A MICROCOMPUTER PROGRAM FOR CENTRAL LOUDSPEAKER ARRAY DESIGN

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A MICROCOMPUTER PROGRAM FOR CENTRAL LOUDSPEAKER ARRAY DESIGN

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ABSTRACT:

A microcomputer program is described which accurately calculates the direct-field SPL at points on a seating area generated by an arbitrary configuration of loudspeakers. The program solves inverse square losses as seen through the loudspeaker's directional pattern at up to 230 points on the seating plane. Whenm multiple loudspeakers are used, their coverage patterns are merged by two strategies: phasor summation takes into account interference phenomena, while non-phasor combination provides the maximum envelope of response that can be expected of the combination of loudspeakers. When acoustical data is provided, direct-to-reverberant ratios can be calculated, and estimates of intelligibility, using the method of Peutz, can be made. A graphics portion of the program provides front, side, and top orthographic views of the loudspeaker array.

0. INTRODUCTION:

Historically, the design of large loudspeaker arrays for sound reinforcement has not been a direct process. Working with limited directional information on HF horns and LF enclosures, system designers have aimed these components much as one might aim spotlights, and adjusted drive levels by taking into account relative sensitivities. The final adjustment of systems in the field has always taken much time, and many a loudspeaker cluster has had to be reaimed after installation.

In recent years, many manufacturers have made available directional information on their devices in the form of isobars or three-dimensional directional files. With such information, it is possible to devise three-to-two-dimensional projections that help the designer to lay out system components rationally. Such mapping systems have been developed by McCarthy (1), Becker (2), and

Uzzle (3). While all of these mapping methods have some degree of error, they represent nonetheless giant steps beyond the older intuitive design methods. More recently, Prohs and Harris (4) have devised a projection scheme which is free of distortion.

During 1982, JBL Incorporated began working on a microcomputer program that had as its goal the direct solution to the problems of loudspeaker coverage of a seating area. Taking into account the capabilities of today's standard personal computers, the problem is quite straightforward, and the graphics capabilities of many models of computers offer attractive benefits in terms of design and drafting time.

The first form of the program was introduced in May 1983, and it is called CADP (Central Array Design Program).

1. GENERAL DESCRIPTION OF CADP:

CADP is menu driven; that is, the user is prompted by a heirarchy of three menu levels to enter data and to choose display options. Figure 1 shows the first two levels in the menu structure. The general procedured calls for the user to enter dimensional information on the seating plane or planes. Following that, loudspeaker information is entered. The program then calculates levels as they exist at the seating area, and the user chooses the display he wishes.

CADP is contained on one single-sided 14 cm diskette and is written in Microsoft BASIC, running under PC DOS, version 1.1, on the IBM Personal Computer. The program has been compiled for speed of operation. Two disk drives are required, as is 96-kilobyte memory capability. Three data diskettes provide all pertinent directional files and three-dimensional drawing files.

The contents of the first-level, or Main Menu, are:

1. Define Room Parameters
2. Define Loudspeaker Parameters
3. Select Display of Design Data
4. Print Hardcopy of Design Data
5. Enter Job Description
6. Retrieve Data
7. Save Data
8. End Current Job Session

1.1 Room Parameters:

Working from architectural drawings or sketches, the designer establishes a set of Cartesian coordinates and labels each corner of one or more seating planes. In the second-level Room Menu, the designer is asked to enter the coordinates of the corners sequentially, and this process is continued until the entire seating area has been entered. If a mistake has been made at any point, a plane can be deleted and reentered. The designer is given the option of using either metric or English units.

The user can add reference lines to the seating planes for convenience in outlining functional areas. For example, aisles can be indicated, as can playing areas of gymnasiums and the like.

The next step is to enter pertinent acoustical data for the enclosed space. The third-level Acoustical Menu asks for the volume, surface area, and either reverberation time or average absorption coefficient for the space. The equations used in making calculations here are the familiar Norris-Eyring equations:

$$\text{Reverberation Time } (T) = .16V/-S\ \ln(1 - \bar{a})$$

$$\bar{a} = 1 - \exp(-.16V/ST)$$

1.2 Loudspeaker Menu:

Using the same coordinate system, the designer enters a trial location for a loudspeaker. Then, the azimuth, elevation, and rotation angles for the loudspeaker are entered, as are the pertinent octave frequency band and the power drive level. After each loudspeaker entry, its effect on the seating area can be observed. Then, if desired, it can be re-aimed or re-located for better coverage.

When it is desired to look at the acoustical coverage, the designer enters the Display Menu.

1.3 Display Menu:

1.3.1 Seating, Oblique View:

This display shows the seating area in an oblique view, and its main purpose is to inform the designer that he has entered all data properly.

1.3.2 Normalized Direct Field:

If the normalized direct field display is selected, the computer then scales the plan view of the seating area, determines the maximum number of possible display points, or slots, and then calculates the inverse square loss at the center of each the slot as "seen" through the directional pattern. The levels at the seating plane are then normalized; the highest value is set at zero, with all other values negative with respect to it. Figure 2 shows the process as it takes place for each slot in the display.

Figure 3 shows the form in which polar data is read on each device. A reading is made at each ten degrees in both latitude and longitude directions, and a total of 18-by-36, or 648, points are stored, including the degenerate poles, at each octave frequency of interest. For HF devices, the files are currently available at 0.5, 1, and 2 kHz; for LF devices, the files are available at 0.5 and 1 kHz. In the future, directional files will be generated for HF devices at 4 and 8 kHz.

1.3.3 Direct-to-reverberant Ratio:

In the direct-to-reverberant display, the actual direct field level at each display point is compared with the reverberant level, and the difference is displayed. The assumption is made that the reverberant level is uniform throughout the seating area. In determining this, a calculation of the total acoustical power radiated into the space is made. For each loudspeaker in the array we calculate its efficiency from the following equation:

$$10 \log EFF = Sensitivity - 109 - DI$$

In this equation, the sensitivity is stated in dB-SPL for an input of one watt referred to one meter; DI is the directivity index of the device at the frequency of interest.

The efficiency is then calculated for each device, and products of efficiency and power input are summed for the entire array to get the total acoustical power, W.

The room constant, R, is calculated from the following:

$$R = S\bar{a}/(1 - \bar{a})$$

Finally, the reverberant level in the room is calculated from:

$$Level = 126 + 10 \log (W/R)$$

A variant of the room constant, R', as suggested by Augspurger (5), may be used if it is likely that a good portion of the direct sound from the array is incident on the audience. At 2 kHz, the absorption coefficient of the audience is about 0.9. Thus, if we assume that roughly two-thirds of the sound power is directed at the audience, we can modify R as follows:

$$R' = S\bar{a}/(.4 - \bar{a}/3)$$

Using R' instead of R for determining reverberant level gives a somewhat lower value for the reverberant level, more in keeping with what would be expected. Note that this calculation is valid only in the 2 kHz region, where the intelligibility estimate is made.

1.3.4 Intelligibility Estimates:

Taking note of the direct-to-reverberant ratio and the reverberation time in the 1-to-2 kHz range, we can, using the method of Peutz (6), estimate the system intelligibility. An assumption is made here that the ambient noise level is at least 25-to-30 dB below speech peak levels. Figure 4 shows the relations by which the estimate is made. At each display point on the plan view, the designer will observe EX (excellent), GD (good), OK (acceptable), or QU (questionable). These legends correspond to:

Probable Articulation Loss of Consonants

Excellent	Less than 5%
Good	5% to 10%
Acceptable	10% to 15%
Questionable	Greater than 15%

The intelligibility estimate can be made using either R of R', so that best and worst cases can be studied.

Commenting in general on the accuracy of the program, Peutz states that his intelligibility estimate has an accuracy of about 10%; therefore, it is appropriate to break that part of the display into four broad areas, as listed above. The directional files themselves have an accuracy of plus or minus 1 dB, and the reverberant field calculation further assumes that the field is uniform throughout the space, which is not usually the case. For these reasons, the intelligibility estimates should be taken more as trends than as facts. Field verifications of the direct field estimates have consistently been made within 1.5 dB of the values displayed by the program.

1.3.5 Maximum Direct Field:

For this display, the direct field is modified by increasing the power input level up to the point where the most marginal element in the array reaches its electrical power input limit. The maximum levels at the seating area are then displayed.

1.3.6 Graphics Display:

In this option, the designer can observed the front, side, and top views of either individual components in the array or the entire array itself. The data for each component is stored on disk in the form of a drawing file. Scaling factors have been worked out so that the designer, at his option, can set the scale of the display so that the resulting printout on a dot matrix printer is one inch per foot (in English units) or 0.1 meter per meter.

The graphics display is orthographic, and hidden lines are visible. An indication of the center of gravity for the array is present at all times.

2. SUB-PROGRAMS:

2.1 Room Module Program:

In cases where reverberation time is not known, or where a building project is not yet completed, the Room Module program can provide a rough estimate of reverberation time. In using this program, a rectangular solid is constructed which provides a "best fit" to the space at hand. Average absorptions coefficients for each of the six sides are entered, and the program will calculate the volume, surface area, average absorption coefficient for the entire room, and the reverberation time, using the Norris-Eyring equation. More than one room module can be placed together to model more complex spaces.

2.2 Access to Directional Files:

The user can construct his own directional file if access is had to directional data in a usable form, or if it can be inferred from data on hand.

In addition to the directional data, the file requires the following: maximum input power rating, DI, sensitivity (one watt, one meter), and frequency band.

2.3 Access to Drawing Files:

The user can construct a drawing file to go with a set of directional files on a given device. The user is instructed to enter a drawing with the (0,0,0) coordinates at the center of gravity. This simplifies the calculation of the center of gravity of the entire array, and it also provides a reference point for actually locating the device in the array. It is required that the weight of the device be entered into this file.

2.4 Print Screen Capability:

The program includes a versatile print screen program which accesses each pin in the dot matrix printer, allowing any screen display to be copied directly. the program is designed to work on an Epson MX80 or MX100-type printer that has the Graphtrax option installed.

2.5 Hardcopy Capability:

Hardcopy printouts of all data input on the room and the loudspeaker can be easily accessed and the data stored for future reference.

2.6 Save, Retrieve and Labelling Options:

At several points in the program, data which has been entered can be stored and recalled as needed. All displays can be provided with legends that describe the job at hand.

3. PATTERN MERGING STRATEGIES:

Up to 20 loudspeakers may be used in the program at one time. When multiple elements are combined, two pattern merging strategies are carried out simultaneously:

1) non-phasor summation and

2) phasor summation.

The non-phasor merging strategy disregards phase effects in summing the individual direct field levels from each source. The summation assumes that all pressure contributions are in phase at the summing point, with only inverse square losses and source pattern effects taken into account. The resulting pattern can be thought of as representing the maximum direct-field levels that exist at the summation point, providing in essence a maximum envelope for the observed response. This strategy is most useful in examining the conbination of large arrays of elements over an octave-wide, or greater, band of frequencies.

The phasor strategy assumes phase and amplitude addition of all the individual elements in the array at each display point in the seating area. It is most useful in looking at interference effects on a frequency-by-frequency basis when laying out line arrays. With this merging strategy, the user must be aware of a phenomenon akin to frequency aliasing in digital recording systems. This happens when the discrete nature of the polar pattern changes more rapidly than the distribution of interferences and cancellations resulting from phasor summation.

Figure 5 indicates the general effect of each strategy. The designer has his choice of either view when levels in the seating area are displayed.

In the phasor strategy, the acoustic center of all devices is assumed to be effectively at its center of gravity. This is a reasonable assumption at fairly long wave lengths; however, above, say, 4 kHz, this is not an accurate assumption, and the phasor merging strategy should not be used at those frequencies for combinations of different devices. However, for arrays made up of a single type of element, the tracking of the acoustic centers with respect to frequency will ensure accurate calculations.

4. DESIGN EXAMPLES:

4.1 A Large Theater (theoretical example):

Figure 6 shows details of the Eastman Theater in Rochester, NY, as given by Beranek (7). The main floor and balcony seating areas were entered into the program, and a single central array was located over the edge of the stage extension at a height of about 30 feet. The central array consists of six 90-degree-by-40-degree 800-Hz constant coverage horns and two LF enclosures, each containing a pair of 380 mm transducers.

The following displays were printed via the copyscreen program:

Figure 7. An oblique view showing the main floor and balcony. Note that the main floor has been entered as a single plane, while the arced balcony has been approximated by three planes. The curved apron of the stage is visible at the lower left of the display.

Figure 8. Normalized direct field, main floor. Note scaling along bottom and right side of views. In English units, the marker is every 10 feet, and in metric the marker is every 5 meters. Directly below the loudspeaker array is a small array of dots, indicating that the components of the loudspeaker are directly overhead.

The non-phasor merging strategy is used in the examples shown in Figures 8 through 13.

Figure 9. Direct-to-reverberant Ratio for R.

Figure 10. Direct-to-reverberant Ratio for R'. Note that there is about a 4 dB difference in the reverberant level between the two conditions.

Figure 11. Estimated Intelligibility, using R'. Since the reverberation time in the space is fairly low and the direct-to-reverberant ratio is high, the estimated intelligibility is excellent throughout the space.

Figure 12. Maximum Direct Field, Main Floor. These levels were calculated at 2 kHz for the HF portion of the system only before attenuation to match the LF part of the system. The represent the sound pressure levels with full rated power to the HF array.

Figure 13. Maximum Direct Field, Balcony.

Figure 14. Central Array, Side View. Small circle in the middle of the lower LF enclosure indicates the center of gravity. The lines extending oiut from the back of each element originate at the center of gravity. They are used as visual construction aids in the layout of the array.

Figure 15. Central Array, Top View.

Figure 16. Central Array, Front View.

4.2 Observing Interference Effects:

The clearest way to observe the phasor merging program is to look at simple examples. In Figure 17A, we are examining the 1 kHz interference pattern between a pair of omnidirectional radiators separated horizontally by 0.4 meter at a height of 20 meters. The room dimensions are 40 by 70 meters. Note the occurence of two null zones, indicated by the dotted lines, and the appearance of minor lobes outside the null zones. In Figure 17B, we are examining the same array in a non-phasor summation. Note the effect essentially of inverse square losses.

In Figure 18A, the radiators have been stacked vertically, again at a distance of 0.4 meter. The interference pattern here takes the form of a circular zone, beyond which the response picks up again. Again, for comparision, we show at Figure 18B the non-phasor combination.

5. FINAL COMMENTS:

JBL is grateful to the many consultants and professional sound contractors who commented so constructively on the CADP program when it was introduced in May 1983. Many of their suggestions have been incorporated into the present form of the program, and future forms of CADP will be even more flexible than it presently is.

The initial menu structure and developmemt of CADP was worked out by James Day, based upon requirements outlined by John Eargle and Ronald Means. Don Keele was instrumental in working out many of the mathematical aspects of the program. Since January 1983, Dave Albertz has assumed the role of refining the program and incorporating all changes.

REFERENCES:

1. F. G. McCarthy, "Loudspeaker Arrays - A Graphic Method of Designing" (Presented at AES Convention, New York, November 1978. Preprint number 1398)

2.F. M. Becker, "A Polar-plot Method of Loudspeaker Array Design," J. Audio Engineering Society, Vol. 30, No. 6 (1982)

3. T. Uzzle, "Loudspeaker Coverage by Architectural Mapping," J. Audio Engineering Society, Vol. 30, No. 6 (1982)

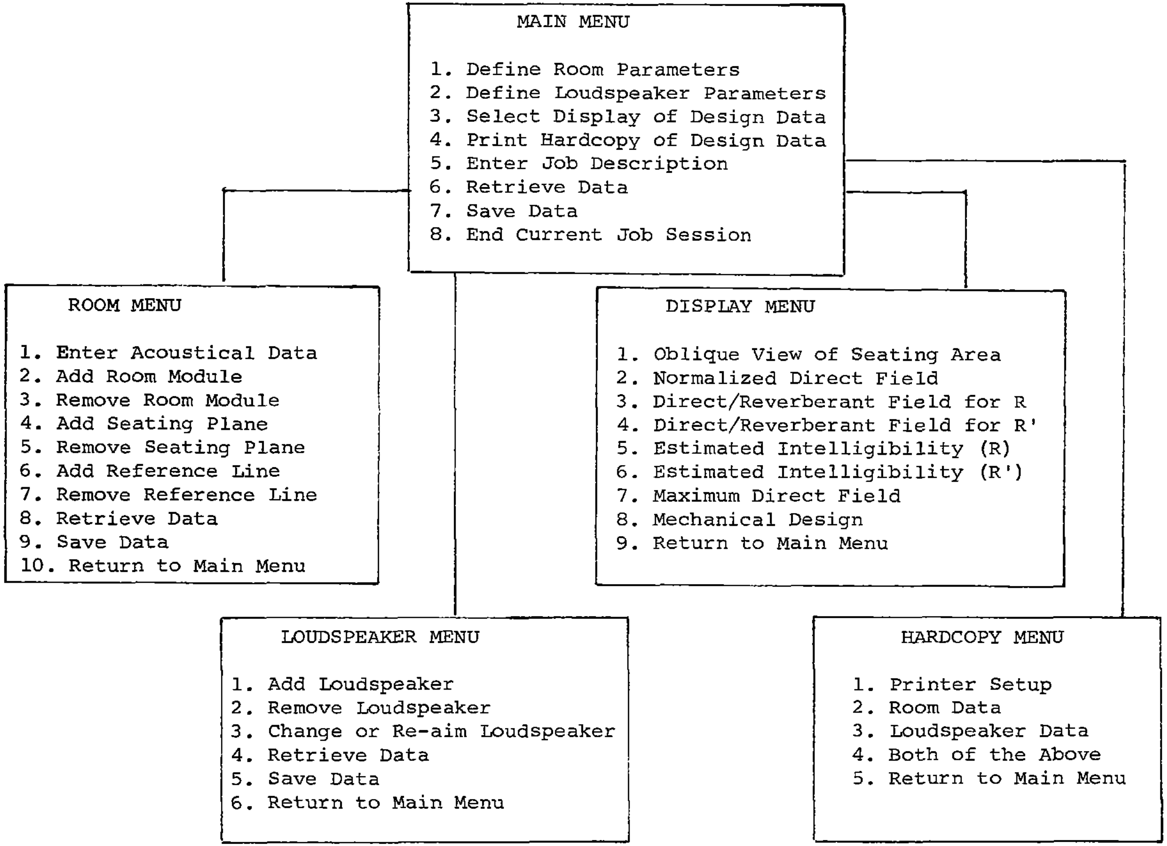
4. J. Prohs and D. Harris, "An Accurate and Easily Implemented Method of Modelling Loudspeaker Array Coverage" (Presented at AES Convention, Anaheim, October 1982. Preprint number 1941)

5. G. Augspurger, "More Accurate Calculation of the Room Constant,"J. Audio Engineering Society, Vol, 23, No. 5 (1976)

6. V. M. A. Peutz, Articulation Loss of Consonants as a Criterion for Speech Transmission in a Room, J. Audio Engineering Society, Vol. 19, No. 11 ,(1971)

7. L. Beranek, Music, Acoustics and Architecture, J. Wiley & Sons (New York 1962)

Figure 1. First and Second Level Menus



MAIN MENU

1. Define Room Parameters
2. Define Loudspeaker Parameters
3. Select Display of Design Data
4. Print Hardcopy of Design Data
5. Enter Job Description
6. Retrieve Data
7. Save Data
8. End Current Job Session

ROOM MENU

1. Enter Acoustical Data
2. Add Room Module
3. Remove Room Module
4. Add Seating Plane
5. Remove Seating Plane
6. Add Reference Line
7. Remove Reference Line
8. Retrieve Data
9. Save Data
10. Return to Main Menu

DISPLAY MENU

1. Oblique View of Seating Area
2. Normalized Direct Field
3. Direct/Reverberant Field for R
4. Direct/Reverberant Field for R'
5. Estimated Intelligibility (R)
6. Estimated Intelligibility (R')
7. Maximum Direct Field
8. Mechanical Design
9. Return to Main Menu

LOUDSPEAKER MENU

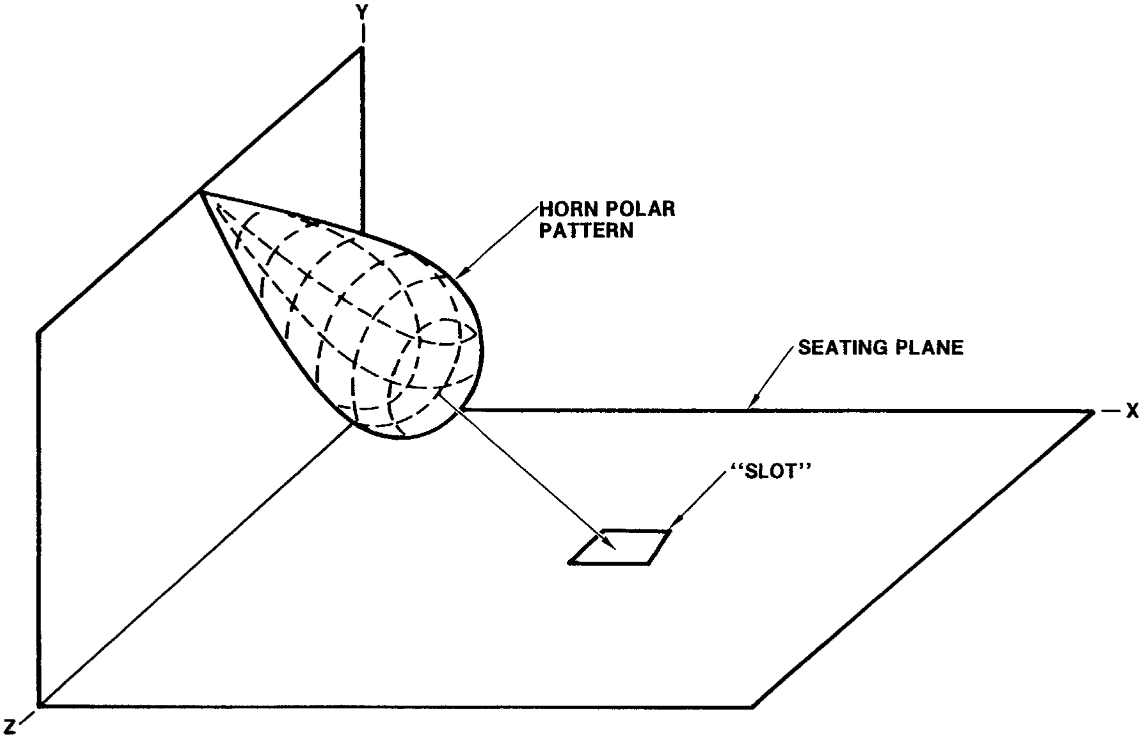
1. Add Loudspeaker
2. Remove Loudspeaker
3. Change or Re-aim Loudspeaker
4. Retrieve Data
5. Save Data
6. Return to Main Menu

HARDCOPY MENU

1. Printer Setup
2. Room Data
3. Loudspeaker Data
4. Both of the Above
5. Return to Main Menu

Figure 2

HORN AIMING, DIRECT FIELD CALCULATIONS



LEVEL AT SLOT = SENSITIVITY + DRIVE LEVEL + INVERSE SQUARE LOSS + PATTERN LOSS

Figure 3. Directivity Data in Spherical Coordinates

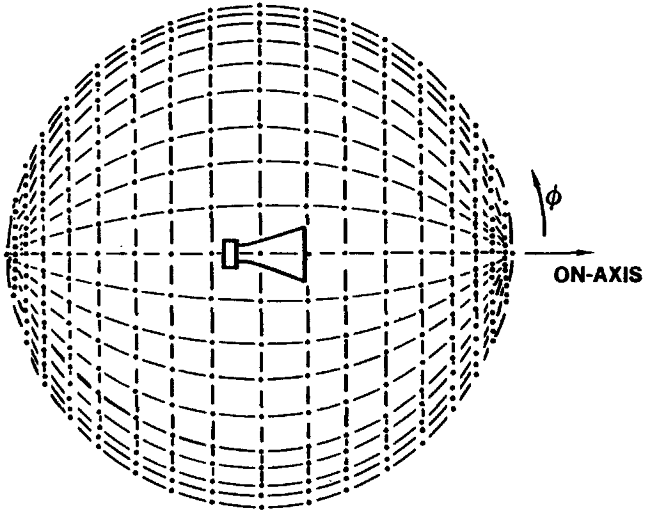


Figure 4. Intelligibility Estimates

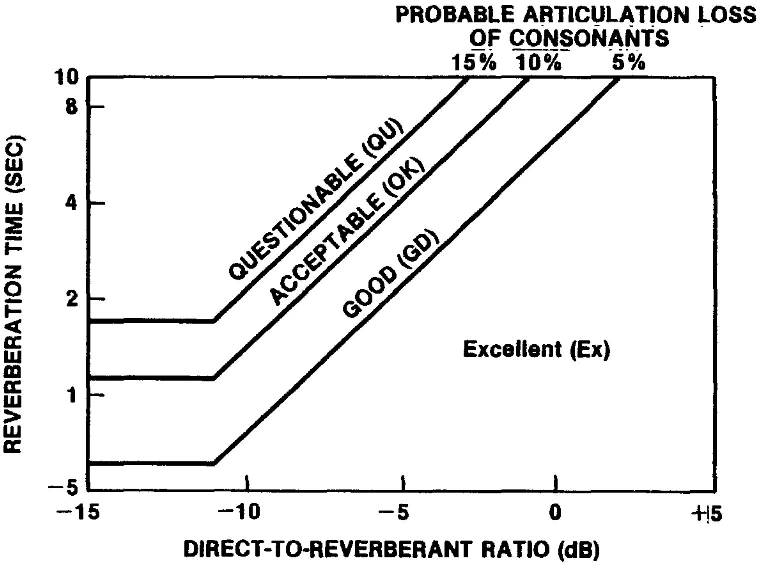
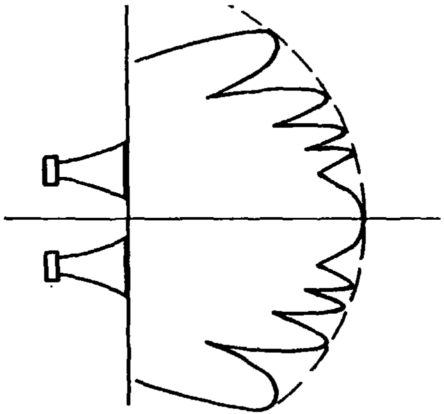


Figure 5. Merging of Loudspeaker Polar Patterns



SOLID LINE INDICATES ACTUAL POLAR RESPONSE. DOTTED LINE IS THE EFFECTIVE RESPONSE IF PHASE EFFECTS ARE IGNORED

Figure 6. Elevation and Plan Views of Eastman Theater, Rochester, NY

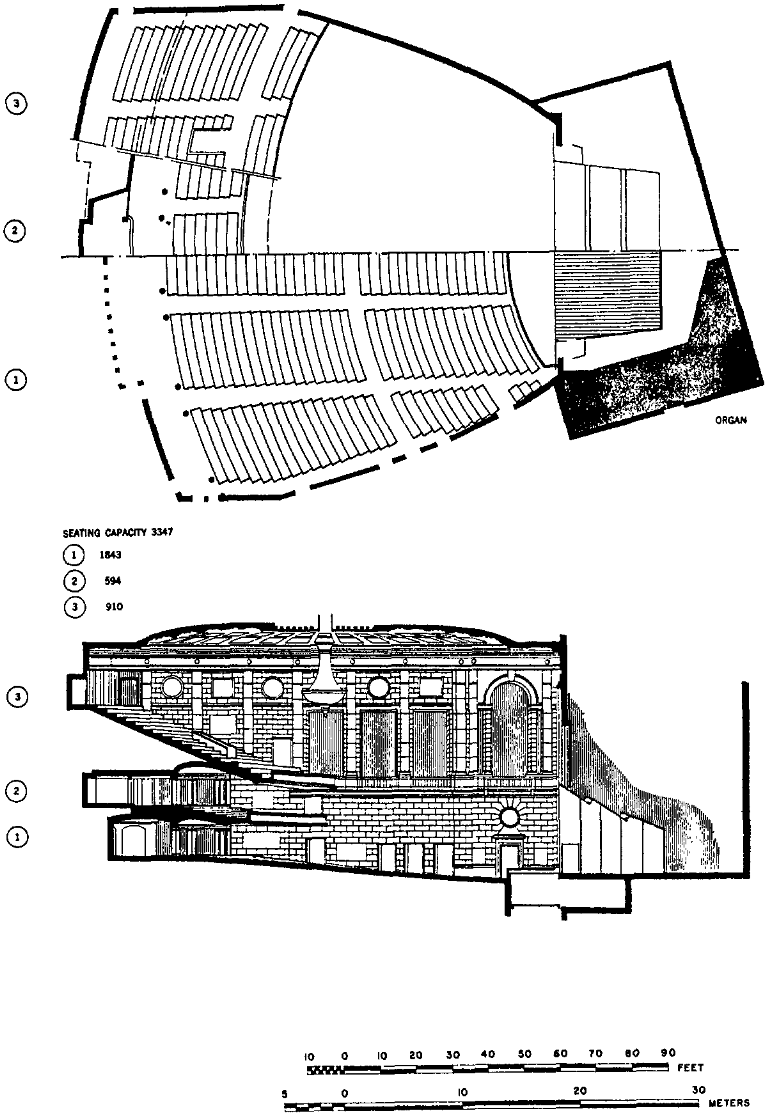
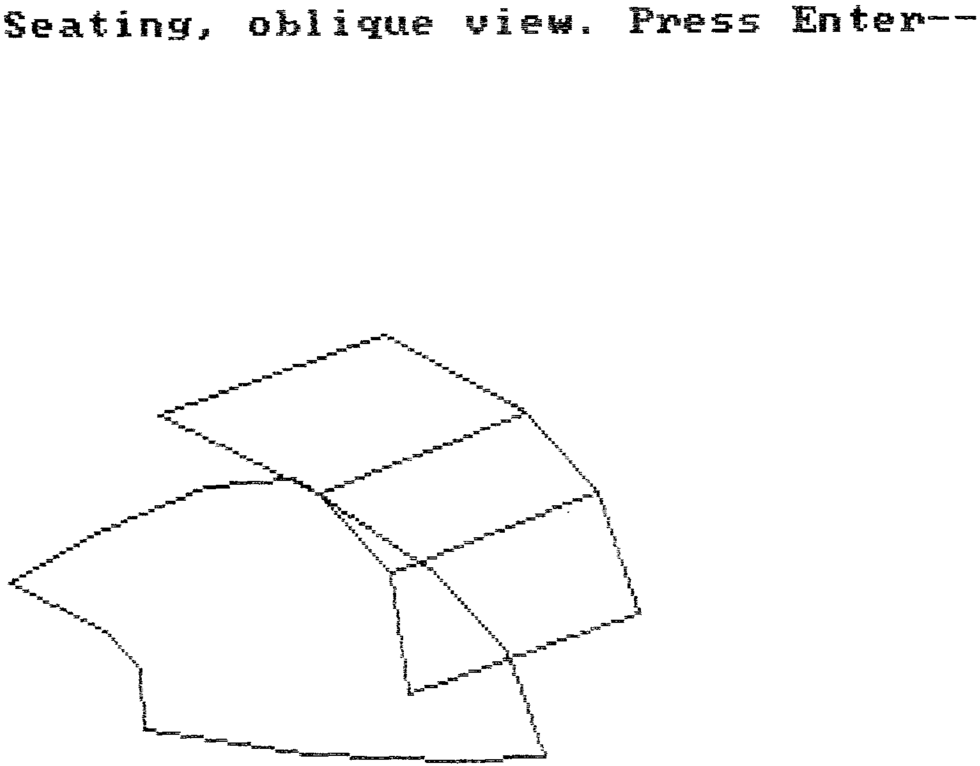


Figure 7



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Seating, oblique view. Press Enter--
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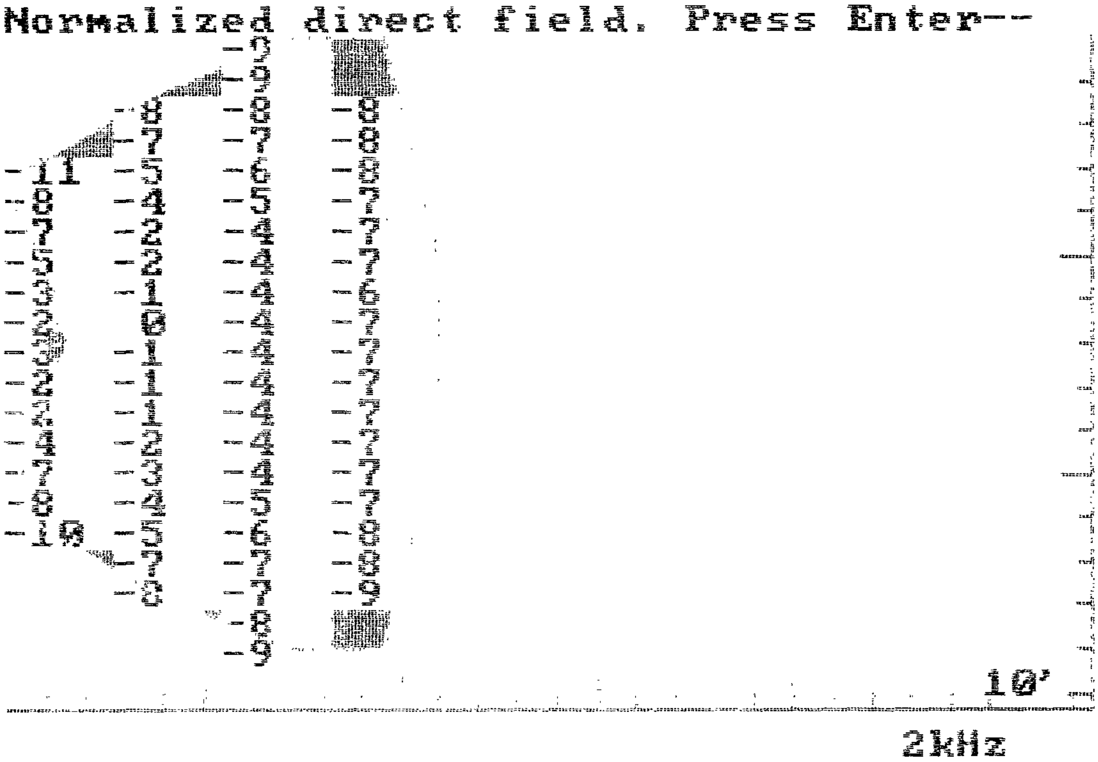
Figure 8



Normalized direct field. Press Enter--

Figure 9

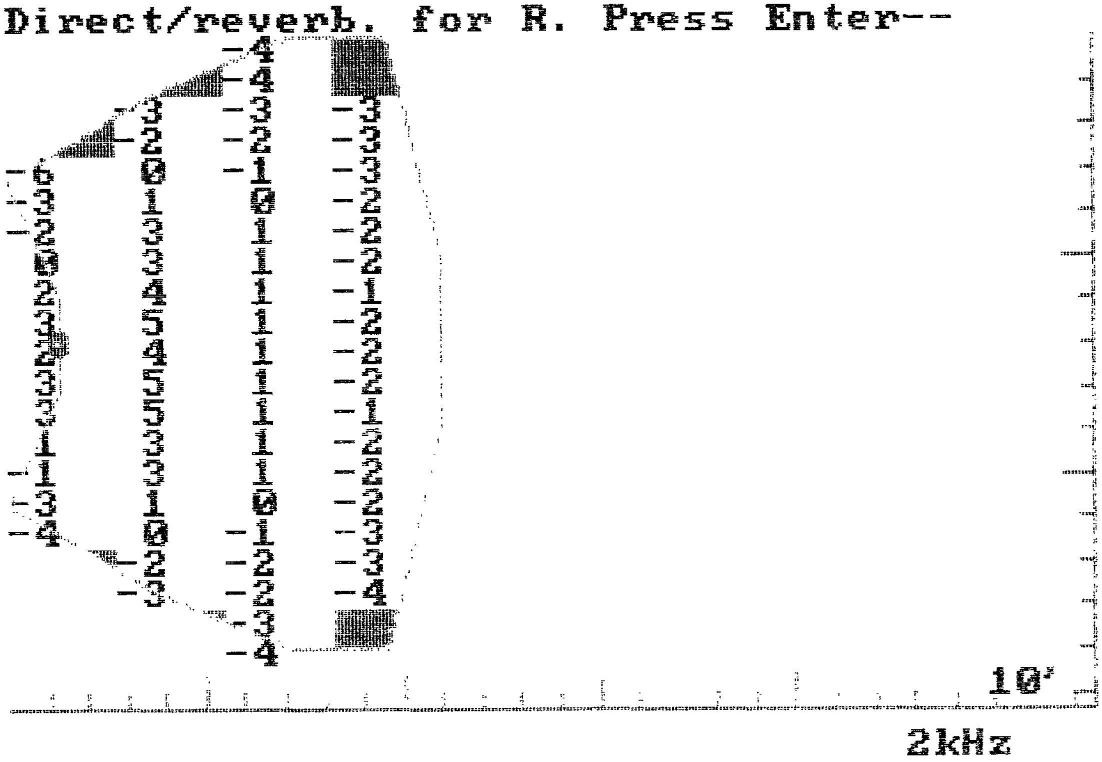
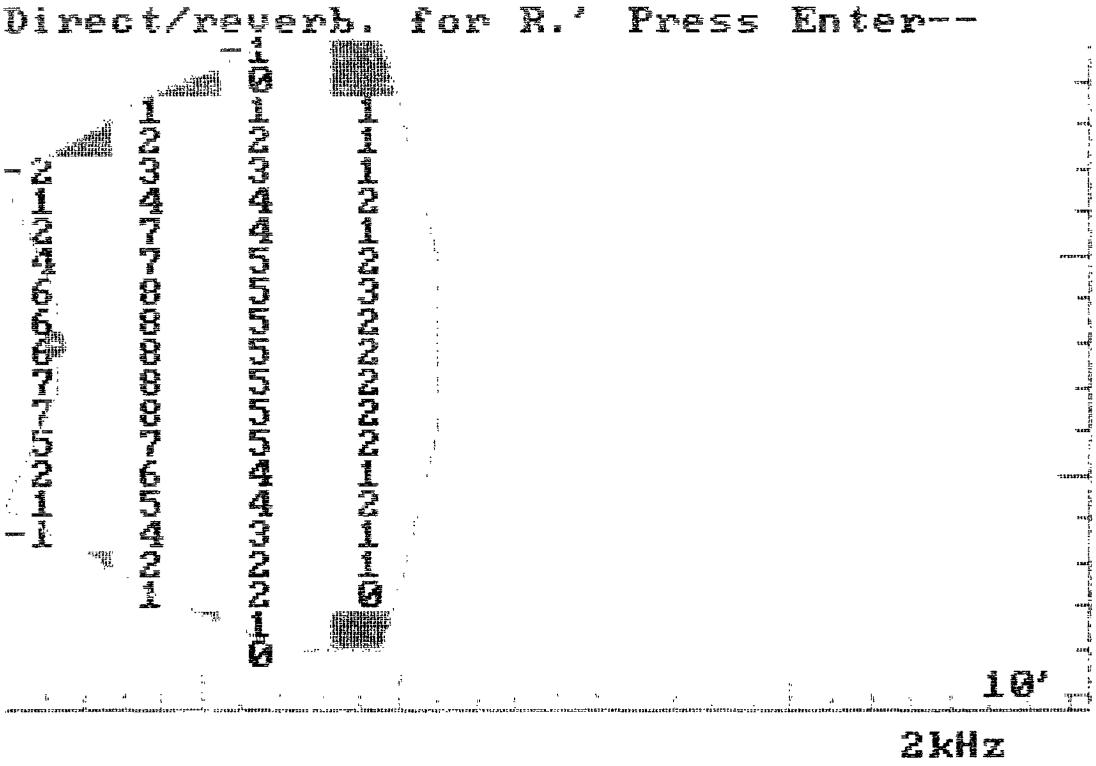


Figure 10



Direct/reverb. for R.' Press Enter--

Figure 11

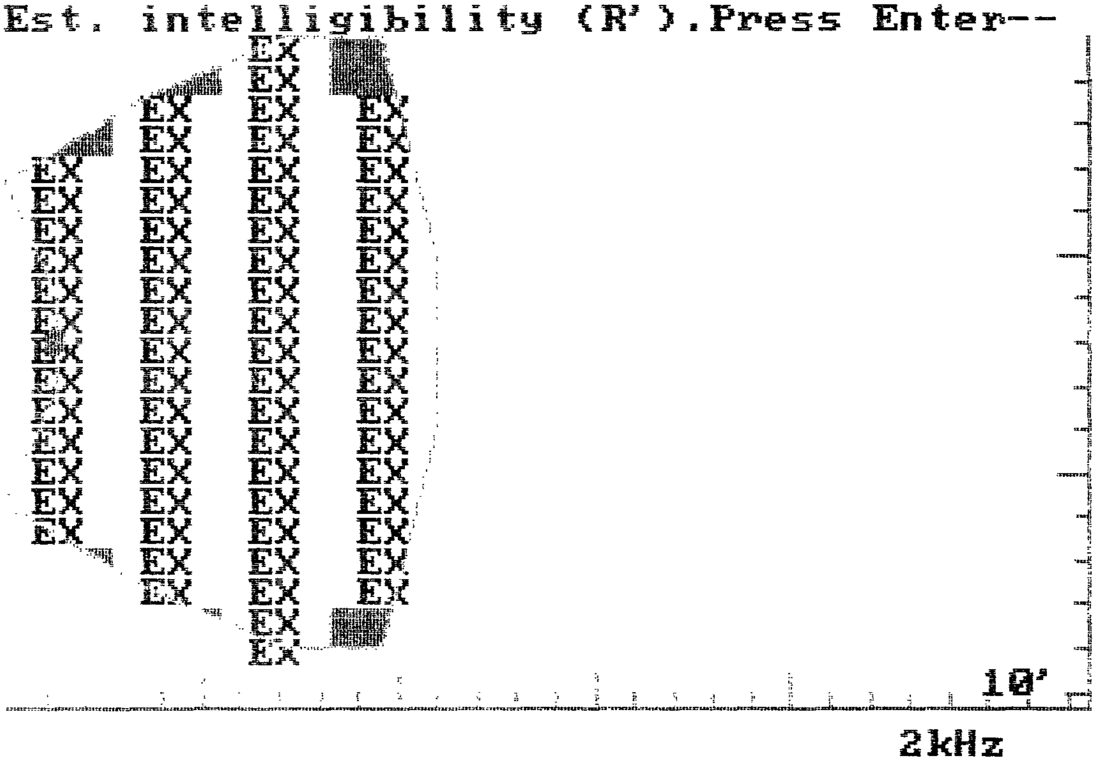
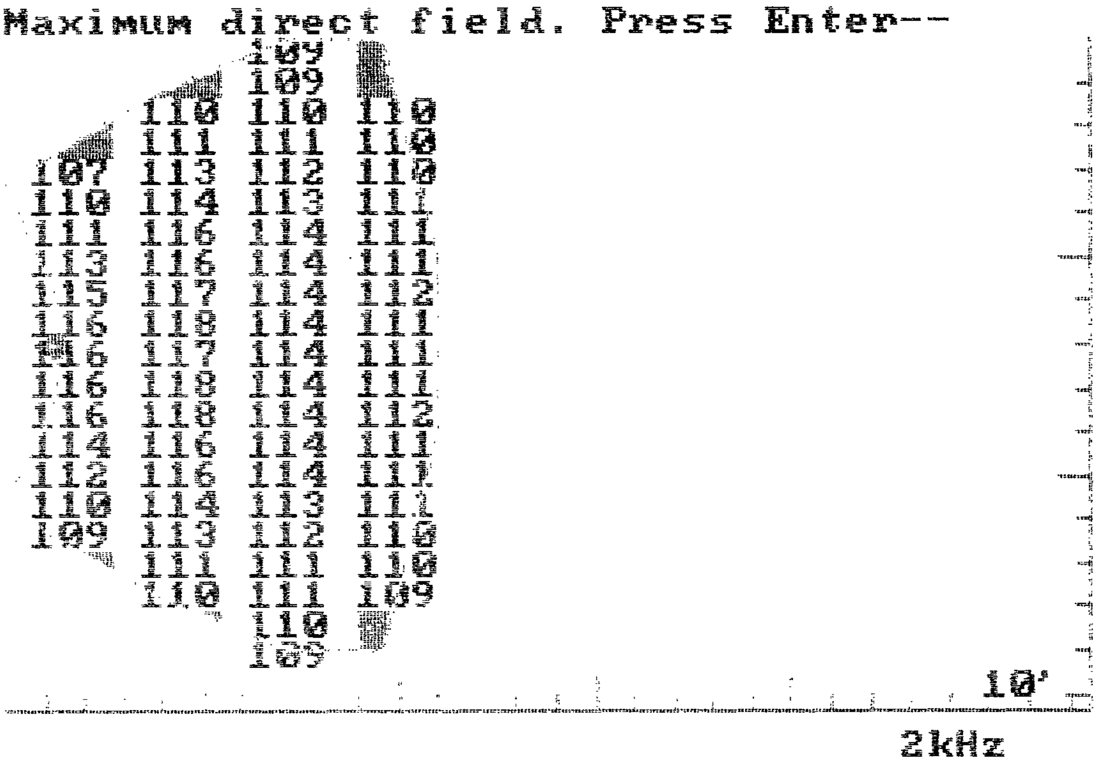
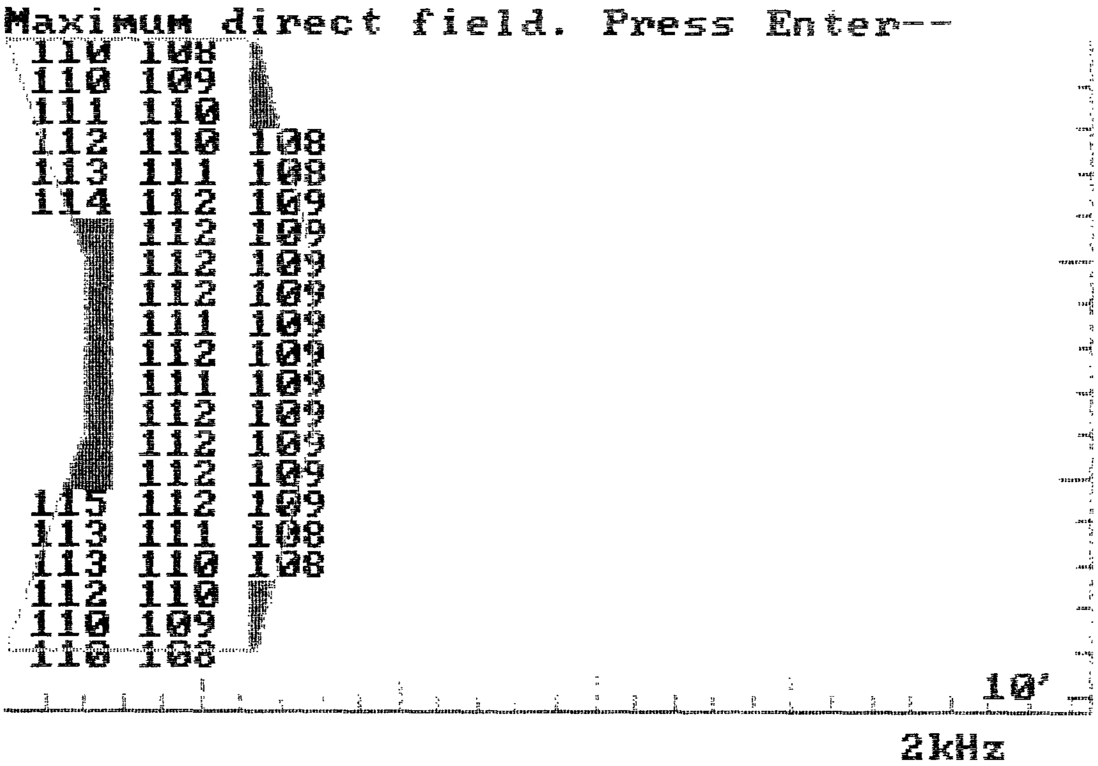


Figure 12



Maximum direct field. Press Enter--

Figure 13



Maximum direct field. Press Enter--

Figure 14

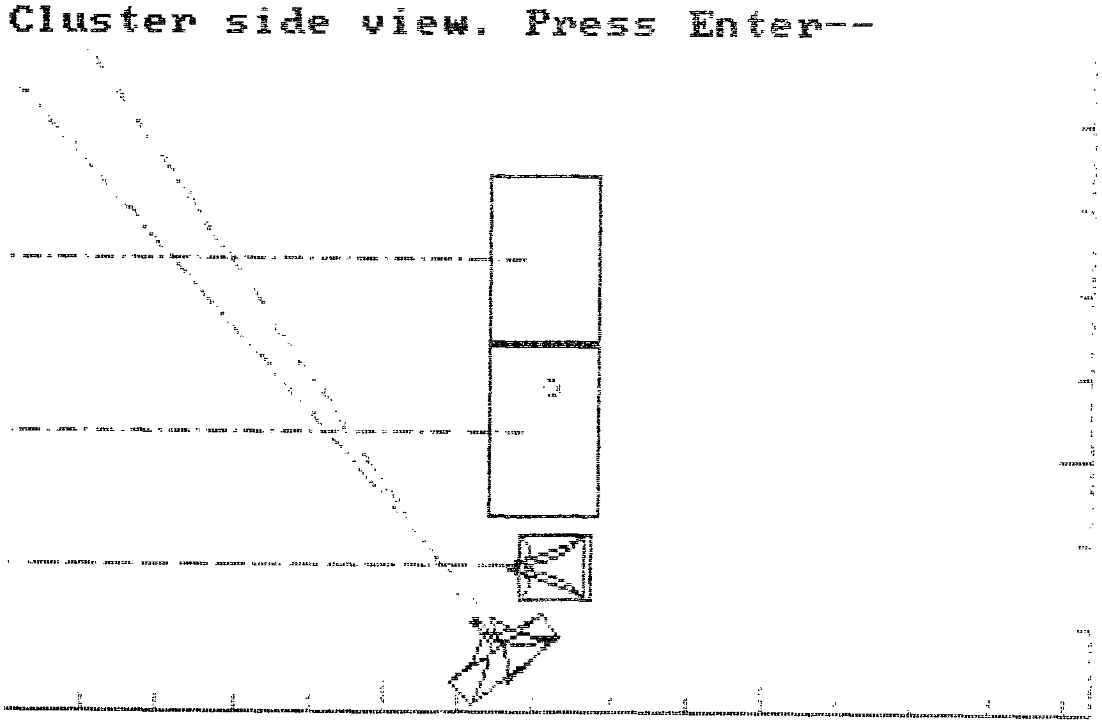
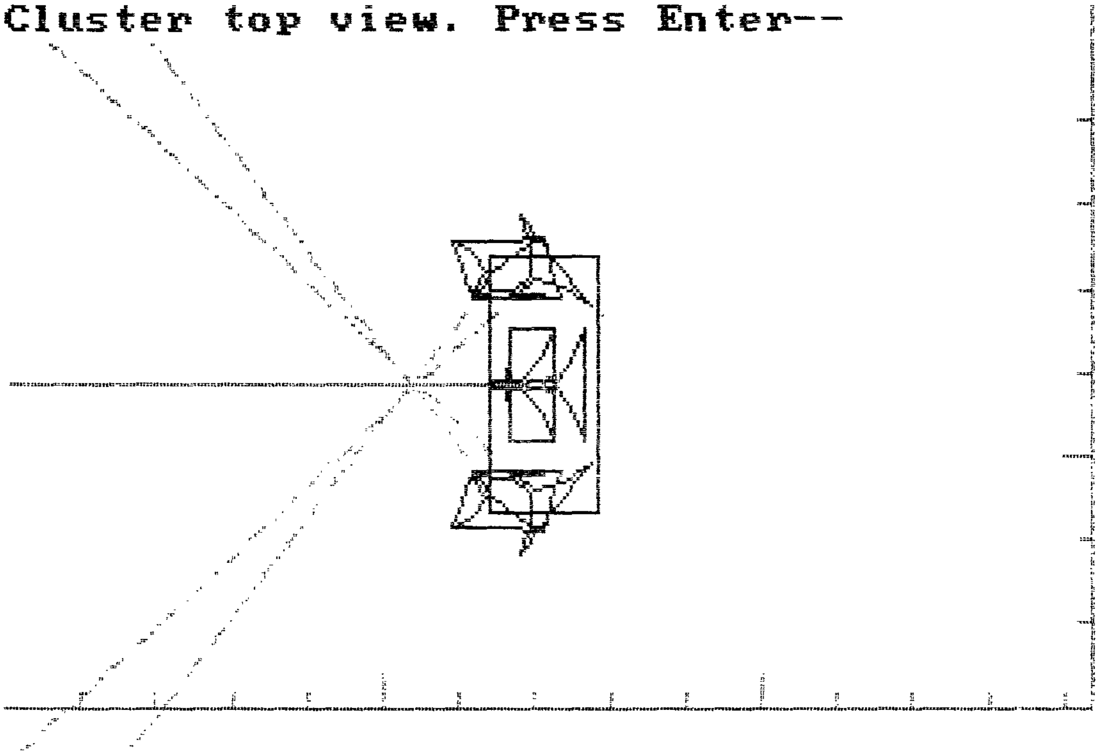
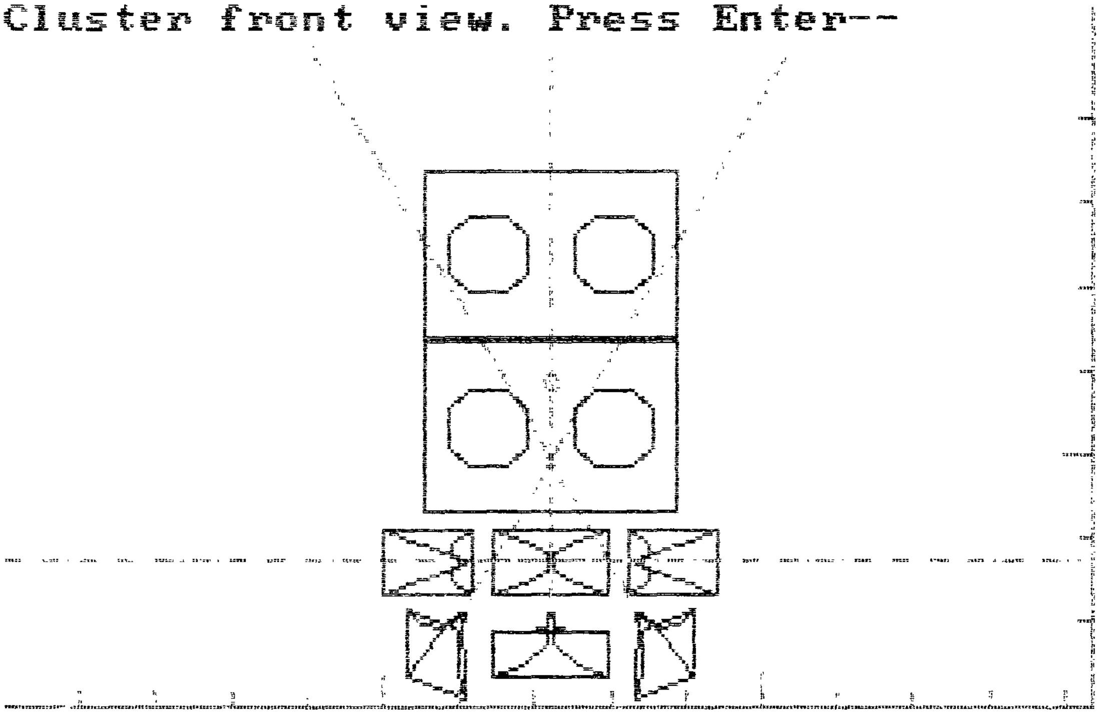


Figure 15



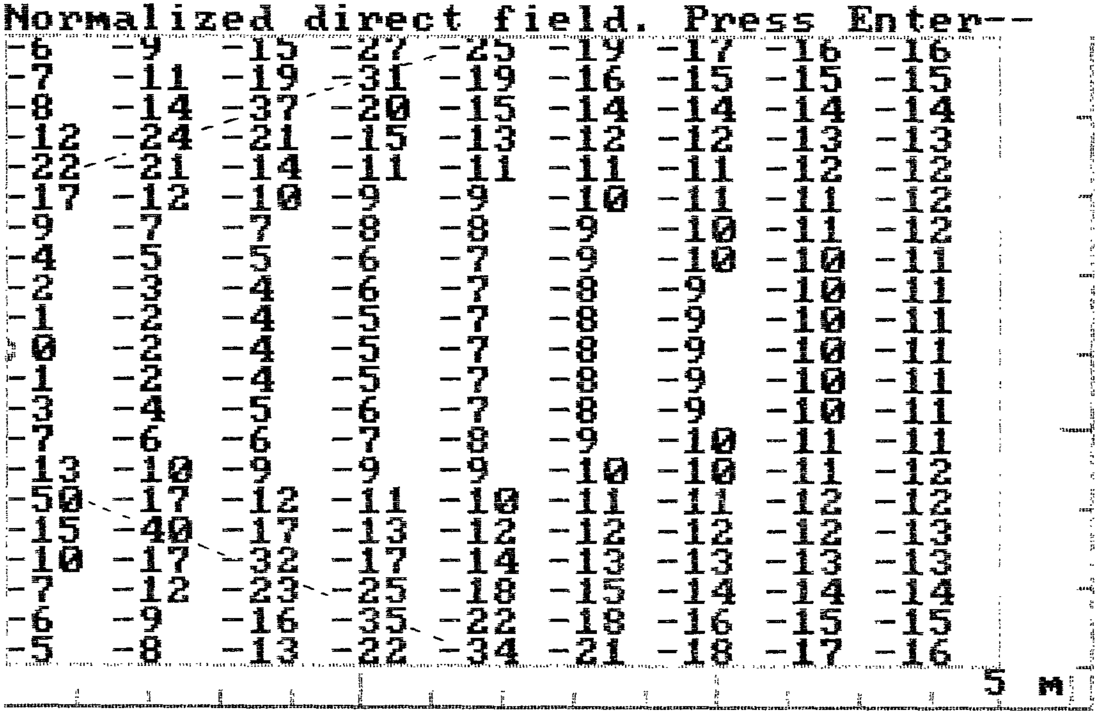
Cluster top view. Press Enter--

Figure 16



Cluster front view. Press Enter--

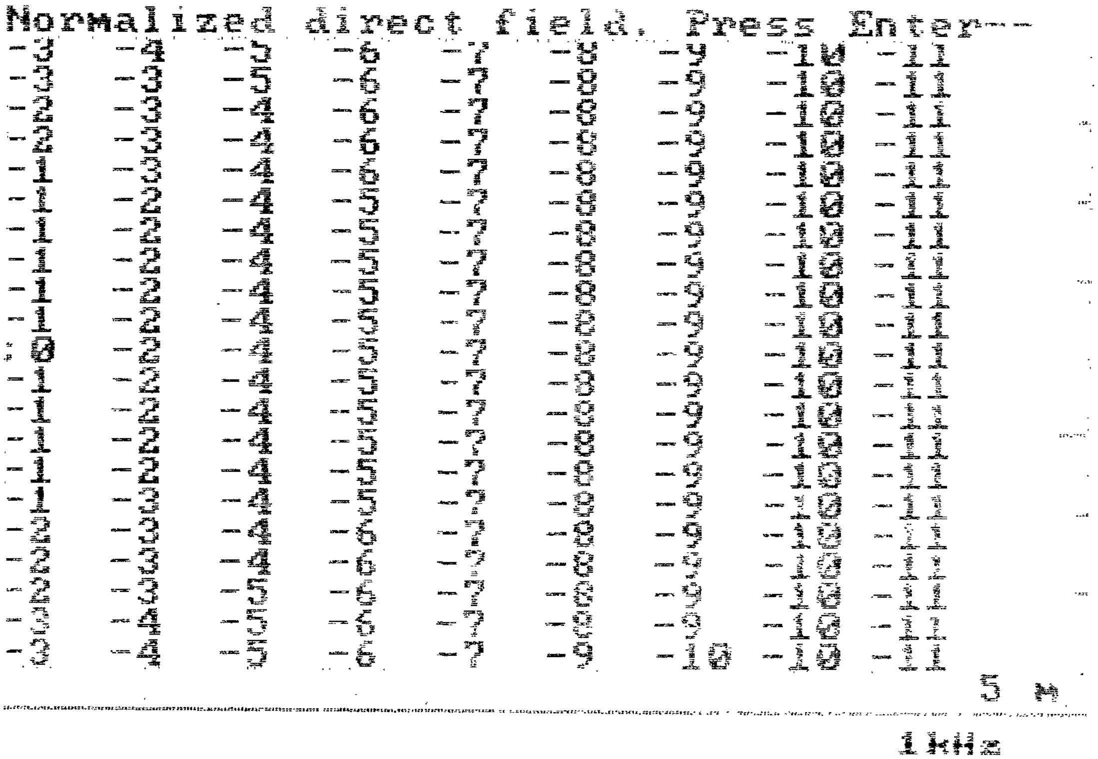
Figure 17A



```
Normalized direct field. Press Enter--
-6   -9   -15  -27  -25  -19  -17  -16  -16
-7   -11  -19  -31  -19  -16  -15  -15  -15
-8   -14  -37  -20  -15  -14  -14  -14  -14
-12  -24  -21  -15  -13  -12  -12  -13  -13
-22  -21  -14  -11  -11  -11  -11  -12  -12
-17  -12  -10  -9   -9   -10  -11  -11  -12
-9   -7   -7   -8   -8   -9   -10  -11  -12
-4   -5   -5   -6   -7   -9   -10  -10  -11
-2   -3   -4   -6   -7   -8   -9   -10  -11
-1   -2   -4   -5   -7   -8   -9   -10  -11
 0   -2   -4   -5   -7   -8   -9   -10  -11
-1   -2   -4   -5   -7   -8   -9   -10  -11
-3   -4   -5   -6   -7   -8   -9   -10  -11
-7   -6   -6   -7   -8   -9   -10  -11  -11
-13  -10  -9   -9   -9   -10  -10  -11  -12
-50  -17  -12  -11  -10  -11  -11  -12  -12
-15  -40  -17  -13  -12  -12  -12  -12  -13
-10  -17  -32  -17  -14  -13  -13  -13  -13
-7   -12  -23  -25  -18  -15  -14  -14  -14
-6   -9   -16  -35  -22  -18  -16  -15  -15
-5   -8   -13  -22  -34  -21  -18  -17  -16
                                                5 m
```

1kHz

Figure 17B



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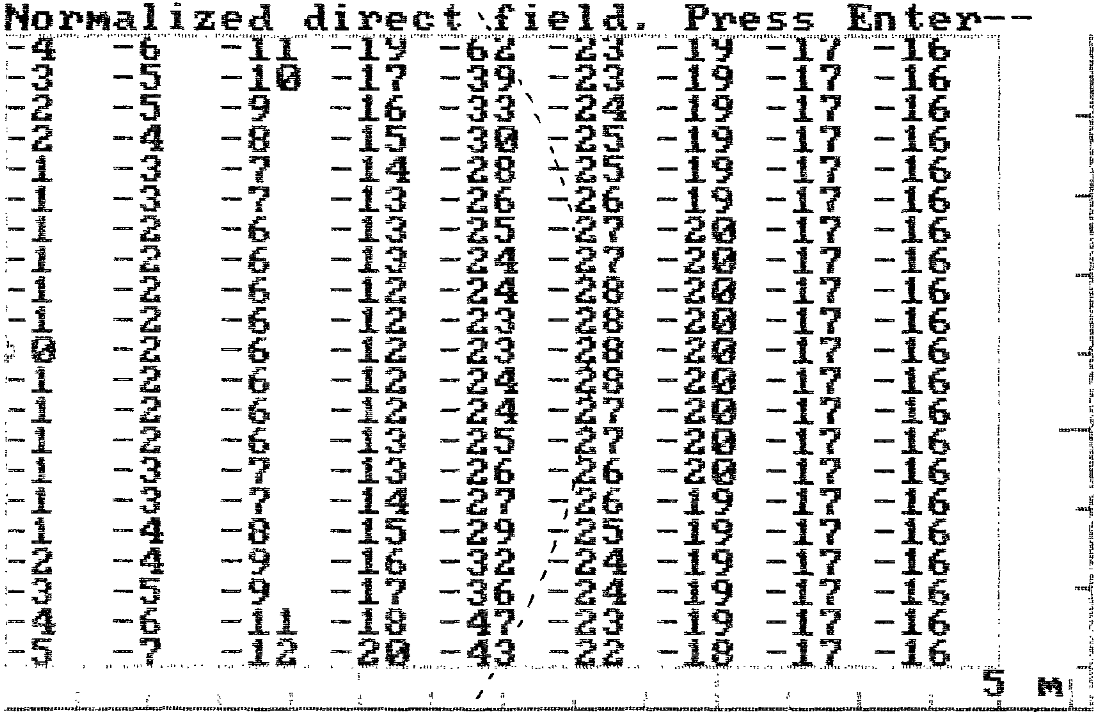
Normalized direct field. Press Enter--
-3    -4    -5    -6    -7    -8    -9    -10   -11
-3    -3    -5    -6    -7    -8    -9    -10   -11
-2    -3    -4    -6    -7    -8    -9    -10   -11
-2    -3    -4    -6    -7    -8    -9    -10   -11
-1    -3    -4    -6    -7    -8    -9    -10   -11
-1    -2    -4    -5    -7    -8    -9    -10   -11
-1    -2    -4    -5    -7    -8    -9    -10   -11
-1    -2    -4    -5    -7    -8    -9    -10   -11
-1    -2    -4    -5    -7    -8    -9    -10   -11
-1    -2    -4    -5    -7    -8    -9    -10   -11
 0    -2    -4    -5    -7    -8    -9    -10   -11
-1    -2    -4    -5    -7    -8    -9    -10   -11
-1    -2    -4    -5    -7    -8    -9    -10   -11
-1    -2    -4    -5    -7    -8    -9    -10   -11
-1    -2    -4    -5    -7    -8    -9    -10   -11
-1    -2    -4    -5    -7    -8    -9    -10   -11
-3    -3    -4    -6    -7    -8    -9    -10   -11
-2    -3    -4    -6    -7    -8    -9    -10   -11
-2    -3    -5    -6    -7    -8    -9    -10   -11
-3    -4    -5    -6    -7    -8    -9    -10   -11
-3    -4    -5    -6    -7    -8    -10   -10   -11
                                                       5  M
                                                   1 kHz
```

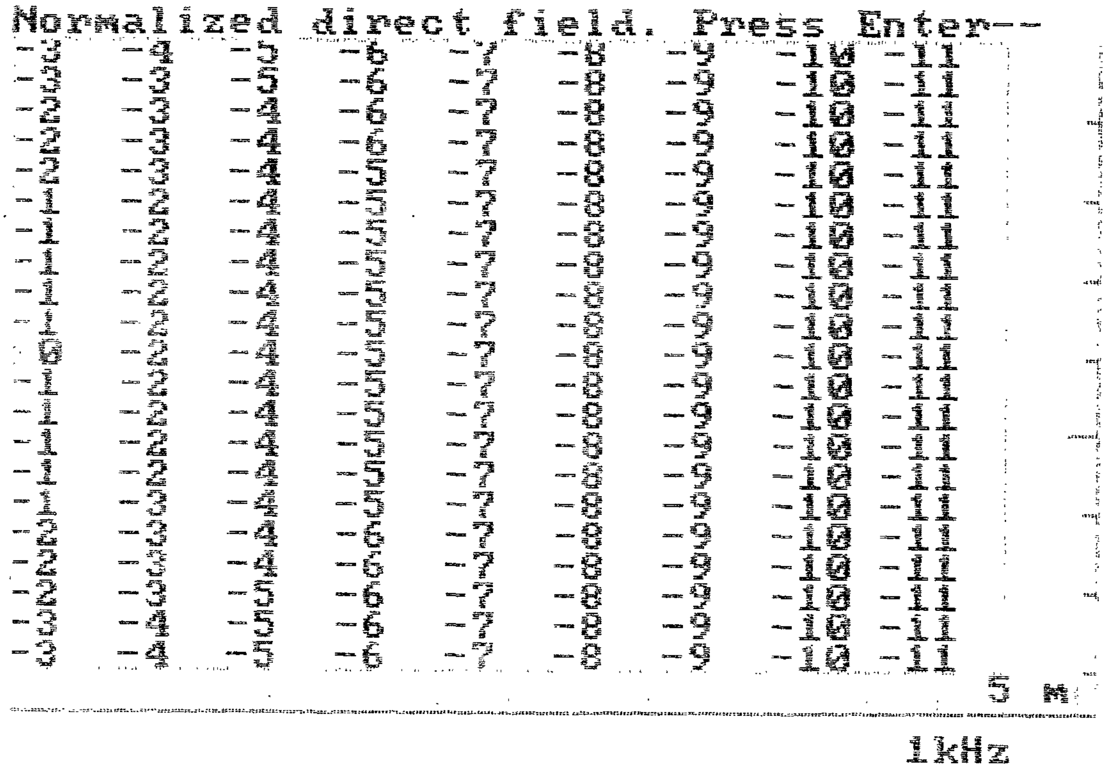
Figure 18A



```
Normalized direct field. Press Enter--
-4   -6   -11  -19  -62  -23  -19  -17  -16
-3   -5   -10  -17  -39  -23  -19  -17  -16
-2   -5   -9   -16  -33  -24  -19  -17  -16
-2   -4   -8   -15  -30  -25  -19  -17  -16
-1   -3   -7   -14  -28  -25  -19  -17  -16
-1   -3   -7   -13  -26  -26  -19  -17  -16
-1   -2   -6   -13  -25  -27  -20  -17  -16
-1   -2   -6   -13  -24  -27  -20  -17  -16
-1   -2   -6   -12  -24  -28  -20  -17  -16
-1   -2   -6   -12  -23  -28  -20  -17  -16
 0   -2   -6   -12  -23  -28  -20  -17  -16
-1   -2   -6   -12  -24  -28  -20  -17  -16
-1   -2   -6   -12  -24  -27  -20  -17  -16
-1   -2   -6   -13  -25  -27  -20  -17  -16
-1   -3   -7   -13  -26  -26  -20  -17  -16
-1   -3   -7   -14  -27  -26  -19  -17  -16
-1   -4   -8   -15  -29  -25  -19  -17  -16
-2   -4   -9   -16  -32  -24  -19  -17  -16
-3   -5   -9   -17  -36  -24  -19  -17  -16
-4   -6   -11  -18  -47  -23  -19  -17  -16
-5   -7   -12  -20  -43  -22  -18  -17  -16
                                              5  m
```

1kHz

Figure 18B



```
Normalized direct field. Press Enter--
-4   -4   -5   -6   -7   -8   -9   -10  -11
-3   -3   -5   -6   -7   -8   -9   -10  -11
-3   -3   -4   -6   -7   -8   -9   -10  -11
-2   -3   -4   -6   -7   -8   -9   -10  -11
-2   -3   -4   -5   -7   -8   -9   -10  -11
-2   -2   -4   -5   -7   -8   -9   -10  -11
-1   -2   -4   -5   -7   -8   -9   -10  -11
-1   -2   -4   -5   -7   -8   -9   -10  -11
-1   -2   -4   -5   -7   -8   -9   -10  -11
-1   -2   -4   -5   -7   -8   -9   -10  -11
 0   -2   -4   -5   -7   -8   -9   -10  -11
-1   -2   -4   -5   -7   -8   -9   -10  -11
-1   -2   -4   -5   -7   -8   -9   -10  -11
-1   -2   -4   -5   -7   -8   -9   -10  -11
-1   -2   -4   -5   -7   -8   -9   -10  -11
-1   -2   -4   -5   -7   -8   -9   -10  -11
-2   -3   -4   -6   -7   -8   -9   -10  -11
-2   -3   -4   -6   -7   -8   -9   -10  -11
-2   -3   -5   -6   -7   -8   -9   -10  -11
-3   -4   -5   -6   -7   -8   -9   -10  -11
-3   -4   -5   -6   -7   -8   -9   -10  -11
                                              5 M
                                           1kHz
```