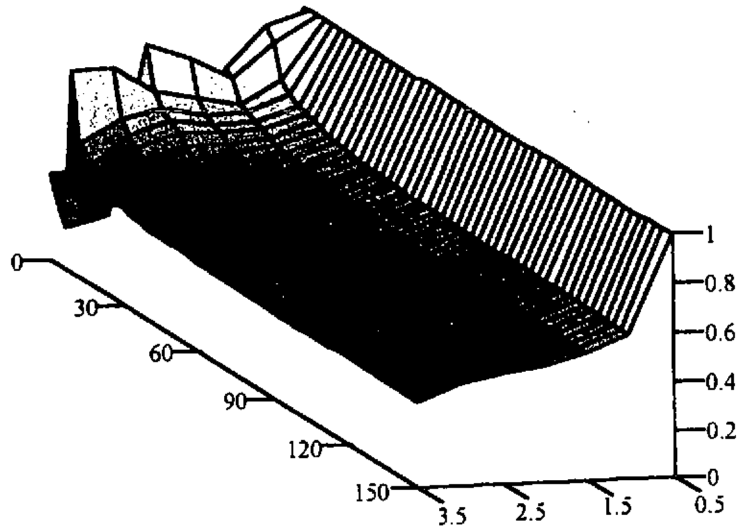


FIGURE 10 CROSS CORRELATION FUNCTION (CCF) IN - ROOM MEASUREMENTS
PA1 PANEL + PRD1

Closed Back panel



JBL Control 1

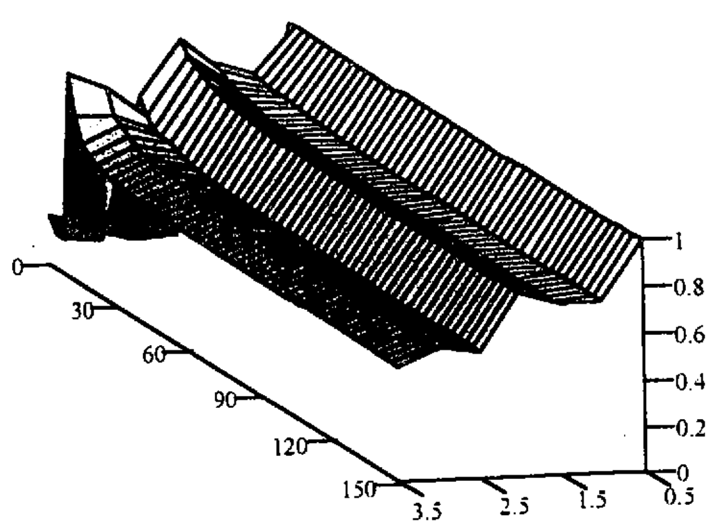
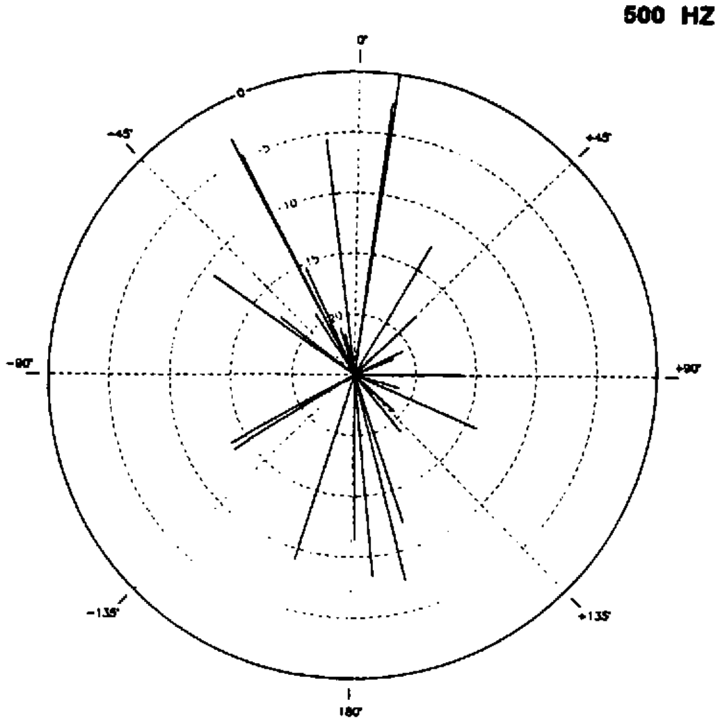


FIGURE 11 CROSS CORRELATION FUNCTION (CCF) IN - ROOM MEASUREMENTS CLOSED BACK DM PANEL + JBL CONTROL 1



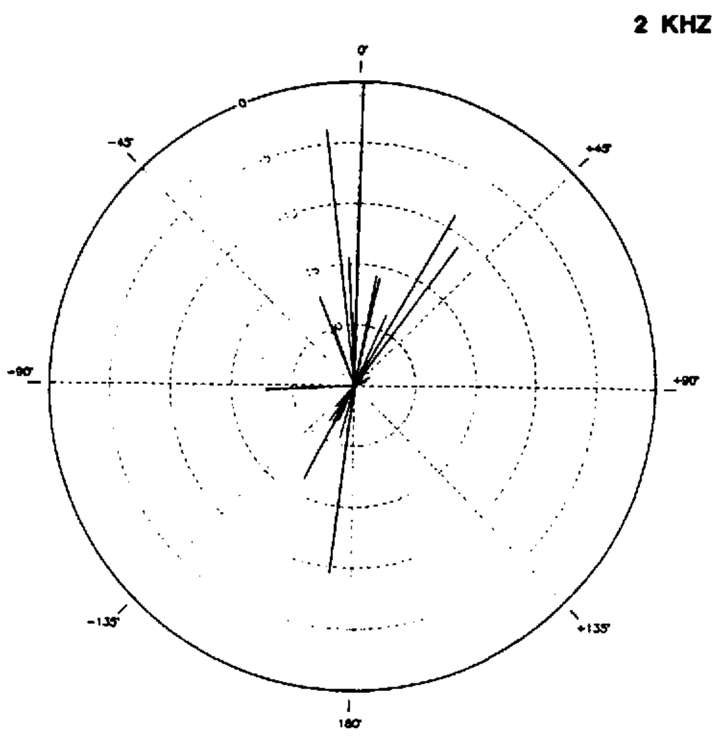
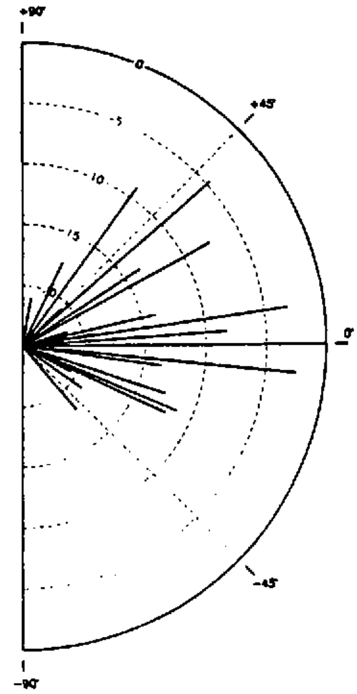


FIGURE 12 POLAR REFLECTOGRAM FOR JBL CONTROL 1 AT 500 HZ & 2 KHZ (HORIZONTAL PLANE)

500 HZ



2 KHZ

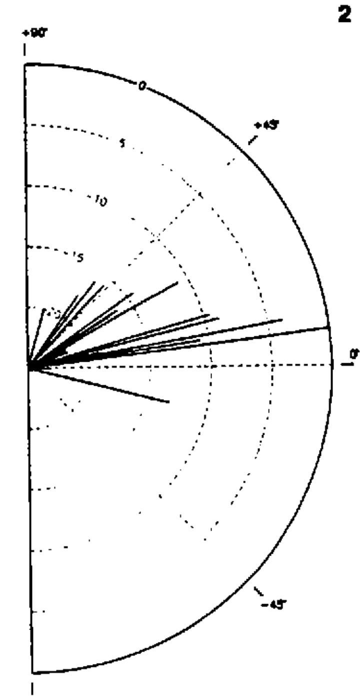
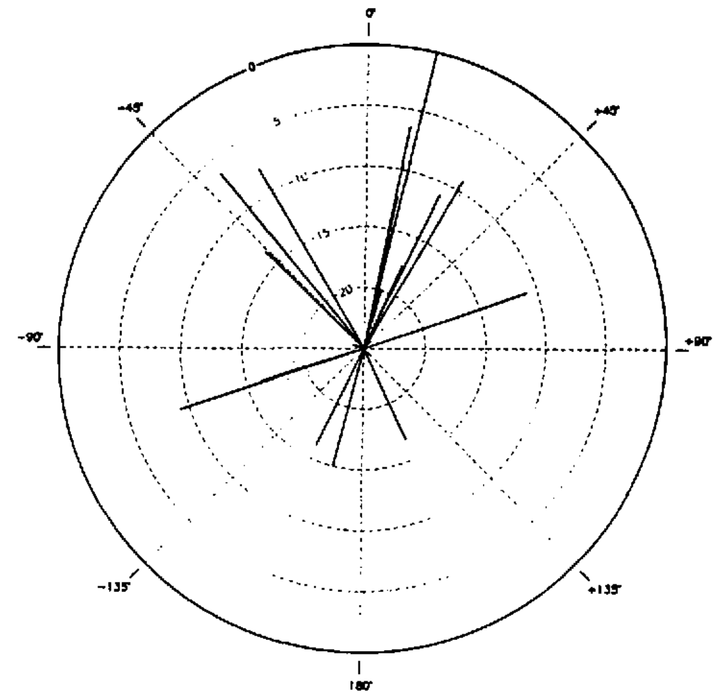


FIGURE 13 POLAR REFLECTOGRAM FOR JBL CONTROL 1 AT 500 HZ & 2 KHZ (VERTICAL PLANE)

500 HZ



2 KHZ

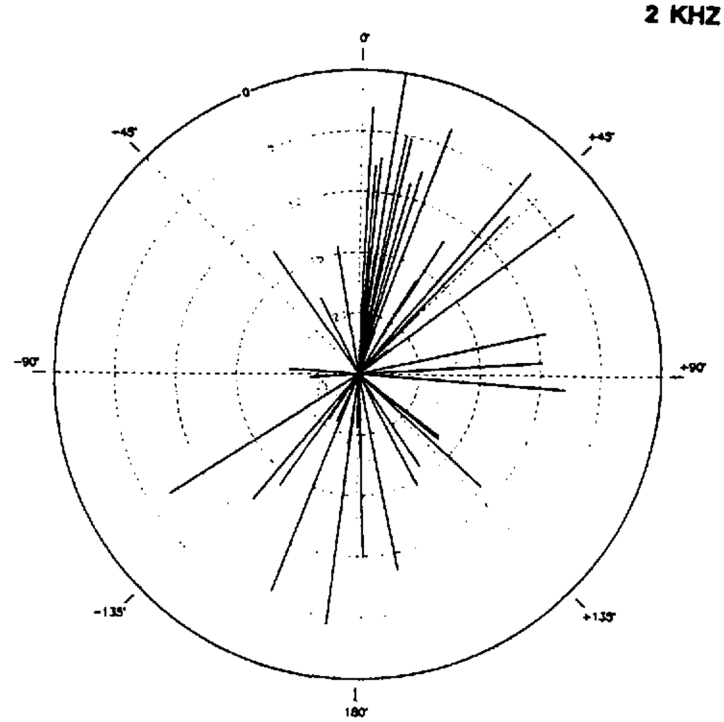


FIGURE 14 POLAR REFLECTOGRAM FOR PA1 PANEL AT 500 HZ & 2 KHZ (HORIZONTAL PLANE)

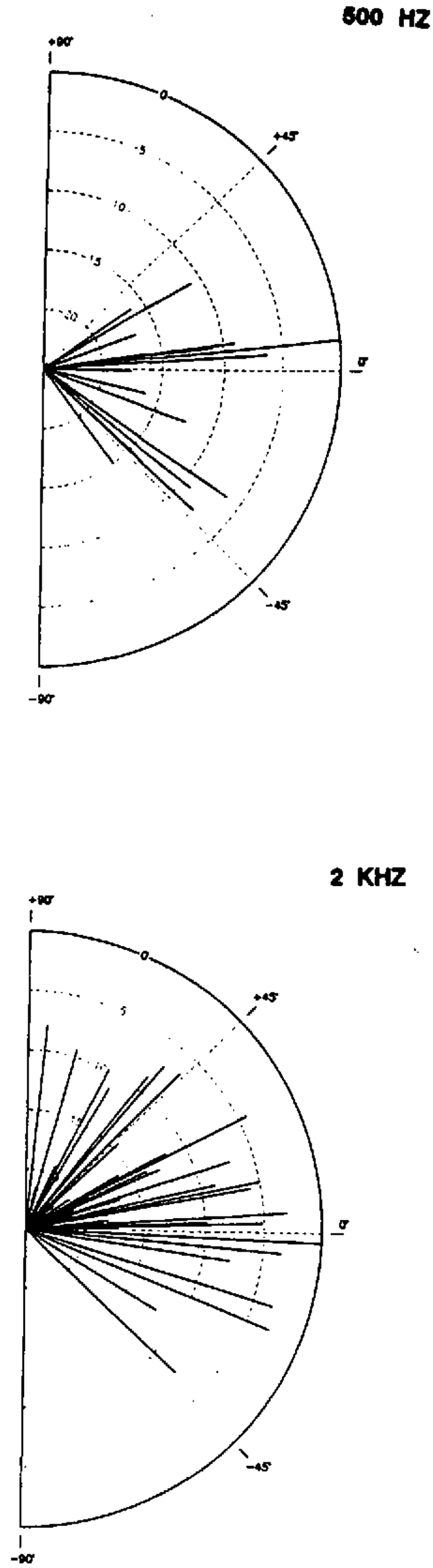


FIGURE 15 POLAR REFLECTOGRAM FOR PA1 PANEL AT 500 HZ & 2 KHZ (VERTICAL PLANE)