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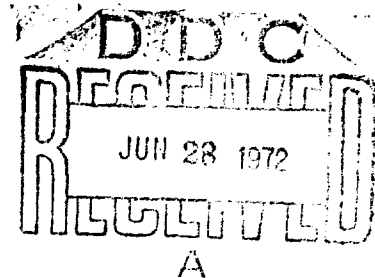
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LRAPP VERTICAL ARRAY
PRELIMINARY DESIGN STUDY
PHASE I

Technical Report for Period
October 11, 1971 to February 11, 1972
Contract N00014-72-C-0120

April 14, 1972



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ABSTRACT

Under contract to the Office of Naval Research, and as part of their LRAPP program, a design study was made of a vertical array that was to be suspended from a research vessel called the SPAR (Seagoing Platform for Acoustic Research). This array will be suspended from a cable at depths up to 20,000 feet to collect data on shipping noise as a function of vertical angle, depth, and frequency. The preliminary design proposes that the array be distributed over 1000 feet and that it contain 57 hydrophones geometrically spaced. The data will be collected and processed over a frequency range from 10 Hz to 333 Hz at any desired depth.

A review of the literature relating to the vertical directionality of ambient noise is provided. A specific array geometry is proposed after considering several geometries and evaluating them with a computer program for a set of discrete sources. A variety of hydrophone elements are compared, and the performance of a low noise amplifier is given. The signals received by the hydrophones and the sensors are combined in an electronics package so that information can be transmitted to the surface on a single coaxial cable. Specific cables and connectors are recommended.

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INTRODUCTION

In order to intelligently design long range suspended surveillance systems of the future, it is desirable to know as precisely as possible the ambient noise level, ANL, characteristics in the deep ocean, i.e. the ANL characteristics as a function of vertical directionality, as a function of depth and as a function of frequency.

The research ship, NOL's SPAR, has been chosen as the platform from which to make the noise measurements. The array to be suspended from the SPAR is primarily intended as a tool for support of the various long range surveillance studies. There is a tendency in selecting the characteristics of a new array for measuring ambient noise to try to cover the needs of all systems requiring such data; a statement of priorities is appropriate.

The primary frequency band which is to be covered is the low frequency range of 10 Hz to 333 Hz over which long range attenuation losses are negligible permitting shipping noise to propagate for long distances. It would be desirable to record a wide bandwidth in order to measure time of arrival differences of broadband signals as a technique for measuring arrival angles. Another highly desirable feature would be the ability to sweep the narrow beam over as wide a vertical range as possible in order to determine the directivity of all sources of noise. The hydrophone should be acceleration canceling and it should have low noise and high sensitivity. The hydrophone preamplifier noise level should be below the lowest ambient noise level that one is likely to want to measure, e.g. the lower Wenz curve, Figure 3, in Chapter 2.

The tilt of the array under the influence of current is a limitation on the array capability for measuring vertical directionality of shipping noise. A single vertical line array can obtain no azimuth

information and so the elevation pattern can not be corrected for tilt. If the tilt angle is small compared to the vertical resolution of the array, then it will not greatly distort the resulting data.

An important characteristic of the total ambient noise is the range of arrival angles of the long range shipping noise. Unfortunately this characteristic is difficult to measure because it requires high angular resolution at low frequencies. Such data is desired in order to be able to accurately reproduce the ANL characteristics for if the predominant long range low frequency shipping noise arrives within two narrow beams approximately $\pm 13^\circ$ from the horizontal, a system with sufficient vertical discrimination could be designed which could minimize the masking of acoustic signals from other targets which don't arrive along the same paths as the long range shipping. Verification of theoretical models of ambient noise is required to permit logical design and this one characteristic is believed to be most important in major system improvement.

The vertical directionality of sea state noise is also important but will generally not predominate in the frequency band for long range detection and will not require as much array directionality as the long range shipping paths.

I. REVIEW OF ARRAY SIGNAL PROCESSING

1. Noise Directionality

"Problems Associated with the Measurement of Ambient-Noise Directivity by Means of Linear Additive Arrays" JASA v34, No. 3, March 1962 pp 328-333 by Julian Stone is a good introduction to the subject. Stone points out that, by examining the Fourier transform or the array angular response, over a given frequency band, the spatial frequencies which can be measured by an array are restricted by the aperture. Any higher spatial frequency components in the actual vertical noise directionality are completely eliminated and components near the limiting value are usually attenuated. This bears directly on the problem of measuring the long range shipping noise component. This array frequency limitation results in a sampling theorem which defines the number of steering angle measurements required to define the information obtainable with the array.

Stone also points out that the noise power response of an array can be calculated from outputs of correlators at spacings corresponding to all possible interelement spacings.

Stone, in following the approach of V. C. Anderson, calculates a "discrimination factor" for a noise model which is basically isotropic except for a small solid angle of higher level noise (again similar to the shipping noise component). The discrimination factor is the ratio of the array output when steered at and away from that source. Plots show the ratio is surprisingly low for anticipated cases and that the ratio does not improve as the main lobe is narrowed. This insensitivity of the array can cause small experimental errors to result in large uncertainties in the results.

"Aerial Smoothing in Radio Astronomy," Australian Journal of Physics, V7, 1954, pp 615-640 by R. N. Bracewell and J. A. Roberts is a basic reference in the field in addition to formulating the problem later discussed by Stone. This article also proposes a "principal solution" to the problem of recovering the actual noise distribution from the array measurements. The principal solution contains all spatial frequency components, unattenuated, below the cutoff frequency of the array. It is recognized that due to the Gibbs phenomenon this may result in negative power at some points on this principal solution. Despite this the "principal solution" is accepted by the more recent workers in the field.

"Vertical Directionality of Ambient Noise in the Deep Ocean at a Site Near Bermuda" JASA V37, No. 1, January 1965, pp 77-83 by E. H. Axelrod, B. A. Schooner, and W. A. VonWinkle and "Ambient-Noise Directivity Measurements" JASA V36, No. 8, August 1964, pp 1537-1540 by George R. Fox were both written about data taken from the Trident array during overlapping time periods. Results and a description of the data processing methods were presented in each case.

"Analysis of an Integral Equation Arising from the Investigation of Vertical Directivity of Sea Noise" JASA V45, No. 5, pp 1129-1133, 1969 by M. W. Anderson and R. L. Tittle discusses the problem of calculating the "principal solution" from array measurements; an easily programmed method of solution from a finite number of array measurements is presented. The solution is presented in terms of basic functions which are appropriate for the power response of parts of elements which are separated by all possible interelement spacings in the array. They suggest an array which has element spacings that are harmonically related and allows determination of the coefficients of the series solution by a technique that is similar to Fourier analysis and thus avoids a matrix inversion. The effect of errors is not considered.

2. Data Analysis Techniques

Stone points out the need for using the array measurements and the known beam pattern of the array to try to infer the undistorted noise field and in particular the frequency components below the array cutoff frequency. Two figures are reproduced from Stone's paper to demonstrate the need. Figure 1 shows the noise field model used. T_1 is the RMS voltage in all directions except in the solid angle ψ where it is T_2 . Figure 2 shows the dependence of the discrimination factor γ as a function of ψ/ψ_A , where ψ_A is the solid angle subtended by the main lobe of the linear array and ψ is the solid angle of the peak noise power. For the case shown, $\psi = 1/2$ steradian, i.e. if the long range shipping noise all arrived in a vertical sector between the angles of $+8^\circ$ and $+13^\circ$, but omnidirectional in azimuth, then the solid angle would be approximately $1/2$ steradian. The ratio between the noise intensity peak and the background intensity is $\sigma = T_2^2/T_1^2$. When the omnidirectionally measured shipping noise is 10 dB above the sea state noise and concentrated into a $1/2$ steradian solid angle $\sigma = 250$ and $\psi = 1/2$.

The ordinate γ is called the "discrimination factor" of the array. It is defined as the power ratio of the maximum array response to its minimum response to the noise field as the beam is scanned in a vertical direction. Note that reducing the array beamwidth has little effect when the array beamwidth is smaller than the noise peak angle, ψ .

Figure 3 from Stone's paper shows the difficulty of trying to infer the ambient noise magnitude even if the peak noise amplitude and width are known. It can be seen that a small error in measuring the value of γ will result in a large error in the calculated value of σ and thus T_1 .

It is of interest to use Stone's equations and to plot the discrimination ratio γ for values of σ less than 1 for the condition $\psi = \psi_A$. Figure 4 shows that the ability to measure a decrease in the sound level below the general background level is even more limited

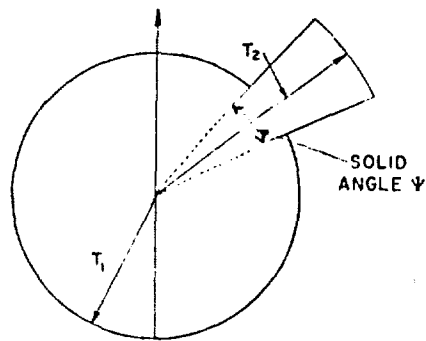


Fig. 1 - Schematic presentation of the angular distribution of the noise voltage.

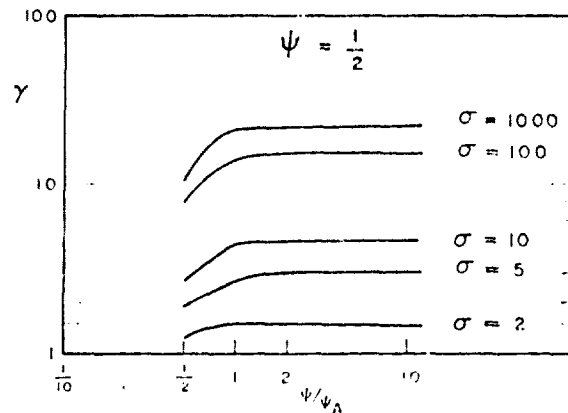


Fig. 2 - Dependence of discrimination factor on matching of array beam width to width of power peak.

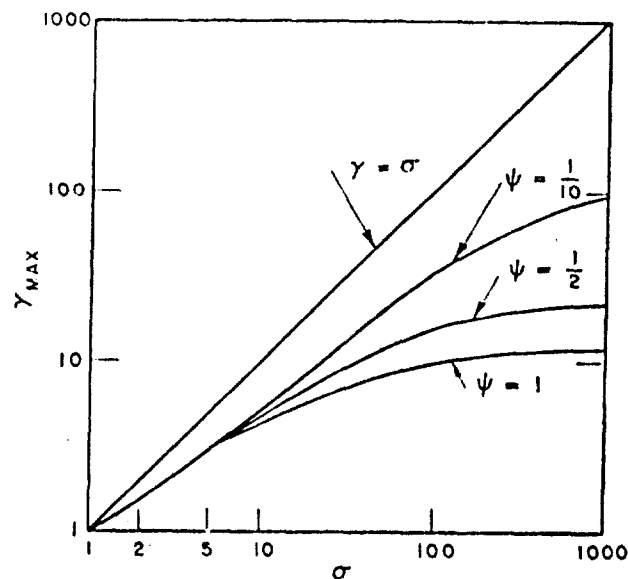


Fig. 3 - Maximum discrimination factor vs power ratio.

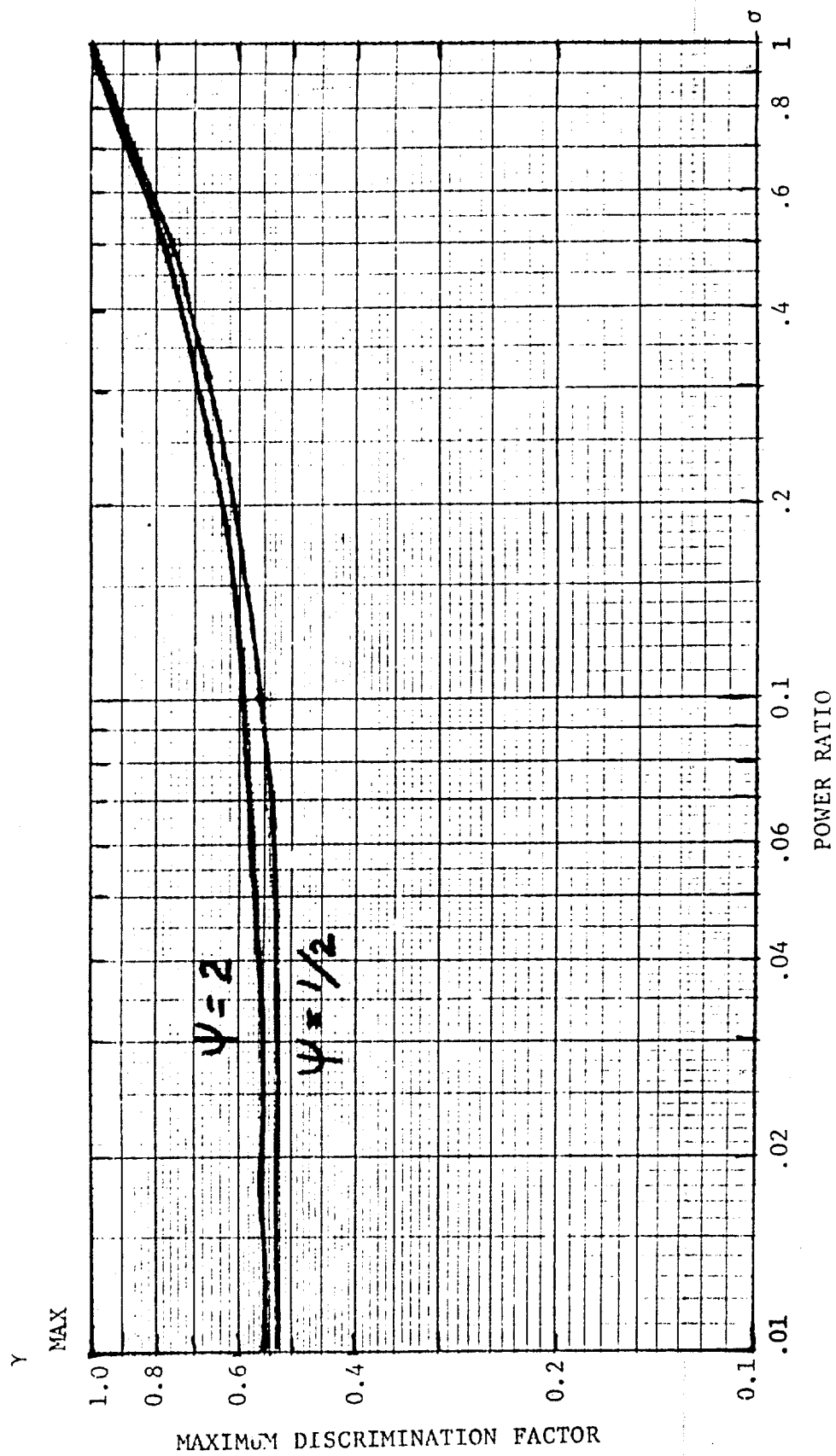


Fig. 4 - Maximum discrimination factor for low values of power ratio

than the ability to measure a peak. A decrease in the shipping noise is predicted near the horizontal, and so the curves shown in Fig. 4 are of practical importance.

Bracewell and Roberts recommend a method of "Successive Substitutions" to restore the detail lost by measuring with a finite array. The method assumes first that the measured data is correct and, using the array beam pattern calculates the measurements which would have occurred if the first assumption had been correct. The differences between the first assumption and the result of the calculation are then used to modify the original assumption. The beam pattern is again used to calculate the results which should have been obtained if the second assumption was correct, etc. Bracewell and Roberts claim that when the process converges, it converges to the "principal solution".

Axelrod, Schoomer and VonWinkle, after proving that the procedure minimizes mean square error, essentially form the equation:

$$N(\theta)\sin\theta = \sum C_k g_k(\theta)$$

where $N(\theta)$ is the noise field directivity, C_k are constants to be determined and $g_k(\theta)$ is the beam pattern when steered in the k^{th} direction. They multiply by $g_j(\theta)$ and integrate over the vertical angle range.

$$\int_0^\pi N(\theta)\sin\theta d\theta = \sum C_k \int_0^\pi g_k(\theta)g_j(\theta)d\theta = U_j$$

The left side of the equation is U_j , the array output measured when the array is steered in the j^{th} direction and the integral on the right is computable. It only remains to solve for the C_k and substitute in the original equation. In essence this is a simultaneous solution of the equations Bracewell and Roberts solve interactively.

Fox uses a very similar technique; he writes

$$V_m^2 = 2\pi K^2 \int_{\Theta_{n_1}}^{\Theta_{n_2}} F_m(\Theta) N(\Theta) \sin(\Theta) d\Theta$$

where V_m^2 is the array output when it is steered in the m^{th} direction and $F_m(\Theta)$ is the beam pattern when steered in the m^{th} direction and $N(\Theta)$ is the noise directivity. He approximates $N(\Theta)$ as a stepped function and writes;

$$V_m^2 = 2\pi K^2 \sum_n N_n \int_{\Theta_{n_1}}^{\Theta_{n_2}} F_m(\Theta) \sin \Theta d\Theta = 2\pi K^2 \sum_n A_{m,n} N_n$$

where

$$A_{m,n} = \int_{\Theta_{n_1}}^{\Theta_{n_2}} F_m(\Theta) \sin \Theta d\Theta$$

and is easily calculated. It only remains to solve for the N_n , which are values on the function $N(\Theta)$. This is an even more direct simultaneous solution of Bracewell and Roberts' equations.

Fox reports that the inverse of $A_{m,n}$ matrix was extremely sensitive to small measurement errors; and he then used Bracewell and Roberts' method. Axelrod, Shoomer and VonWinkle smoothed their data before attempting the inversion.

Anderson and Tittle use a procedure which is similar to that of Axelrod, Schoomer and VonWinkle except that instead of writing the noise directivity function as a sum of beam patterns they write both the noise directivity function and the beam pattern as a sum of beam patterns for pairs of elements with the array interelement spacings and then solve the coefficients for these functions.

This emphasizes the point that the output of an array can be calculated from the output of pairs having each interelement spacing if the assumption is made that all pairs with the same spacing would have the same output. When two signals of the same frequency are arriving simultaneously from two different directions then separate output pairs will not produce the same output.

Anderson and Tittle also propose an array which is evenly spaced except for a group of closely and evenly spaced elements between the first and second elements. They point out that the element spacings are harmonically related and that all element spacings in the series are present. This reduces the number of elements to achieve all interelement spacings in the series, reduces the number of interelement spacings, and hence, the size of the matrix to be inverted. Further, this allows the noise directivity function and the array output to be written as Fourier series and allows the coefficients to be determined by a process equivalent to Fourier analysis (instead of matrix inversion) when the element spacings are all multiples of $\lambda/2$. The Fourier expansion of the noise directivity function principal solution is then a partial expansion of the true directivity function out to the array cutoff frequency.

All of these data reduction schemes suffer from a self-imposed restriction that inherently makes it difficult to recover the principal solution; they start from the array measurements instead of the element outputs. The array has a cutoff frequency and a lowpass characteristic in the spatial frequency domain. Recovery of the high frequency portion of the spatial frequency spectrum (up to the cutoff) is analogous to the problem in design of a repeater to restore high frequency line losses or in the design of a servomechanism compensating lead network. The process of inferring the correct value from a small residual inevitably is sensitive to noise. Bracewell and Roberts use the example of a uniformly illuminated antenna. The power response vs angle is

$$A(\phi) = \frac{\lambda}{\omega} \left\{ \frac{\sin \frac{\pi \phi \omega}{\lambda}}{\pi \phi} \right\}^2$$

and the Fourier transform of the angle response in the spatial frequency domain $|s|$ is the convolution of two rectangular functions or a triangular function as shown in Fig. 5 reproduced from Bracewell and Roberts. They continue and show the effect of such an array on the spatial frequency representation of a noise directivity function. See Fig. 6.

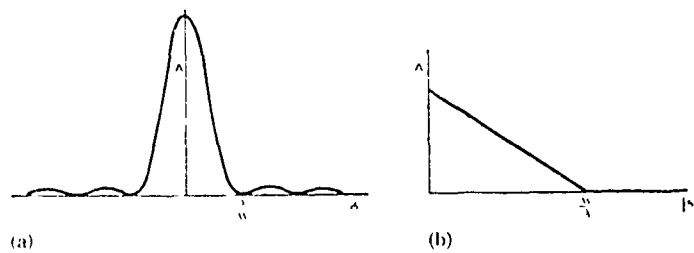


Fig. 5 - The response to a point source, $A(\phi)$, and its Fourier transform $\bar{A}(s)$ for a uniformly illuminated aperture.

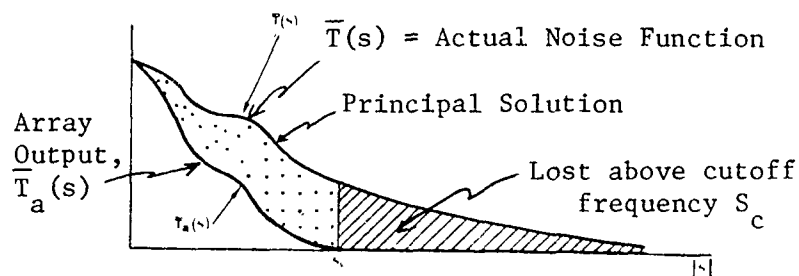


Fig. 6 - Showing how the spectrum of a smoothed distribution, $\bar{T}_a(s)$, is related to the spectrum of the original distribution $\bar{T}(s)$.

They also point out that the unattenuated high spatial frequency components can be obtained from an interferometer used at all spacings from zero up to the aerial width. Similarly, the outputs from array element pairs with different spacings may be used to obtain these high frequency components without attenuation. Using Stone's notation, the instantaneous voltage response of an array of omnidirectional elements is

$$R(t) = \sum_{n=1}^N a_n \int_{\Omega} F_n(t, \Omega) d\Omega$$

where $a_n F_n(t, \Omega)$ is the response of the n^{th} element due to noise sources in the solid angle element Ω and the integration is over the complete sphere. If the array output is square law detected and averaged, one obtains

$$\frac{1}{T} \int_0^T R^2(t) dt = \sum_{m=1}^N \sum_{n=1}^N a_m a_n \frac{1}{T} \int_0^T dt \int_{\Omega, \Omega'} d\Omega d\Omega' F_m(t, \Omega) F_n(t, \Omega')$$

If one could assume that the noise sources in different directions were independent, then one could make the simplification

$$\frac{1}{T} \int_0^T R^2(t) dt = \sum_m \sum_n a_m a_n \int_{\Omega} P_{mn}(\Omega) d\Omega$$

where

$$P_{mn}(\Omega) = \frac{1}{T} \int_0^T dt F_m(t, \Omega) F_n(t, \Omega)$$

This formulation shows that the array output is the sum of the time averaged products of all possible combinations of element pairs including the squares of the individual elements.

Each element pair measures a spatial frequency related to the spacing. The response of the array at each spatial frequency depends upon the number of element pairs having the spacing corresponding to that frequency. Adding all the element outputs and squaring is an inexpensive method of mechanizing a large number of product operations

but has limitations, e.g. the output is always positive and the response to the low spatial frequencies is higher than the response to high spatial frequencies. Faran and Hills (The Application of Correlation Techniques to Acoustic Receiving Systems; Harvard Acoustics Research Laboratory, T.M. 28, November 1, 1952) described systems of correlators, calculated signal-to-noise ratio performance of these systems, and pointed out that they resulted in beam patterns with zero average sidelobes. For applications where a "principal solution" is desired, a system combining the Anderson and Tittle array and a modified form of the Faran and Hills correlator processor might be used to find the principal solution directly. For example, consider the fifteen element array shown in Fig. 7 which is similar to the Anderson and Tittle array. With these fifteen elements it is possible to find pairs of elements spaced with all integral multiples of $\lambda/2$ from zero through 63. The average of the sum of the products of these pair outputs may be obtained as shown in Fig. 7 and as required for the principal solution. Appendix A gives an example of beam patterns using the above technique.

Even with a convenient means of measuring the principal solution that requires fewer hydrophones than a full line array, the question must be asked whether the "principal solution" is really desired. The concept of the radio astronomers that all spatial frequency components lower than the cutoff frequency should be recorded with their original amplitude is an appealing concept but this flat response in the spatial frequency domain implies a $(\sin x)/x$ beam pattern which is considered undesirable in the fields of sonar or frequency analysis where sidelobes and filter skirts as large as those expressed by $(\sin x)/x$ are unacceptable. In these other fields the decision between a narrow main lobe or low sidelobe is almost always resolved in favor of greatly reducing the sidelobes at the expense of a modest increase in the main lobe width. Thus in this case also it is recommended that the principal solution be abandoned in favor of a weighting function that reduces the sidelobes.

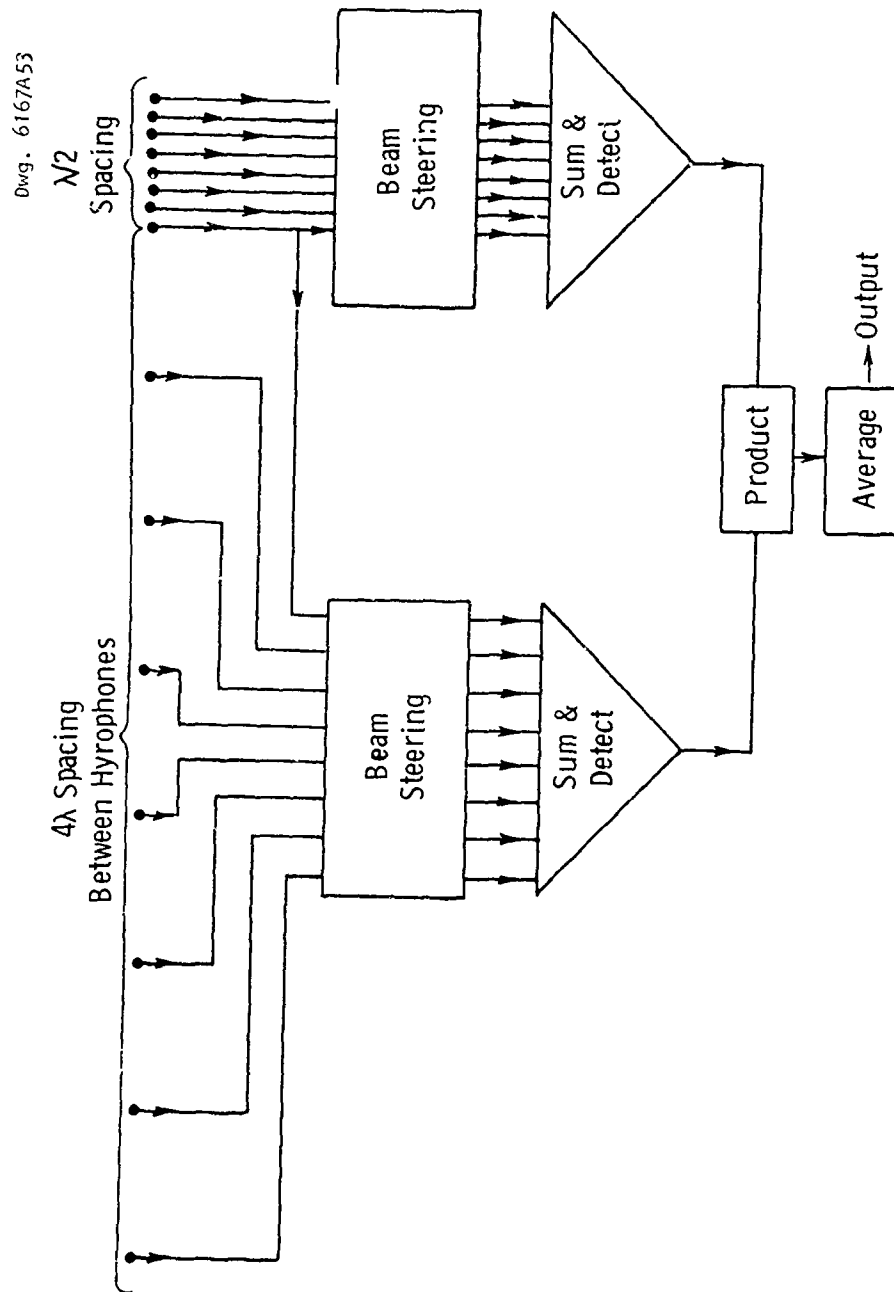


Fig. 7 - Anderson and Tittle Array with Faran and Hills Correlator

In selecting the actual beam pattern to be used, it is useful to examine the analogy between array processing and the time series analysis which was practiced before the advent of the FET. The lagged products which are the sample points on the auto-covariance function are analogous to the average element pair cross product, P_{mn} ; the spectral windows are analogous to the beam patterns. Blackham and Tukey (The Measurement of Power Spectra; Dover, 1959) review the theory and present the lag window-spectral window Fourier transform pairs. One of the best (the Hanning window) is obtained by averaging a spectral measurement with one half of the sum of the two adjacent measurements. By analogy, the weighted average of three adjacent principal solution measurements should give an excellent beam pattern. The spectral windows obtained by Hanning, and hence the beam pattern in the sonar case, have sidelobes with near zero average value as contrasted to the positive sidelobes obtained when element outputs are all summed and squared. This resolves part of the problem pointed out by Stone relative to sidelobe levels, but even if the mean sidelobe level is zero, a large sidelobe variance can make the measurements near a large peak meaningless. This introduces the other point emphasized by Blackman and Tukey; that whitening of the spectrum before measurement may be essential. The analog in the sonar case is the first stage of the adaptive signal processing as described by Edelblute, Fisk and Kinnison, "Criteria for Optimum-Signal Theory for Arrays," JASA, January 1967, pp 199-205. As pointed out by Blackman and Tukey, the whitening need only be approximate and might be calculated from previous data, preliminary results, or noise modelling; it is only required to reduce the effect of large source sidelobes; it is not the primary measurement.

It should not be inferred that the array with dual spacing described on the previous page is equivalent in performance to a filled array of the same length. The basic requirement is the measurement of the element pair averaged cross products. In the dual spacing array each element pair spacing is represented only once; in the filled array some of the spacings are represented many times and the

measurement can therefore be obtained to the same accuracy in a shorter time by averaging the large number of independent measurements. For this reason the basic recommendation is that the largest array that can be supported reliably be used. V. C. Anderson has stated that reduction of the sample variance in a situation that is nonstationary is one of the fundamental problems and multiple measurements are required.

In a program aimed at finding the arrival angle of sonic signals produced by ships as a function of frequency, it would seem desirable to use an array geometry and a processing method that can detect arrival angles at a single frequency for a number of sources. In practice, two or more signals arrive at an array from a single ship by different paths. They are time coherent but not space coherent because they arrive at different elevation angles. Therefore the signals received by one pair of hydrophones will generally be different from those received by another equally spaced pair at some other elevation. At any time there are hundreds of ships in the ocean, so that during a short observation time there will sometimes be signals from two or more vessels which both fall within a narrow frequency band. Therefore a processing method should be used which is capable of processing any number of signals of the same frequency coming from different directions.

II. ARRAY GEOMETRY AND PATTERNS

1. Array Geometry Considerations

Figure 1 illustrates the array geometry that was chosen for evaluation. It consists of 57 elements distributed vertically along a 1000 ft. length of cable. A longer cable with more elements would provide a better angular resolution. Figure 2 illustrates graphically the relationship between array length, minimum frequency, number of elements and beamwidth. The 5° , 10° and 20° loci assume that equal angular resolution is desired between some minimum frequency and a maximum frequency of 600 Hz.

Figure 3 from G. M. Wenz, JASA No. 34, p 1952 (1962) has two heavy solid lines that indicate the limits of the prevailing noise in the ocean. The area shaded with horizontal parallel lines indicates the signal level produced by using shipping traffic. It is above the lower noise curve from 7 Hz to 700 Hz. Therefore, it would be desirable to cover these two decades. However, at wind forces greater than Beaufort 2, the noise caused by the wind will be greater than the usual shipping noise at frequencies above 330 Hz. Therefore, the array was designed on the assumption that data would be collected at frequencies up to 330 Hz. To make the 1000 ft. array useful up to 660 Hz would require 72 elements and twice the bandwidth. Table 1 indicates how elements could be placed in such an array.

If hydrophone cost and bandwidth were not important considerations then it would be desirable to place elements one half wavelength apart for the entire length of the array. A 1000 ft. array with a top frequency of 330 Hz would then contain 134 elements. The angular resolution as a function of frequency is shown in Fig. 4. Such an array would require 2.4 times as much bandwidth as the 57 element array.

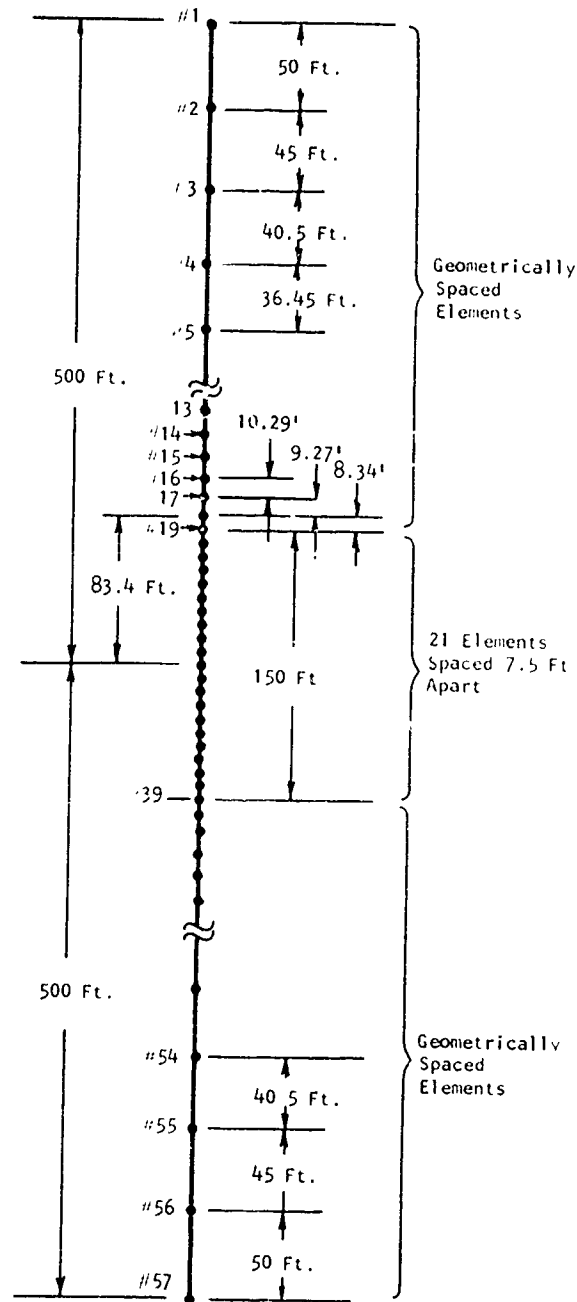


Fig. 1 - A 57 element hydrophone array with uniform center spacing and geometric outer spacing

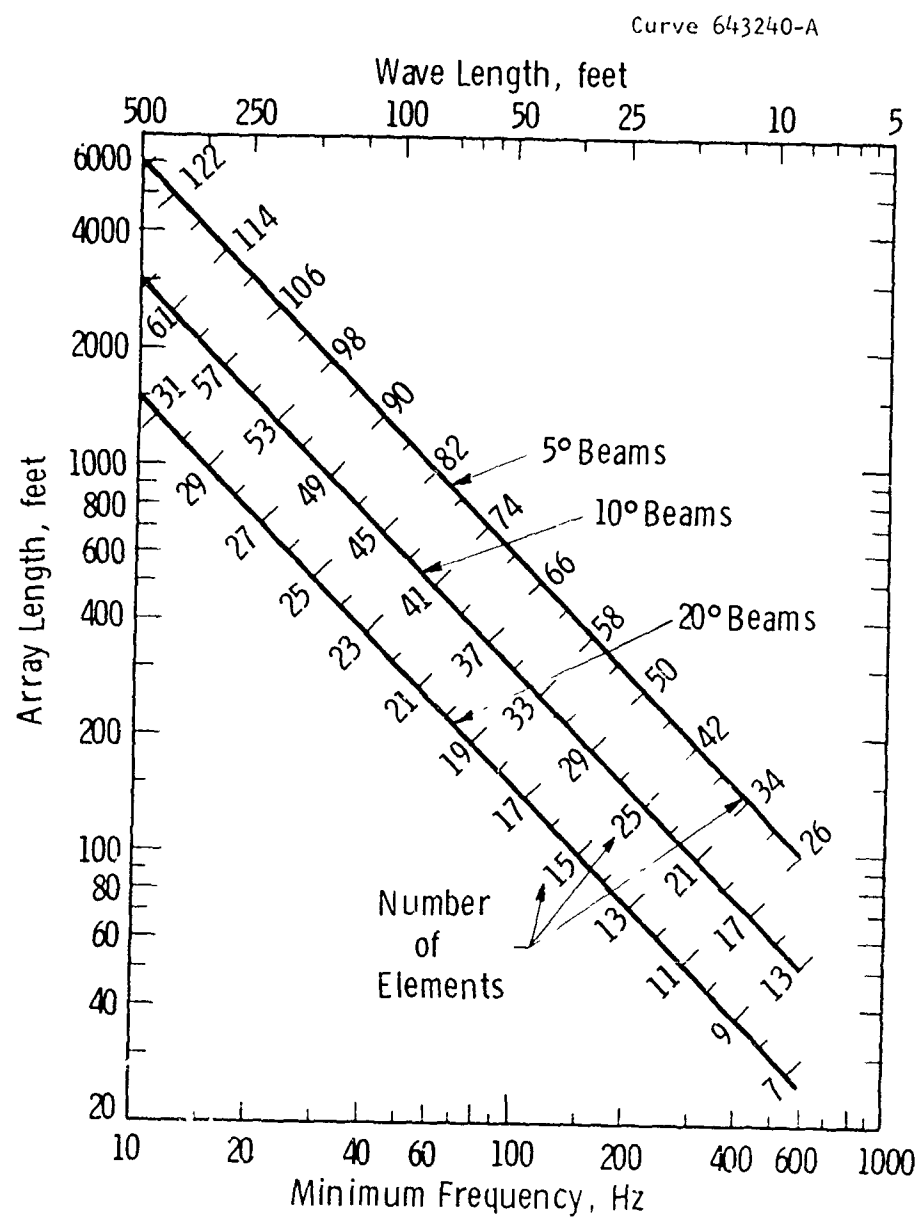


Fig. 2 - Number of transducers and array length for 5, 10, or 20 degree beams up to 600 Hz.

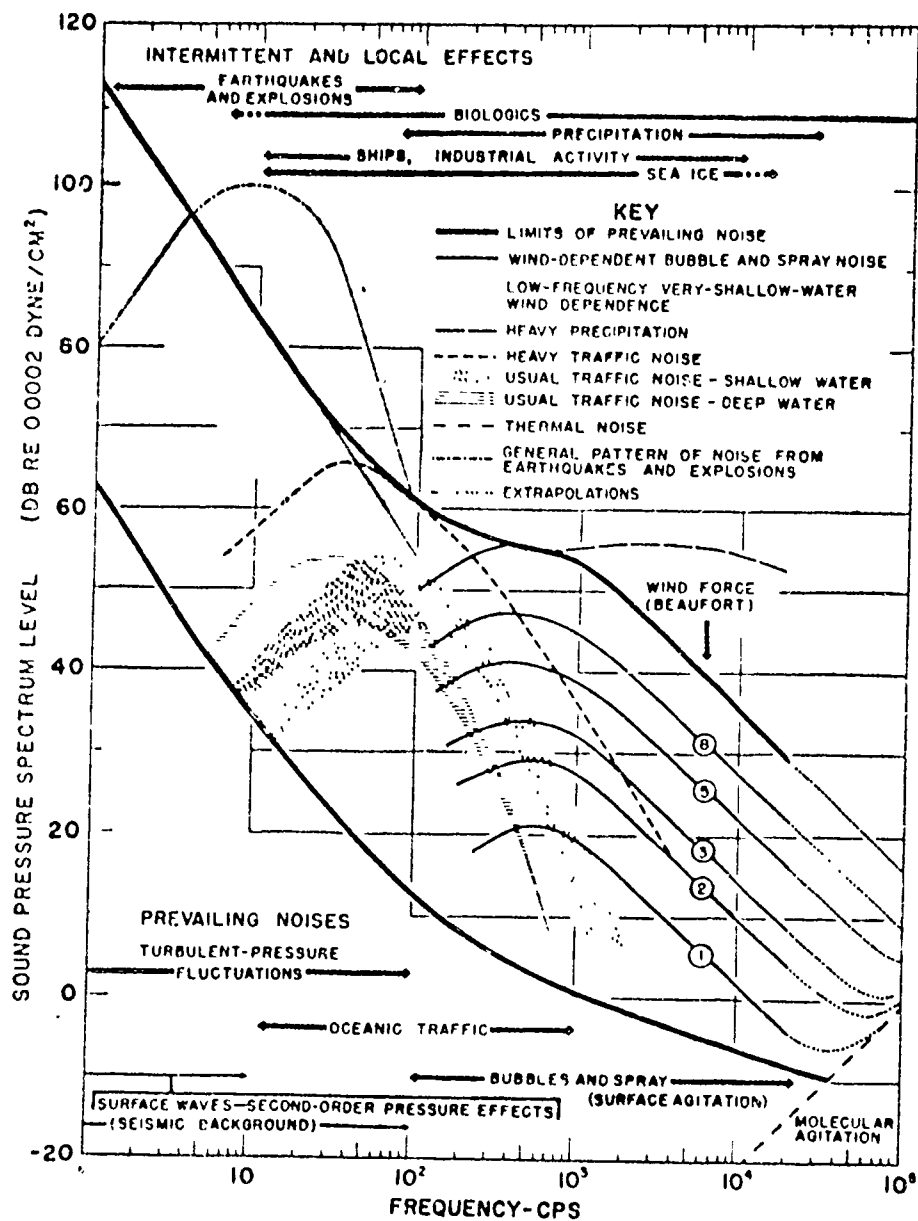


Fig. 3 - Acoustic ambient noise in the ocean as described by Wenz

Table 1 - Element Locations for the Top Half of a
71 Element Array Useful up to 666 Hz

Element No.	Distance from array center feet
1	500
2	450
3	405
4 to 18	Same as Table I
19	75
20	67.5
21	60.8
22	54.7
23	49.2
24	44.3
25	39.9
26	37.5
27	33.7
28	30.0
29	26.3
30	22.5
31	18.7
32	15.0
33	11.2
34	7.5
35	3.8
36	0

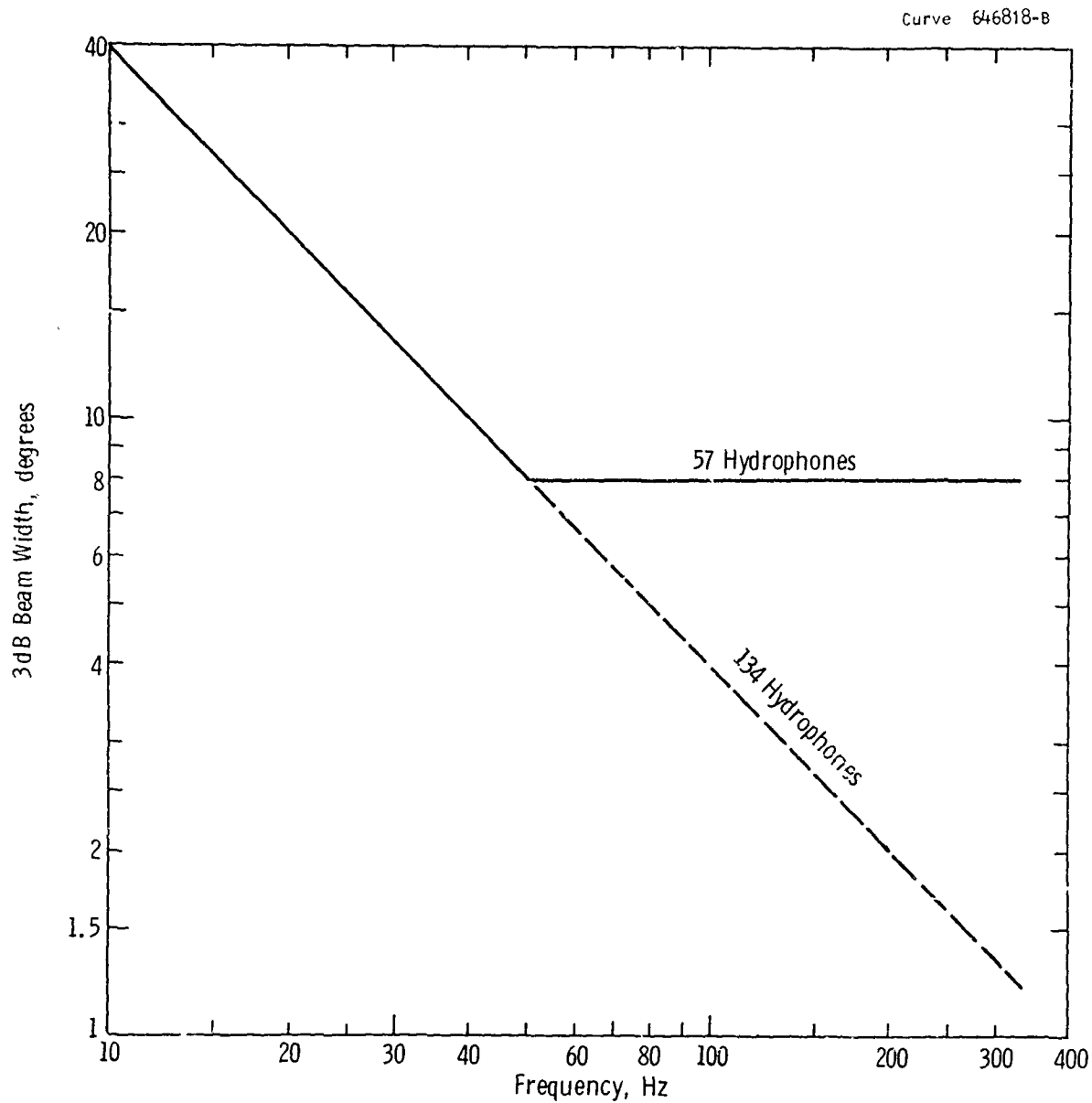


Fig. 4 - Angular resolution vs. frequency for a 1000 ft array with 134 hydrophones

At every frequency it is desirable to use as long an array as possible in order to achieve good angular resolution. However, when elements are used that are separated by more than one half wavelength ($\lambda/2$) then spurious signals or "grating lobes" appear. At $\lambda/2$ spacing no spurious response is produced by sources near the horizontal, but sources near $+90^\circ$ can not be distinguished from sources near -90° . If the primary region of interest is from $+75^\circ$ to -75° then spacing as great as $\lambda/2$ can be used. Table 2 lists the top frequency used by each element of the array. For example at a frequency of 104 Hz the 7 elements at each end of the array would be given zero weight because they are separated by more than $\lambda/2$. Since signals from all of the elements will be recorded, they all can be used if deemed desirable for a particular signal processing program.

2. Shading Function

A modified Dolph-Chebyshev shading function has been employed at a frequency of 333 Hz using the center 21 elements which are equally spaced and are one half wavelength apart at this frequency. This shading contour is plotted in Fig. 5. The dotted curve is a normal or Gaussian distribution which is very similar. At the low frequencies, 10 Hz to 50 Hz, signals from the entire 57 element array can be used. The shading function for any element was found on this curve and was then multiplied by a number equal to the distance of that element to its nearest neighbor. Table 2 illustrates the resulting weighting numbers. These range from 80 to 205. If we are interested only in frequencies below 50 Hz we would have used an element spacing which was inversely proportional to the desired shading function. This would have resulted in equal weight for all elements when we did our beam forming and signal processing. However, such a spacing would not be as satisfactory in the frequency range from 50 Hz to 330 Hz.

The weighting function chosen reduced spurious response below the 30 dB level and achieved an eight degree angular resolution near the horizon between the -3 dB points. A more severe weighting function

Table 2 - Element Locations and Shading Functions
for the Top Half of the 57 Element Array

Element Number	Distance from Array Center ft.	Distance to Nearest Element ft.	Maximum Frequency Hz.	50 Hz Shading	333 Hz Shading
1	500.0	50.00	50	80	0
2	450.0	45.00	56	96	0
3	405.0	40.50	62	131	0
4	364.5	36.45	69	155	0
5	328.0	32.80	76	179	0
6	295.2	29.52	85	189	0
7	265.7	26.57	94	205	0
8	239.1	23.91	105	204	0
9	215.2	21.52	116	201	0
10	193.7	19.37	129	194	0
11	174.3	17.43	143	183	0
12	156.9	15.69	159	173	0
13	141.2	14.12	177	162	0
14	127.1	12.71	197	151	0
15	114.4	11.44	219	139	0
16	102.9	10.29	243	128	0
17	92.7	9.27	270	116	0
18	83.4	8.34	300	106	0
19	75.1	7.51	333	96	12
20	67.5	7.50	333	97	16
21	60.0	7.50	333	98	25
22	52.5	7.50	333	98	36
23	45.0	7.50	333	99	48
24	37.5	7.50	333	99	61
25	30.0	7.50	333	99	73
26	22.5	7.50	333	100	84
27	15.0	7.50	333	100	93
28	7.5	7.50	333	100	98
29	0.0	7.50	333	100	100

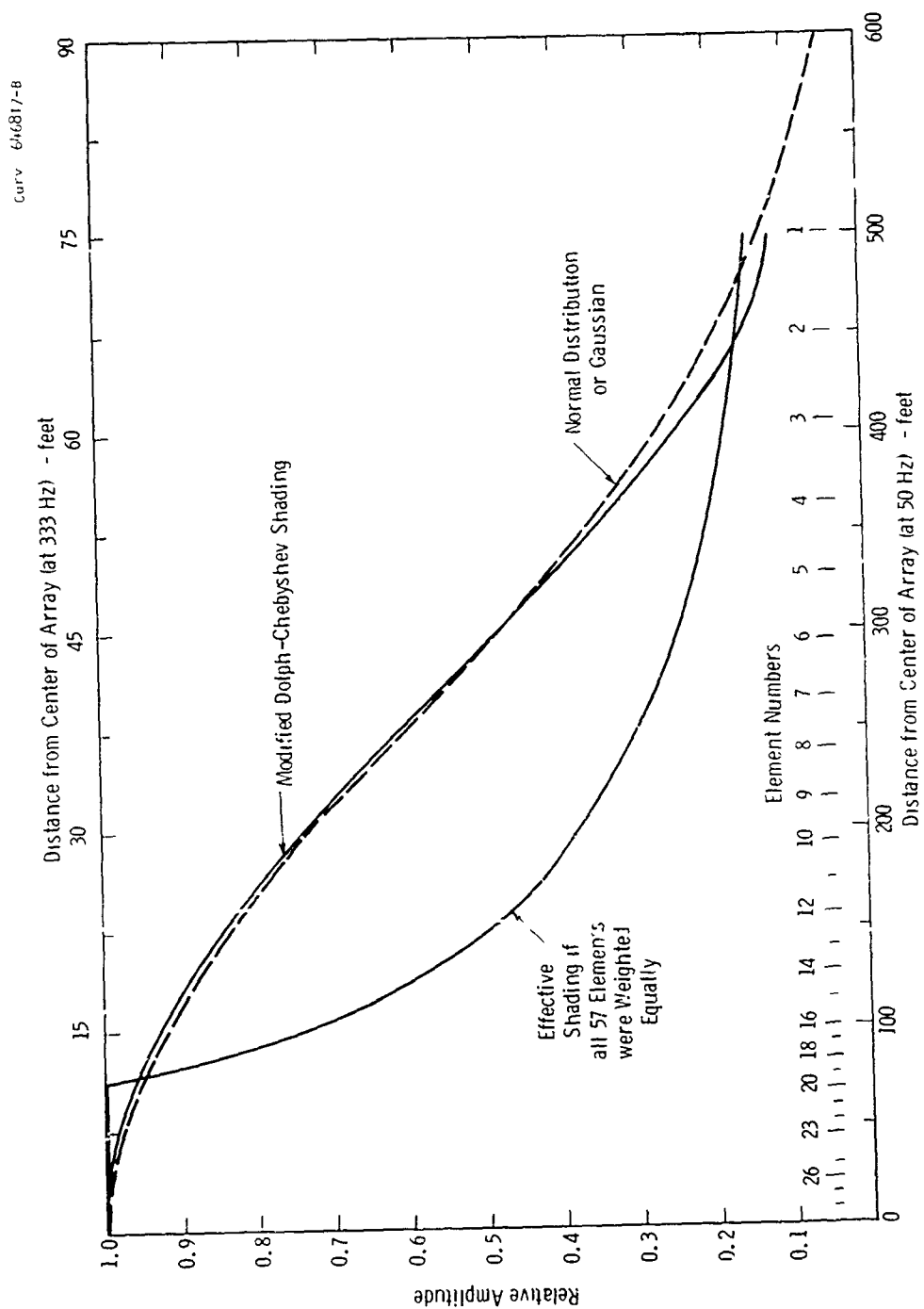


Fig. 5 - Shading functions

would have decreased the angular resolution. Conversely a flatter shading function would have provided better angular resolution but would have raised the level of the spurious signals.

With the array geometry shown in Fig. 1, and with equal weight applied to all elements, the resulting effective shading would be that shown by the lower curve of Fig. 5. This would yield poor vertical angular resolution at frequencies of 50 Hz and less.

3. Computer Simulated Patterns

To evaluate the effectiveness of the array at frequencies from 33 Hz to 330 Hz a set of four point sources were assumed. These were:

Angular Position	Relative Amplitudes	Relative Phase
+60°	10 -20 dB	100°
+14°	100 -0 dB	109°
-16°	80 -2 dB	-133°
-45°	32 -10 dB	-65°

The phase angles were picked from a random number table. A computer program was written to determine the amplitude and phase of the signals received at each element of the array for any frequency of interest. These signals are stored and can be processed in a variety of ways.

One very simple and practical way to determine the distribution of energy as a function of vertical angle is to apply a suitable shading or weighting function to the element of the array. This is to obtain good array directivity with low side lobes. The receive pattern is then reconstructed by forming the conjugates of these shaded receive vectors and considering them as sources. A computer simulated transmit pattern is obtained which is identical with the actual receive pattern and shows the resolution to which the direction of the 4 point sources is determined.

The computer program multiplies each of the received signals by a predetermined weighting function and reverses the sign of the phase angle to obtain a set of conjugate signals. If signals proportional to each of the conjugate signals were to be transmitted by the array, a unique vertical pattern would be produced. Such a pattern provides a good measure of the angular distribution of received energy. At any frequency of interest, such a pattern can be calculated and the signal level as a function of vertical angle can be produced. Since the hydrophones are reciprocal the transmit pattern and the receive pattern of the array are identical.

3.1 Center 21 Elements with No Shading

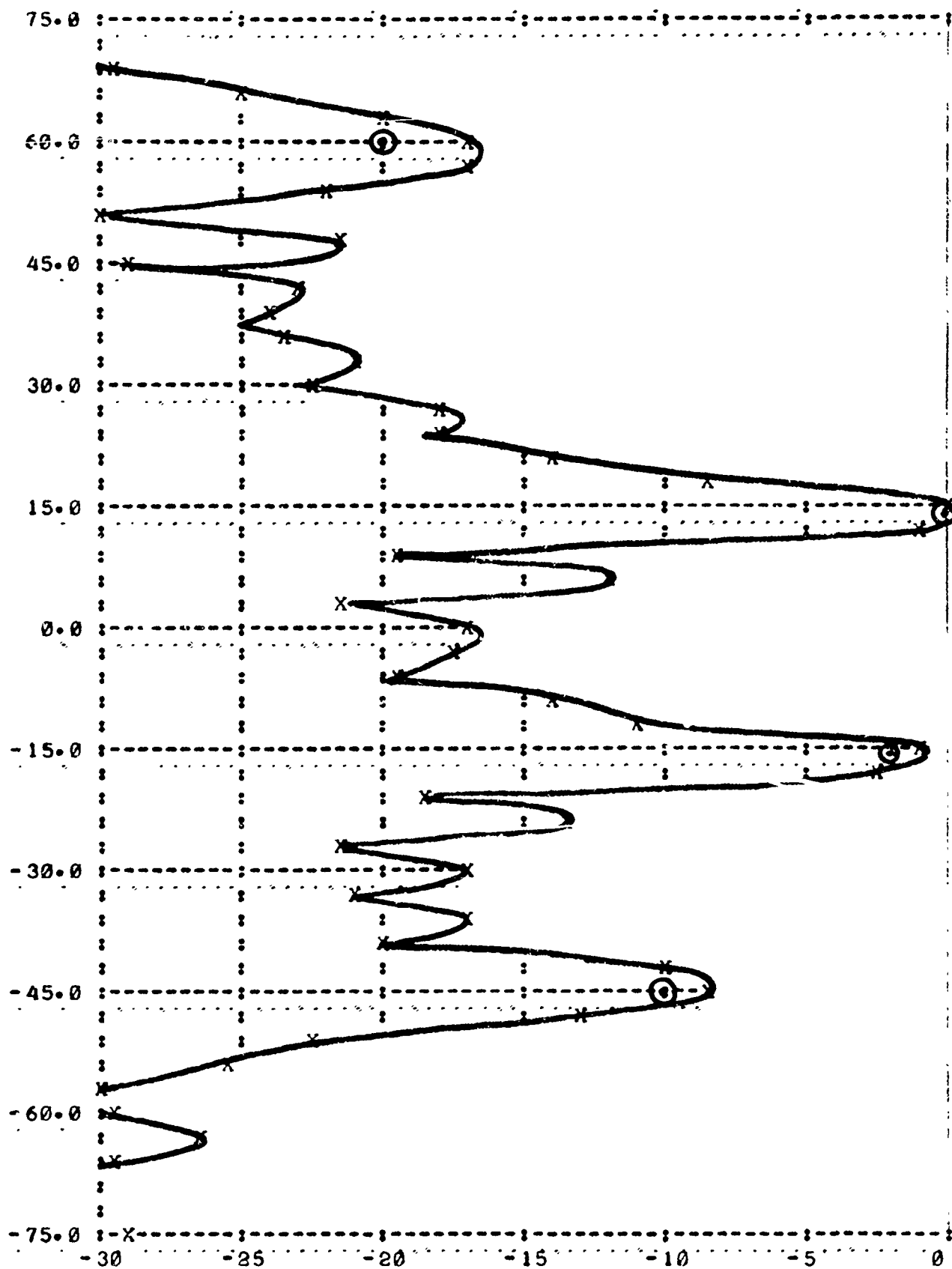
Figure 6 illustrates what a reconstruction pattern would look like at 333 Hz if unity shading were applied to the center 21 elements of the array and zero shading to all other elements. The four circled points indicate the four point sources. It is evident that the approximate positions and amplitudes of these sources are correctly reproduced, but that many other spurious response peaks are obtained.

3.2 Center 21 Elements with Shading

Figure 7 illustrates the type of pattern obtained at 333 Hz when the shading function shown in Table I was applied to the signals received by the center 21 elements of the array. Note that all four source signals are accurately displayed in both amplitude and position. All spurious responses at other angles are more than 30 dB below the strongest signal and so they are not visible in Fig. 7. Note that the beamwidths at -45° and $+60^\circ$ are greater than those at $+14^\circ$ and -16° . This is to be expected because the effective aperture of the array is proportional to the cosine of the elevation angle.

3.3 Entire 57 Elements at 50 Hz

When the shading function of Fig. 5 is modified to correct for the nonuniform spacing of elements the shading values shown in



Vertical angle in degrees vs. signal level in dB

Fig. 6 - 333 Hz, 21 elements, no shading, no noise, 4 point sources

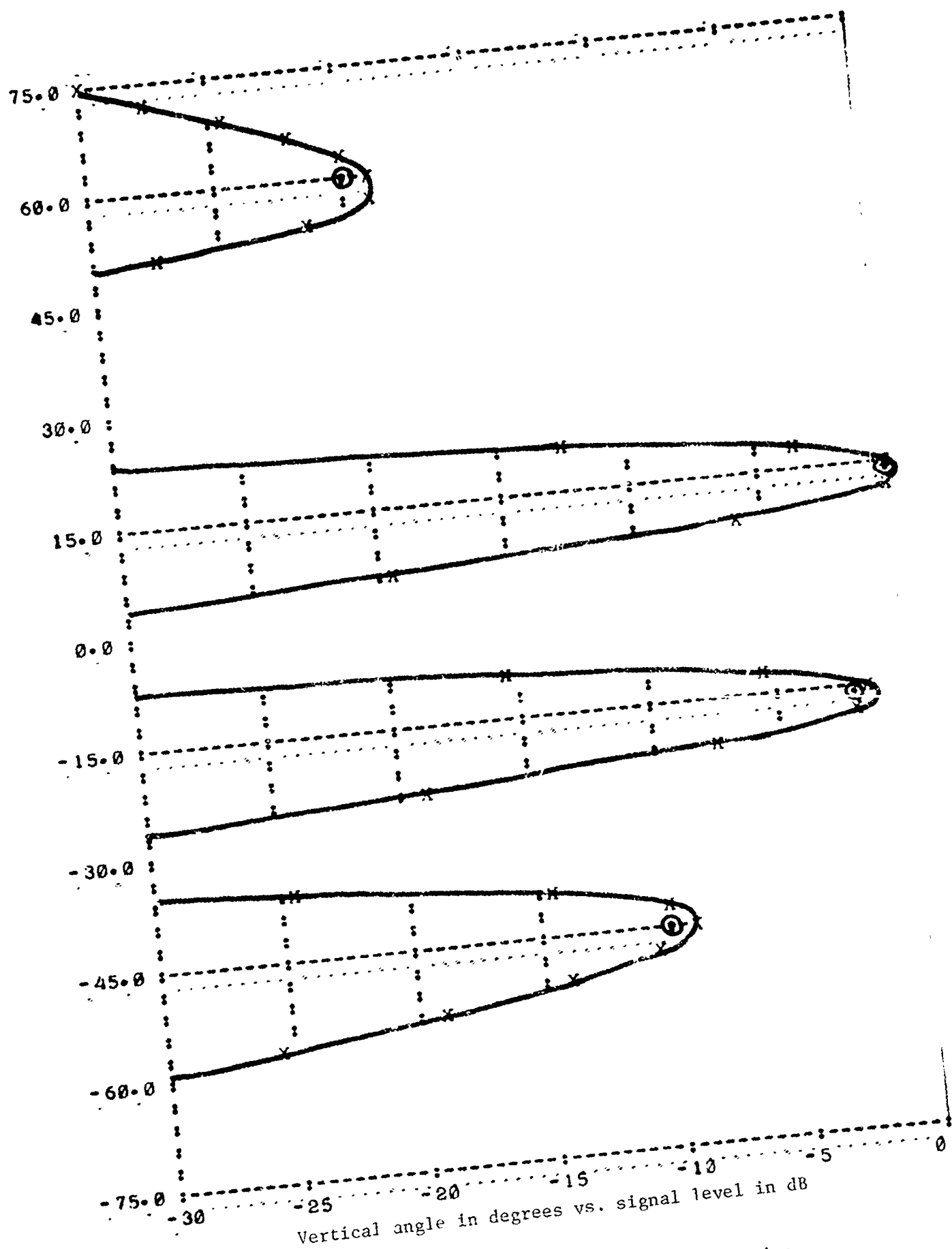


Fig. 7 - 333 Hz, 21 elements, good shading, no noise

Table 2 are obtained. At a frequency of 50 Hz the resulting pattern shown in Fig. 8 was obtained when the set of 57 received signals were processed by the computer program. Note that the resulting pattern is almost identical to that which was obtained at 333 Hz; compare Figs. 7 and 8. By using proper weighting functions, similar patterns can be obtained at all frequencies from 50 Hz to 333 Hz.

3.4 Frequencies below 50 Hz

At frequencies below 50 Hz the patterns are similar to that of Fig. 8, except that the resolution is reduced. Sidelobe levels remain unchanged. Figure 9 illustrates the resulting pattern at 33 Hz.

3.5 Frequencies above 333 Hz

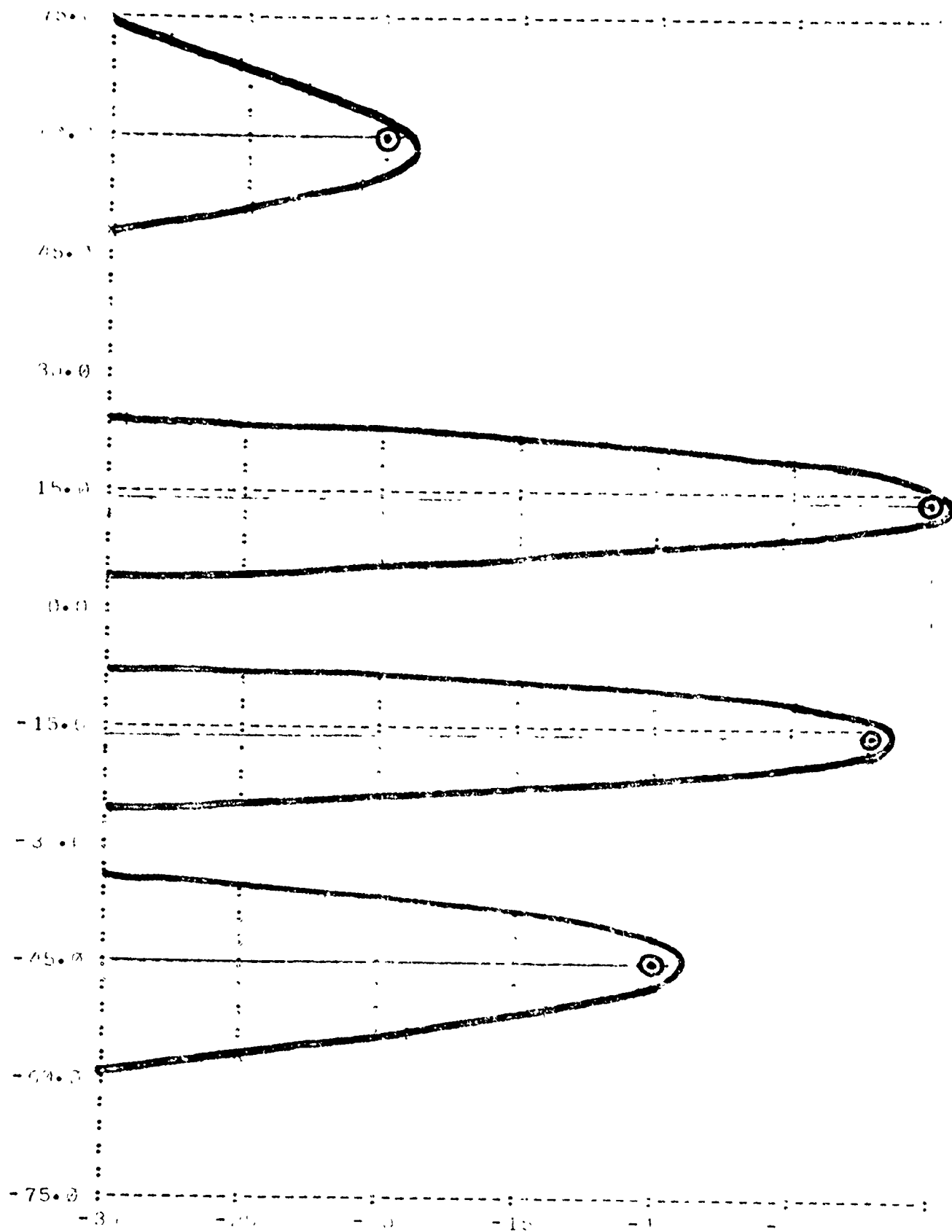
The center 21 elements of the array are $\lambda/2$ at 333 Hz so that at any higher frequency false responses are obtained which are sometimes called grating lobes. This is illustrated in Fig. 10 where the center 21 elements were used to detect the set of four sources at 400 Hz.

3.6 Improper Shading

When elements are used which are spaced further apart than $\lambda/2$ then the beam resolution is increased but ambiguous signals or sidelobes are produced. In Figs. 11, 12a and 12b, 100 Hz and 200 Hz signals were processed using the shading function that was proper for 50 Hz. The patterns are not satisfactory because the two weaker signals are badly distorted. When the proper shading function is used, the patterns given in Figs. 7 and 8 are obtained at 100 Hz and 200 Hz.

3.7 Effects of Noise

It is of interest to see how much the resulting pattern is degraded by Gaussian noise. The root mean square (RMS) noise level was compared to the RMS received signal level. The noise had a random phase and was assumed to be uncorrelated between hydrophone elements.



Vertical angle in degrees vs. signal level in dB

Fig. 8 - 50 Hz, 57 elements, good shading, no noise

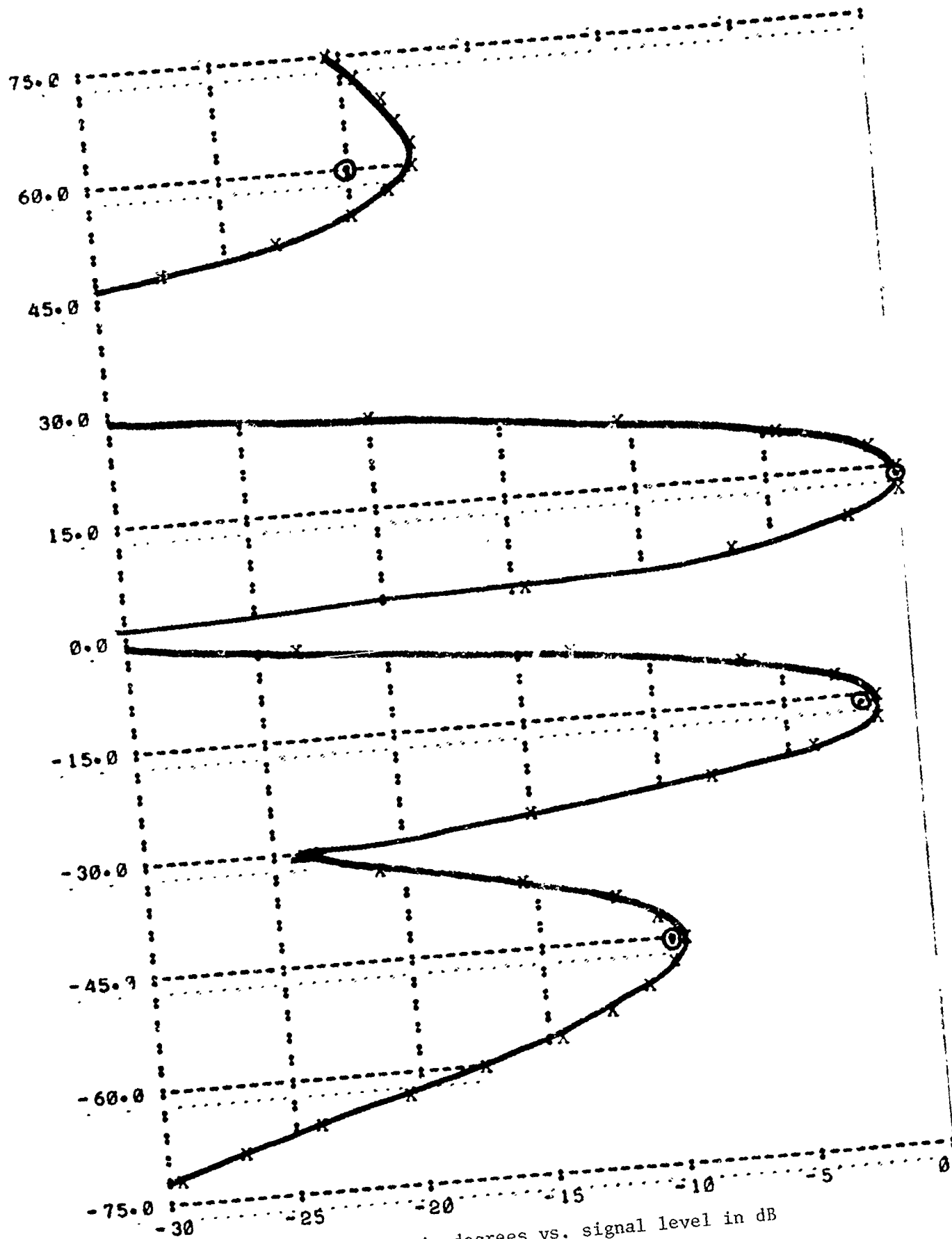
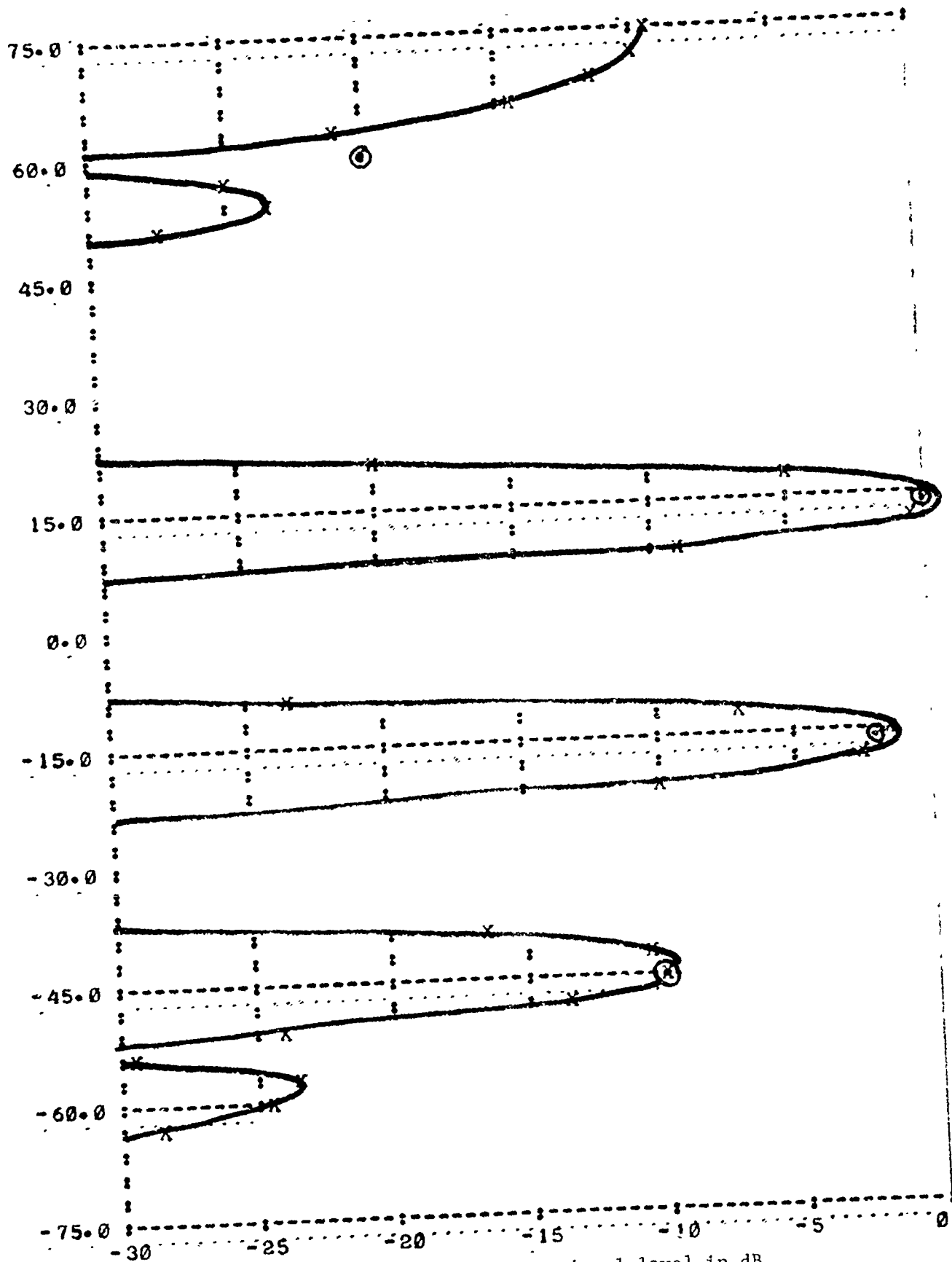


Fig. 9 - 33 Hz, 57 elements, good shading, no noise



Vertical angle in degrees vs. signal level in dB

Fig. 10 - 400 Hz, 21 elements, with shading, no noise

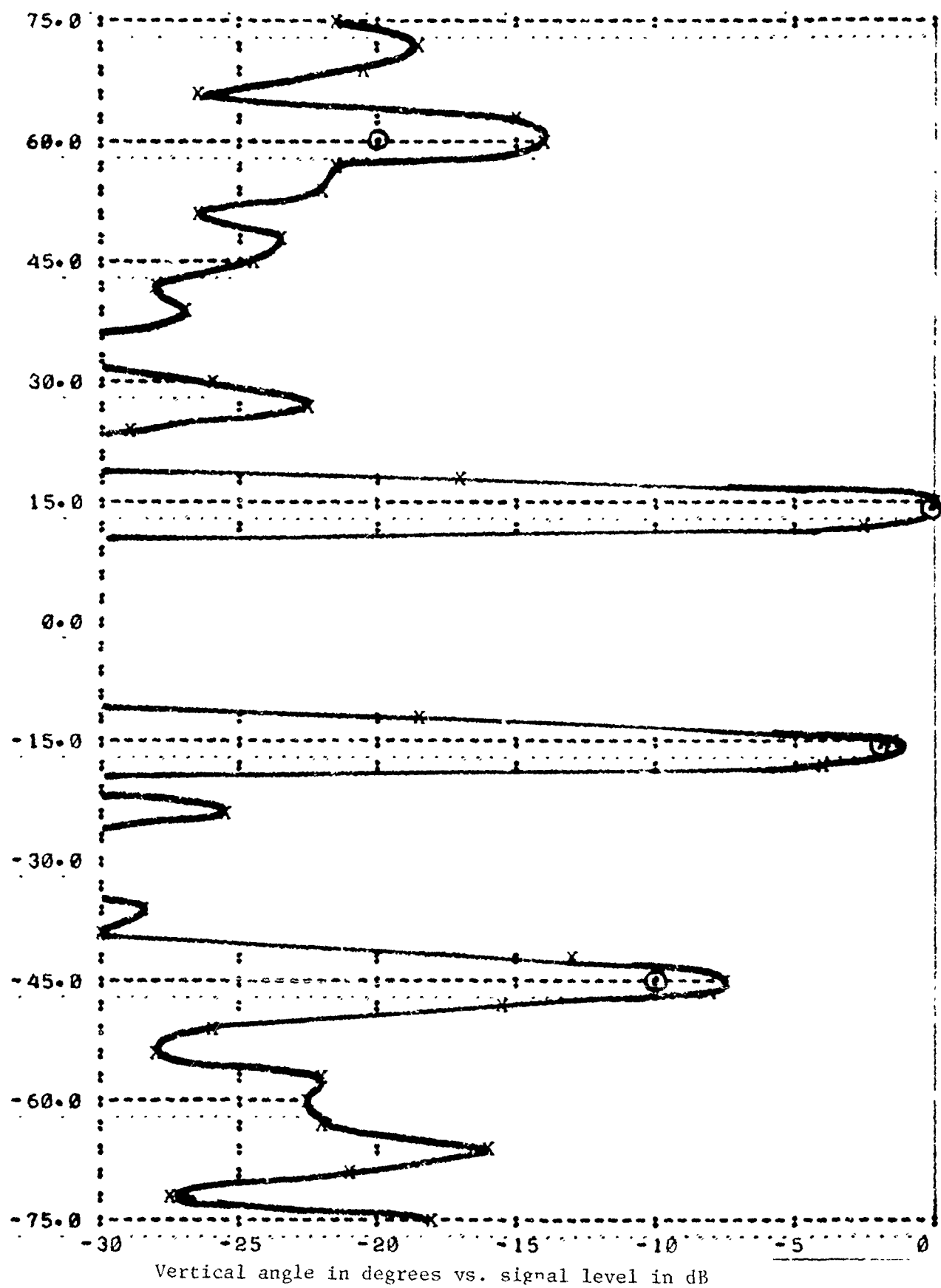


Fig. 11 - 100 Hz, 57 elements, poor shading, no noise

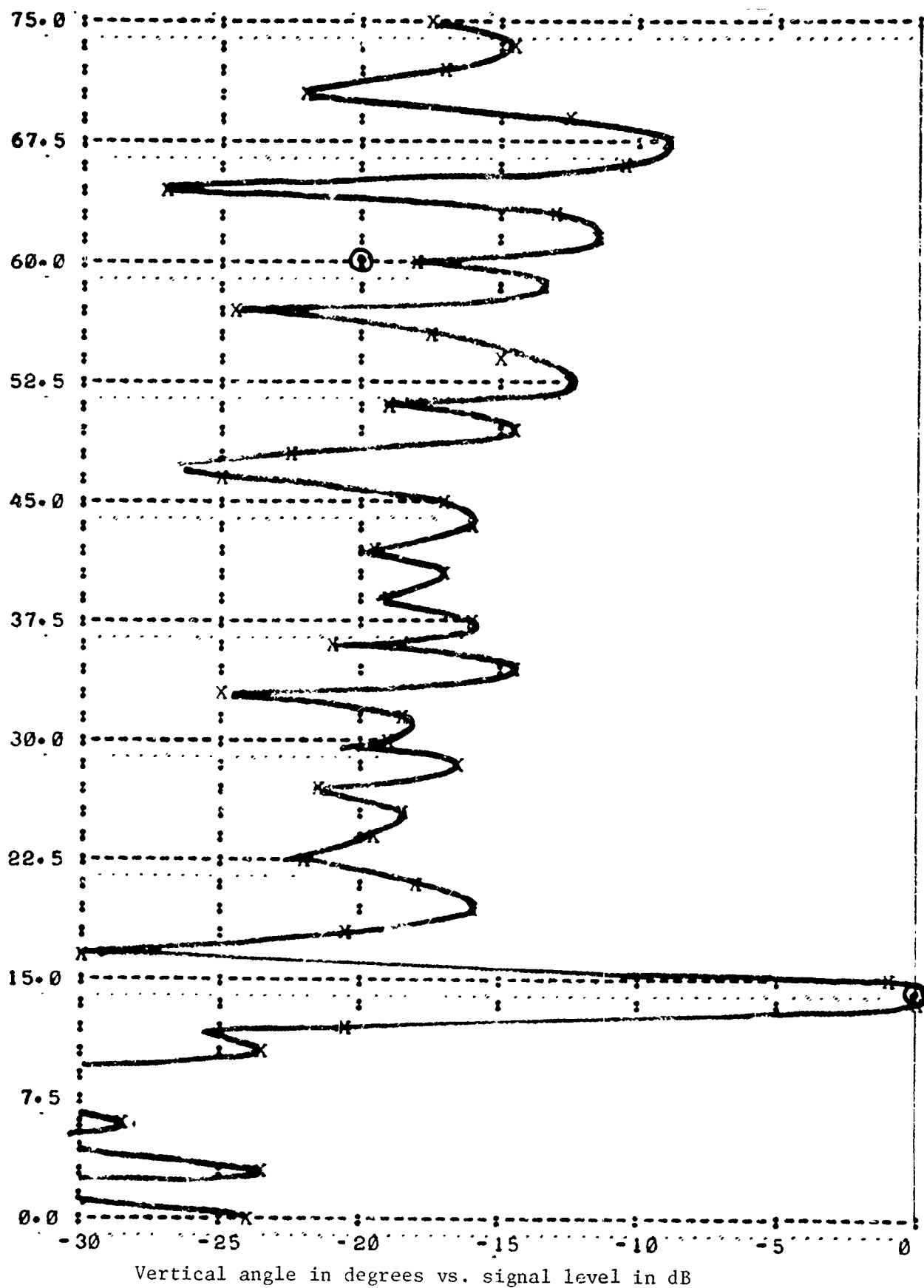
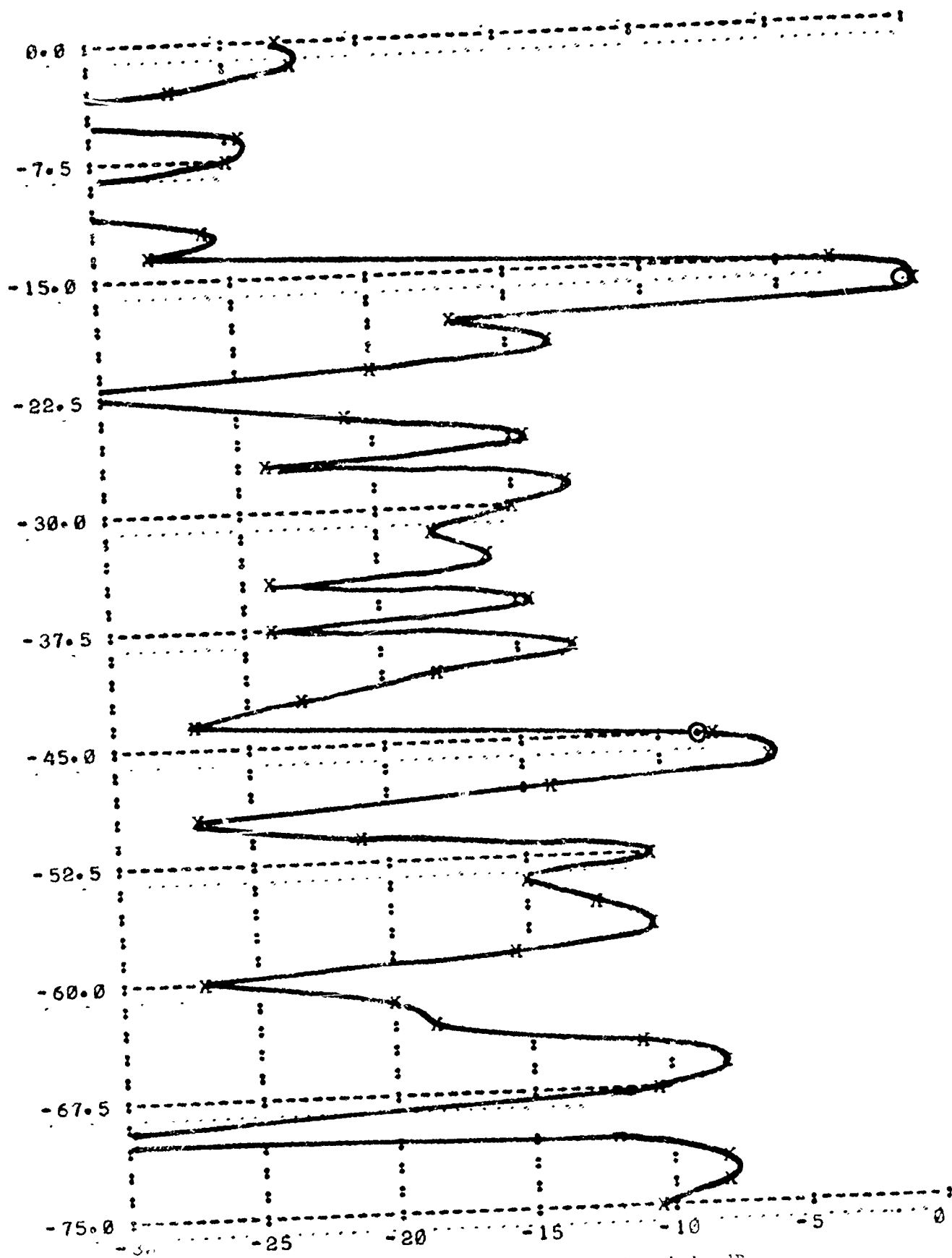


Fig. 12a- 200 Hz, 57 elements, poor shading, no noise



Vertical angle in degrees vs. signal level in dB
 Fig. 12b - 200 Hz, 57 elements, poor shading, no noise

It could be due to receiver noise and/or wind noise. Signal to noise (S/N) ratio of 20 dB and 0 dB are illustrated in Figs. 13a and 13b. A S/N ratio of 20 dB produced little distortion of the amplitude and elevation angle of the four sources, whereas S/N ratio of 0 dB showed considerable distortion of the noise source.

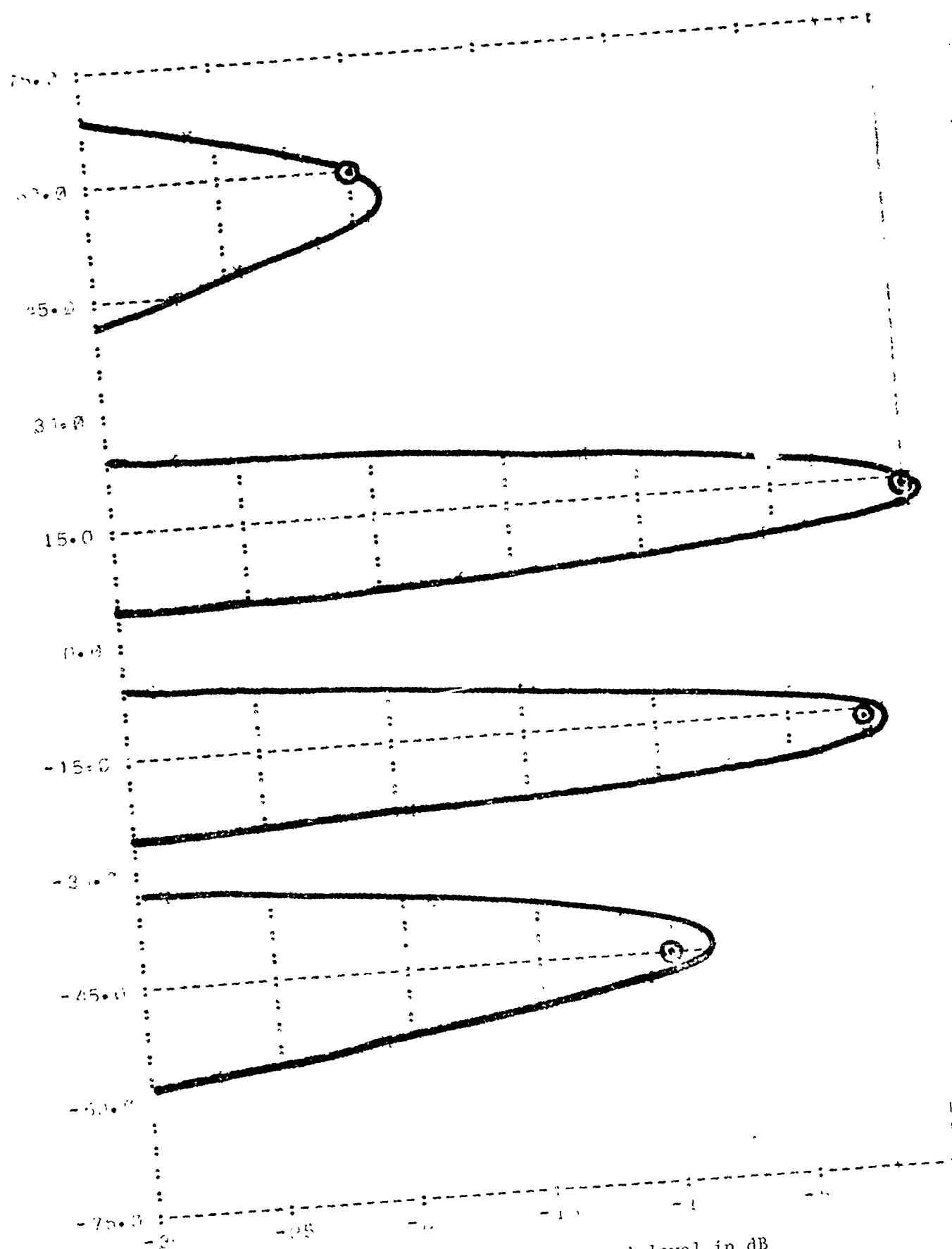
3.8 Beamwidth

With the shading function illustrated in Fig. 5, the beamwidth near the horizontal is about 8° . This is illustrated in Fig. 14. The beamwidth at the 15 dB points is 15° and at the 30 dB points is 19.5° .

3.9 Groups of Sources

An array of hydrophones can not distinguish between a single point source and a group of sources that occupy an angle smaller than half the beamwidth. Consequently in computing the angular distribution of shipping noise at any frequency nothing is gained by taking readings at intervals closer together than half the beamwidth of the array. Figure 15 illustrates the pattern resulting from a set of 7 point sources one degree apart in elevation having random phases. A comparison of Figs. 14 and 15 reveal that the beamwidth produced by the group of sources distributed over a 6° angle is only slightly different from the beam produced by the single point source

It is also of interest to see what type of pattern would be produced from a large number of sources distributed over a wide angle. This is illustrated in Fig. 16. A set of equal amplitude, random phase sources were placed at 5° intervals at angles from $+80^\circ$ to $+15^\circ$ and also from -15° to -80° . The circles indicate the locations of the sources. The X's are computed points on the resulting pattern. Note that the signal level between $+15^\circ$ and -15° is the same as it would have been if there had been only two point sources, one at $+15^\circ$ and one at -15° . Between $+80^\circ$ and -80° the level is below -30 dB.



Vertical angle in degrees vs. signal level in dB
 Fig. 13a - 50 Hz, 57 elements, good shading, S/N = 20 dB

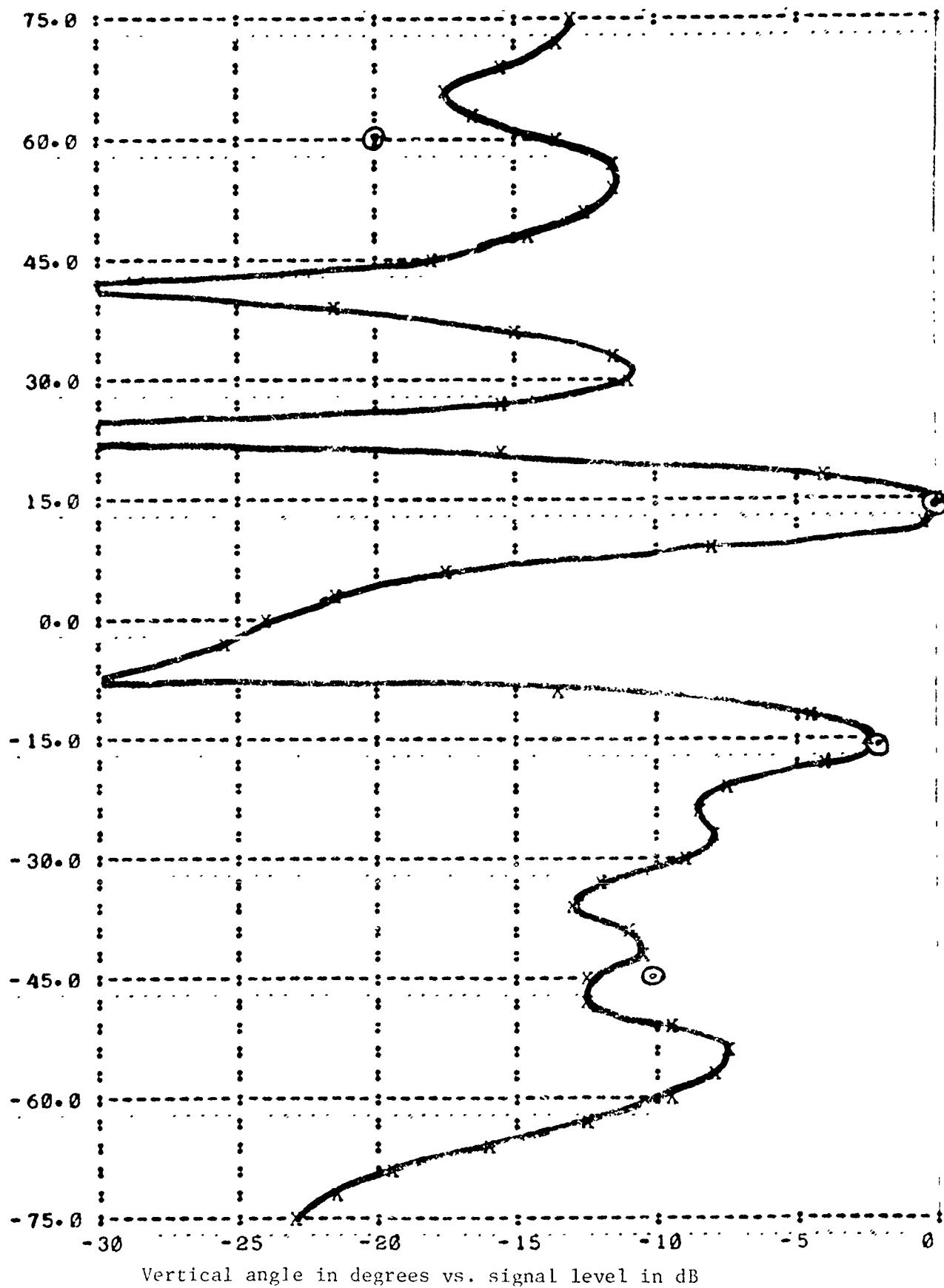


Fig. 13b - 50 Hz, 57 elements, good shading, S/N = 0 dB

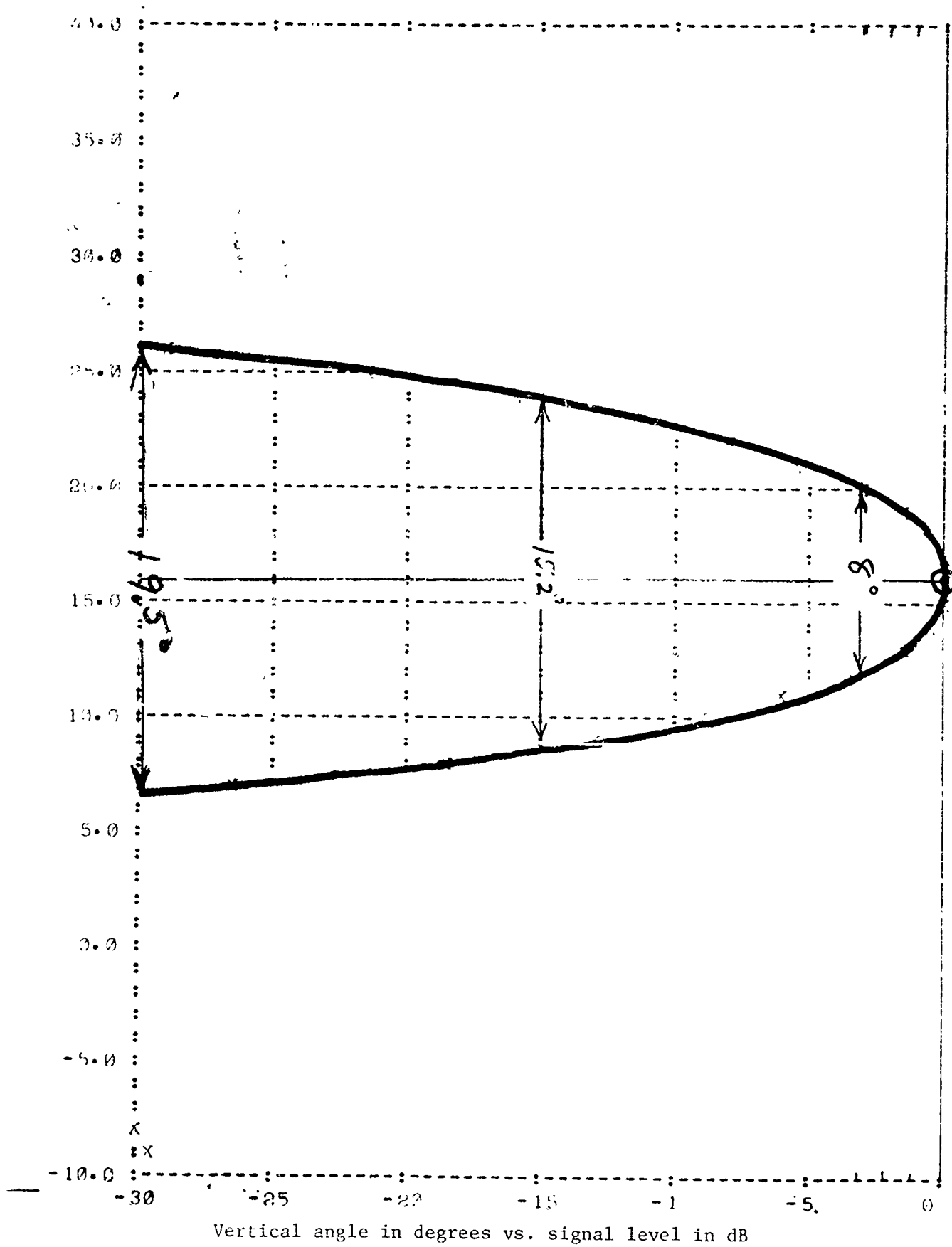


Fig. 14 - 50 Hz, 57 elements, good shading, no noise, single point source

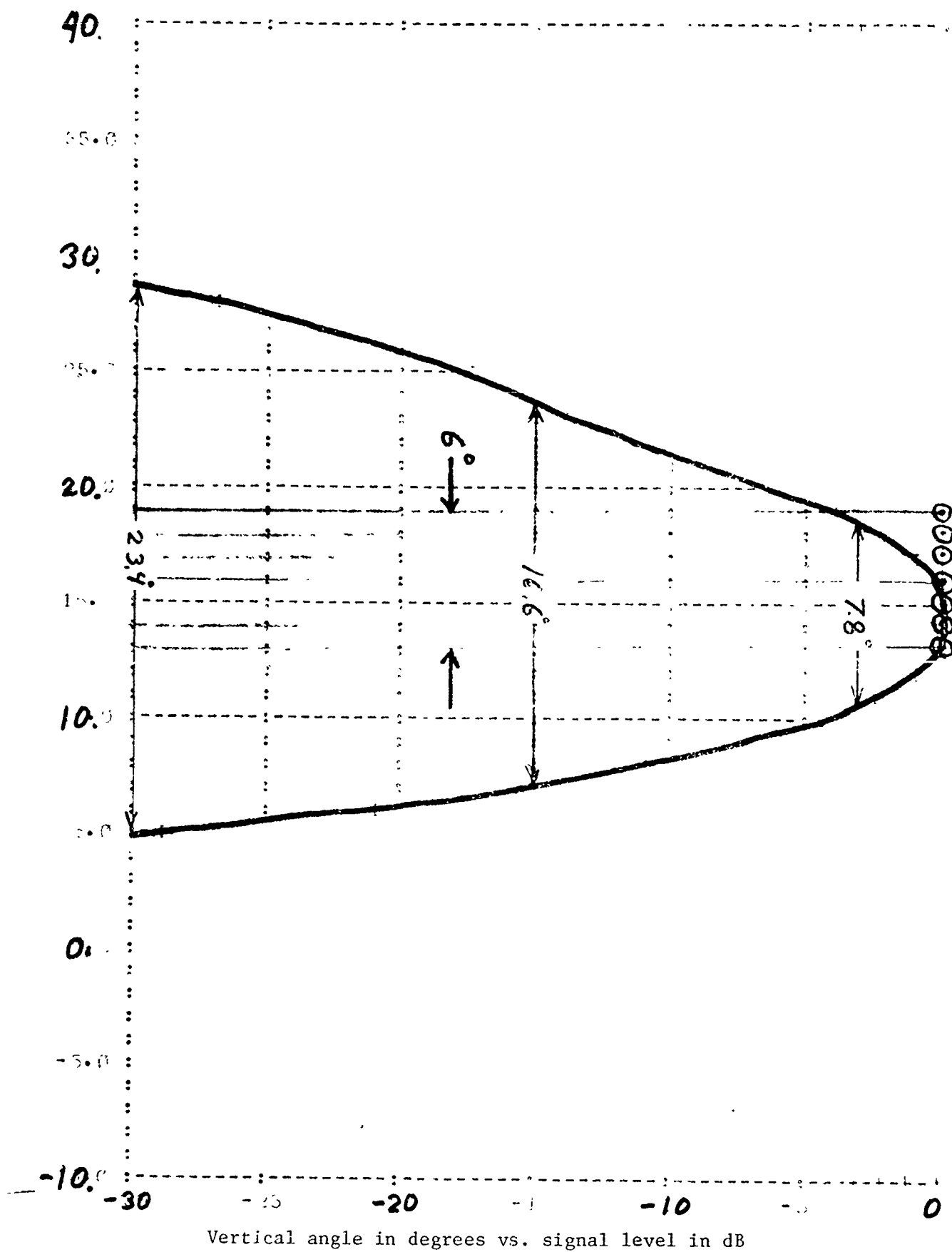
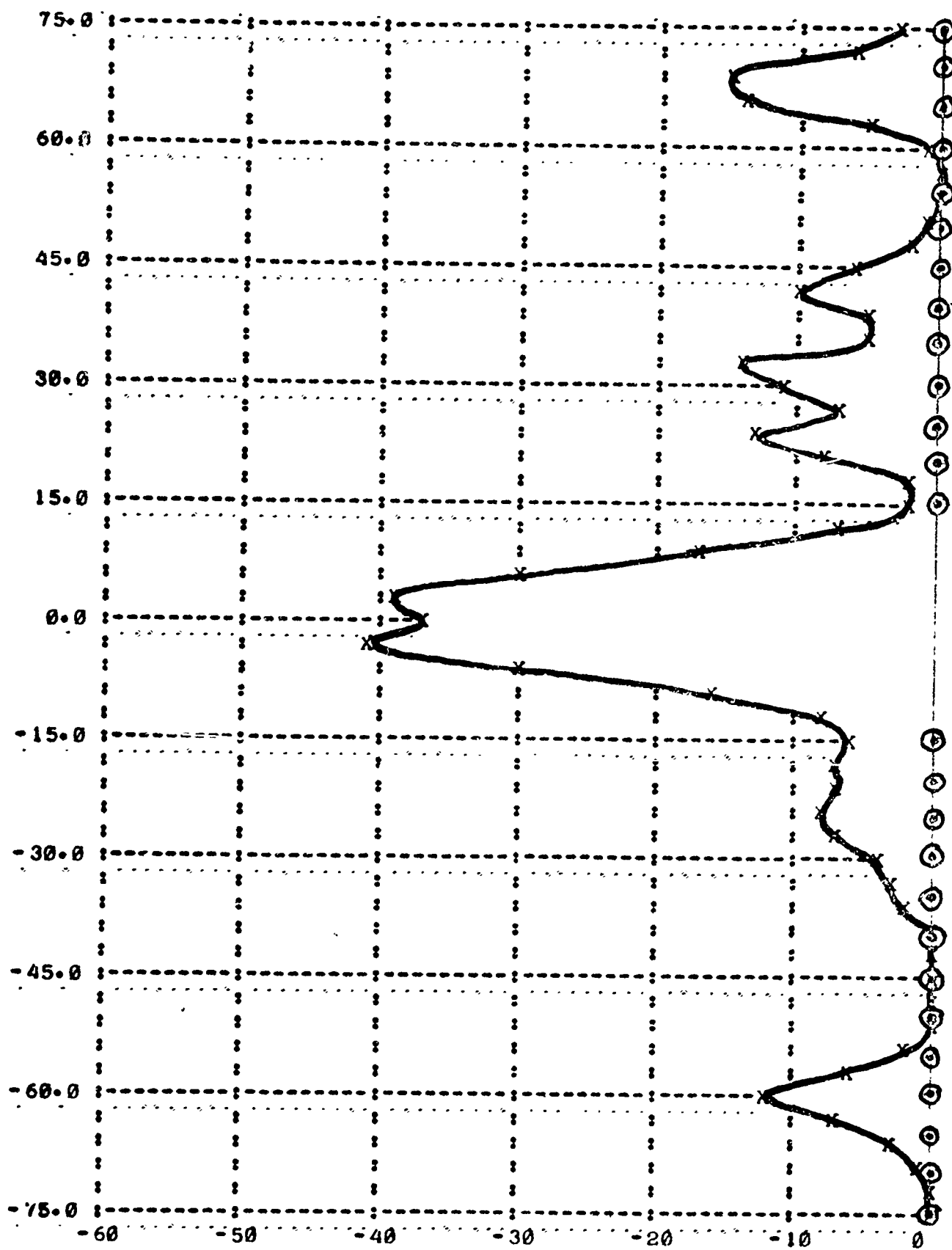


Fig. 15 - 50 Hz, 57 elements, good shading, no noise, 7 point source



Vertical angle in degrees vs. signal level in dB

Fig. 16 - 50 Hz, 57 elements, good shading, no noise, 28 point source

4. Spatial Frequencies

The pattern associated with an array of hydrophones can be considered to be composed of a set of harmonically related component frequencies. These can be found by taking the Fourier transform of the acoustic distribution. The highest spatial frequency present is called the cut off frequency. The inverse of this spatial frequency is an angle called the cut off period ϕ_c , and

$$\phi_c = \frac{\lambda}{w}$$

where w is the aperture width. For example, at 50 Hz, $\lambda = 100$ ft. and a 1000 ft. array will have a cut off period of 0.10 radian or 5.7° . Any observed distribution can be completely specified by calculating signal strength at discrete intervals which are no greater than $0.5 \phi_c$.

5. Cross Correlation Processing

If the signals from each of the ships were very broad band then all of the arrival angles could be determined using only two hydrophones. The output signals from the top element would be delayed a time $\pm \tau$ and multiplied by the signal from the lower element. Each value of τ would correspond to a particular elevation angle. The maximum delay τ used would be equal to the time it takes sound to travel from one hydrophone to the other. This would correspond to an arrival angle of 90° . In principle the two hydrophones could be close together but then a small noise would cause a large error in angle. Therefore a large separation would be desirable. However, if the elements are separated by more than one half wavelength at the lowest received frequency there will be an ambiguity in the arrival angle. In the proposed array we are interested in finding the arrival angle of a set of received signals that are all within a narrow frequency band.

Using the conjugate processing method, any number of sources having frequencies within the bandwidth of interest can be located.

III. HYDROPHONE AND PREAMPLIFIER

1. Input Spectrum

The frequency range of interest for passive array programs is from 10 Hertz to 2-1/2 kilohertz, and it is desired to measure the ambient sea noise in this region. Particular emphasis on the band from 10 Hz to 300 Hz is desired for long range reception. An estimate of the signal levels within this frequency band is necessary to the establishment of the system preamplifier requirements. Fortunately there exists the summaries of ambient noise measurements by Wenz,* plotted such that the abscissa is frequency in Hertz and the ordinate is sound pressure spectrum level related to one microbar. The lower Wenz level referred to hereafter is the sound pressure level as a function of frequency which is exceeded 95% of the time by a composite of wind dependent bubble and spray noise (for wind force 1) and usual traffic noise (deep water). Noise contributions generated in the hydrophone and preamplifier can be plotted in the same way through the use of the Free Field Voltage Sensitivity (FFVS) of the hydrophone. The following sections discuss the hydrophone and preamplifier as they relate to the Wenz curve and to acceleration canceling.

2. Acceleration Canceling Hydrophone

The Westinghouse acceleration canceling hydrophone provides a high acoustic-to-acceleration response ratio. It was specifically designed for long vertical arrays which required the hydrophones to be wound up on the drum of a winch. It is a cylinder 2.5 in. in diameter

*"Acoustic Ambient Noise in the Ocean: Spectra and Sources" Gordon M. Wenz. JASA Vol. 34, No. 12, p. 1936.

by 2.5 in. long. This small hydrophone achieves high signal power sensitivity through the use of a "thin" cylinder. Its thinness increases the ceramic stress, as well as the free (unclamped) capacity, both of which increase the cylinder's power sensitivity. Because of the reduced mass of the cylinder, the response to accelerations is minimized. The hydrophone is rugged and readily connected electrically and mechanically to the cable. A small preamplifier is potted with the hydrophone in each unit. Some of the salient features of the hydrophone are:

- Acceleration canceling in all directions
- A high acoustic-to-inertial response ratio
- A sensitivity of -90 dB v/ μ bar with a free capacity of 5000 picofarads
- Pressure equalization for deep sea operation
- Broad band operation of 5 to 10,000 Hz

It has complete acceleration canceling in all directions since the end support is symmetrically brought back to the center of gravity of the cylinder before attachment is made to the cable. Thus, cable acceleration (vibration) is introduced at the center of symmetry and produces signal canceling positive and negative stress variations in the cylinder. Care has been taken that the mechanical coupling of parts is not only symmetrically balanced but is sufficiently stable from a temperature, creep, and shock aspect to remain balanced. It detects low level, low frequency signals that are normally masked by noise from cable vibration or strumming.

A sensitive, very thin-walled piezoceramic cylinder is the heart of the sensor. The ceramic is poled lead titanate-lead zirconate which is quite stable from a temperature and aging standpoint. It has closed ends, but is free-flooded with compliant silicone oil internally and externally. The oil is coupled to the sea water by a thin elastomeric window protected from abrasion by a perforated stainless steel cover. A capillary tube restriction connects the internal and external oil cavities. The time delay associated with the restriction and internal

volume is such that below 5 Hz the cylinder is essentially free flooded and static pressure balanced. From 5 Hz up the cylinder has effectively closed ends and is very sensitive to acoustic pressure variations. It is off resonance and has a flat response of -90 dB v per μ bar from 5 Hz up to 10 kHz. Its response is also essentially independent of depth.

The elements have been tested at sea with results that show the system noise to be 10 dB lower than sea state zero noise. The hydrophone elements have been mechanically tested by passing them under load, back and forth over a sheave 1000 times without affecting the acceleration canceling.

A review was made relative to our hydrophone work carried out ten years ago for the inertia balanced units used for vertical arrays (see Appendix B). One of our old models was refitted with a new pre-amplifier with lower noise characteristics and sent to the Marine Physical Laboratories of Scripps, San Diego who under Dr. V. C. Anderson has been evaluating numerous hydrophones relative to acceleration response. Although the acceleration balance of this phone was roughly 10 dB noiser than the average of the phones produced in 1961-62 it has between 5 and 10 dB less response to acceleration than the best phones tested by MPL. In addition the new amplifier proved to be 10 dB quieter than the 1962 amplifier model.

A noise simulation computer program was written which included the following factors:

1. Minimum 5% Wenz sea noise as the input signal
2. Thermal noise of hydrophone due to its loss factor
3. Thermal noise of preamplifier input resistor
4. Equivalent series noise voltage of the preamplifier input field effect transistor (FEⁿ)
5. Equivalent shunt noise current of the input field effect transistor
6. Capacitance of the hydrophone

Good agreement was achieved between calculated noise and measured noise with the -90 dBV re 1 microbar, 5000 Pf hydrophone coupled to the new low noise preamplifier. Figure 1 shows the printout for the present hydrophone and latest preamplifier. For this case the piezoelectric cylinder had the following characteristics:

1. Three electrode pairs in series
2. An input resistance to the preamplifier of 22 megohms
3. A hydrophone sensitivity of -90 dBV per microbar
4. A hydrophone capacitance of 5000 picofarads and a loss factor of .005
5. A preamplifier gain of 40 dB
6. A preamplifier voltage noise of -161 dBV per Hz bandwidth
7. A preamplifier current noise of 5×10^{-14} amperes per Hz bandwidth

The first column of the results is the frequency. Column two and three each contain a pair of numbers. The top numbers in the second column are the Wenz level in dB re 1 microbar of sound level. The top numbers in the third column are the electrical noise from the hydrophone and preamplifier referred to an equivalent sound pressure level, i.e. dB re 1 microbar. The last column gives the free field voltage sensitivity of the hydrophone and preamplifier combination in dBV per microbar of sound pressure. The bottom numbers in the second column are the electrical output from the preamplifier for the lower Wenz sea noise signal. The bottom number in the third column is the electrical output noise of the preamplifier with no sound into the hydrophone.

Figure 2 shows a run for six electrode pairs in series with the other parameters the same. Here we get an increased sensitivity of 6 dB and a capacitance decrease of 4:1. Figure 3 shows a run with one single pair of electrodes. Here the sensitivity has decreased 10 dB and the capacitance increased by a factor of 9 over the 3 pair of electrodes. To get a comparison of the three runs, the Wenz noise level and the equivalent acoustic level for the electrical noise have been plotted against frequency on Fig. 4. The three electrode pair is probably the best compromise for operating from 10 Hz to 300 Hz.

NOISE.VER 01-MAR-72 13:49

HYDROPHONE & PREAMP NOISE
-VERSION OF 1-MAR-72

DESCRIPTION:

? STD PHONE WITH 3 ELECTRODE PAIRS

Fig. 1

TYPE IN INPUT RESISTANCE OF PREAMP MEGOHMS

? 22

TYPE IN HYDROPHONE SENSITIVITY DBV RE 1 MICROBAR

? -90

TYPE IN HYDROPHONE CAPACITANCE PICOFARADS & LOSS FACTOR

? 5000.005

OUTPUT OF HYDROPHONE + 40 DB PREAMP

FREQ HZ	WENZ LEVEL DB RE 1 UB	ELEC. NOISE DB RE 1 UB	FFVS (PHONE & PREAMP) DBV/UB
	WENZ OUT DB RE 1 VOLT	ELEC. NOISE OUT DB RE 1 VOLT	
10	-39 -89.0961	-44.7869 -94.883	-50.0961
20	-47 -97.0258	-50.7428 -100.769	-50.0258
50	-56 -106.005	-58.3969 -108.402	-50.0049
100	-61 -111.002	-63.623 -113.625	-50.0015
200	-66 -116.001	-67.579 -117.58	-50.0005
500	-71 -121.	-70.0982 -120.098	-50.0002
1000	-73 -123.	-70.6909 -120.691	-50.0001

ELECTRICAL PREAMP NOISE IS REFERRED TO HYDROPHONE INPUT
TYPE '1' TO REPEAT ELSE '0'

? 1

HYDROPHONE & PREAMP NOISE
-VERSION OF 1-MAR-72

DESCRIPTION:

? STD UNIT WITH 6 ELECTRODE PAIRS

Fig. 2

TYPE IN INPUT RESISTANCE OF PREAMP MEGOHMS

? 22

TYPE IN HYDROPHONE SENSITIVITY DBV RE 1 MICROBAR

? -84

TYPE IN HYDROPHONE CAPACITANCE PICOFARADS & LOSS FACTOR

? 1250, .005

OUTPUT OF HYDROPHONE + 40 DB PREAMP

FREQ HZ	WENZ LEVEL DB RE 1 UB	ELEC. NOISE DB RE 1 UB	FFVS (PHONE & PREAMP) DBV/UB
	WENZ OUT DB RE 1 VOLT	ELEC. NOISE OUT DB RE 1 VOLT	
10	-39 -84.2735	-38.781 -84.0545	-45.2735
20	-47 -91.3608	-44.7911 -89.152	-44.3608
50	-56 -100.063	-52.7108 -96.7735	-44.0628
100	-61 -105.017	-58.6413 -102.658	-44.017
200	-66 -110.005	-64.3969 -108.402	-44.0049
500	-71 -115.001	-71.0773 -115.078	-44.0011
1000	-73 -117.	-74.462 -118.464	-44.0004

ELECTRICAL PREAMP NOISE IS REFERRED TO HYDROPHONE INPUT
TYPE '1' TO REPEAT ELSE '0'

? 1

HYDROPHONE & PREAMP NOISE
-VERSION OF 1-MAR-72

DESCRIPTION:

? STD UNIT WITH ONE PAIR OF ELECTRODES

Fig. 3

TYPE IN INPUT RESISTANCE OF PREAMP MEGOHMS

? 22

TYPE IN HYDROPHONE SENSITIVITY DBV RE 1 MICROBAR

? -100

TYPE IN HYDROPHONE CAPACITANCE PICOFARADS & LOSS FACTOR

? 45000, .005

OUTPUT OF HYDROPHONE + 40 DB PREAMP

FREQ HZ	WENZ LEVEL DB RE 1 UB	ELEC. NOISE DB RE 1 UB	FFVS (PHONE & PREAMP) DBV/UB
	WENZ OUT DB RE 1 VOLT	ELEC. NOISE OUT DB RE 1 VOLT	
10	-39 -99.0018	-52.8886 -112.89	-60.0018
20	-47 -107.001	-57.0919 -117.093	-60.0006
50	-56 -116.	-59.9384 -119.939	-60.0002
100	-61 -121.	-60.6372 -120.637	-60.0001
200	-66 -126.	-60.8693 -120.869	-60.
500	-71 -131.	-60.9616 -120.962	-60.
1000	-73 -133.	-60.984 -120.984	-60.

ELECTRICAL PREAMP NOISE IS REFERRED TO HYDROPHONE INPUT
TYPE '1' TO REPEAT ELSE '0'

? 1

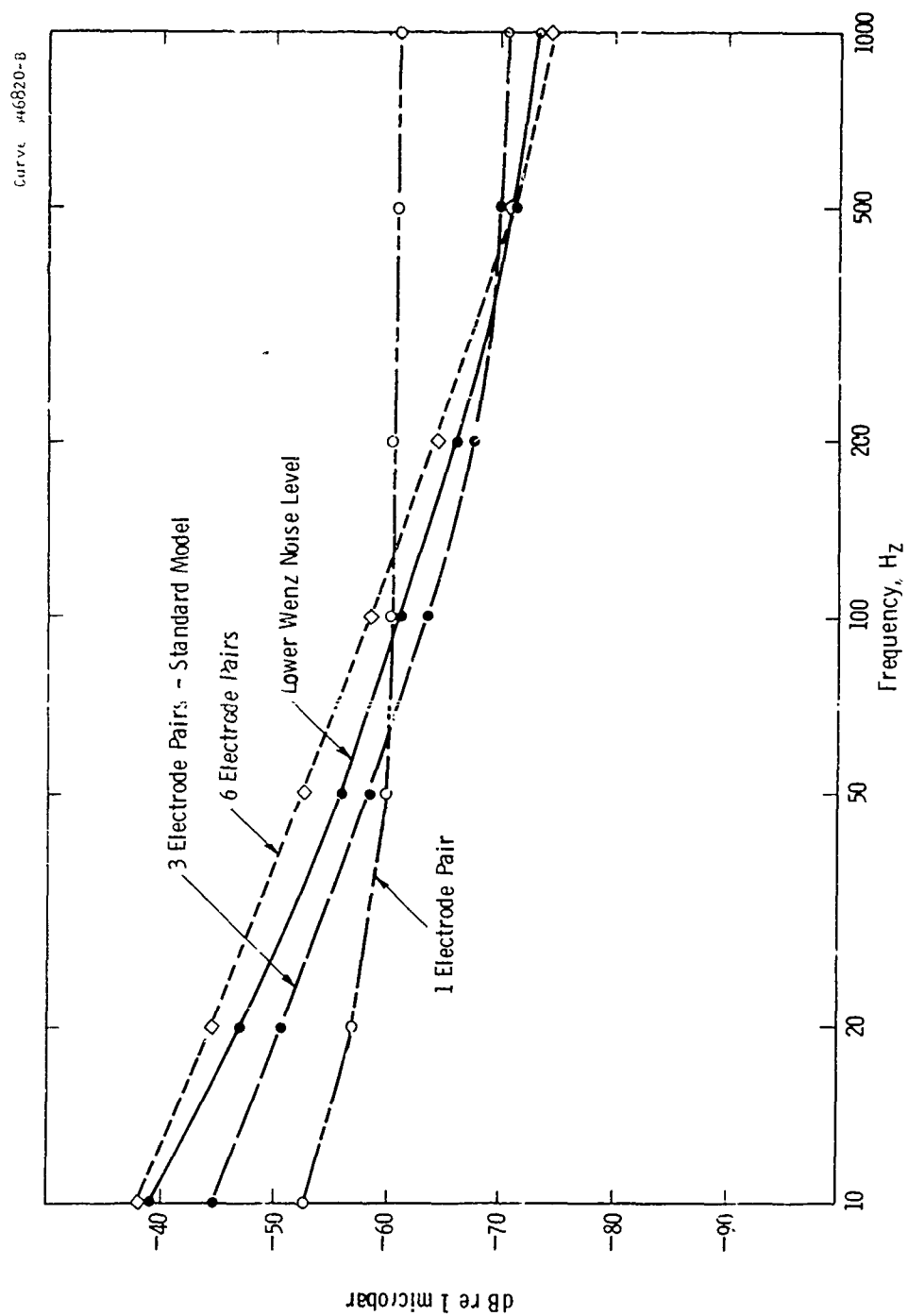


Fig. 4 - Wenz level and self noise for various electrode configurations on present hydrophone and preamplifier

3. Improved Design

By eliminating the passage of the cable through the transducer the volume of the compliant fluid backing can be increased and the basic voltage sensitivity will be increased approximately 6 dB, which is equivalent in power sensitivity to combining four of our present models in cascade. Figures 5, 6 and 7 show the results for 3, 6 and 1 pair of electrodes. Figure 8 shows a comparison of the three cases with the increased backing compliance. In these cases the three electrode configuration again appears to be the optimum for the frequency range from 10 Hz to 300 Hz when using the latest preamplifier.

Our redesign will consider the following factors or properties:

1. We will employ a thin, piezoelectric cylinder design to obtain high power sensitivity and low acceleration response as with present design.
2. Compliant silicone fluid will be used for high compliant backing as with present model.
3. The elements are to be mounted in a cage structure and supported by highly compliant spring members to isolate element from cage structure.
4. The preamp components will operate at full hydrostatic pressure. The amplifier employs semiconductors, resistors, and ceramic capacitors. No electrolytic capacitors are used which might contaminate the compliant fluid. The resistors in the feedback loop are the only critical items. These are reasonably stable with pressure. Semiconductor changes are nullified because of negative feedback.
5. The preamp will be placed in the compliant chamber. Note that no pressure drop exists across the terminal seals so that problems of water diffusion are eliminated.
6. Variable control will be employed in preamp feedback loop to adjust each element to the same sensitivity. This will help in reducing manufacturing costs.

HYDROPHONE & PREAMP NOISE
-VERSION OF 1-MAR-72

Fig. 5

DESCRIPTION:

? IMPROVED WESTINGHOUSE PHONE WITH 3 PAIRS OF ELECTRODES

TYPE IN INPUT RESISTANCE OF PREAMP MEGOHMS

? 22

TYPE IN HYDROPHONE SENSITIVITY DBV RE 1 MICROBAR

? -84

TYPE IN HYDROPHONE CAPACITANCE PICO FARADS & LOSS FACTOR

? 5000.,.005

OUTPUT OF HYDROPHONE + 40 DB PREAMP

FREQ HZ	WENZ LEVEL DB RE 1 UB	ELEC. NOISE DB RE 1 UB	FFVS (PHONE & PREAMP) DBV/UB
	WENZ OUT DB RE 1 VOLT	ELEC. NOISE OUT DB RE 1 VOLT	
10	-39 -83.0961	-50.7869 -94.883	-40.0961
20	-47 -91.0258	-56.7428 -100.769	-41.0258
50	-56 -100.005	-64.3969 -108.402	-44.0049
100	-61 -105.002	-69.623 -113.625	-44.0015
200	-66 -110.001	-73.579 -117.58	-44.0005
500	-71 -115.	-76.0982 -120.098	-44.0002
1000	-73 -117.	-76.6909 -120.691	-44.0001

ELECTRICAL PREAMP NOISE IS REFERRED TO HYDROPHONE INPUT
TYPE '1' TO REPEAT ELSE '0'

? 1

HYDROPHONE & PREAMP NOISE
-VERSION OF 1-MAR-72

Fig. 6

DESCRIPTION:

? IMPROVED WESTINGHOUSE PHONE WITH 6 ELECTRODE PAIRS

TYPE IN INPUT RESISTANCE OF PREAMP MEGOHMS

? 22

TYPE IN HYDROPHONE SENSITIVITY DBV RE 1 MICROBAR

? -78

TYPE IN HYDROPHONE CAPACITANCE PICOFARADS & LOSS FACTOR

? 1250.005

OUTPUT OF HYDROPHONE + 40 DB PREAMP

FREQ HZ	WENZ LEVEL DB RE 1 UB	ELEC. NOISE DB RE 1 UB	FFVS (PHONE & PREAMP) DBV/UB
	WENZ OUT DB RE 1 VOLT	ELEC. NOISE OUT DB RE 1 VOLT	
10	-39 -78.2705	-44.781 -84.0545	-39.2735
20	-47 -85.3608	-50.7911 -89.152	-38.3608
50	-56 -94.0628	-58.7108 -96.7735	-38.0628
100	-61 -99.017	-64.6413 -102.658	-38.017
200	-66 -104.005	-70.3969 -108.402	-38.0049
500	-71 -109.001	-77.0773 -115.078	-38.0011
1000	-73 -111.	-80.464 -118.464	-38.0004

ELECTRICAL PREAMP NOISE IS REFERRED TO HYDROPHONE INPUT
TYPE '1' TO REPEAT ELSE '0'

? 1

HYDROPHONE & PREAMP NOISE
-VERSION OF 1-MAR-72

Fig. 7

DESCRIPTION:

? IMPROVED WESTINGHOUSE PHONE WITH ONE ELECTRODE PAIR

TYPE IN INPUT RESISTANCE OF PREAMP MEGOHMS

? 22

TYPE IN HYDROPHONE SENSITIVITY DBV RE 1 MICROBAR

? -94

TYPE IN HYDROPHONE CAPACITANCE PICO FARADS & LOSS FACTOR

? 45000, .005

OUTPUT OF HYDROPHONE + 40 DB PREAMP

FREQ HZ	WENZ LEVEL DB RE 1 UB	ELEC. NOISE DB RE 1 UB	FFVS (PHONE & PREAMP) DBV/UB
	WENZ OUT DB RE 1 VOLT	ELEC. NOISE OUT DB RE 1 VOLT	
10	-39 -93.0018	-58.8866 -112.89	-54.0018
20	-47 -101.001	-63.0919 -117.093	-54.0006
50	-56 -110.	-65.9384 -119.939	-54.0002
100	-61 -115.	-66.6372 -120.637	-54.0001
200	-66 -120.	-66.8693 -120.869	-54.
500	-71 -125.	-66.9616 -120.962	-54.
1000	-73 -127.	-66.984 -120.984	-54.

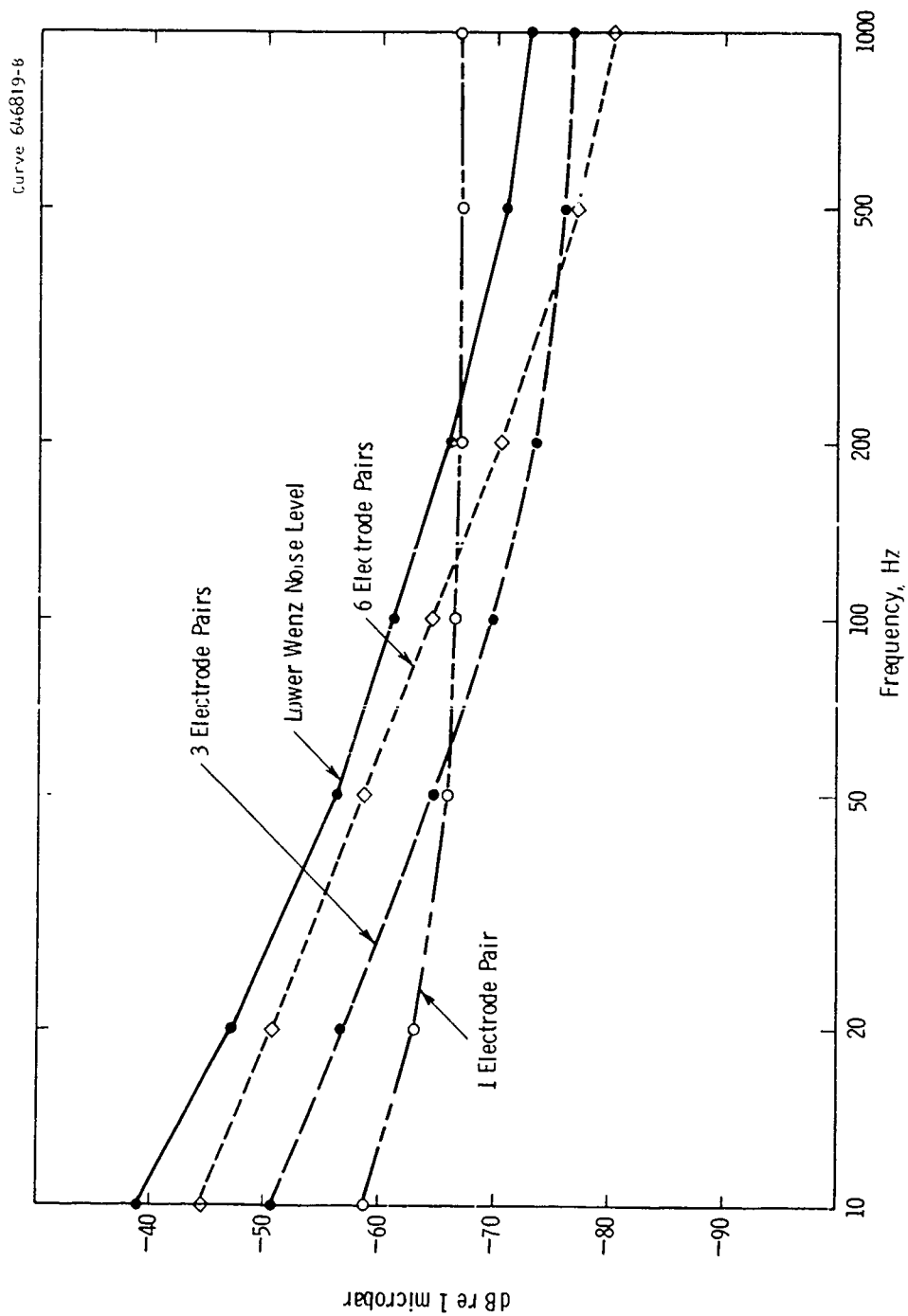


Fig. 8 - Wenz level and self noise for various electrode configurations on improved hydrophone and present preamplifier

7. We will use one pair of wires for both power and signal.
8. We plan to reduce machining costs by simplifying the previous design, since the coaxial construction with concentric cable is not required.
9. Material capable of withstanding environment for five to ten years will be used.

The proposed acceleration balanced element with preamp will be approximately 2-1/2 in. long and 2-1/2 in. in diameter. The cage dimensions will be dependent upon cable support requirements.

4. Ultra Low Noise Preamplifier

The preamplifier noise contribution comes primarily from the first stage, and in order to assure low noise performance the device and the circuit in which it is used must be chosen with great care. It is generally conceded that FET devices offer more in the way of low noise performance than do bipolar transistors. Either can be characterized as to noise performance independent of the circuit in which it is used by means of two noise generators. They are the equivalent open circuit noise current $\bar{i}_n$, and the equivalent short circuit noise voltage, $\bar{e}_n$, each referenced to the input of the device and expressed in current or voltage units per "root Hertz". The superiority of the FET over the bipolar is evident when the contributions of these generators are compared for the two devices selected for low noise operation; the total noise for the FET is generally lower (since it is a majority carrier device and thus free of recombination noise) and moreover it remains lower as the frequency decreases. Both types exhibit a $1/f$ frequency dependence of the total noise. The corner frequency of the FET is generally one to two kilohertz.

If the improved Westinghouse preamplifier employs carefully selected input FET's with a noise current of 5×10^{-15} amps, the expected results from the simulation is that shown in Figs. 9 and 10. Figure 11 shows a plot of this data. Note that the electrical noise in the 10 Hz to 100 Hz range is from 11 dB to 14 dB below the Wenz 5% curve with the

Fig 2

DESCRIPTION:

? IMPROVED WESTINGHOUSE PHONE WITH LOW NOISE PREAMP 10
IN=5E-15 AMPS

TYPE IN INPUT RESISTANCE OF PREAMP MEGOHMS

? 10

TYPE IN HYDROPHONE SENSITIVITY DBV RE 1 MICROBAR

? -84

TYPE IN HYDROPHONE CAPACITANCE PICOFARADS & LOSS FACTOR

? 5000, .005

OUTPUT OF HYDROPHONE + 40 DB PREAMP

FREQ HZ	WENZ LEVEL DB RE 1 UB	ELEC. NOISE DB RE 1 UB	FFVS (PHONE & PREAMP) DBV/UB
	WENZ OUT DB RE 1 VOLT	ELEC. NOISE OUT DB RE 1 VOLT	
10	-39 -83.4317	-53.6359 -98.0676	-44.4317
20	-47 -91.1154	-59.5468 -103.662	-44.1154
50	-56 -100.02	-67.0956 -111.116	-44.0203
100	-61 -105.006	-72.2974 -116.303	-44.0058
200	-66 -110.002	-76.6137 -120.616	-44.0018
500	-71 -115.	-80.3095 -124.31	-44.0005
1000	-73 -117.	-82.1549 -126.155	-44.0002

HYDROPHONE & PREAMP NOISE
-VERSION OF 1-MAR-72

Fig 10

DESCRIPTION:

? IMPROVED WESTINGHOUSE PHONE WITH LOW NOISE PREAMP
IN=5E-15 AMPERES PER HZ BANDWIDTH

10

TYPE IN INPUT RESISTANCE OF PREAMP MEGOHMS

? 100

TYPE IN HYDROPHONE SENSITIVITY DBV RE 1 MICROBAR

? -84

TYPE IN HYDROPHONE CAPACITANCE PICO FARADS & LOSS FACTOR

? 5000.005

OUTPUT OF HYDROPHONE + 40 DB PREAMP

FREQ HZ	WENZ LEVEL DB RE 1 UB	ELEC. NOISE DB RE 1 UB	FFVS (PHONE & PREAMP) DBV/UB
	WENZ OUT DB RE 1 VOLT	ELEC. NOISE OUT DB RE 1 VOLT	
10	-39 -83.0058	-62.4298 -106.436	-44.0058
20	-47 -91.0018	-67.6763 -111.678	-44.0018
50	-56 -100.	-73.4752 -117.476	-44.0005
100	-61 -105.	-76.7046 -120.705	-44.0002
200	-66 -110.	-79.0594 -123.059	-44.0001
500	-71 -115.	-81.0737 -125.074	-44.
1000	-73 -117.	-82.4315 -126.431	-44.

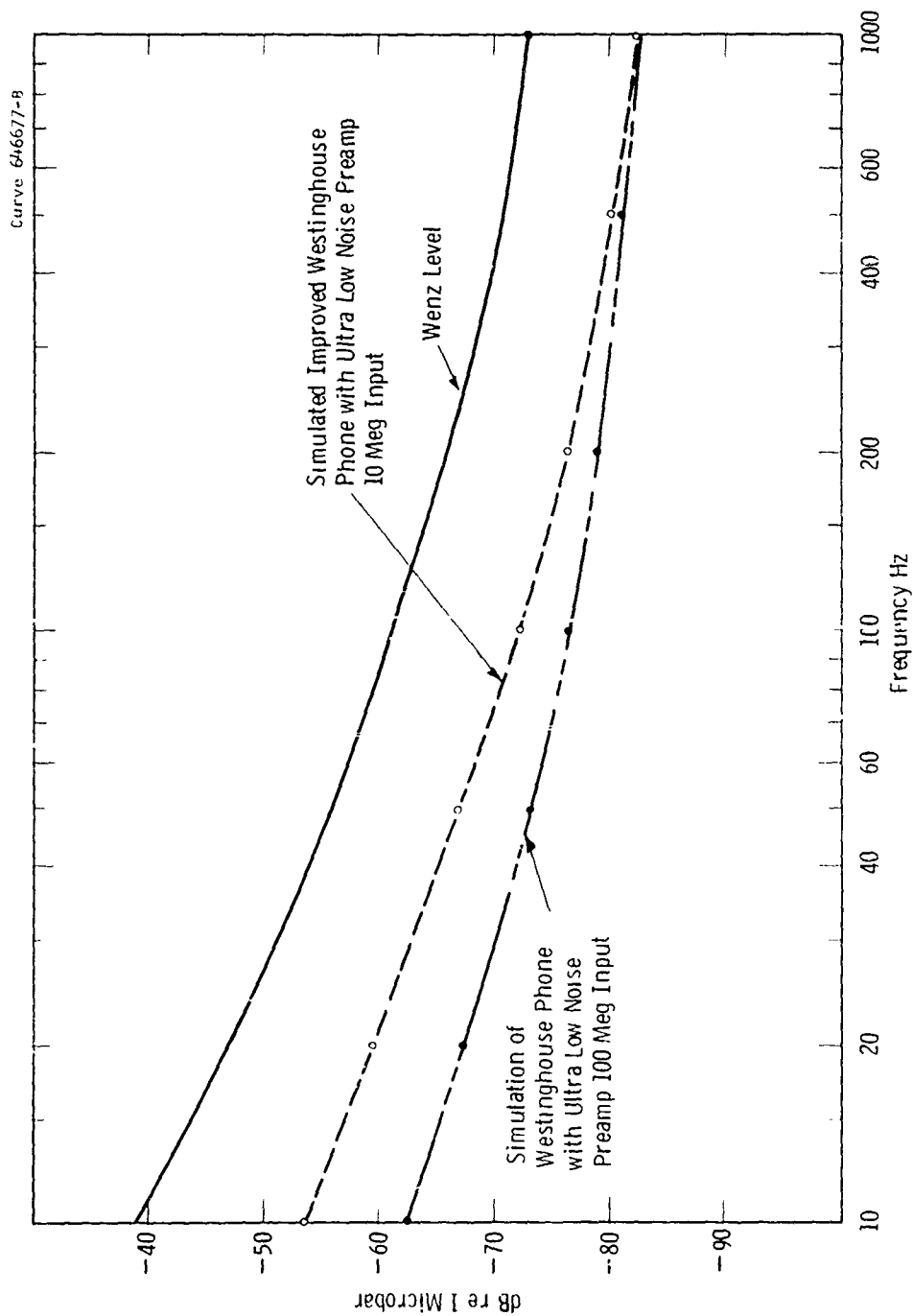


Fig. 11 - Wenz level and self noise for improved Westinghouse phone and ultra low noise preamp

ultra low noise amplifier. By increasing the number of electrode pairs to 6 electrode pairs the element sensitivity is -78 dBV re 1 microbar and the capacitance 1250 picofarads. This arrangement with the ultra low noise amplifier will give results 23 dB to 12 dB below the Wenz curves from 10 Hz to 300 Hz.

5. Conclusions

The present three electrode phone with the latest preamplifier is probably satisfactory from the standpoint of getting low electronic noise, Fig. 4. However, without the necessity of passing the cable through the unit, the construction costs can be reduced. The performance curves, Fig. 8, for the three electrode pair model should be adequate for the frequency range of 10 Hz to 300 Hz where the electrical noise is approximately 5 dB to 10 dB below the Wenz level.

We believe that it is important to employ a hydrophone—pre-amplifier unit that has low susceptibility to cable noise and a self noise that is below the 5% Wenz curve. Whether 10 dB or 20 dB below the Wenz curve is of academic interest but of little practical importance.

IV. MULTIPLEXING EQUIPMENT

1. General Consideration

The system design of the cable multiplex system has to take several factors into account. The major points of concern are:

1. The bandwidth of the 19,000 ft. supporting cable for the array.
2. The maximum diameter of the cable that the winch can handle.
3. The difficulty of constructing a reliable small diameter coaxial cable with breakouts for the hydrophones.
4. Possible maintenance problems if hydrophone assemblies cannot be removed from the cable after installation.
5. Minimization of the cable drag over the hydrophone array in order to minimize the bottom weight necessary to hold the array within one or two degrees of the vertical in a 0.3 knot current.

In addition of course, the cable strengths have to be such that they can withstand the loads applied including their own weight in water.

The total cable configuration can exist in several forms as shown in Fig. 1.

Method 1 - Here the hydrophones are connected to breakouts from a coaxial cable which is a continuous cable from the surface to the bottom weight.

- Advantage: No separate electronic bottle is required.
- Disadvantage: Small diameter coax cable breakouts are not very practical and can be a source of mechanical difficulties where an upper breakout failure can disconnect all hydrophones below the failure. The hydrophone assemblies are more complicated than just a transducer and amplifier as each unit requires power supplies and analog-digital conversion together with frequency/time multiplex equipment. Also, down-going sequence instructions are usually required for time division multiplexing.

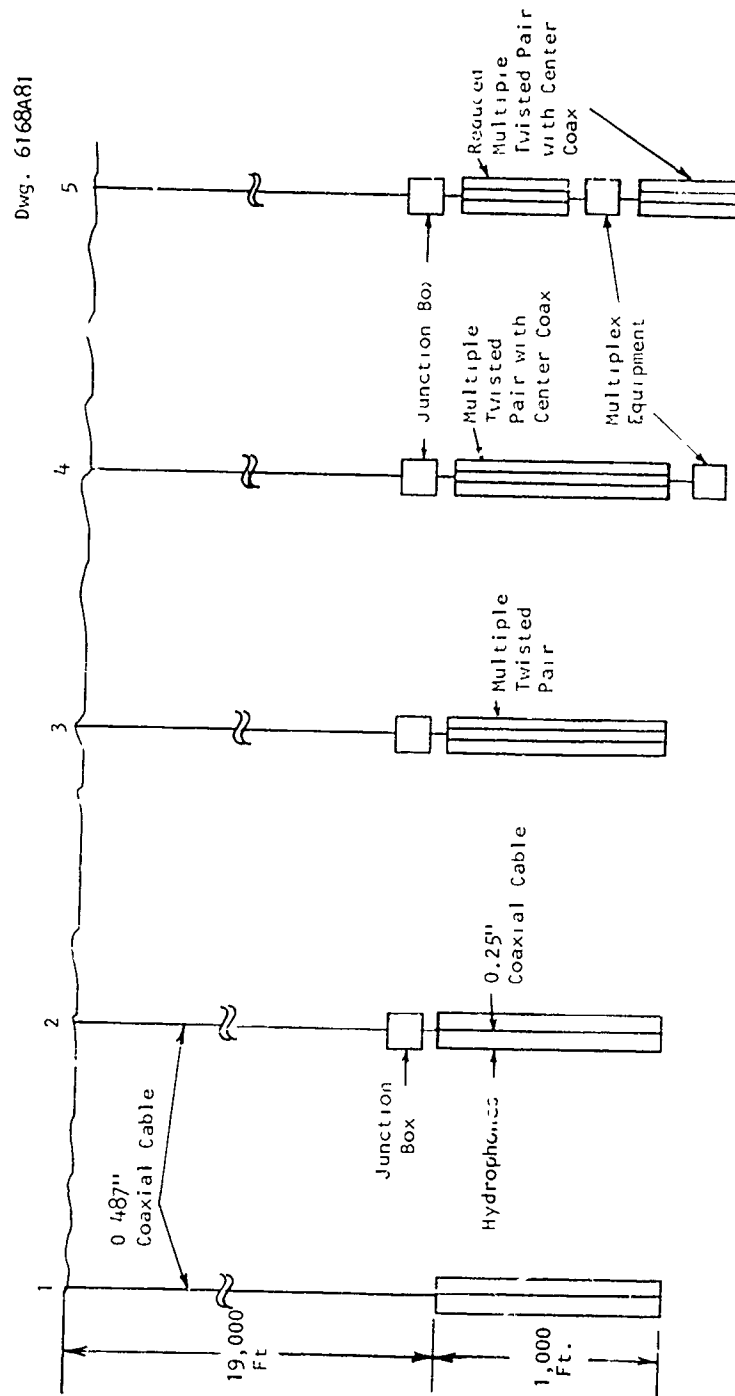


Fig. 1 - Possible cable configurations

Method 2 - The hydrophone array is connected to a smaller diameter cable (0.25 in.) to minimize drag and then connected to the main cable at a junction box.

- Advantage: Array cable more vertical with less drag on cable.
- Disadvantage: Small diameter cable breakouts almost impossible to construct reliably.

Method 3 - Similar to method 2 except that intermediate power amplifier and cable multiplex unit is connected at the top end of the array and signals are brought from hydrophones by twisted pairs.

- Advantage: Could drive increased bandwidth on the main cable.
- Disadvantage: Increased cable drag because of increased cable diameter.

Method 4 - Similar to method 3 except that the multiplex unit is located at the bottom of the cable.

- Advantage: When the bottle is removed from the cable, there is no cable below to increase the handling weights.
- Disadvantage: Bottle drag is placed at the least desirable location, and the array cable requires a coaxial conductor in addition to the multi pair cable.

Method 5 - Multiplex bottle located in the center of the array.

- Advantage: Only 50% of the twisted pairs required in the array cable which reduces the cable drag over methods 3 and 4. The effect of the bottle drag is less than in method 4.
- Disadvantage: None over methods 3 and 4.

Method 5 has been chosen as the most promising approach. Cable manufacturers have stated that to make the twisted pair cable breakouts reliable a connector should be potted onto the cable at the breakouts. Because of this, and the desirability of removing the hydrophone assemblies for repair and testing, it is proposed that the hydrophone assemblies be carried in cages attached to the cable. The connections will then be made via pigtails into the cable molded connectors.

The use of conductive coupling to each hydrophone by means of twisted pairs is recommended. The twisted pair will carry the DC power from the electronics bottle to the preamplifier unit located in the hydrophone housing and will also carry the amplified hydrophone signal back to the electronic package. Neither wire will be connected to the hydrophone shell or cage.

During the design of the inductive coupler system for the NOAA National Data Buoy program, there has been an extensive analysis of the effects of inductive couplers, the cable limitations, and general restrictions of the use of such devices. As a consequence a very successful system has been designed for the NDB program, but for the proposed array the use of the couplers is not recommended for the following main reasons:

(1) Inductive couplers are primarily current operated devices. This means that until the coupler loss becomes significant, the core output is proportional to frequency. This is a severe restriction on any frequency multiplex system. Time multiplex would have to be used which increases the hydrophone assembly complexity.

(2) Unless a complex cable construction is employed, current must only flow one way through the array cable and return via a different path, e.g. the seawater. If this is done, to avoid considerable losses, the ground plate must be quite large say 10-15 sq. ft., which is hard to handle manually.

(3) The power transfer efficiency is poor unless the cable is constructed as a twisted pair with one wire arranged to bypass the coupler. This is because much of the input power is used to establish the cable magnetic field.

(4) Without the partial inductive component cancelation, the frequency response of a 1000 ft. cable is deceptively poor. For example, the NDRS cable 500 meters long has a quarter wave resonance at about 12 kHz. This effect causes large impedance variations on the cable unless it is terminated.

2. Multiplex Method

With 57 hydrophone signals, a sensor channel and two synchronizing channels, there are 60 channels to be monitored. Since the top frequency of interest is 333 Hz, then each channel could be sampled at a 1 kHz rate. To sample 60 channels, requires a sampling frequency of 60 kHz and the sampled signal will have a bandwidth of 60 kHz. If this analog signal were transmitted up the cable there would be some distortion due to cable noise. Therefore, it is desirable to code the signal in some manner. This will increase the bandwidth but will reduce the likelihood of information distortion due to cable noise. Table 1. lists a variety of coding methods. The first method is a simple binary code produced by an analog to digital (A to D) converter. The output signal always has a value of either +1 or -1 unit. If a dynamic range of 72 dB is desired, then 4096 voltage levels must be preserved. This requires a 12 bit A to D unit. Twelve time slots are required to transmit each sampled voltage, and so 12 times the bandwidth is required. In place of transmitting only two levels up the cable it is practical to use 4, 8, 16, or 64 levels. The corresponding bandwidths required are 360, 204, 180 and 120 kHz

Assuming a maximum excursion of 10 volts at the bottom end of the cable, the minimum voltage change is tabulated for each case. At the top of the cable the minimum and maximum voltage excursions are tabulated. For the proposed cable, the largest minimum excursion at the top of the cable is found to be in the four level or quaternary system. This system will have the least susceptibility to cable noise. As long as the peak value of the cable noise is less than half of 0.18 volts = .09 volts, there will be no distortion of the received signal due to the cable. It is important to realize that the optimum coding method depends on the cable attenuation. For example, with a short length of cable having small attenuation, the binary method would be better; and for a much longer cable or one with much higher attenuation, the "eight level" method would be superior.

Table 1 A Comparison of Six Methods for Transmitting 720,000 bits/sec

Band- width kHz	Trans. Levels	Time slots and Bandwidth Factor	Information Levels	Cable Loss* dB	Voltage Ratio	Voltages at Package		Voltages at Ship	
						Min. Step Volts	Max. Volts	Min. Step Volts	Max. Volts
720	2	12	$2^{12} = 4096$	36	63.	10.0	10	0.16	0.16
360	4	6	$4^6 = 4096$	25	18.	3.3	10	0.18	0.55
240	8	4	$8^4 = 4096$	20.5	10.	1.4	10	0.14	1.0
80	16	3	$16^3 = 4096$	17.7	7.1	0.67	10	0.04	1.4
120	64	2	$64^2 = 4096$	14.4	5.3	0.15	10	0.03	1.9
60	4096	1	$4096^1 = 4096$	10.	3.2	.0024	10	0.00075	3.1

*Assumes 19,000 ft. of RG 5/U plus 500 ft. of RG 58/U

Figure 2 illustrates how 2, 4 and 8 level signals can be generated. In each case an analog to digital (A to D) unit generates twelve parallel signals. In the binary system these twelve signals are converted to a single signal in with a parallel to series (P to S) converter. The output signal has 12 times the bandwidth of the input signal. The quaternary system uses two P to S units. One unit has a binary output of +2 or -2 units. The other unit has an output of +1 or -1 unit. The sum of these two outputs yield four possible output levels: +3, +1, -1 or -3. In a similar manner the 8 level unit uses three P to S units with eight possible sums: +7, +5, +3, +1, -1, -3, -5, or -7. There is only 1 dB difference in noise susceptibility between the binary and quaternary system, and so with the proposed cable, it makes little practical difference which of the two coding methods is used.

In the processing method described in Chapter 2, the outer elements of the array are not used at the high frequencies. Table 2 (p. 24) shows the top frequency associated with each element. By transmitting only the frequencies below this value on every unit a theoretical bandwidth saving of about 35% could be realized. This would require sampling different elements of the array at different rates. In a practical sampling sequence a bandwidth saving of only 25% would be realized. Consequently, for the 57 element array with a top processing frequency of 333 Hz, the added circuit complexity is not warranted.

The sensor information rate can be much slower than 1000 samples per second so that these signals can be sampled at a slow rate and the resulting signal fed to one channel of the high speed sampler.

Test patterns generated by the computer show that an RMS noise level that is 20 dB below the RMS signal level produces little distortion of the pattern. Therefore, a dynamic range of 40 dB in the D to A converter may be adequate. This would require only a seven bit converter. This would reduce the bandwidth and cable attenuation considerably.

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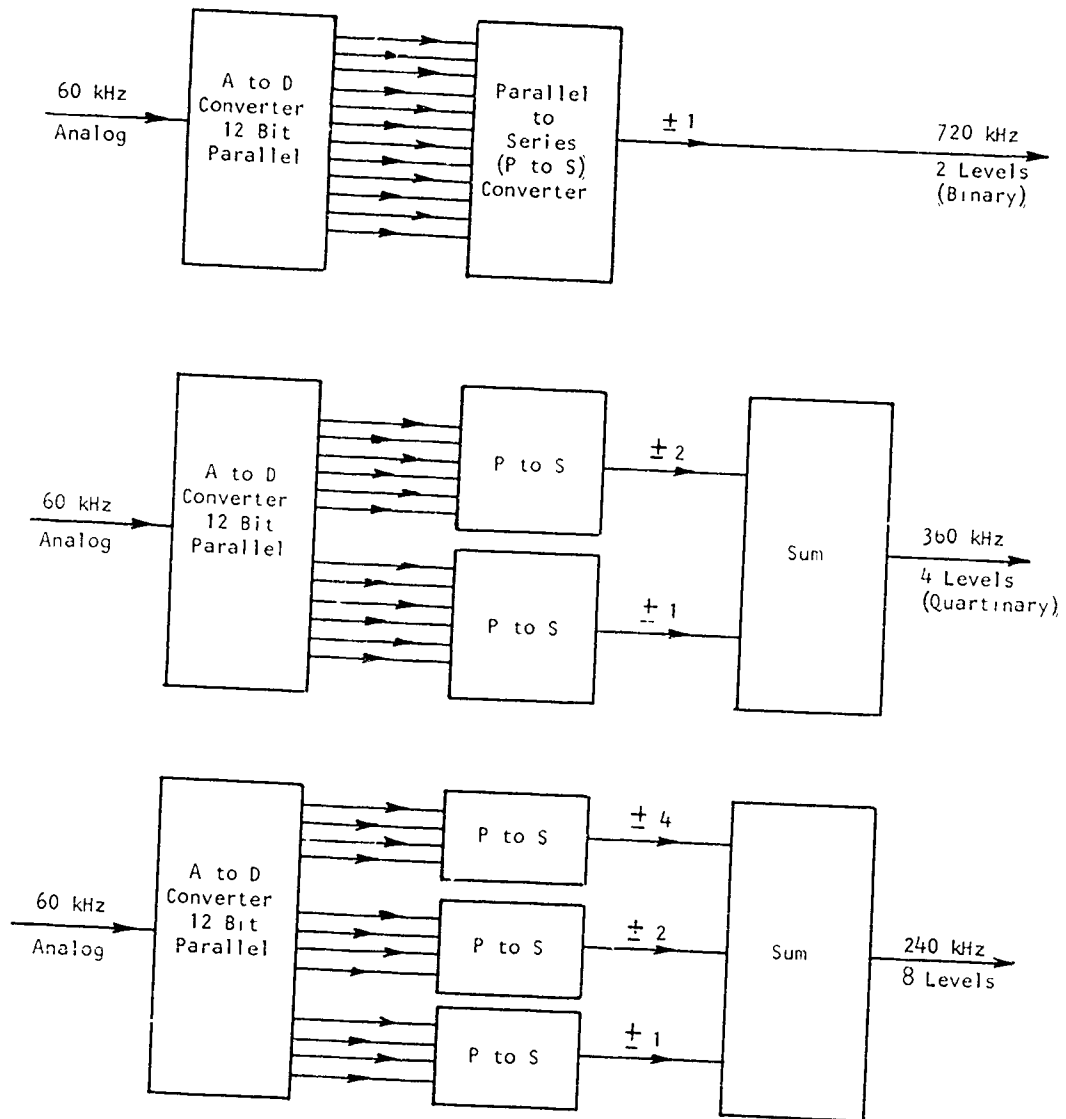


Fig. 2 - Circuits for generating quantized outputs from analog inputs

3. Electronics Bottle

3.1 Sampling Switch and A to D Converter

A block diagram of the proposed system is shown in Fig. 3. The transducer is coupled to a low noise preamplifier whose closed loop gain is 40 dB and the signal and power are sent over the same pair of wires. The output voltage appears across the remote load resistor and the power is supplied by individual constant current sources consisting of one transistor for each supply. The voltage across the resistor is then coupled to an amplifier, whose gain can be varied from 90 dB to 30 dB. This gain reduction is applied equally to each of the hydrophone channels from the output of a channel multiplexing switch. From the variable gain amplifier, the signals are fed to a multiplexing switch and a sample and hold circuit. The data is then applied to an analog-digital converter. The encoding period of the converter is 16.7 μ sec for 11 bits plus sign. The data from the converter is parallel transferred to another register where it is shifted out in serial form while the analog converter is encoding the next channel. The content of the parallel-serial register is then clocked out serially at 750,000 pulses per second into a power amplifier for transmission up the cable. A 750 kHz bandwidth is required. A filter at the output of the amplifier limits the response to cut off frequencies below 3.0 kHz to prevent false signals.

A burst of 2 kHz energy is used to switch the gain of the amplifier to a new value. Similarly a burst of 1 kHz energy is used to turn the acoustic reference signal ON or OFF.

3.2 Signal Levels

The weakest RMS signal to any hydrophone is expected to be that given by the lower Wenz curve. Over the band from 10 Hz to 333 Hz, this will be about -30 dB relative to 1 μ Bar. The sensitivity of a hydrophone with its preamplifier is -50 dBV/ μ Bar so the weakest expected signal is -80 dBV. If a 3 volt RMS signal is desired out of the electronic switch

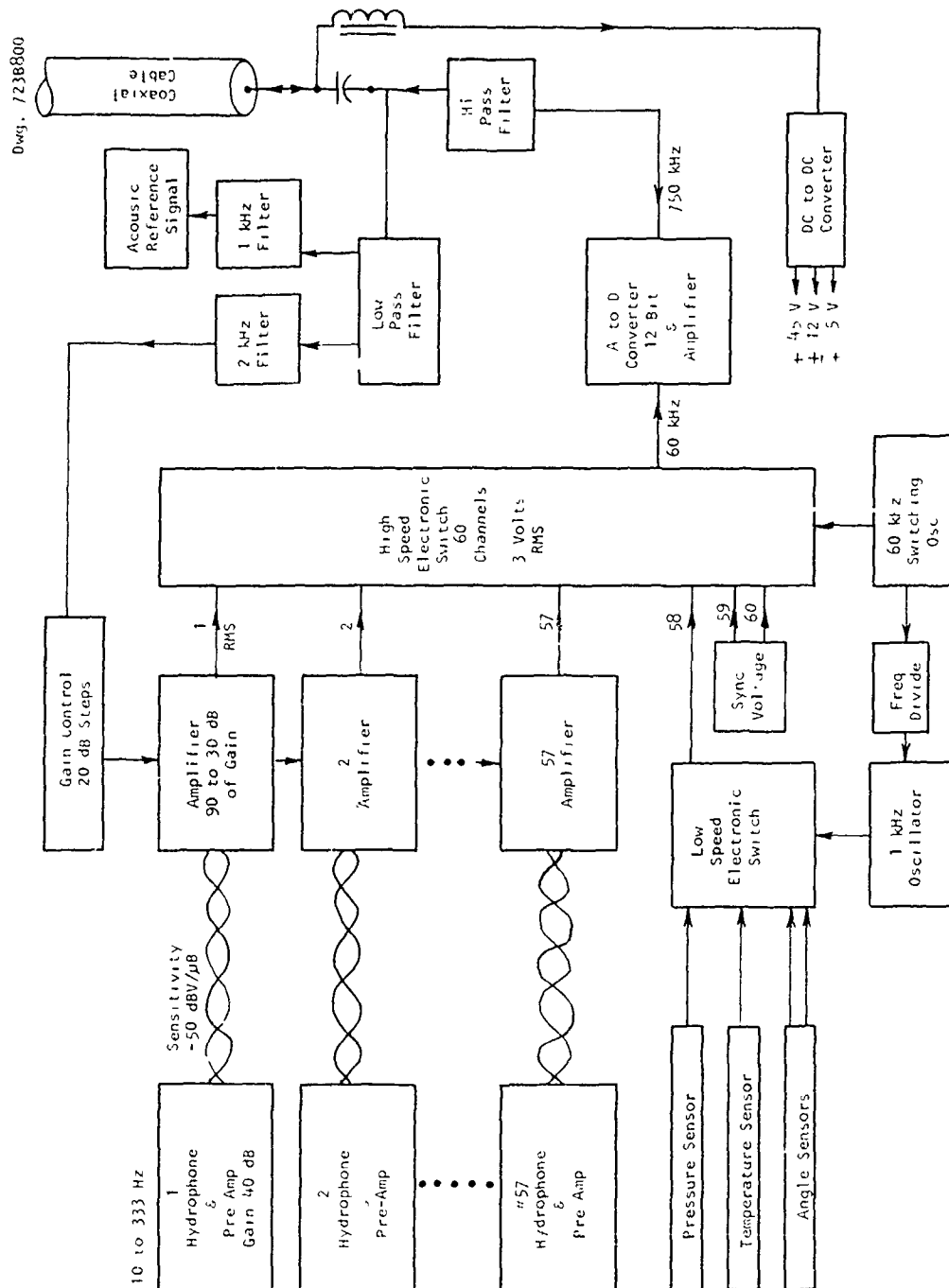


Fig. 3 - Block diagram of electronics bottle

unit under these conditions, then a total gain of 90 dB between pre-amplifier output and electronic switch output is required. The 12 bit A to D converter will handle a dynamic range of 72 dB. The upper Wenz curve indicates that under some conditions the RMS signal level may be increased about 50 dB from the low noise conditions and so it is desirable to be able to decrease the amplifier gain by at least 50 dB. Therefore a remotely activated gain control will be provided to reduce the amplifier gain by 0, 20, 40 or 60 dB. Consequently the gain between the preamplifier output and the electronic switch output will be 90, 70, 50 or 30 dB.

3.3 Sensor Signals

In order to determine the environmental conditions operating on the transducer array it is proposed to transmit up the cable data from three types of sensors located inside the cable multiplex bottle. The sensors are:

1. Pressure
2. Temperature
3. Inclination

Four data words are then involved. Pressure can be obtained over a pressure ratio of 100:1. Temperature, typically from a Rosemont sensor can be obtained to a 0.01°C accuracy. Inclination, typically from a Benthos tilt sensor, can be obtained over $\pm 15^{\circ}$ to a 0.3° accuracy on two orthogonal axes from one unit. Some modification of the sensor power system is involved as it presently operates from 110 VAC. It is proposed to adjust sensor voltages to levels that can be handled by the electronic switch and A to D converter.

A 1 kHz oscillator is used to control a low frequency sampling switch. Each of the sensor signals are sampled in sequence and then two or three dead channels are sampled to provide a reference signal. The two tilt signals can be sampled individually or they can be combined into a single channel, since the tilt is equal to the square root of the sum of the squares of the two orthogonal tilt values.

3.4 Synchronization

The 60 kHz oscillator frequency is derived from the 1 kHz oscillator and so every time the high frequency electronic switch completes one cycle of the 60 channels, the low frequency switch makes contact with a new channel. Channels 59 and 60 have a fixed input voltage and so the digital signals from these two channels provide a means of synchronizing the phase of the 60 kHz switch on the ship.

3.5 Power

DC power will be transmitted down the cable to provide energy for all of the active circuits. The DC to DC converter will employ a chopping frequency above the greatest hydrophone frequency of interest. Care will be taken with shielding and filtering to prevent any harmonics of the chopping frequency from reaching the coaxial cable.

4. Cable Losses

The attenuation of 19,000 ft. of RG 5/U plus 500 ft. of RG 58/U cable is shown as a function of frequency in Fig. 4. It may be desirable at the top of the cable to use an amplifier with a gain that increases 6 or 8 dB per octave to compensate for the cable attenuation. The DC resistance of the two cables is about 85 ohms.

5. Ship Multiplex Equipment

The shipboard equipment is shown in Fig. 5. The system will be powered by storage batteries to eliminate the noise caused by rotating machinery. During the test phase, the system can be powered by a DC power supply. The incoming DC is fed to a DC-DC converter whose chopping frequency is well above the acoustic receive frequencies. Switches to change the system gain and/or the operation of the acoustic reference will cause a burst of 2 or 1 kHz signal to be transmitted down the cable. A filter will be provided at the output of the amplifier so that the upcoming data will not be shorted out by the low output impedance

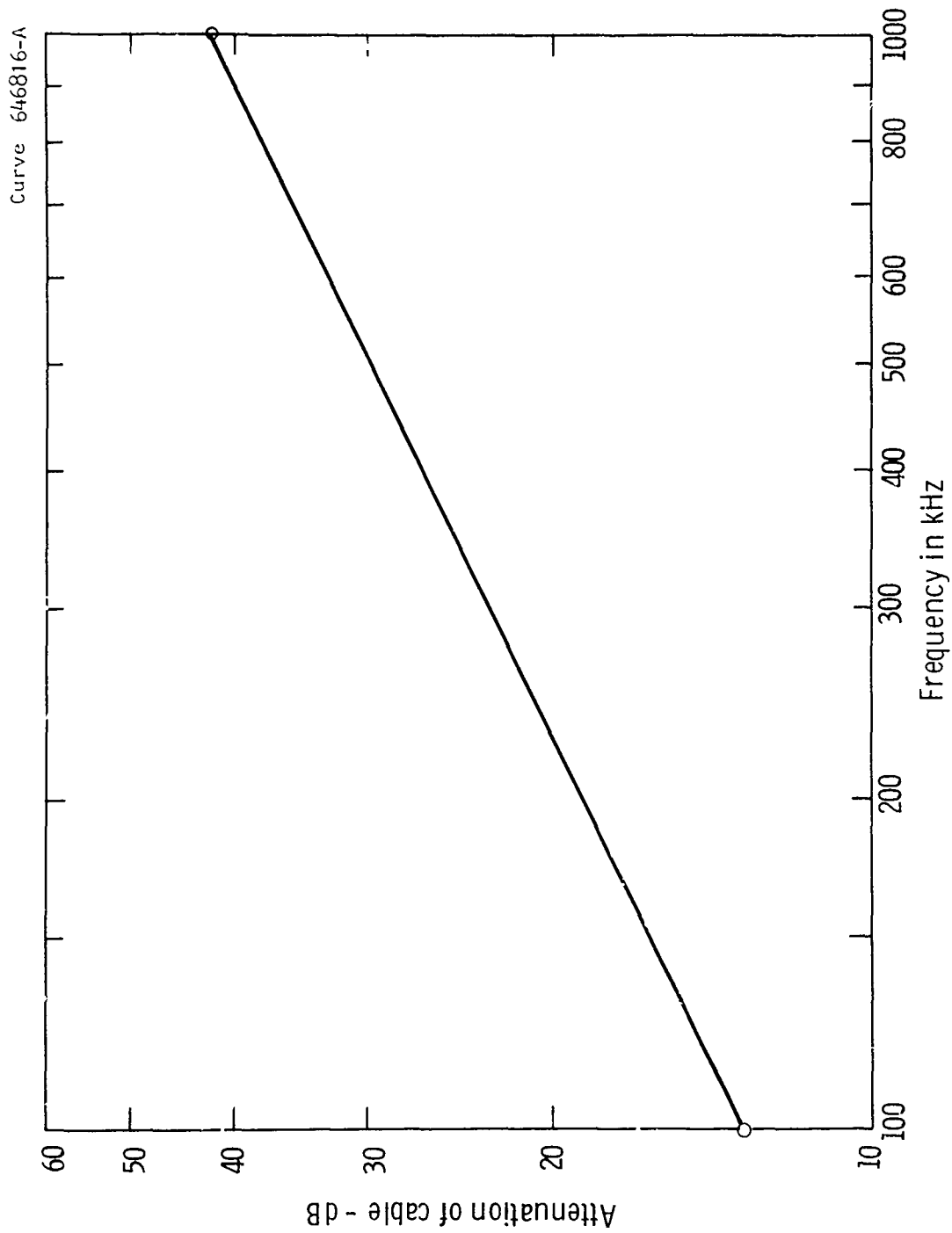


Fig. 4 - Attenuation of 19,000 ft of RG 5/U plus 500 ft. of RG 58/U

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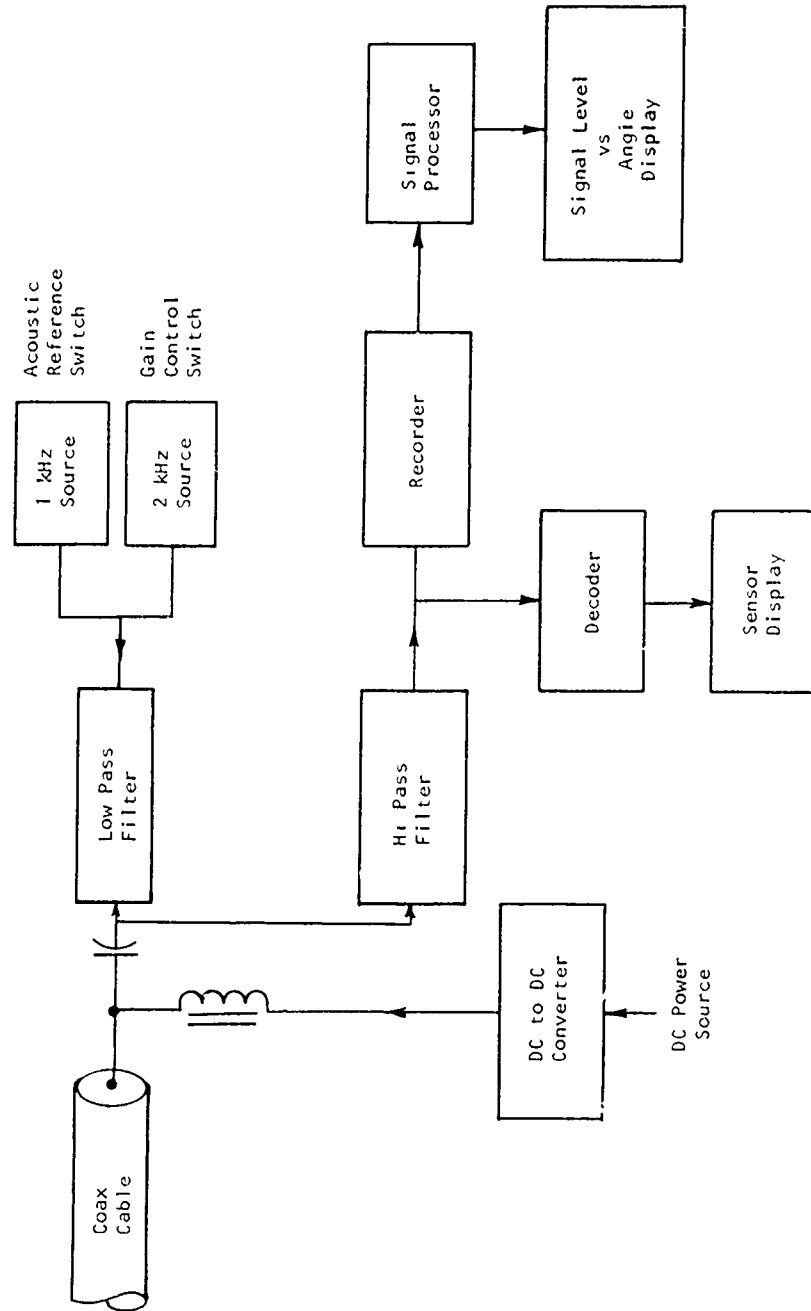


Fig. 5 - Shipboard equipment

of the driver amplifier. The up and down data signals are capacitively coupled to the cable so that the DC down-power can be applied. About 250 watts of power will be required from the DC power supply to drive the cable.

The upcoming data will be fed thru a filter to remove any 1 or 2 kHz and then fed to the digital recorder.

An output filter will be used to buffer the amplifier output against the down going 1 and 2 kHz signals and also to remove any up going signal spectra below 3.0 kHz. This will prevent interference with the command logic. The power applied to the cable must therefore include the filter insertion losses.

The command and data signals are AC coupled to the cable and the DC is fed via an isolating inductor to prevent the DC-DC converter from loading the AC signals. Westinghouse has had extensive experience in multiplexing data over coaxial tow cables. It is from this background that the cable multiplex system described has been designed. The proposed hydrophone multiplex system is much simpler than those already designed and constructed, consequently, no problems are foreseen.

To optimize the low noise preamplifier design, the power drawn by these units is relatively large for transistor systems and constitutes the bulk of the power consumed at the lower end of the cable. The following is an estimate of the total power budget involved:

57 hydrophone preamplifiers		
15 mA at 45 volts		38.4 watts
114 amplifiers at 5.0 mA from ± 12 volts	13.7	
Multiplex switches	3.0	
A to D converter	2.0	
Logic	5.0	
Acoustic reference	0.5	
Sensors	2.0	
Power amplifier	2.5	
Oscillators	2.0	
	Total	68.6
(Average DC-DC conv. Eff. = 85%)		
		80.0 watts - Grand Total

As the bulk of the power is at 45 volts, an incoming voltage greater than 45 volts is desirable so that a high efficiency switching regulator can be used. On the other hand, if the differential voltage is too high the component size and cost increases. A compromise of 60 volts at the multiplex unit has been initially chosen. Thus a line current of $80/60 = 1.33$ amps is required. The cable resistance is 85 ohms so that an input cable voltage of $60 + (85 \times 1.33) = 173$ volts and 230 watts total input power is all that is required.

Three manual controls will be provided to operate the measuring system:

1. System ON-OFF
2. Gain switch
3. Acoustic references ON-OFF

Power for the cable and the ship-borne system will be obtained from batteries to preserve the quiet environment, or from a DC power supply during the testing phase. The applied cable DC voltage may be as high as 200 volts. To preserve a minimum S/N ratio of the data signal of 20 dB, the data band noise level from the DC power supply must be less than 0.07 volts in the band 3.0 to 750 kHz. This means that the noise voltage at the chopping frequency present on the DC output must be at least -72 dB below the power voltage. Although this is not easy to obtain, it is well within the present art of self oscillating DC-DC converters.

V. CABLE SYSTEM

1. Components

The Cable-Array System shown in Fig. 1 consists of the following components starting at the winch and ending at the ballast:

1. Connector at the end of transmission cable leading to the electronics.
2. Dead end cable clamp on winch drum.
3. Transmission cable 19,000 ft. long consisting of a coax and double armor.
4. Electromechanical connection between the transmission and upper array cable.
5. Upper array cable consisting of 32 pairs of conductors, 1 coax and double armor. It is 500 ft. long.
6. Upper array cable hydrophone electromechanical connections (29).
7. Electromechanical connection between lower end of upper array cable and electronics bottle.
8. Electronics bottle.
9. Electromechanical connection between lower end of the electronics bottle and upper end of the lower array cable.
10. Lower array cable consisting of 32 pairs of conductors, 1 coax and double armor. It is 500 ft. long and same as upper array cable.
11. Lower array cable hydrophone electromechanical connections (26).
12. Mechanical swivel connecting lower end of lower array cable to the ballast
13. Ballast.

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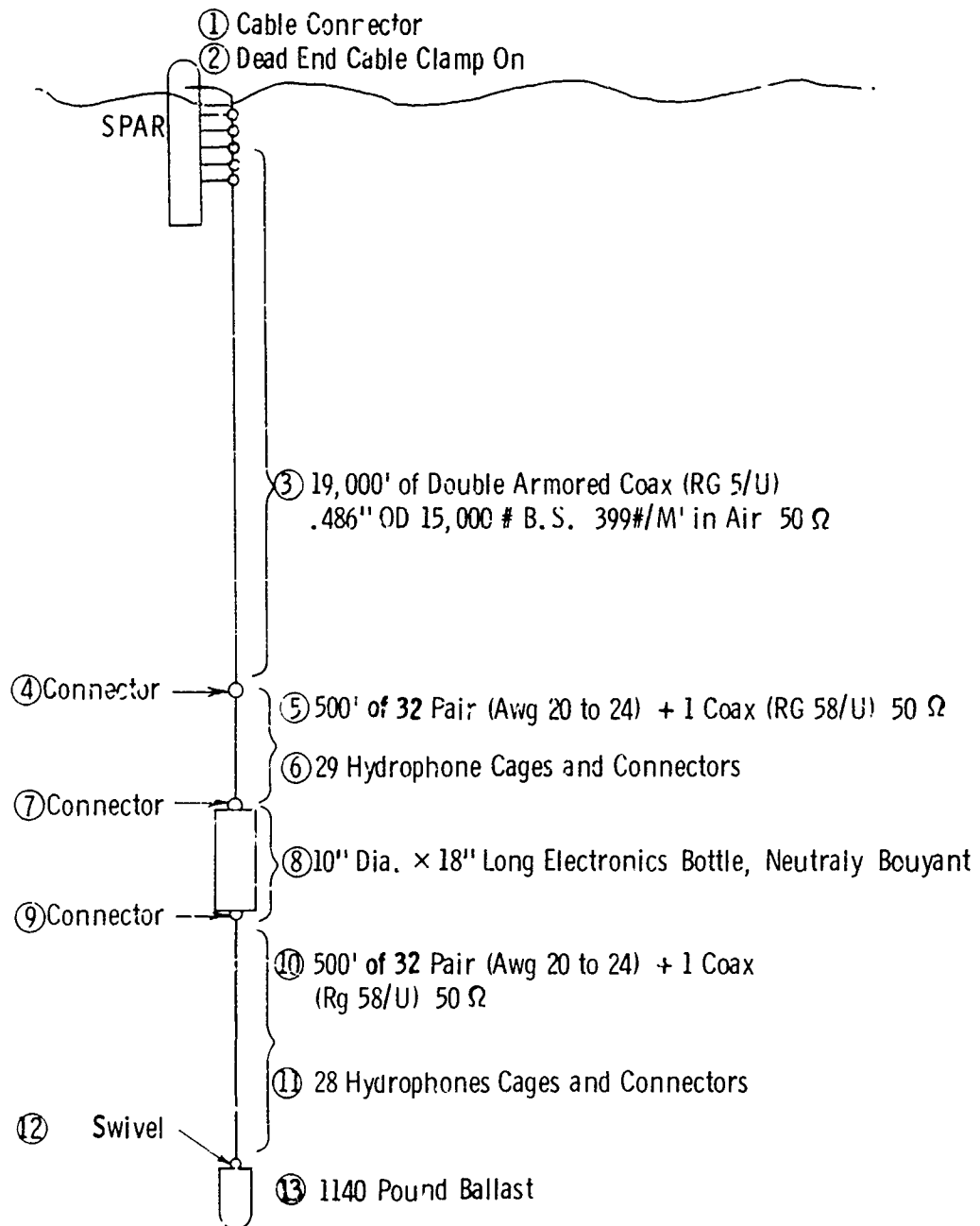


Fig. 1 - Cable system

2. Cables

The Vertical Array Cable System will be comprised of two cable types. The transmission cable which is 19,000 feet long will carry the signals to the surface and transmit power to the electronics bottle. The array cable is in two sections, each 500 feet long, with one end terminating in the electronic bottle. These cables electrically transmit the signals to the bottle and mechanically support the hydrophone.

2.1 Transmission Cable

The transmission cable shown in Fig. 2 is the link between the vessel electronics and the array cable and electronics bottle. It is similar in construction to an oil well logging cable and has been manufactured in the past. It is a coax with double armored construction. Its characteristics are:

Mechanical

O.D.	0.663"
Breaking Strength	32.000#
Weight in Air	625#/1,000'
Weight in Sea Water	500#/1,000'
Strength Member	Torque balanced double armor

Electrical

Impedance	49 Ohms at 1 MHz
Conductor DC Resistance	2.58 Ohms/1,000'
Shield DC Resistance	1.21 Ohms/1,000'
Attenuation:	
100 kHz	0.66 dB/1,000'
1 MHz	2.1 dB/1,000'

2.2 Array Cable

The array cable shown in Fig. 3 consists of two 500 ft. lengths with an electronics bottle between them. It is an electromechanical cable consisting of 32 pairs of conductors and 1 coax. It serves a dual purpose. Mechanically, it supports the hydrophones and has the ballast attached to the lower end. Electrically, it passes the acoustical signals to the electronics bottle, and the upper 500 ft. transmits the signals

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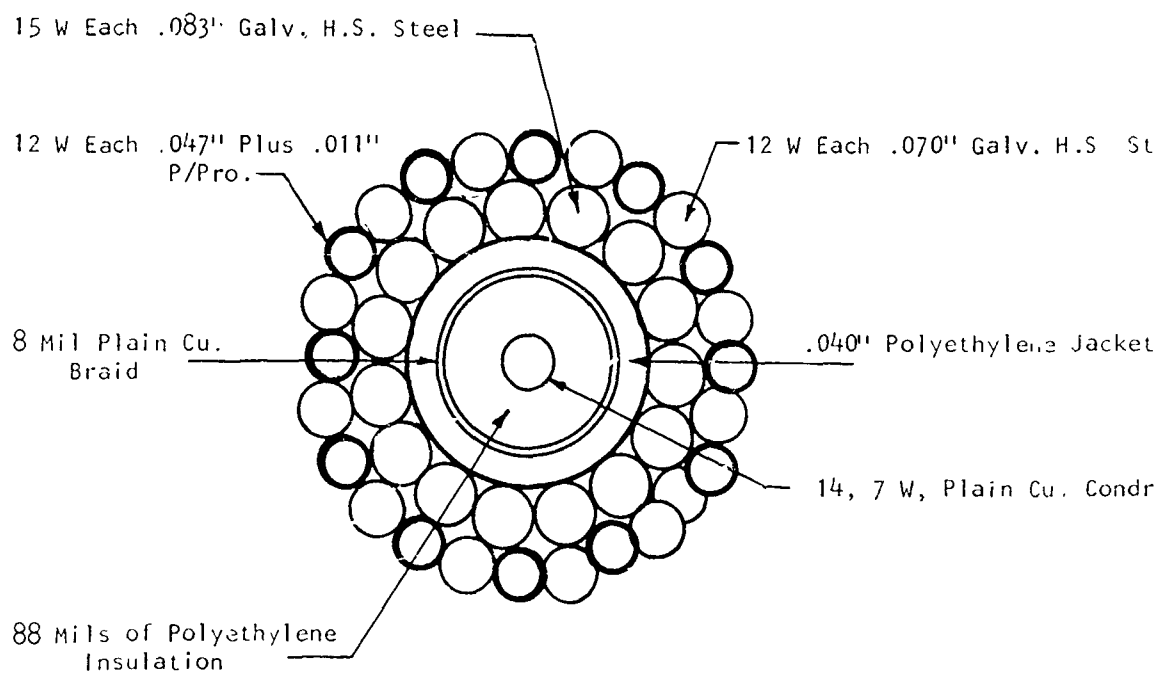
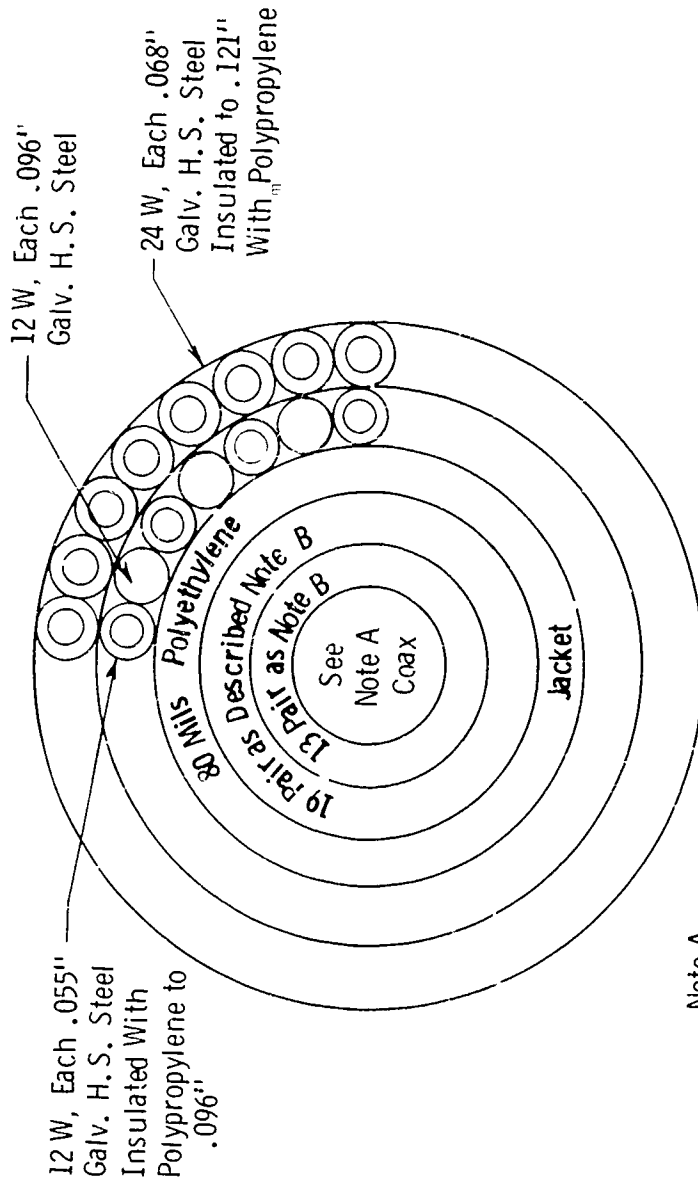


Fig. 2 - Transmission cable



Note A

Similar to RG-58 c/u
7 W Each .012" Tinned Cu., Filling Compound, 40 mils of Polyethylene, A 5 Mil Tinned Copper Braid and an Overall Polyethylene Jacket (Built-up) to .260". Filling Compound in Braid.

Note B

Size # 24, 7 W, Each .008" Tinned Cu Condr., (Filled), 10 mils of Polypropylene Insulation, Color Coded, Two Such Condrs. Paired (No Side Fillers) A Filling Compound to be Applied while Stranding the Pairs into the Core. A Mylar Separator will be used between Layers of Pairs.

Fig. 3 - Array cable

from the electronics bottle to the transmission cable through the coax. Note that the coax is unused in the lower array cable. Its characteristics are:

Mechanical

O.D.	1.15"
Breaking Strength	43,000#
Weight in Air	1,000#/1,000'
Strength Member	Torque balanced double armor

Electrical

Pairs

No. of Pairs	32
Size of Conductor	24 AWG
Resistance	26 Ohms/1,000'

Coax

Impedance	50 Ohms (RG58/U Coax)
Conductor DC Resistance	10.0 Ohms/1,000'
Shield DC Resistance	7.0 Ohms/1,000'
Attenuation:	
100 kHz	1.2 dB/1,000'
1 MHz	3.8 dB/1,000'

3. Connections

The Cable-Array System requires several electromechanical connections which we shall describe in a progression from the winch through the cables and ending at the ballast. The majority of these connections have been used in other applications and can be used "as is" or modified to meet our requirements.

3.1 Winch Connection

The transmission cable must be terminated at the winch. A method of doing this is to pass the cable through a hole in the drum and clamp it to the inside of the flange. It can then pass through the center of the winch bearing and hang loose until the cable is paid out. Once the cable stops, the connector on the terminated end can be connected to the cable leading to the electronic equipment aboard SPAR.

If the winch is used on more than one project, the cable may have to be removed from the drum or a new drum installed for the other projects. If only one drum is used, the cable connector will have to be removed each time so that the cable can be taken off the drum.

3.2 Transmission-Array Cable Connection

The connection between the transmission and upper array cable consists of an electromechanical fitting, (Preformed Line Products, Cleveland, Ohio) which dead ends the armor and allows the electrical core to pass through. One fitting is attached to the transmission cable and a similar fitting is attached to the array cable. A steel sleeve, housing the solder joint between the two cables, completes the fitting. Note that an electrical connector can be used to join the two cables if it is desirable to have the capability of uncoupling the two cables for replacement.

3.2 Hydrophone Connections

The hydrophones will be mounted in line with the cable. This method was selected over an alternate method of attaching the phones to the cable using stand-off brackets. The in-line phones do not have to be "buttoned" and "unbuttoned" from the cable. They can be stowed directly on the winch drum.

The electromechanical fitting is similar to the one mentioned above used for joining the two cables. The cable armor is severed at the point of attachment and a separate fitting used to terminate each break. The electrical core of the cable passes through the fitting center. A perforated split steel sleeve between the two fittings houses the hydrophone. The conductor pair used for the phone is separated from the bundle and an underwater electrical connector potted to the end of it. This mates with the phone connector. Thus, replacement of the phone is relatively simple, entailing only the unbolting of one half the sleeve from the fitting, uncoupling the electrical connector and removing the phone. The new phone is mounted by reverse procedure.

All of the cable work—mounting the fittings and sleeve, and potting the electrical connector—is done at the factory. The phones can be mounted at the factory or in the field. Such a fitting is made by Preformed Line Products, Cleveland, Ohio, and has been used previously on several underwater projects. Modifications of the fitting and the steel sleeve may be necessary in order to accommodate the hydrophone and permit the phones to be stored on the winch.

3.4 Electronics Bottle Connections

The electronics bottle was placed in the center of the array to decrease the cable diameter by cutting the number of conductors essentially in half. The end of the upper array cable is joined to the electronics bottle with the same fitting as mentioned above. The armor is terminated and the electrical core passes through the center.

There are several means of handling the electrical core. Some of these are:

1. Pass the core through a water-pressure-proof compression fitting directly in the bottle. Cable jacket cold flow and problems with this type fitting make this method less desirable than others.
2. Pot the electrical core to a flange which is mounted to the fitting terminating the armor. This flange mates with a flange on the bottle. An O-Ring on the flange insures watertightness. The end of the core can terminate in a standard electrical connector(s) or some other means used for the electrical connections to the bottle electronics.
3. Mount a flange-type electrical connector to the armor termination fitting. This mates with a flange-type electrical connector on the bottle. D. G. O'Brien Co. has made this type of connector for deep depths but with less pins than we require. Other companies such as Marsh Marine, etc. have similar connectors that could be used for deep depth operation. If we cannot get one large connector, two smaller ones can be used. Methods 2 and 3 look quite promising. The same arrangement would be used in the lower end of the bottle to attach the upper end of the array cable.

The upper end of the lower array cable is attached to the electronics bottle per the above suggested methods.

3.5 Array Cable to Ballast Connection

The lower end has the armor dead-ended in a fitting similar to those discussed previously. However, this time, the electrical core is also dead-ended. The ballast helps to keep the 1,000 ft. array as nearly vertical as possible. Since the cable manufacturers object to the cable spinning more than necessary, a swivel can be used between the cable and the ballast. The swivel can be pinned to a clevis which in turn can screw into the cable termination fitting. The other end of the swivel can be pinned to a clevis screwed into the ballast.

4. Array Verticality

Since the vertical resolution angle of the array is about 8° , an array tilt of one or two degrees although undesirable will not degrade the vertical directivity too seriously, however every effort will be made to keep the array as vertical as possible. Currents although small at deep depths, will tip the array out of this range unless a ballast is used. Using a cable diameter of 1.2 in. and an estimated current of 1/3 knot acting on the 1,000 ft. array cable, a ballast of approximately 1,140 lb. would be needed to hold the cable to 1° verticality. Refer to "Tables for Computing the Equilibrium of a Flexible Cable in a Uniform Stream," by Leonard Pote, DTMB Report 687, March 1951. Ocean currents vary in direction as well as magnitude with depth but the uniform velocity represents the worst condition.

5. Cable Strumming

Cable strumming, usually at low frequencies, could cause acoustical problems if within our range of interest. At an assumed 1/3 knot current and cable diameter of 1.2 in., the Reynolds number is within the strumming range of 0 to 10^6 . The Strouhal frequency is about .03 Hz and the cable natural frequency is approximately .09 Hz. High harmonics of the cable natural frequency could be of some concern. However, the amplitude at the frequency band of interest should be fairly small.

6. Safety Factors

6.1 Transmission Cable

A preliminary weight analysis of the Cable-Array System, in water, is as follows:

Transmission Cable (19,000')	10,030#
Array Cable	700
Ballast	1,140
Hydrophones	570
Fittings for Hydrophones	<u>2,050</u>
TOTAL	14,490#

The breaking strength of the transmission cable is approximately 32,500#. Therefore, the safety factor is:

$$\frac{\text{Safety Factor}}{\text{Transmission Cable}} = \frac{32,500\#}{14,490\#} = 2.2$$

This is barely adequate. A minimum of 2.5 is preferred. However, since we are operating from a stable platform, there should be little dynamic loading on the cable. Bouyancy may be added in the form of tied on glass spheres as used in the ACODAC array in order to obtain the 2.5 safety factor.

We shall investigate in detail means of reducing the cable load to increase the safety factor. Increasing the transmission cable diameter is impractical since the winch would have to be made larger. There is a physical size limitation for the winch in the SPAR Antenna Room.

6.2 Array Cable

The array cable must support:

Array Cable (1,000')	700#
Ballast	1,140
Hydrophones	570
Fittings for Hydrophone	<u>2,050</u>
TOTAL	4,460#

The breaking strength of the array cable is approximately 43,000#. Therefore, the safety factor is:

$$\frac{\text{Safety Factor}}{\text{Array Cable}} = \frac{43,000\#}{4,460\#} = 9.6$$

7. Summary

There are several problem areas in the Cable-Array System:

1. The transmission cable safety factor is barely adequate. We shall look at means of reducing the cable load, using higher strength armor, bouyant glass spheres, and reducing the cable length to try to increase the safety factor.
2. Maintaining the array verticality within one or two degrees will be checked thoroughly. The problem here is estimating the currents at deep depths. We cannot overwhelm the problem by using an overdesigned ballast because of the safety factor limitation mentioned in problem (1) above.
3. The proposed array cable will have in-line hydrophone bulges and an in-line electronics bottle. These will have to be handled by the overboarding and level wind sheaves. We have to ensure also that they are capable of being stowed on the winch drum. Special handling techniques are needed to get the bottle past the sheaves.
4. The array cable will have 57 armor discontinuities for the in-line hydrophone mounting. The armor terminates at each fitting and the fitting carries the load. While we have done this previously in VERSUS, and Preformed Line Products has put them in several projects, the number of hydrophones in those systems was considerably less than the 57 here.
5. Corrosion will occur in the armor and reduce the cable strength over a period of time. In all likelihood, this should not affect us during the array life, but it is a potential problem. There will be corrosion problems at the interface between the electronic bottle and the connection to the cable if dissimilar metals are used. The system as a whole will be analyzed to reduce factors which will cause corrosion.

VI. TESTS

There are several mechanical and hydrostatic tests we want to perform on the array to ensure mechanical and electrical integrity under environmental operating conditions.

1. Array Cable

The array cable is a multiconductor, double armored electro-mechanical cable never constructed before. Although similar types of cable have been made, we want to run some life cycling tests over sheaves to make sure it can stand up under the tensions, pressures, and cycling over the operating sheaves.

The cable will also be hydrostatically pressure tested to make sure it can stand the operating depth of 21,000 ft. without water leakage.

2. Hydrophones

Some sample hydrophones will be mounted in the cages and will be subjected to a hydrostatic pressure of 11,000 psi to test for leakage. The pressure will be cycled to simulate reeling in and out. These tests will be repeated at different points in the hydrophone cages bending tests discussed next.

3. Hydrophone Cages

The hydrophone cages will be subjected to bend tests over sheaves of the minimum operating diameter. The cages will be placed under tension and will be cycled to simulate the reeling in and out during operations.

At least one cage will have a hydrophone in it for use in the hydrostatic tests mentioned above.

4. Cable-Array System

The complete Cable-Array System will be wrapped on a reel and placed in a GFE hydrostatic pressure tank. The pressure will be cycled to 11,000 psi to simulate reeling the cable in and out during operation. Cable leads will be passed through the pressure tank wall to monitor the conductors and electronics during the pressure test.

VII. GOVERNMENT FURNISHED EQUIPMENT

1. Winch

Although the winch will be GFE, some features of our array require consideration by the winch designer. The array cable will have built-in cages housing the hydrophones which are nonlinearly spaced. These cages will be wrapped on the drum so they will have to be handled by the level wind. The level wind sheave must take both cable and cages without damaging them. It must also handle the smaller diameter transmission cable. The minimum diameter of the level wind device (sheave, rollers, etc.) should be 28", with a larger diameter preferable to increase the cable life.

The electronics bottle is located between the two 500 ft. array cables. We prefer not to disconnect it for stowage. Perhaps a method can be found to stow it as part of the array on the inside of one of the winch flanges and continue to wrap the remaining 500 ft. of array cable. Note that the bottle will undoubtedly have to be hand carried over the level wind since it is approximately 10 in. in diameter by 18 in. long.

Because of the cages, the winch should have infinite speed control to handle the cages safely. As a minimum, the winch readouts should include:

- Cable Tension
- Cable Length In and Out
- Cable Speed In and Out

The winch control panel should include also a protected button or switch to activate a ballistic cable cutter for emergencies.

The cable must be terminated at the winch with a GFE clamp or similar device. This is described later.

A summary of the components the winch must handle follows:

- 19,000' of 0.665" diameter cable
- 1,000' of 1.330" diameter cable
- 57 hydrophone cages with approximate diameters of 4", lengths of 30", tapered at each end. The taper is included in the 30" length.
- 1 electronics bottle approximately 10" in diameter by 18" long.

2. Overboarding Sheave

This GFE item must have a minimum diameter of 28 in. with a larger diameter preferable for increasing cable life. It should be capable of handling three different diameters for transmission cable, array cable, and hydrophone cages. Note that the electronics bottle will undoubtedly have to be hand-carried over the sheave because of its size. The lower 500 ft. of array cable can be stopped off with a Kellums Grip or some other device while the bottle is eased over the sheave. Clear communication capability with the winch operator inside the antenna room is mandatory during this operation.

3. Ballast Pen

A GFE pen must be provided to stow the ballast attached to the end of the cable. It should allow the cable to be disconnected if required. If ring cable guides are used along the deck, the ballast pen may have to be installed on the stern.

4. Cable Cutter

In the event of an emergency occurring while the cable is being payed out, stationary during operation, or being hauled in, a means of severing it should be available. A GFE ballistic cable cutter could be mounted on deck at the overboarding sheave or inside near the winch. A bolt cutter of sufficient strength may also be used, although it should be tested to ensure capability of cutting through the double armor. In either case, the cable should be severed where whiplash cannot injure personnel.

5. Pressure Test Facility

The complete Cable-Array System less the ballast should be hydrostatically pressure tested to ensure its watertightness. A pressure test tank large enough to hold a 5.5 ft. diameter by 4 ft. traverse reel containing 20,000 ft. of cable, and capable of 11,000 psi is needed. A means of passing cable conductors through the tank wall should be provided for monitoring the conductors and electronics in the array.

VIII. COST AND SCHEDULE ESTIMATES

The following is an estimate for Phase II which includes the detail design, fabrication, and bench testing of the measurement equipment as specified in the above report.

Cable Section

Transmission Cable (1)	Cable Safety Factor Analysis
Array Cables (2)	Analysis of Verticality
Dynagrips, Swivels	Array Handling Development
Winch Bead End Connection	Armor Terminations Study
Transmission Cable Connectors	Corrosion Analysis
Electronic Bottle-Array Connector	Array Cable Test
Array Cable-Ballast Connection	Hydro Test of Phone Package
Ballast Design and Construction	Cable Array System Test
Hydrophone Cages	Consultation with USN on Winch, Sheave, ballast & Stowage, Safety, and Pressure Tests

Electronics and Hydrophone Section

Printed Wiring Assemblies	Dockside Test
Bottle Electronics & Mechanical Design	Technical Manual Preparation
Hydrophone Design and Assembly	Drafting
Topside Electronics	

Cost Estimates

	<u>Cable Section</u>	<u>Electronics & Hydrophones</u>	<u>Total</u>
Material	\$ 49,200	\$ 31,600	\$ 80,000
Engrg. Labor	47,800	115,300	163,100
Shop Labor	35,000	32,500	67,500
Travel	5,400	1,200	<u>6,600</u>
			\$ 318,000
		R&D and G&A	<u>54,500</u>
			372,500
		Profit 10%	<u>37,200</u>
			\$ 409,700

This cost will be considered valid for 60 days from the date of issuance of this report.

VERTICAL ARRAY TIME ESTIMATE

Weeks	0	5	10	15	20	25	30
*	*	*	*	*	*	*	*
Array Cable Procurement							
Communication Cable Procurement							
PLP Modification to							
Array Cable							
Build and Test Hydrophones							
Design, Build and Test Electronics Bottle							
Assembly &							
Test Array							

APPENDIX A

Research Memo 72-1C6-DPSUB-M1
Proprietary Class 2

March 16, 1972

HIGH RESOLUTION, LOW FREQUENCY RECEIVING HYDROPHONE ARRAY

by

C. Howard Jones
Sonic Technology

ABSTRACT

K. Geohegan of OR&EC has suggested how a small number of receiving hydrophone elements can be used to obtain high angular resolution with low side lobes. An example is given for an array 31.5 wavelengths long which contains only 15 elements.

A recent report of K. Geohegans of (W) OR&EC suggested that a linear array of transducers might consist of a first set of widely spaced elements and a second set of closely spaced elements as shown in Fig. 1. To sample a particular direction, the signals from the first set of elements can be properly phased to produce a high resolution beam in that direction. Because of the 4λ spacing, nine beams will be produced of equal amplitude. By employing a Dolf-Tschebyscheff shading of 26, 52, 81, 100, 100, 81, 52, 26. The side lobes can be held to -30 dB. Now if the direction of interest is at -14.5° then the elements can be phased to produce a beam in this direction as illustrated by Fig. 2. If the elements of the second set of transducers are also phased to produce a beam at 14.5° , and no shading is employed, the pattern illustrated by Fig. 3 results. Adding these two dB patterns is the equivalent of taking the product of the two detected signals. This result is shown in Fig. 4. The pattern is similar to what would have been obtained from an array of 57 elements spaced $\lambda/2$ apart with a length of 28λ .

The element locations and shading functions have not been optimized but this one example illustrates that the product technique may provide a useful method for reducing the number of elements required in a receiving array.

In the example illustrated in Figs. 1 to 4 the same results could have been achieved with a 15 element array only 28λ long (see Fig. 5). Arrays in which three or more groups of elements are each steered and the results detected and multiplied should be examined. The effects of noise on arrays that employ product processing needs to be evaluated. Also the bandwidth limitations should be determined. Possibly the technique will be useful in two and three dimensional arrays as well as line arrays.

Figs. 6a and 6b illustrate the nature of the beams produced when eight small elements are spaced 4λ apart and the received signals are all weighted equally. Figs. 7a and 7b are for an eight element array with $\lambda/2$ spacing and -30 dB shading.

Dwg. 6167A53

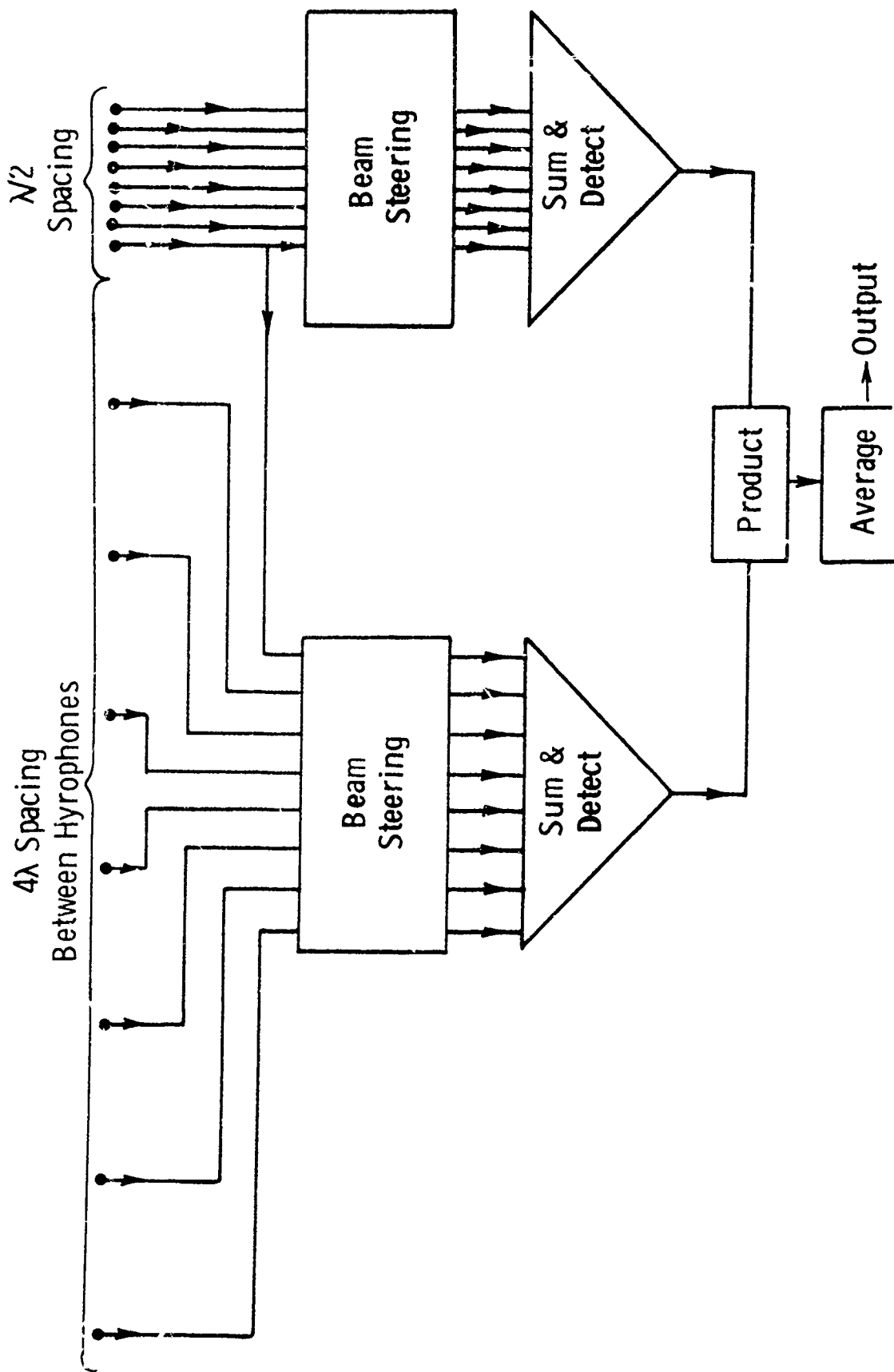


Fig. 1—Anderson and Tittle Array with Faran and Hills Correlator

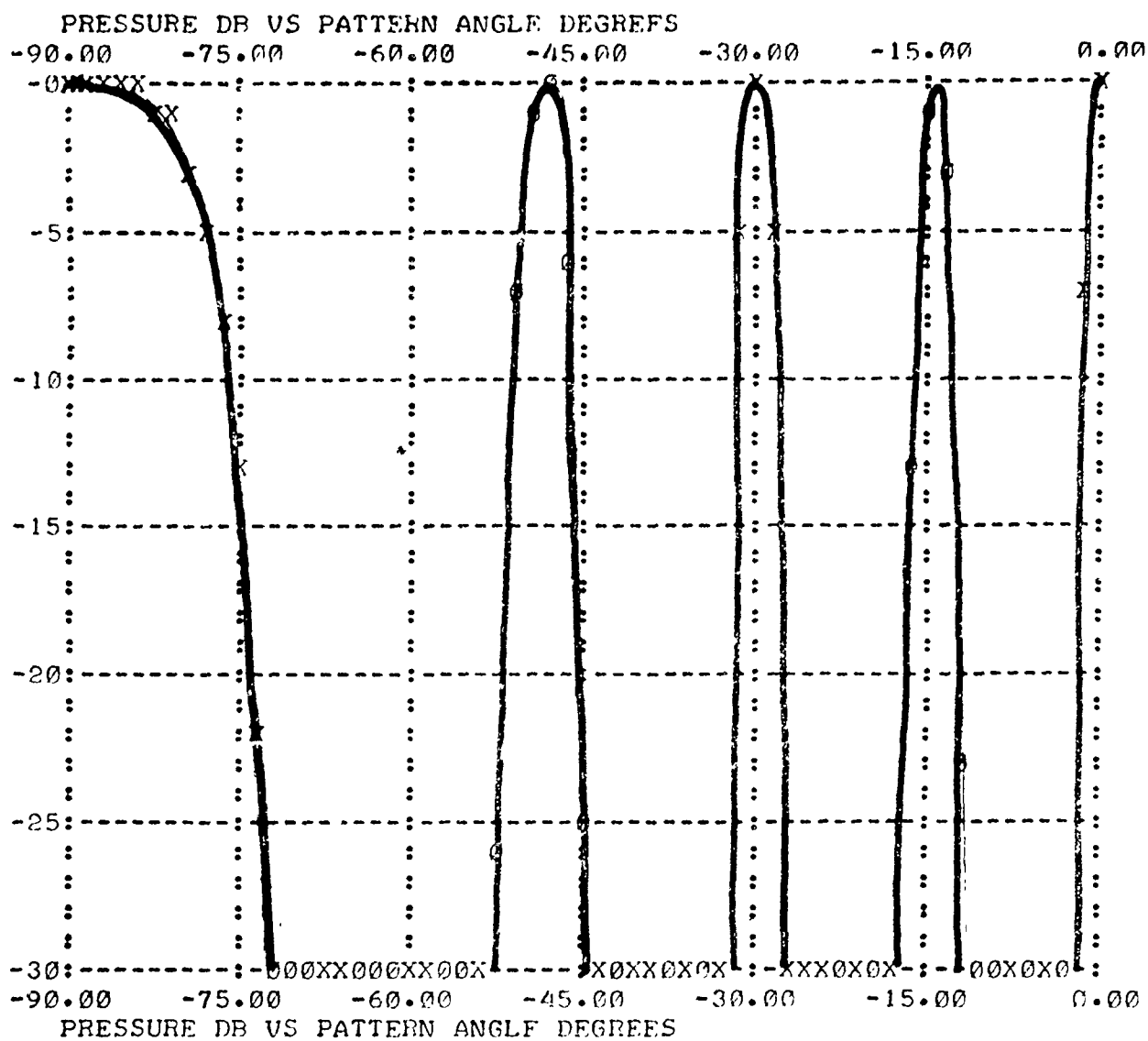


Fig. 2a. Eight elements, 4λ apart, -90° to 0° ,
with shading

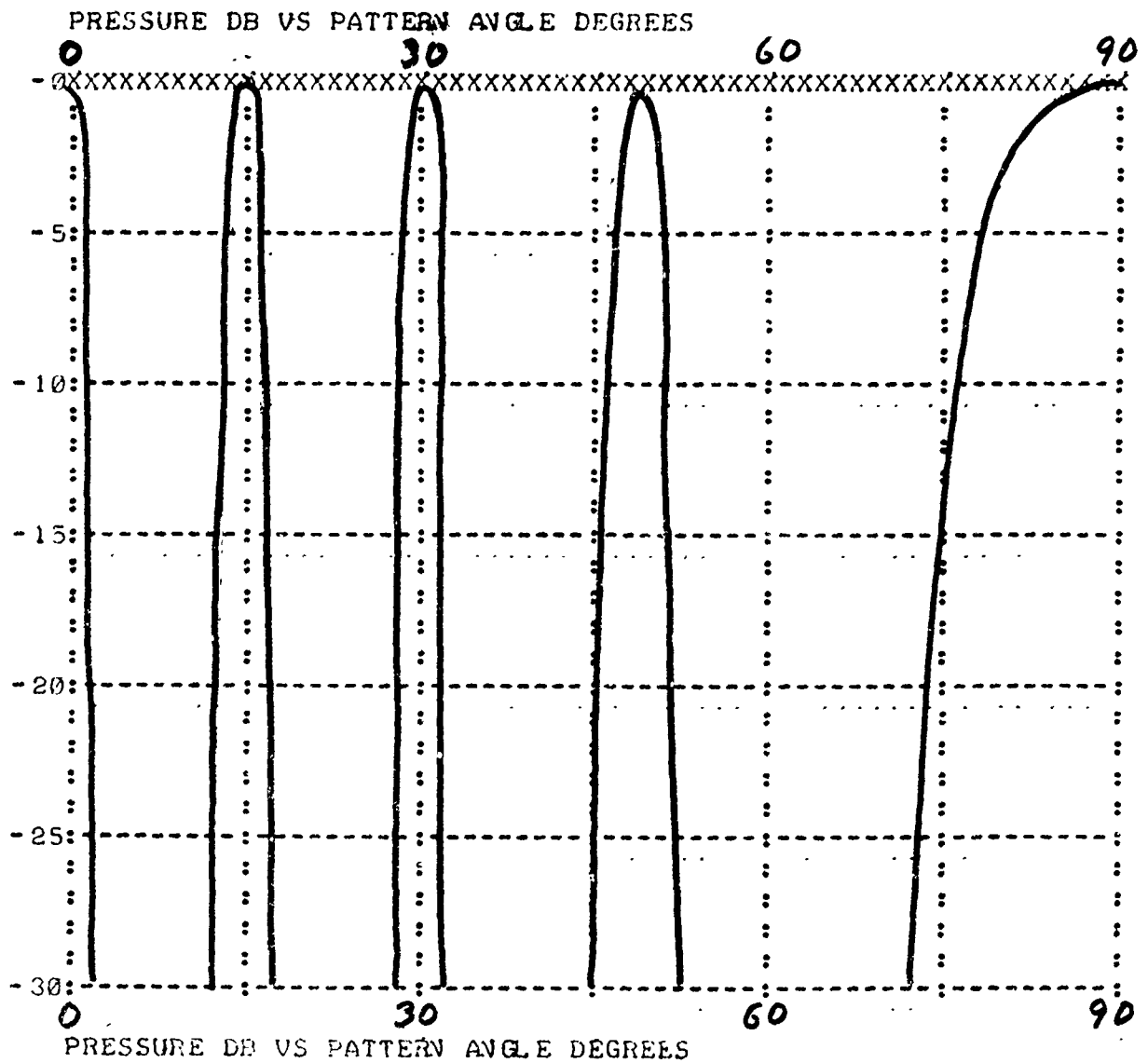


Fig. 2b. Eight elements, 4λ apart, 0° to $+90^\circ$, with shading

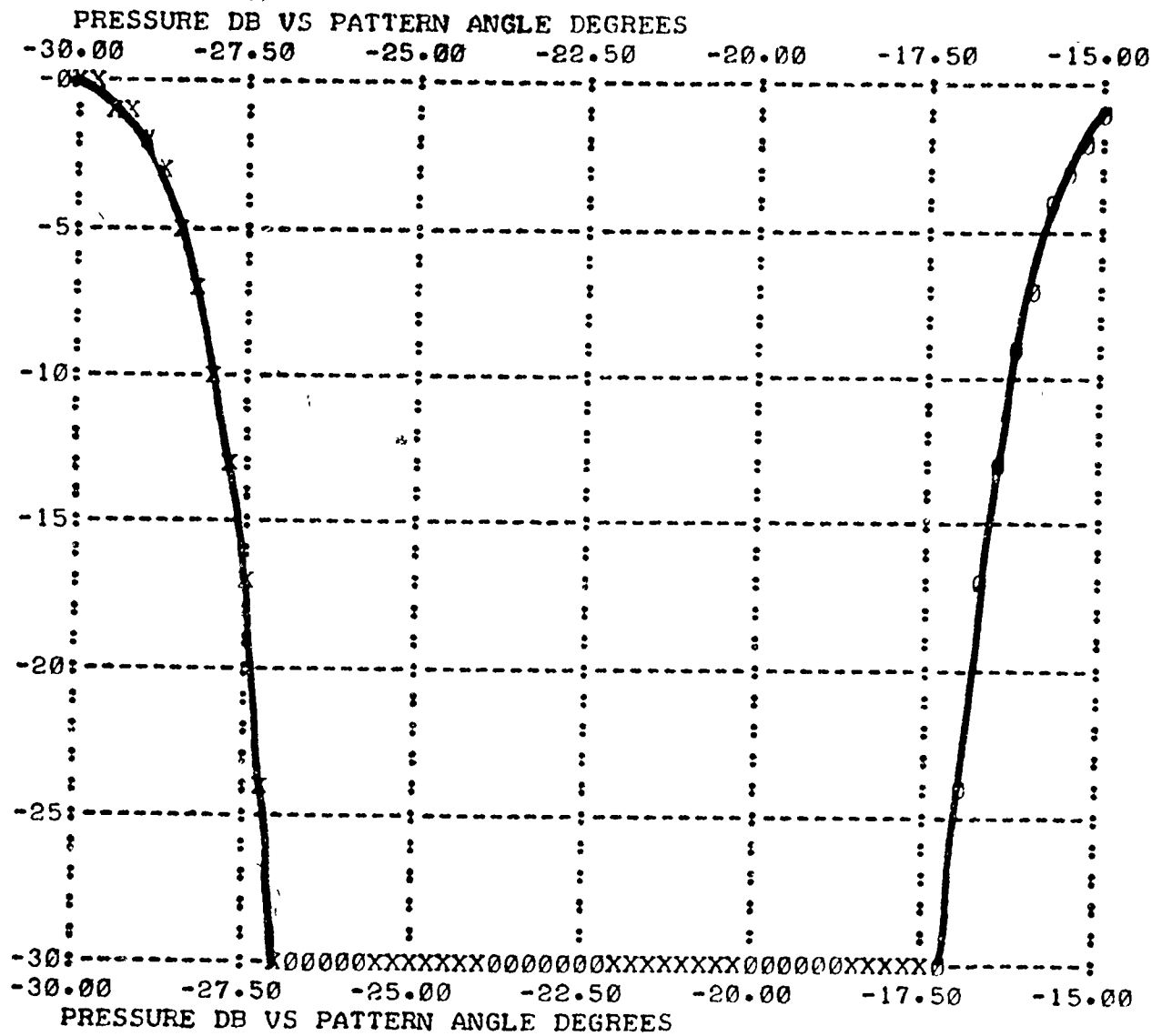


Fig. 2c. Eight elements, 4λ apart, -30° to -15° , with shading

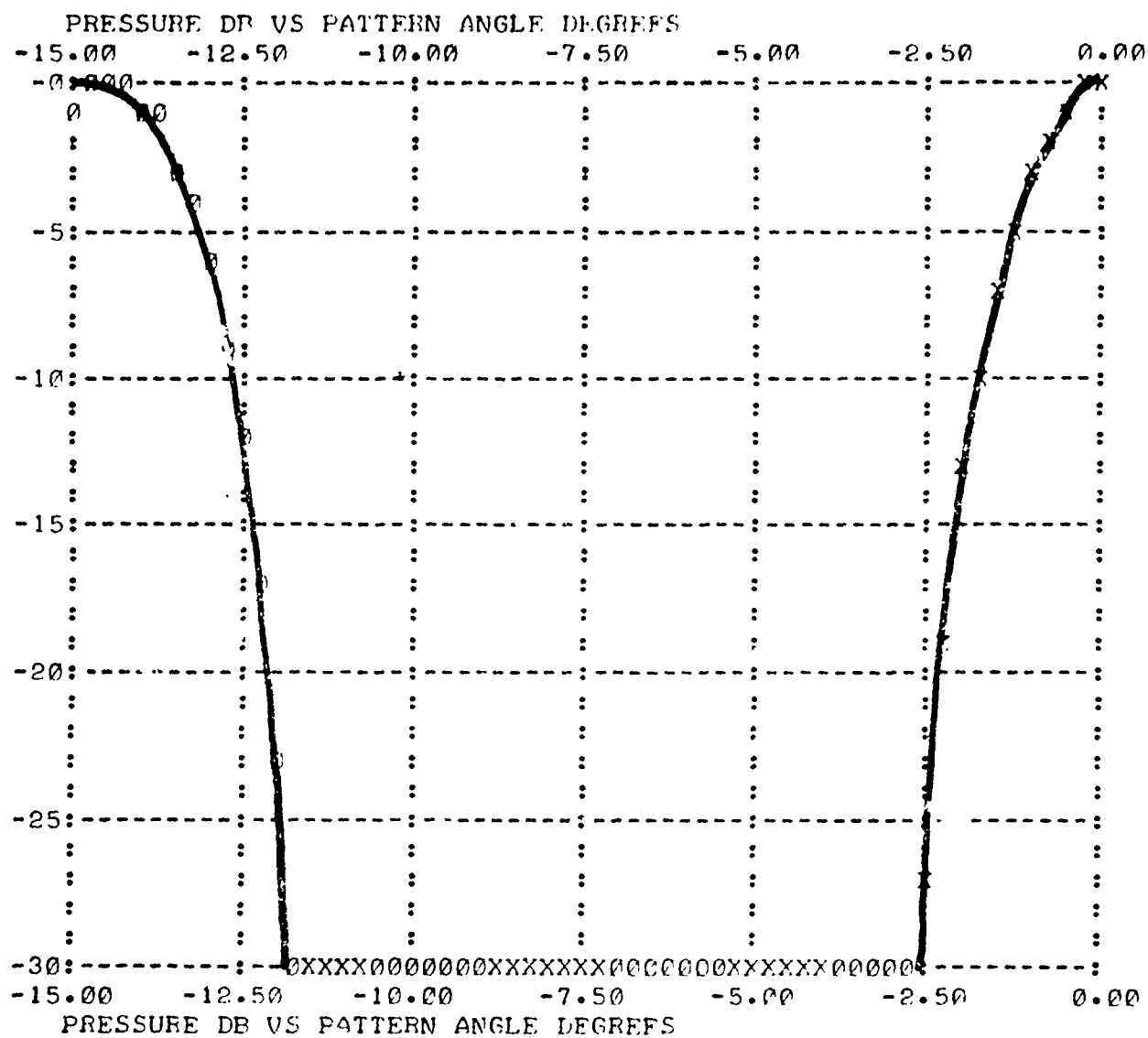


Fig. 2d. Eight elements, 4λ apart, -15° to 0° ,
with shading

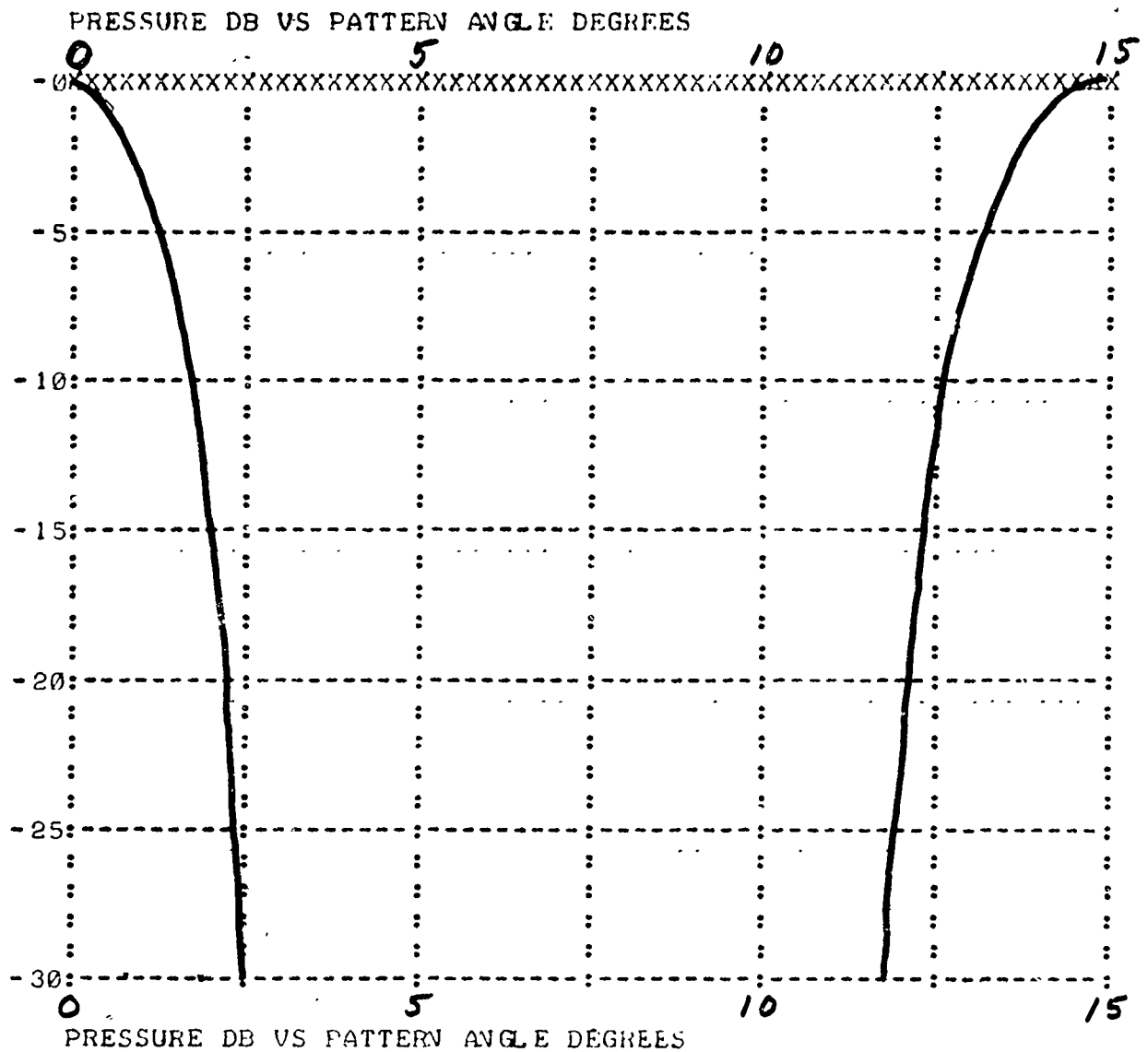


Fig. 2e. Eight elements, 4λ apart, 0° to $+15^\circ$,
with shading

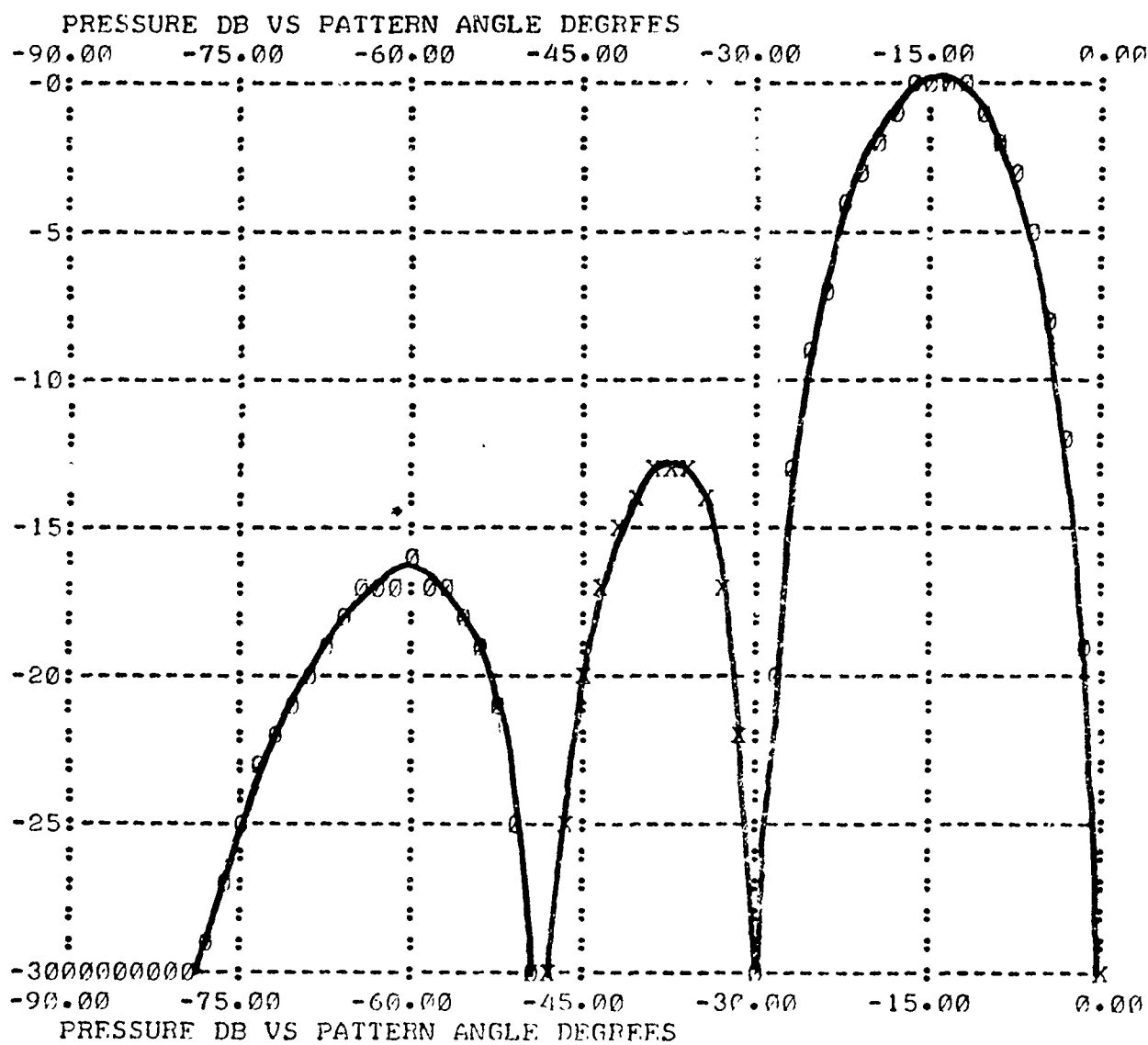


Fig. 3a. Eight elements $\lambda/2$ apart, -90° to 0° ,
no shading

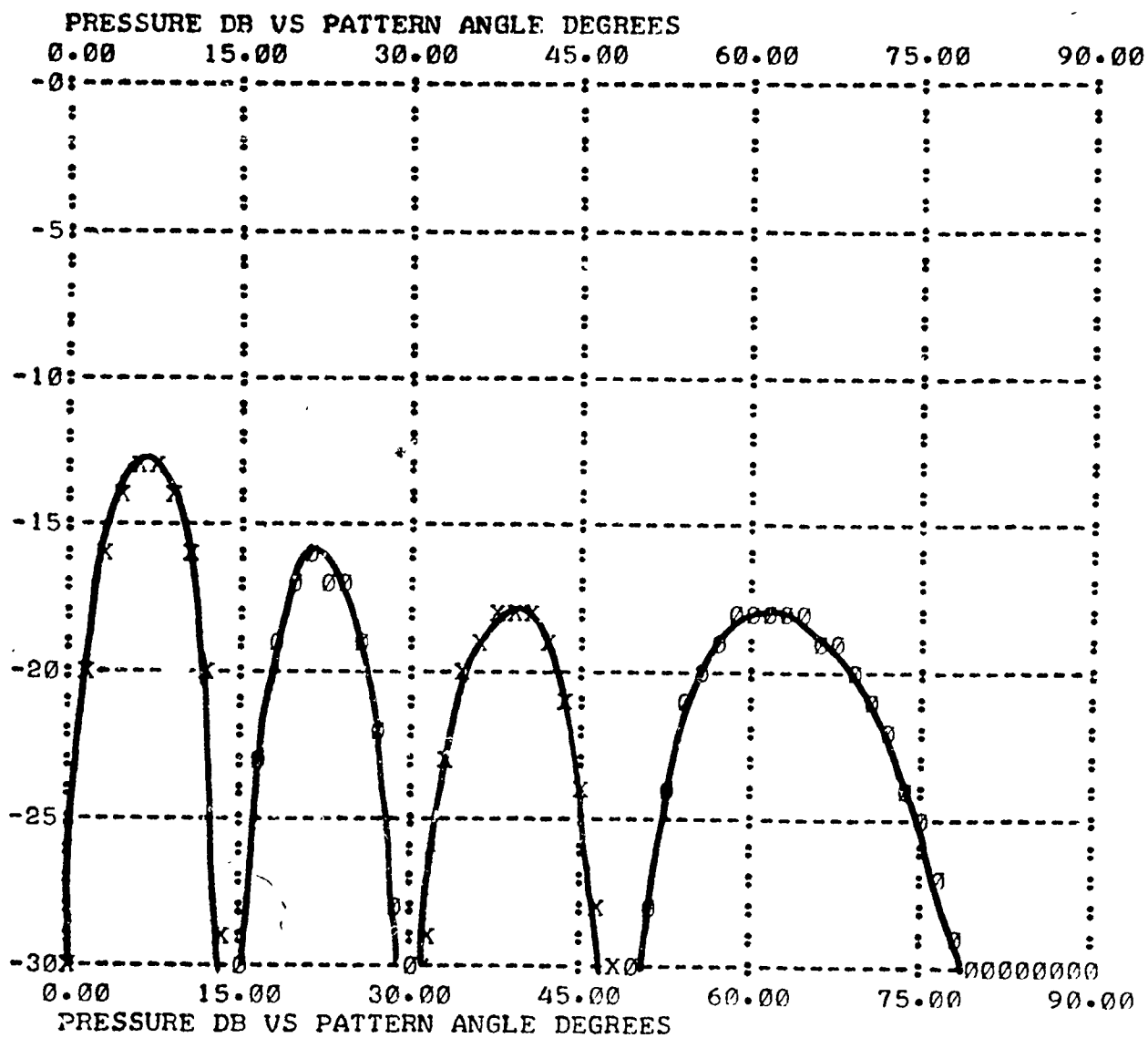


Fig. 3b. Eight elements $\lambda/2$ apart, 0° to $+90^\circ$,
no shading

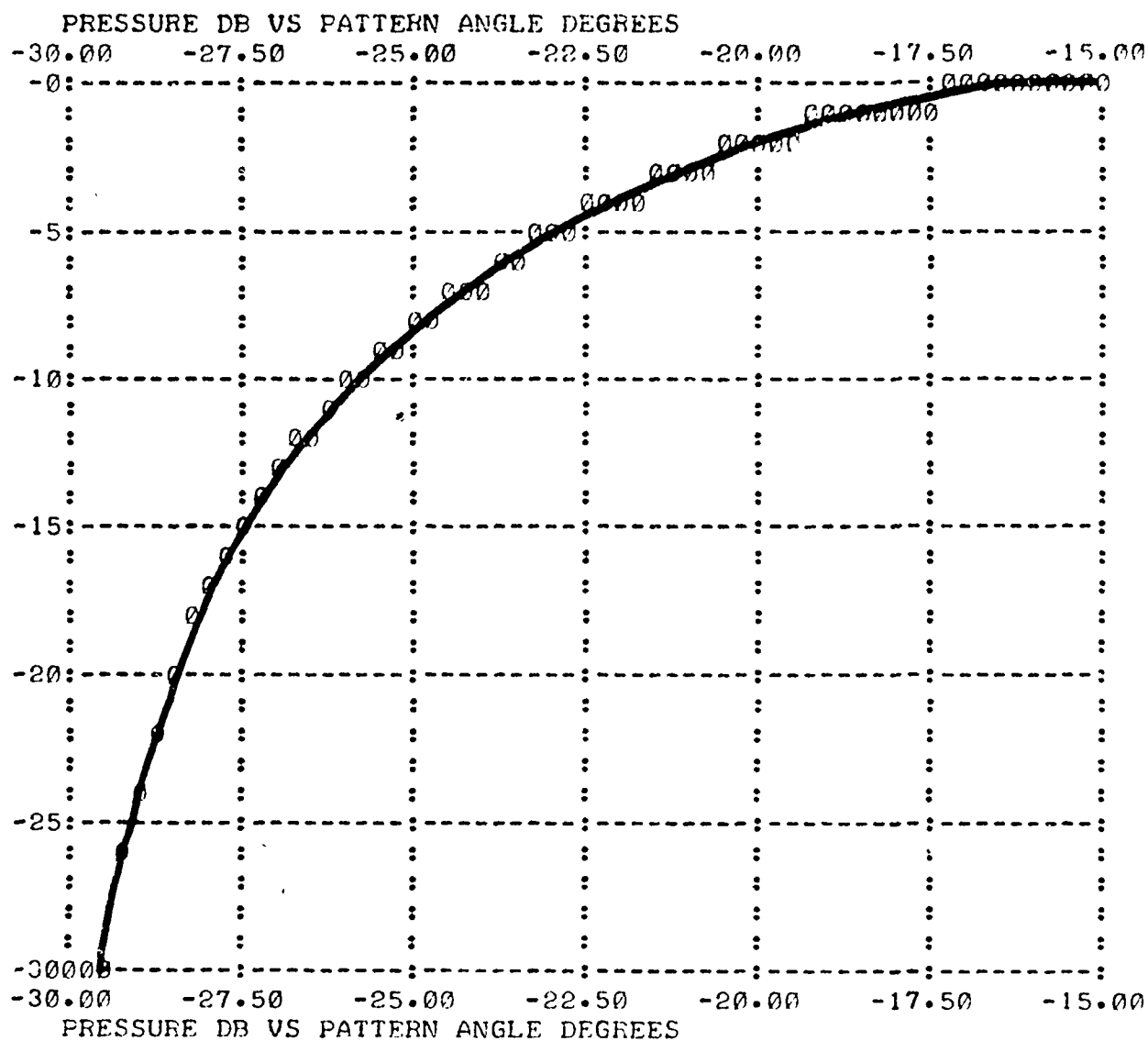


Fig. 3c. Eight elements $\lambda/2$ apart, -30° to -15° ,
no shading

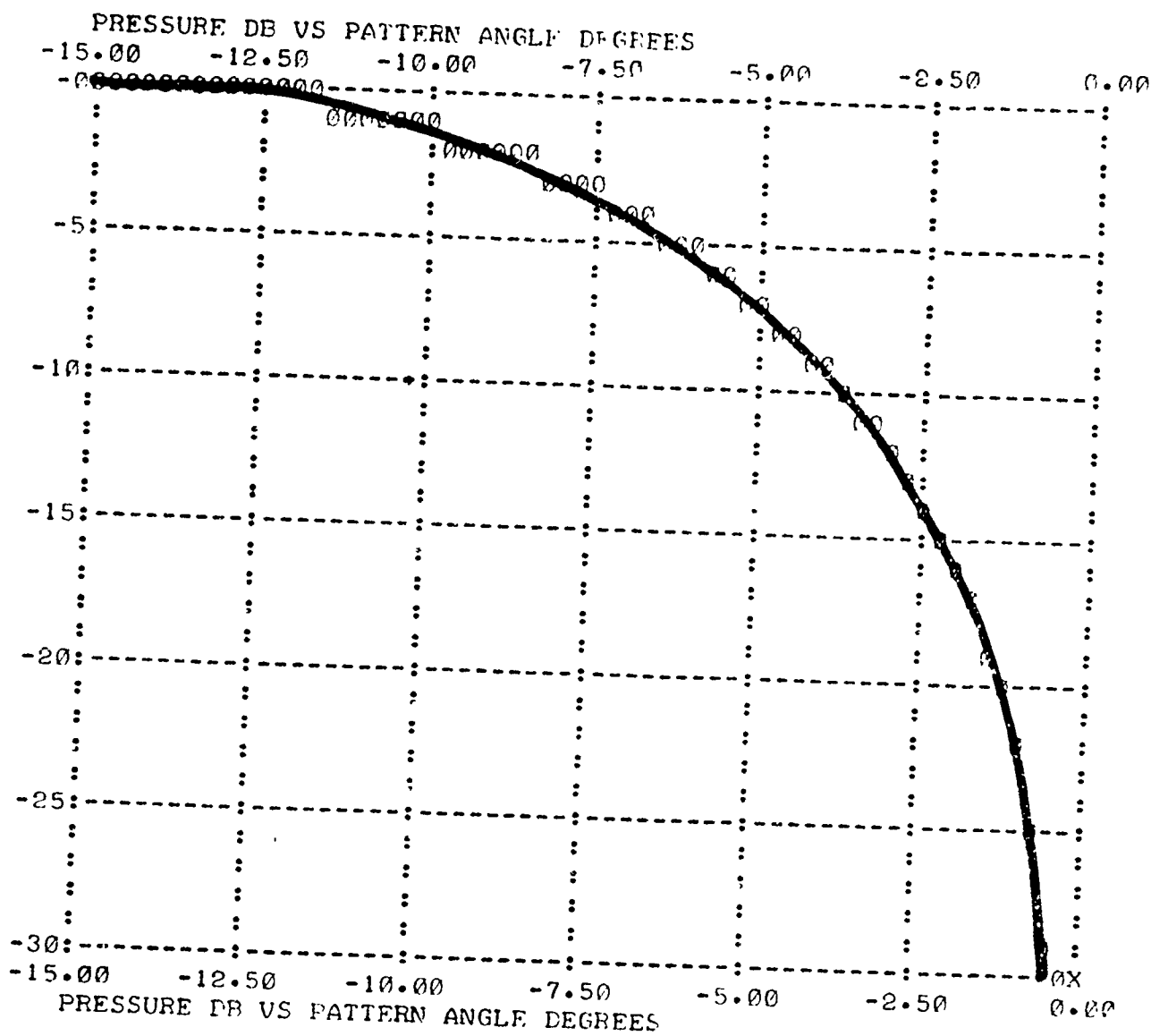


Fig. 3d. Eight elements $\lambda/2$ apart, -15° to 0° , no shading

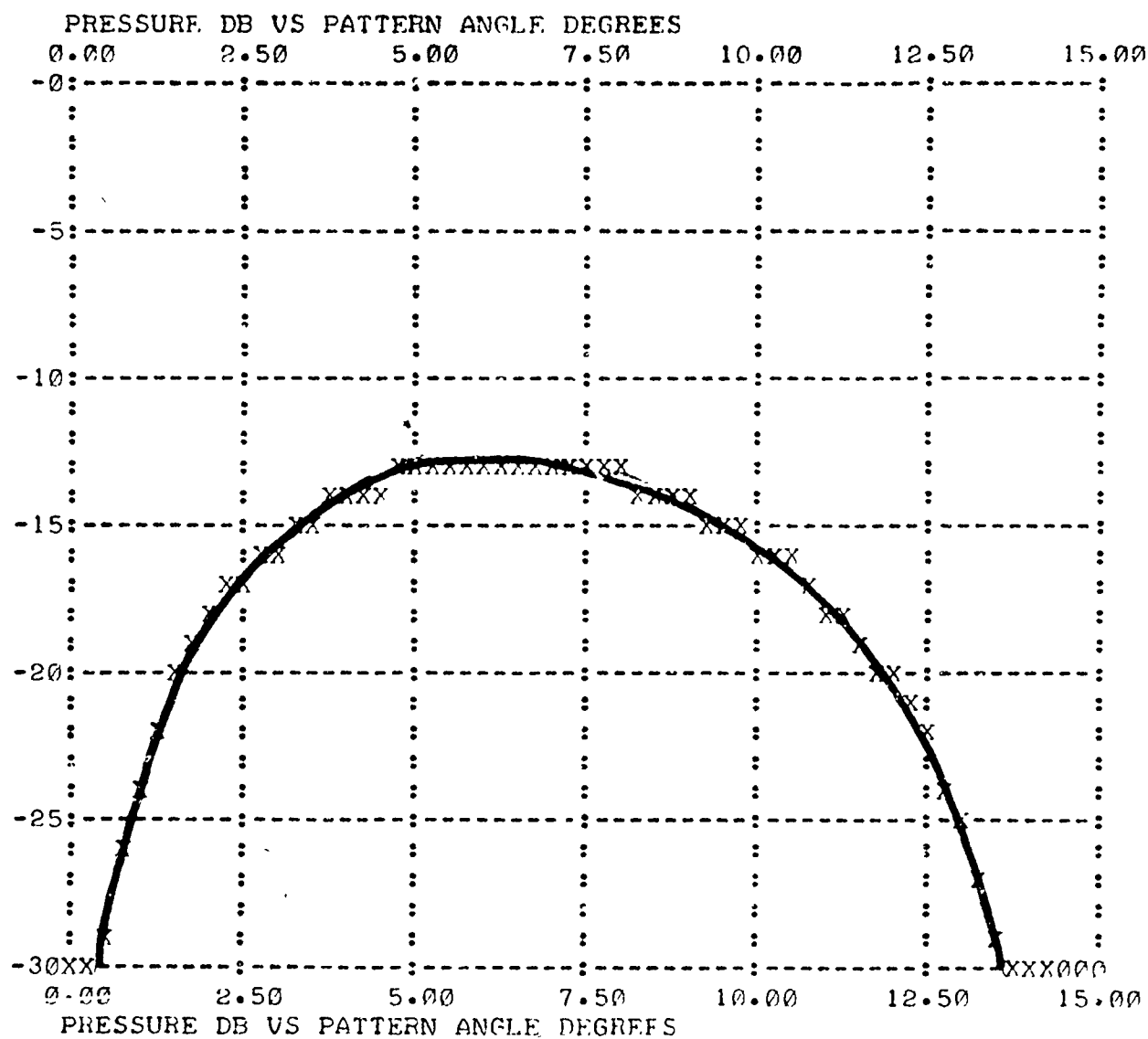


Fig. 3e. Eight elements $\lambda/2$ apart, 0° to $+15^\circ$,
no shading

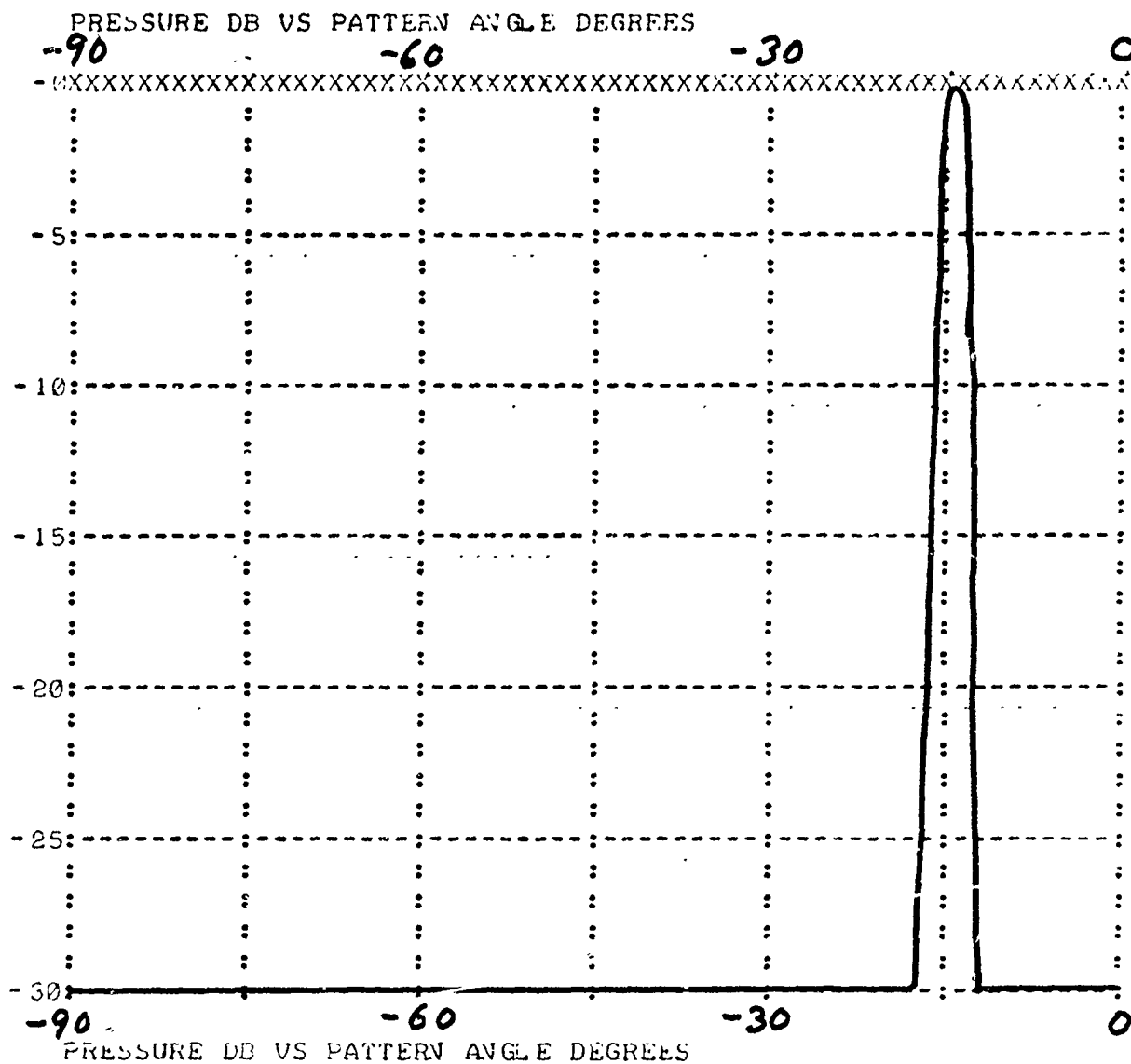


Fig. 4a. Product of two patterns, -90° to 0°

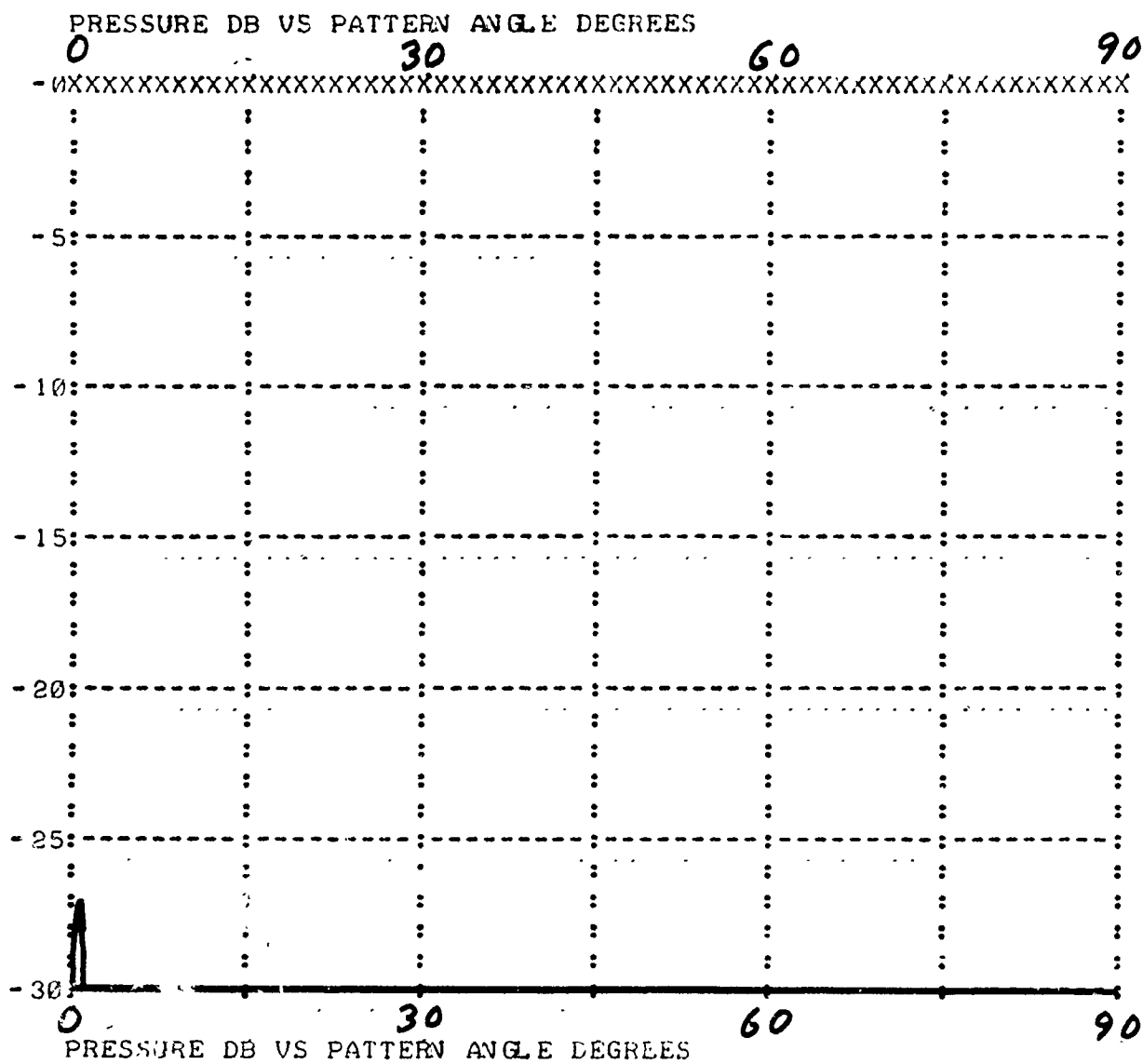


Fig. 4b. Product of two patterns, 0° to +90°

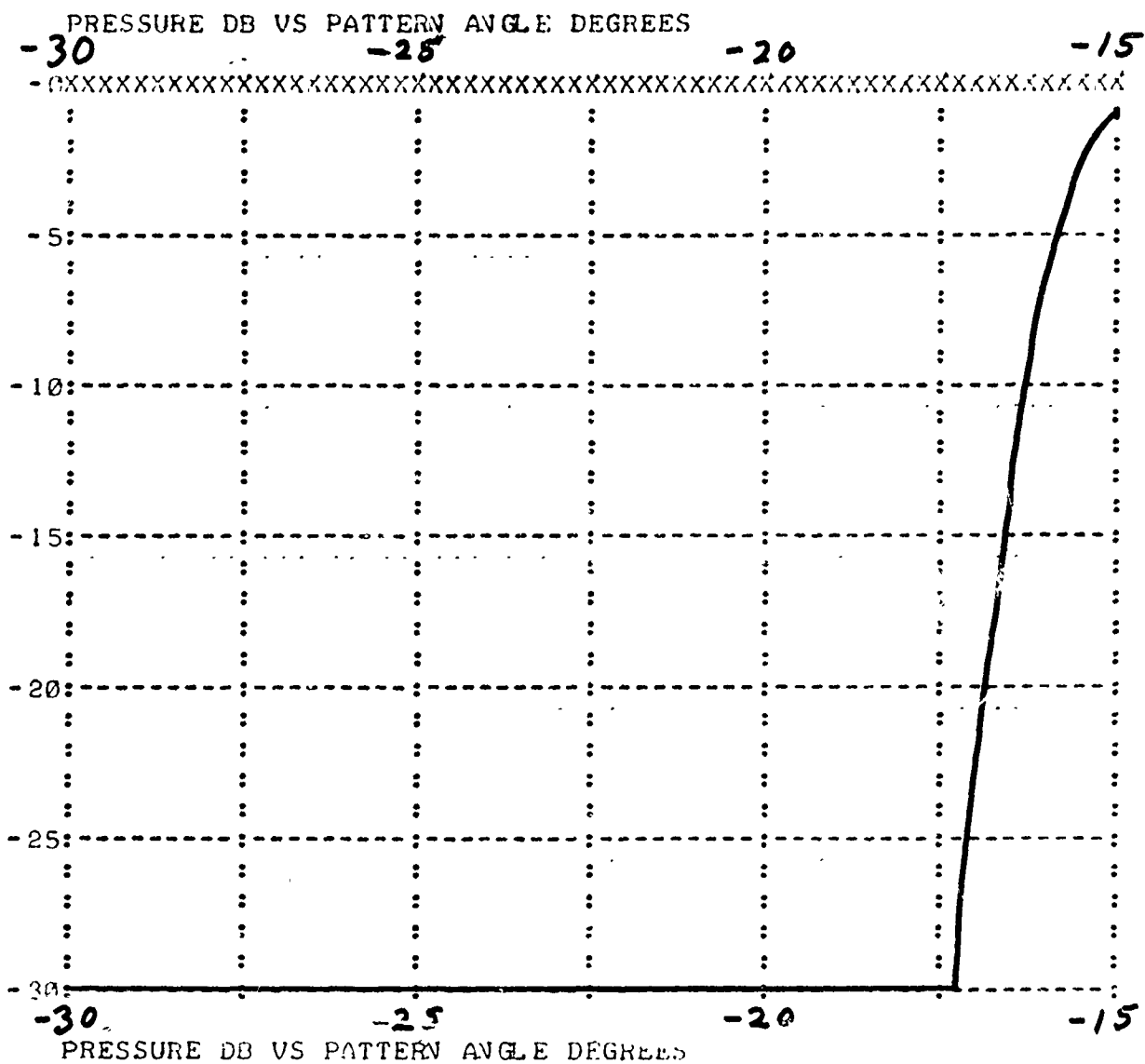


Fig. 4c. Product of two patterns, -30° to -15°

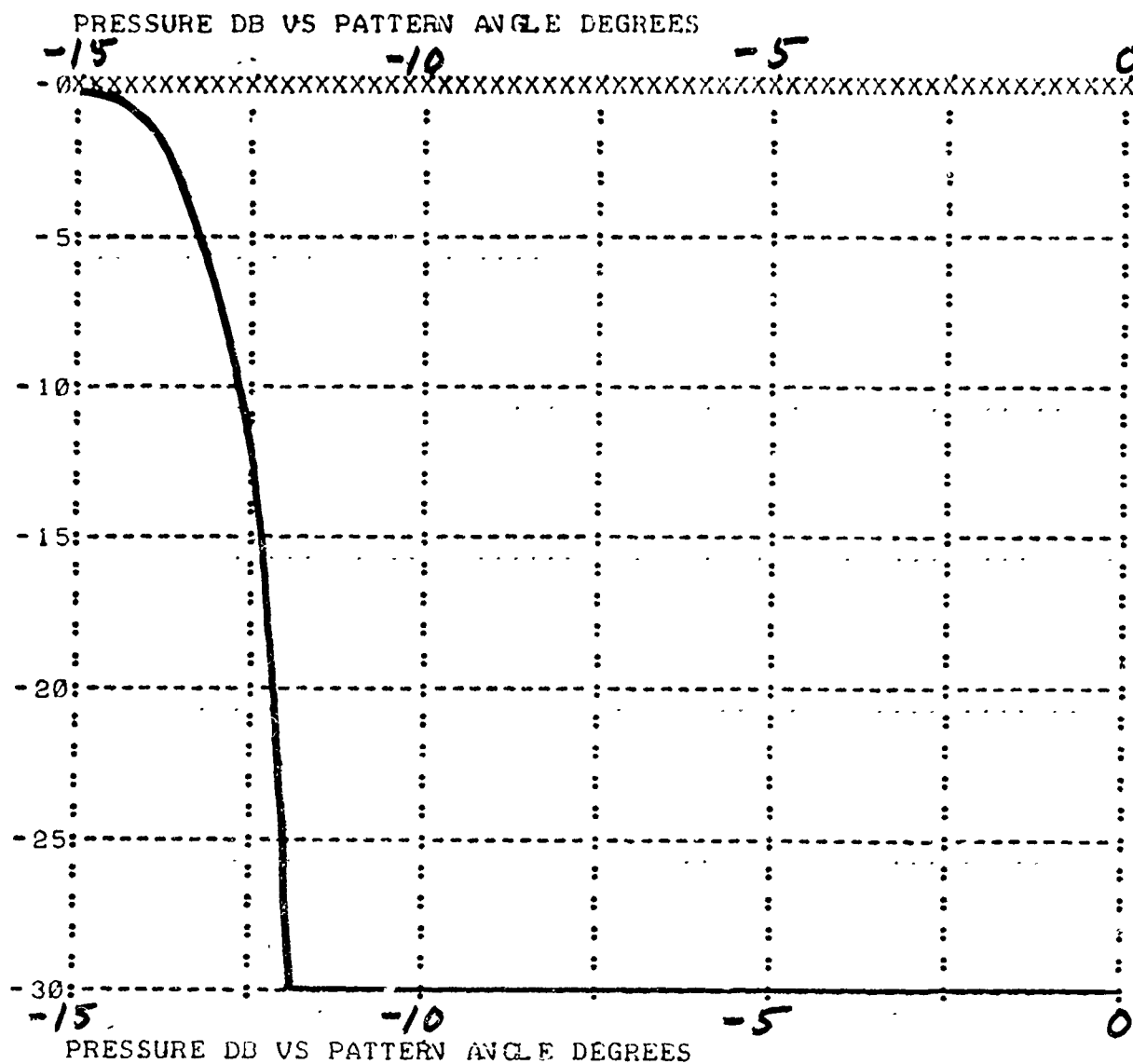


Fig. 4d. Product of two patterns, -15° to 0°

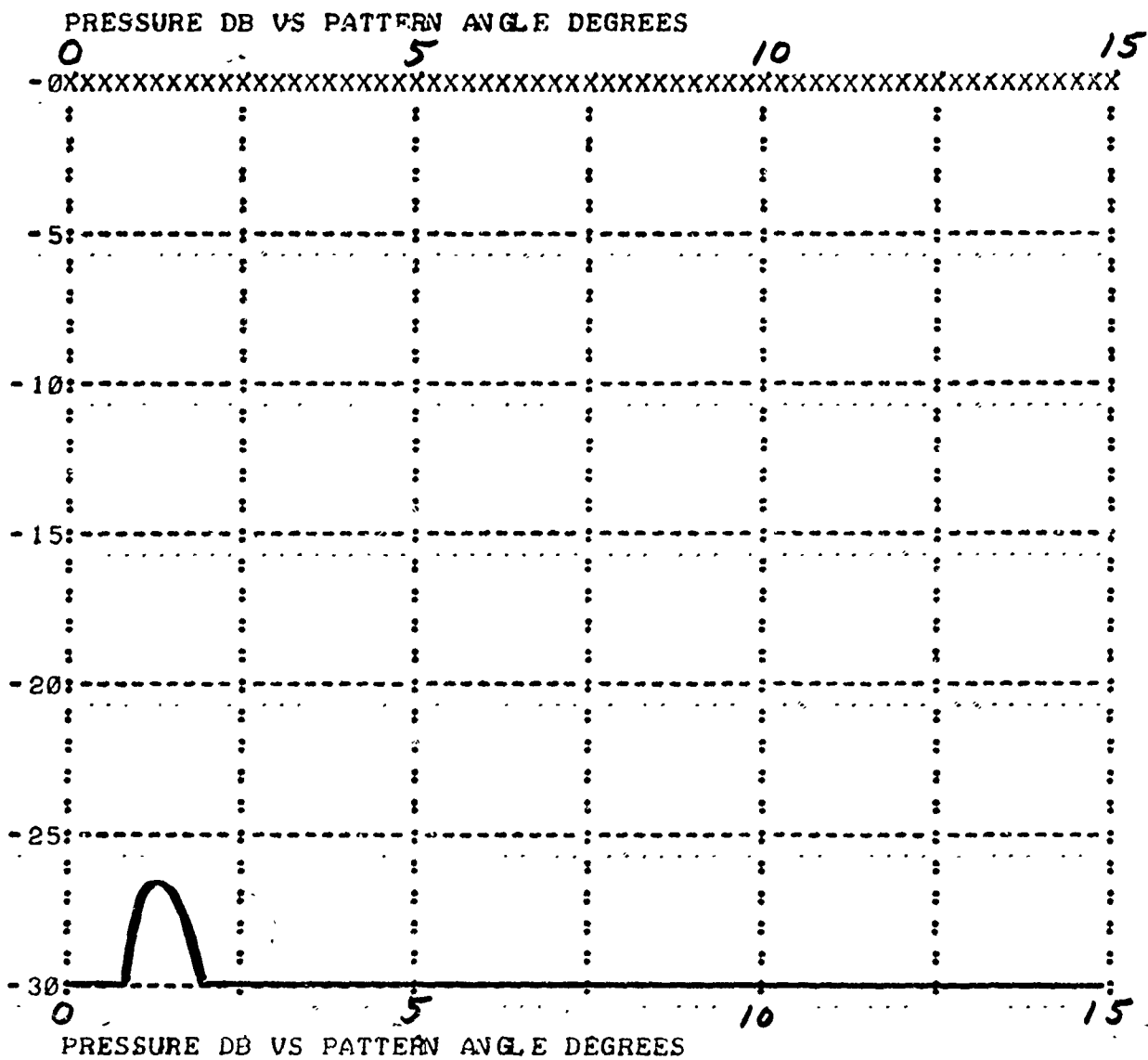


Fig. 4e. Product of two patterns, 0 to +15°

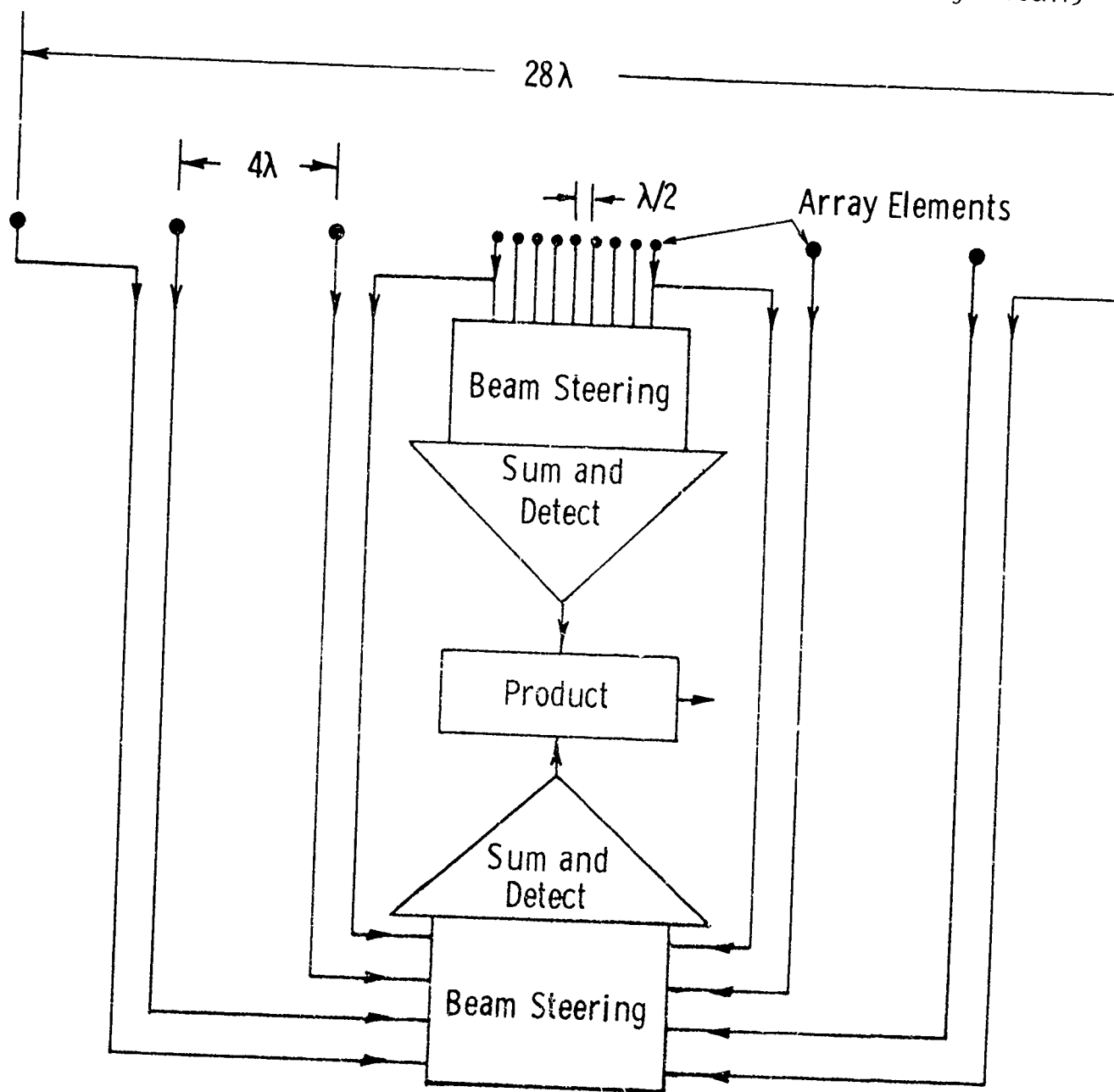


Fig. 5 – Fifteen element 28λ long array

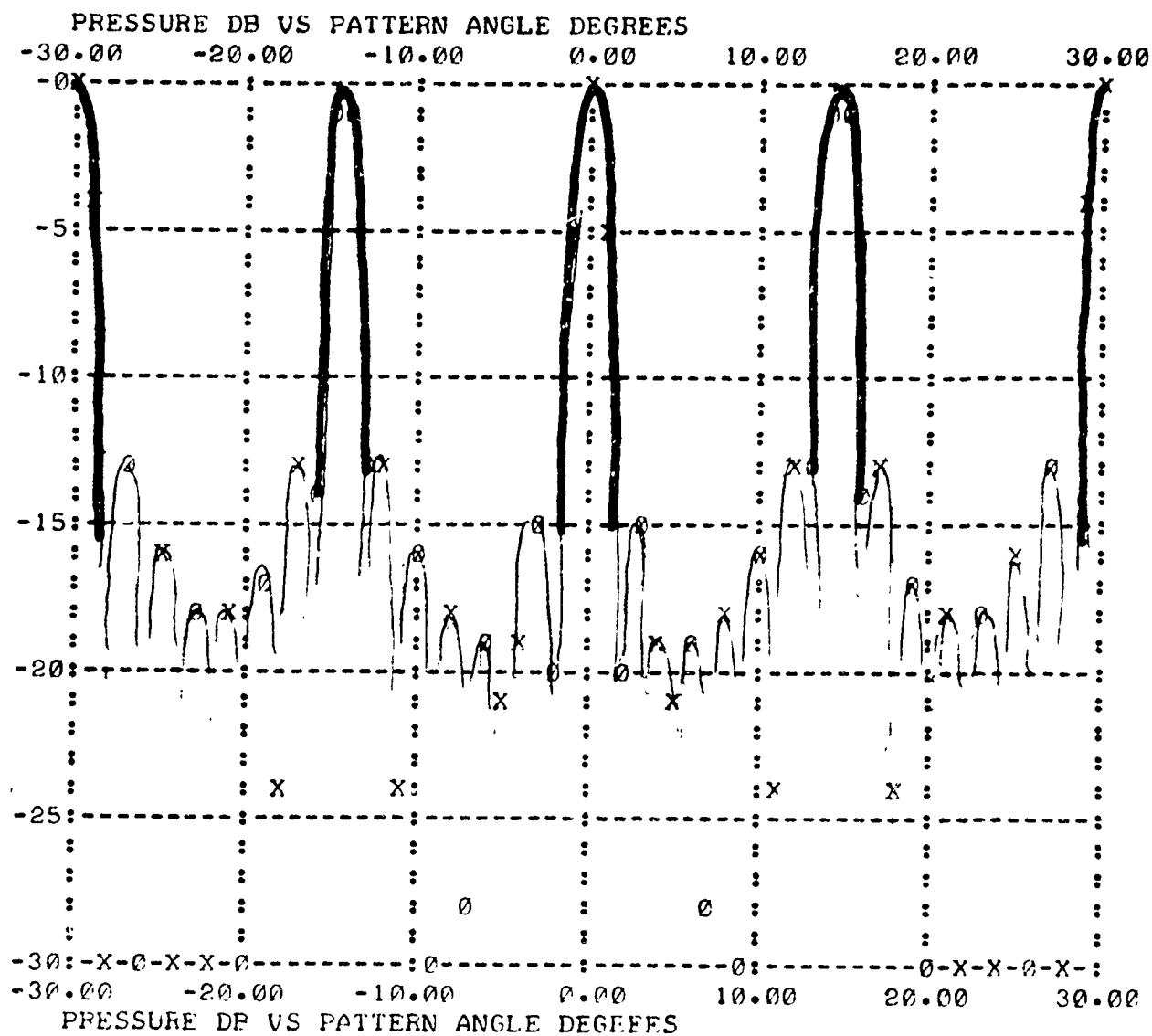


Fig. 6a - Eight elements, 4λ apart, -30° to $+30^\circ$,
no shading

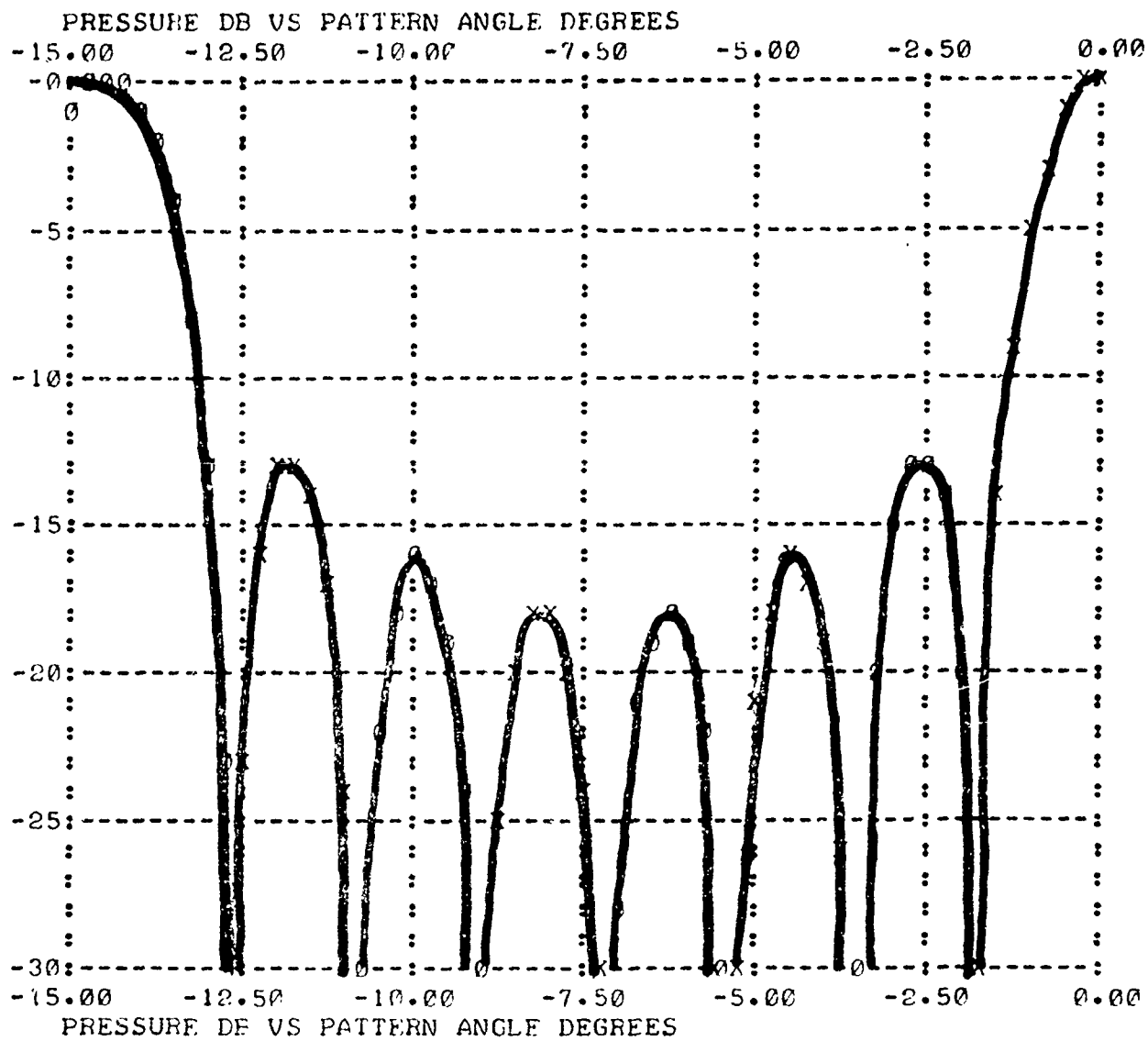


Fig. 6b - Eight elements. 4λ apart, -15° to 0° ,
no shading

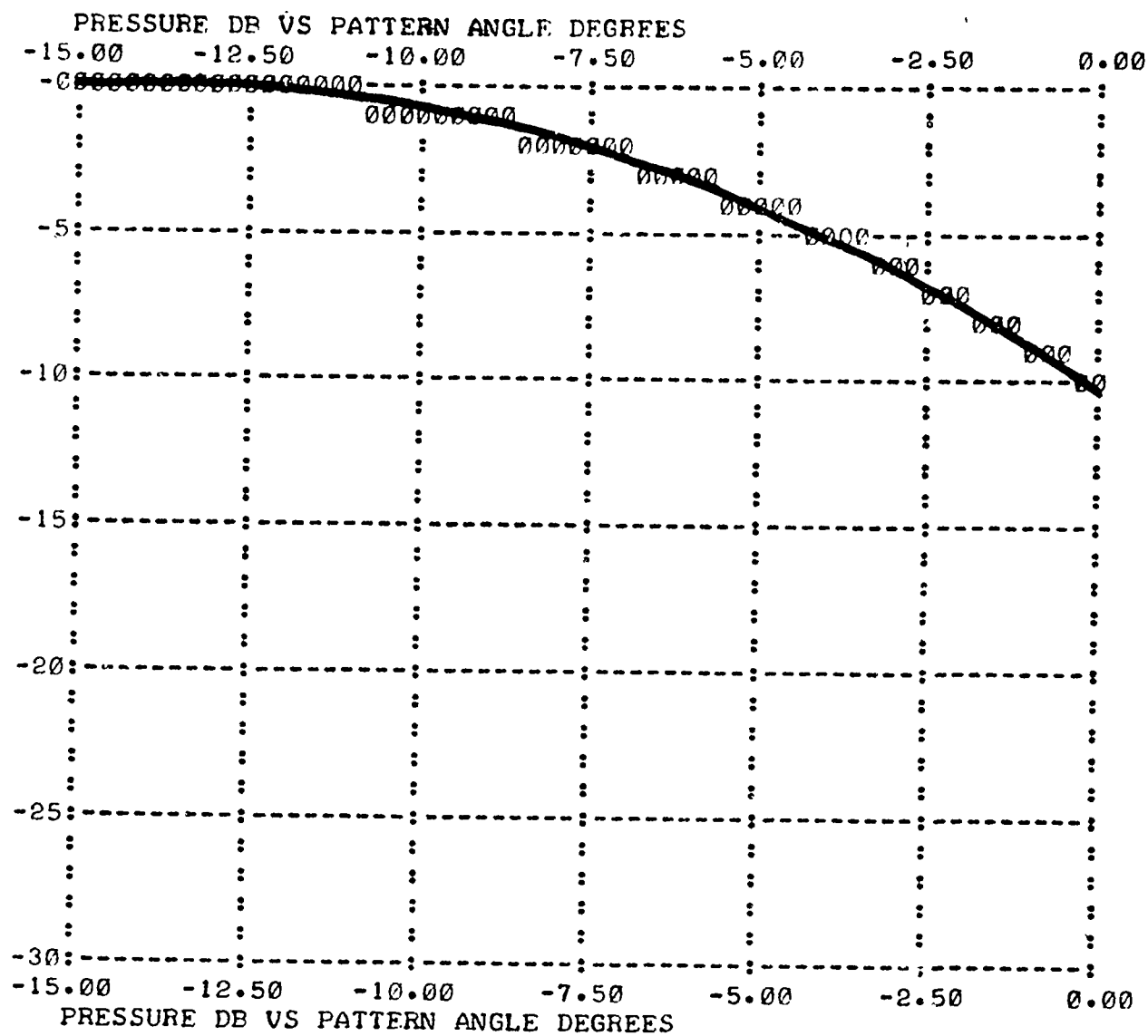


Fig. 7a - Eight elements, $\lambda/2$ apart, -15° to 0° ,
with shading

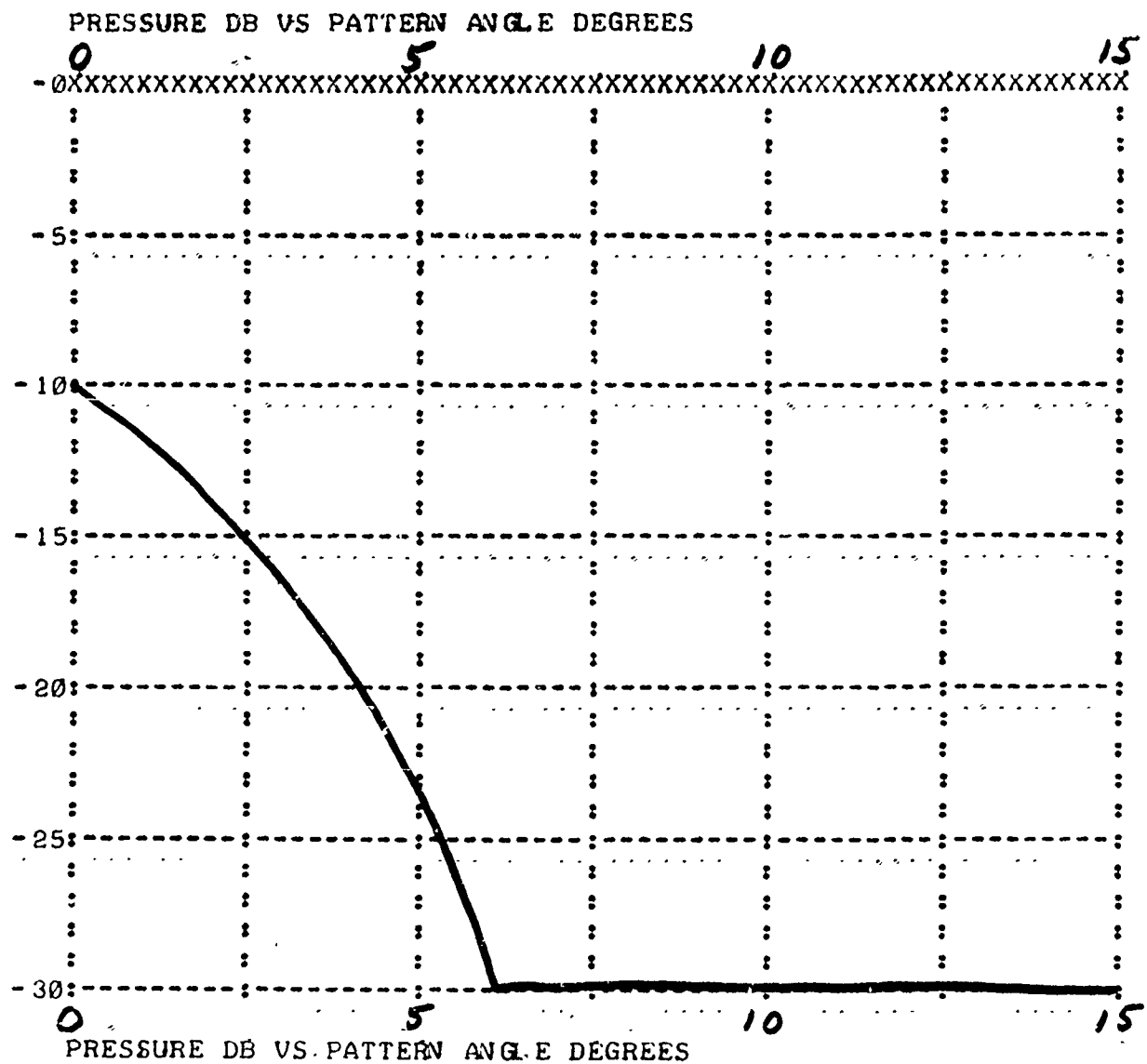


Fig. 7b - Eight elements, $\lambda/2$ apart, 0° to $+15^\circ$,
with shading

APPENDIX B

72-1C6-DUCER-M1
Proprietary Class 2

December 20, 1971

HYDROPHONES FOR LOW FREQUENCY VERTICAL ARRAYS

J. H. Thompson
C. H. Jones
Sonic Technology
Westinghouse Research Laboratory
Pittsburgh, Pennsylvania 15235

ABSTRACT

In 1961 (2) built and tested some hydrophones for use in vertical arrays operating in the 10 Hz to 1000 Hz region. Experimental test data are given for this unit and its associated amplifiers. In 1971 an improved amplifier was designed for these hydrophones. Between 10 and 200 Hz the measured noise of this amplifier is about 3 dB below the minimum sea noise curve published by Wenz.

HYDROPHONE EXPERIENCE AT WESTINGHOUSE

The old acceleration cancelling hydrophone program, in 1960-61, for vertical arrays had many interesting results -- some of which were published and others not. The in-air acceleration measurements were generally from 40 Hz to 300 Hz in the three principle directions and in general, the acceleration response was -60 dBv/g for a hydrophone whose sensitivity was -86 dBv/microbar. Acoustic measurements were made from 30 Hz to 1000 Hz and the unit response was flat to within several dB.

A number of design approaches were tried but were found to be critical during assembly. The model described in the article^{1,2} proved to be very practical in that it required no trimming or balancing to make it functional. Our first experience with an oil filled unit gave us an acceleration response which was about the same as that of an unbalanced inertia unit, approximately -10 to -15 dBv/g. We found that the poor performance was due to air bubbles in the compliant backing fluid. These were eliminated by using a good vacuum filling system. When we started to use ragged polyvinyl windows, we learned again that the placement of the acoustic window and its uniformity in compliance was also important in achieving low acceleration response. The window design shown in the article proved to be the best. The acceleration response of the fluid filled hydrophones in air generally ranged from -55 dBv/g to less than -65 dBv/g. In water most units were -60 dBv/g or greater.

In water tests, care had to be taken to be sure that the vertical vibrational acceleration was not reradiating acoustic energy which in turn was picked up by the hydrophone. The worst case was when the hydrophone was placed at the end of the line. The volume velocity of

the end of the line acted as a monopole and converted the acceleration motion into an acoustic signal. This was overcome by placing the end of the cable 25 feet or more from the hydrophone. Care also had to be taken when making measurements with short cables (less than 100 feet) to take into account the resonance between the transducer mass and the cable compliance. Also, tests made near the surface, where cables with entrapped air were employed, gave poor results because the acoustic volume velocity was greater than that of a cable with no air for a given acceleration level.

With these precautions in mind, cable tests were made with the hydrophone at the Underseas acoustic test facilities. The first test run results are shown on the top curve of Fig. 1 for a frequency range slightly below 10 Hz and extending up to 150 Hz. This particular hydrophone had a sensitivity of -91 dBv/microbar and an acceleration response of -50 dBv/g. The curve, Fig. 1, was flat except for the cable resonance at 38 Hz and then started to increase below 20 Hz. This was surprising and was found to be produced by the pressure gradient in the pond (rediscovery of Pascal's law). The poor acceleration cancelling was the result of an air bubble in the hydrophone and after its removal at the R&D Center in Pgh., the acceleration response became -66 dBv/g. The lower curve shows the expected response vs frequency. Figure 2 shows ambient noise level of the Underseas test pond in Lansdowne, Maryland. The zero sea state level was obtained from 1961 measurements.

Ocean tests were also made on the U.S.S. Allegheny with a similar hydrophone. Runs were made off Long Island, approximately 100 miles out of New York. Figure 3 shows the acoustic results. The channel was 140 feet deep and the hydrophone lowered to 100 feet. An accelerometer was mounted 25 feet above the hydrophone. A weight was mounted 25 feet below the hydrophone. The ship was silent except for the 60 Hz diesel-generator power source. The 60 and 120 Hz spikes on the data were no doubt pick up from the power source. The lower curve

shows the computed acceleration response of the hydrophone from the measured cable acceleration. At frequencies below 40 Hz the pressure gradient effects masked out the acceleration response.

Figure 4 shows the cable acceleration of the submerged cable under similar conditions as given in Fig. 3. This is the acceleration at 75 feet for a weighted 125 foot cable.

PREAMPLIFIER UNITS

The preamplifier used in 1961 consisted of a multistage transistor amplifier with 40 dB gain stabilized with a 20 dB of feedback. The two output leads carried both the signal and the direct current from the preamp to the surface. The amplifier was capable of driving a mile of coax without significant loss for frequencies up to several kHz. Figure 5 shows the equivalent preamp noise as compared to the lower Wenz Sea Noise curve and the sea state 0 noise used in the other figures. Figure 6 shows the ambient noise in the ocean as published by Wenz.³

The noise of the hydrophone internal loss as compared to the 1961 preamp noise and lower Wenz sea noise is shown in Fig. 7. The present problem area is that of getting a low noise input field effect transistor. The best that could be done with the present hydrophone using a perfect noiseless amplifier is shown on the bottom curve of Fig. 7. Figure 8 is a block diagram showing the hydrophone and preamp with associated noise sources. " E_s " is the minimum Wenz sea noise open circuit hydrophone signal. " E_h " is the internal hydrophone noise produced primarily by the internal losses of the piezoceramic. This is equal to the thermal noise of R_t . " E_n " is the equivalent series noise generator of the input transistor. " I_n " is the equivalent shunt noise current of the transistor. " Z_i " is the input impedance of the transistor. " R_t " and " C_t " are the internal equivalent series resistance and capacitance of the hydrophone.

The lowest noise curve shown on Fig. 7 is that from the thermal noise resistance of " R_t ". Transistor technology has reduced " E_n " and " I_n " so that our 1971 preamp has a noise level below the minimum Wenz curve.

In December 1971 a transducer with a built in preamplifier and external amplifier were sent to Dr. V. Anderson for evaluation. The noise level of this amplifier is shown in Fig. 9.

Noise measurements were made with a .005 μ f condenser in series with 10 K resistor used in place of the hydrophone in order to simulate the transducer impedances. Other characteristics of the hydrophone-amplifier combination are given in Table I.

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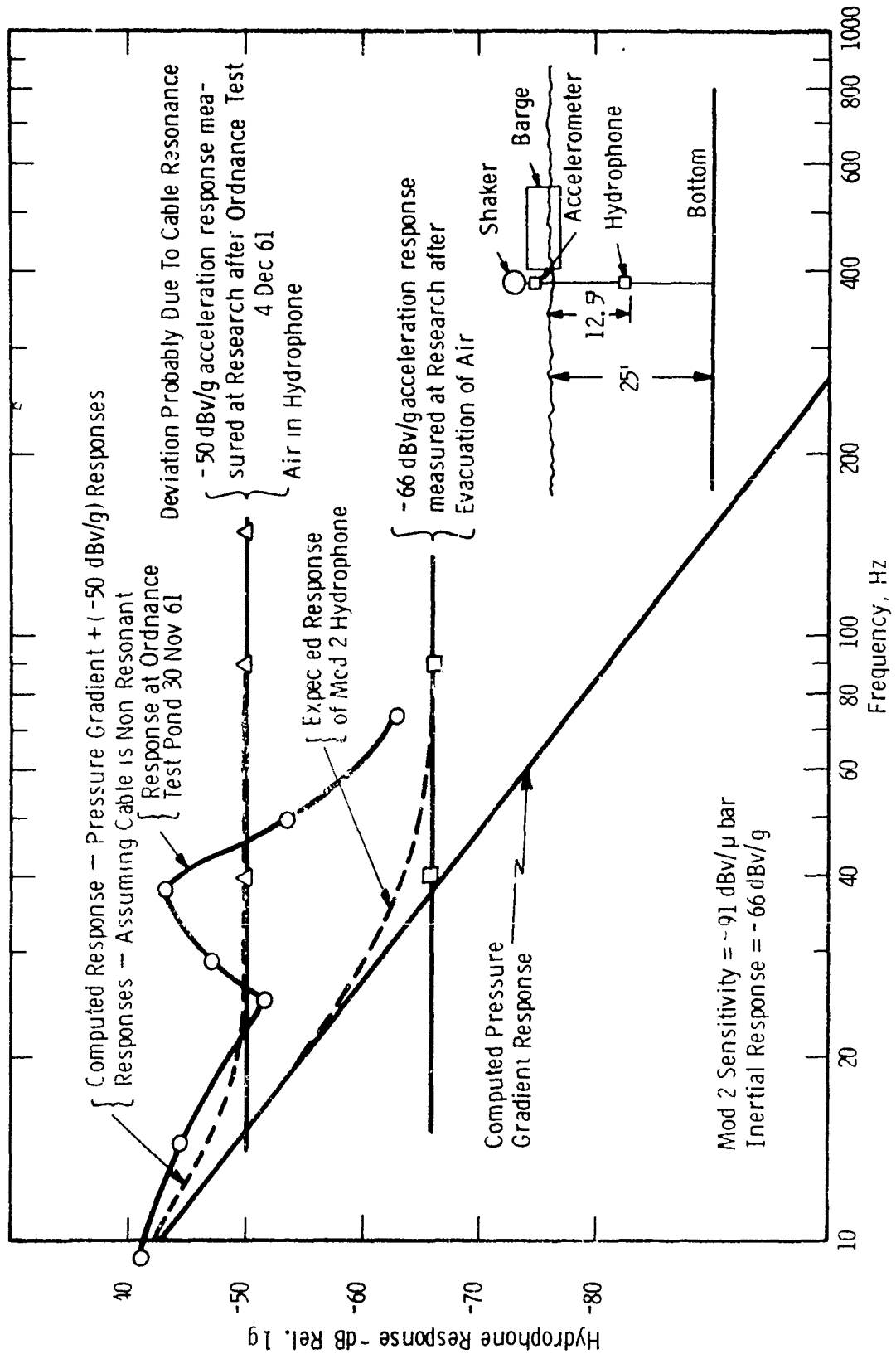


Fig. 1 - Acceleration tests made at Underseas test pond

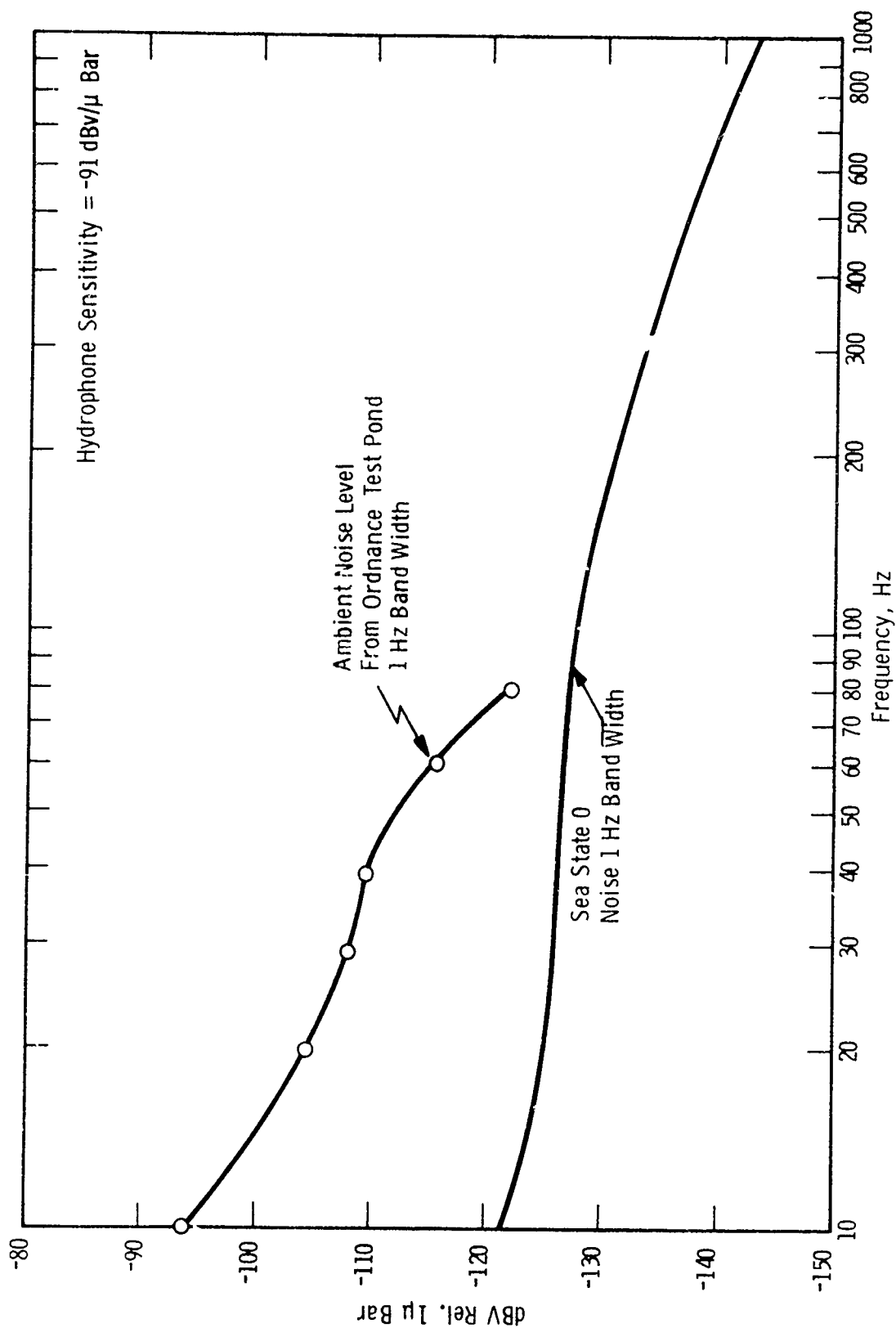


Fig. 2 - Ambient noise at Underseas test pond

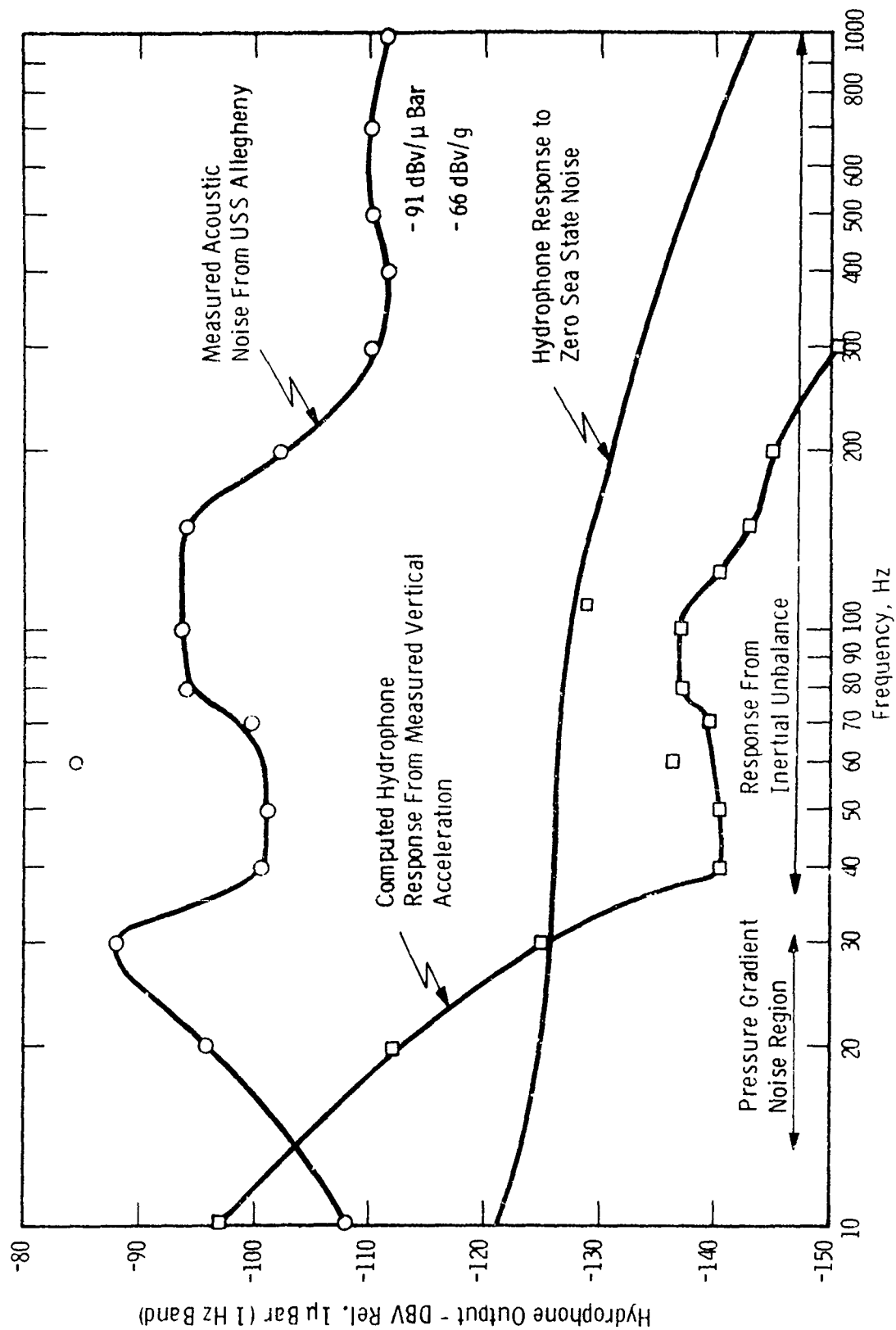


Fig. 3 - USS Allegheny Tests in Long Island Sound

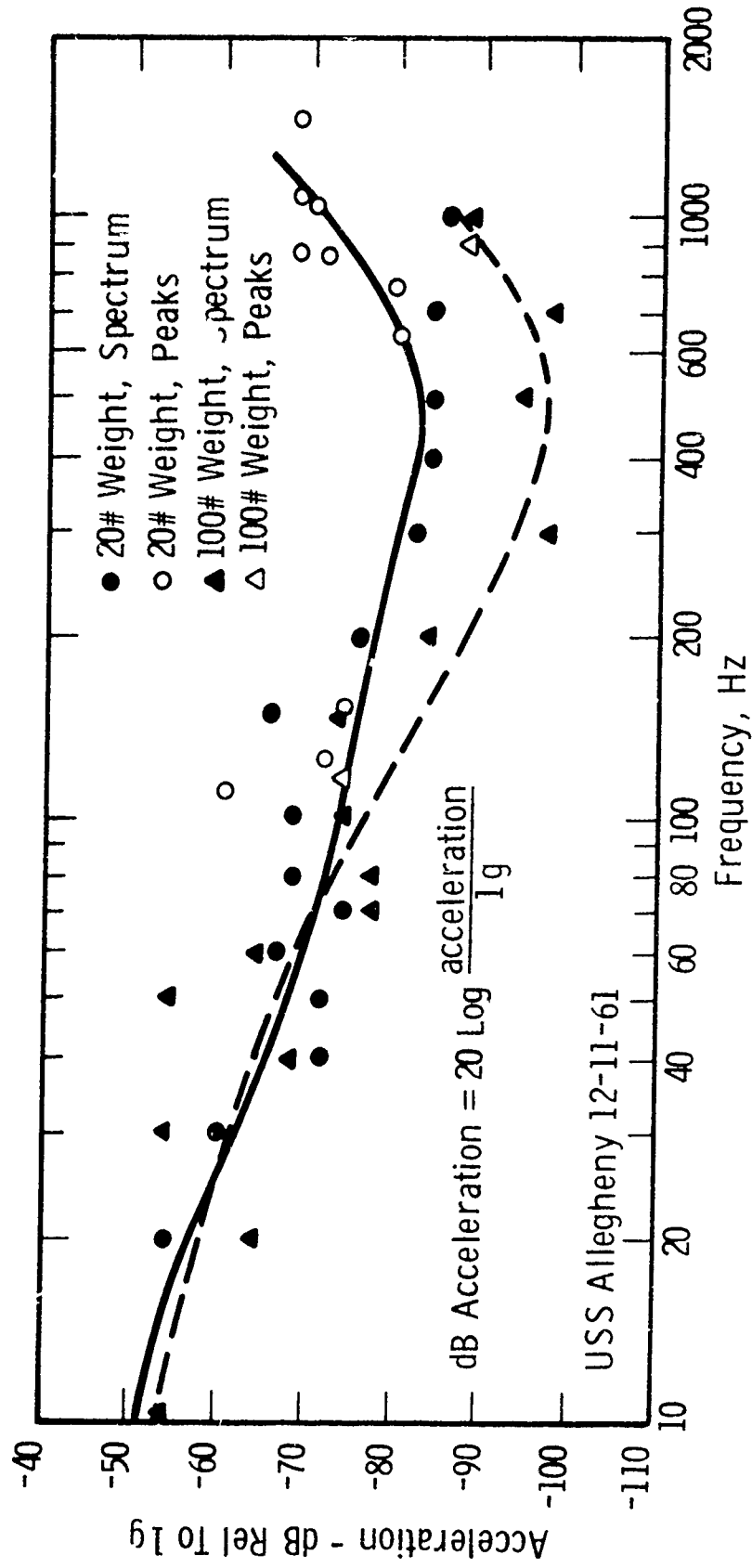


Fig. 4 - USS Allegheny Cable acceleration tests

Curve 645430-A

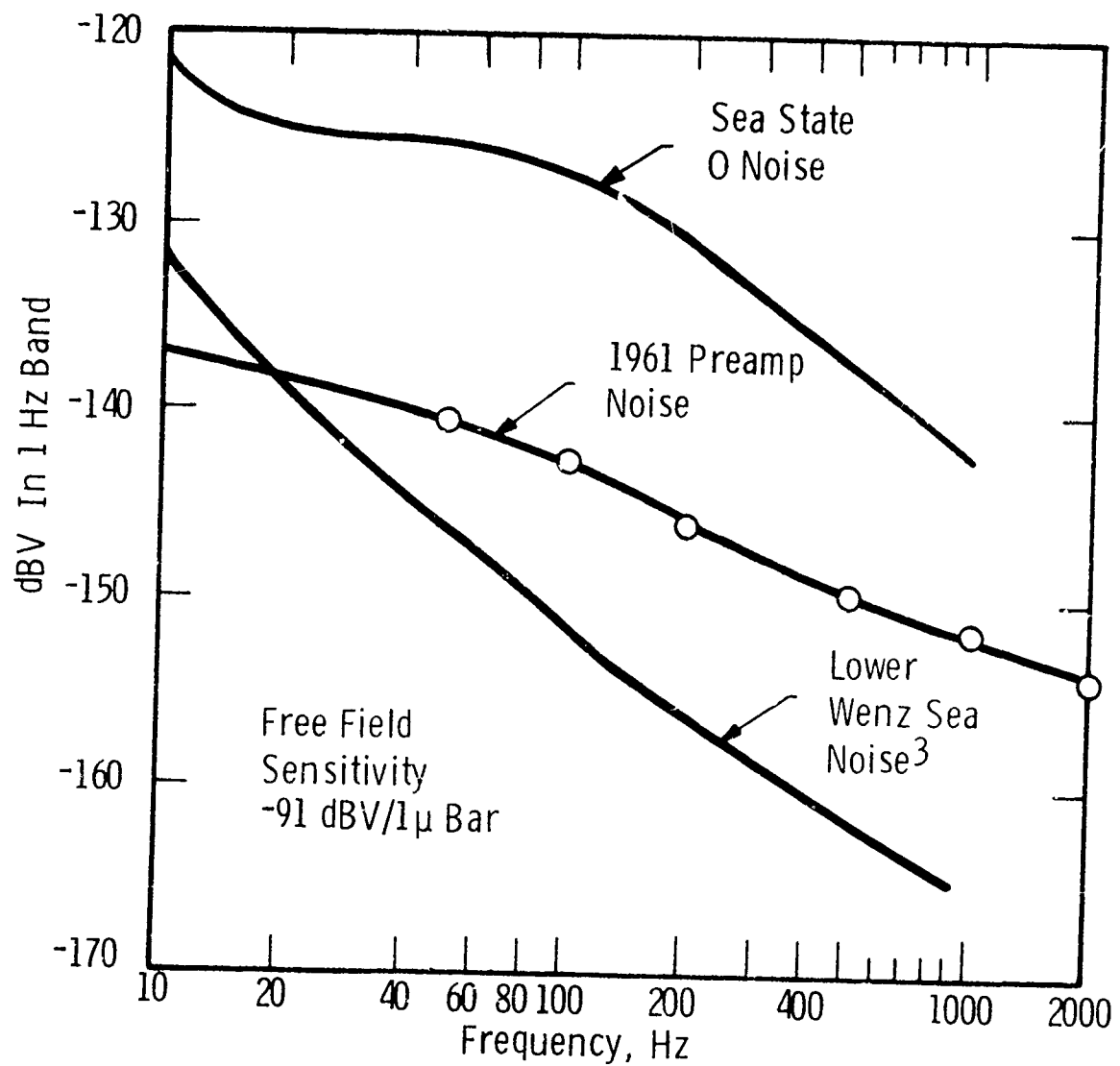


Fig. 5 - Sea State 0, preamp noise, lower limit of Wenz data

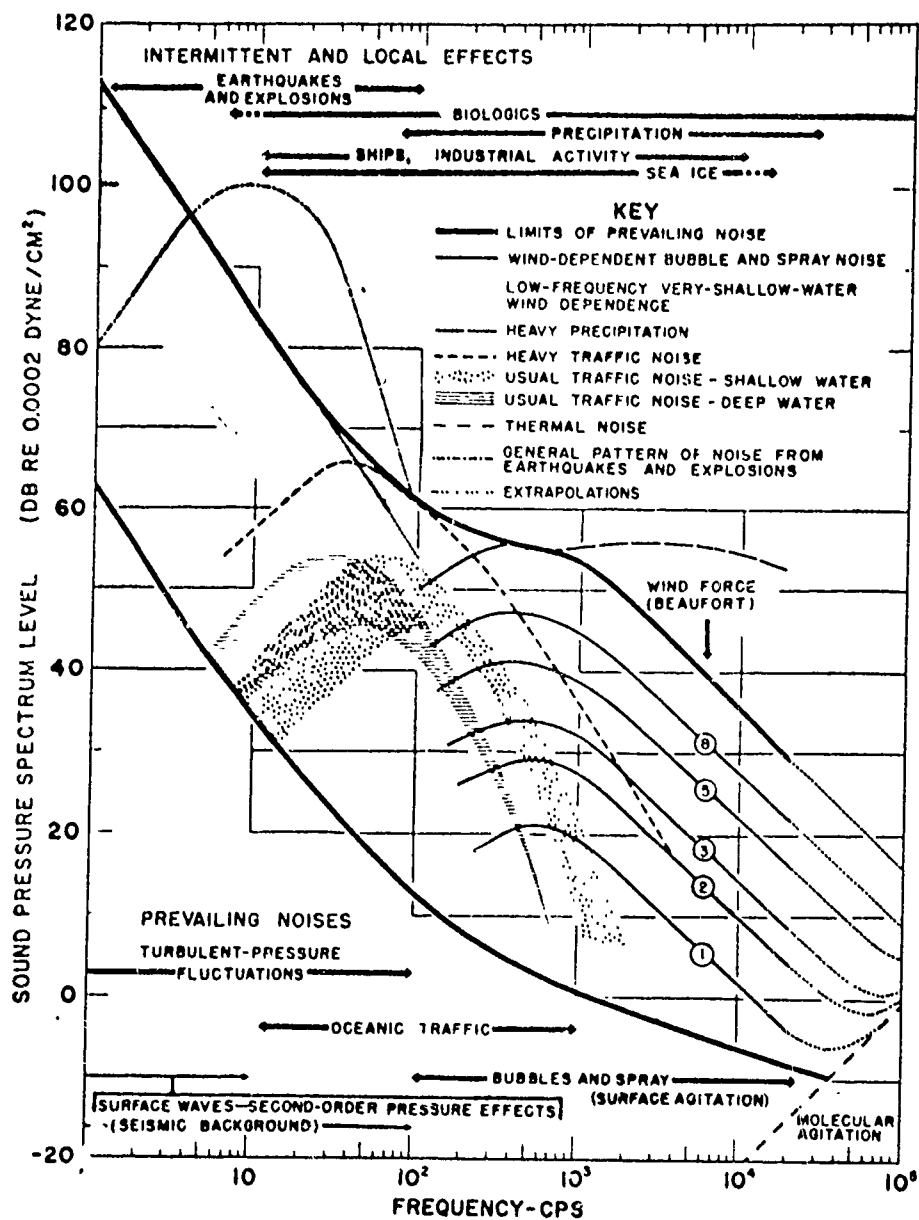


Fig. 6 -- Acoustic Ambient Noise in the Ocean by Wenz³

Curve 645431-B

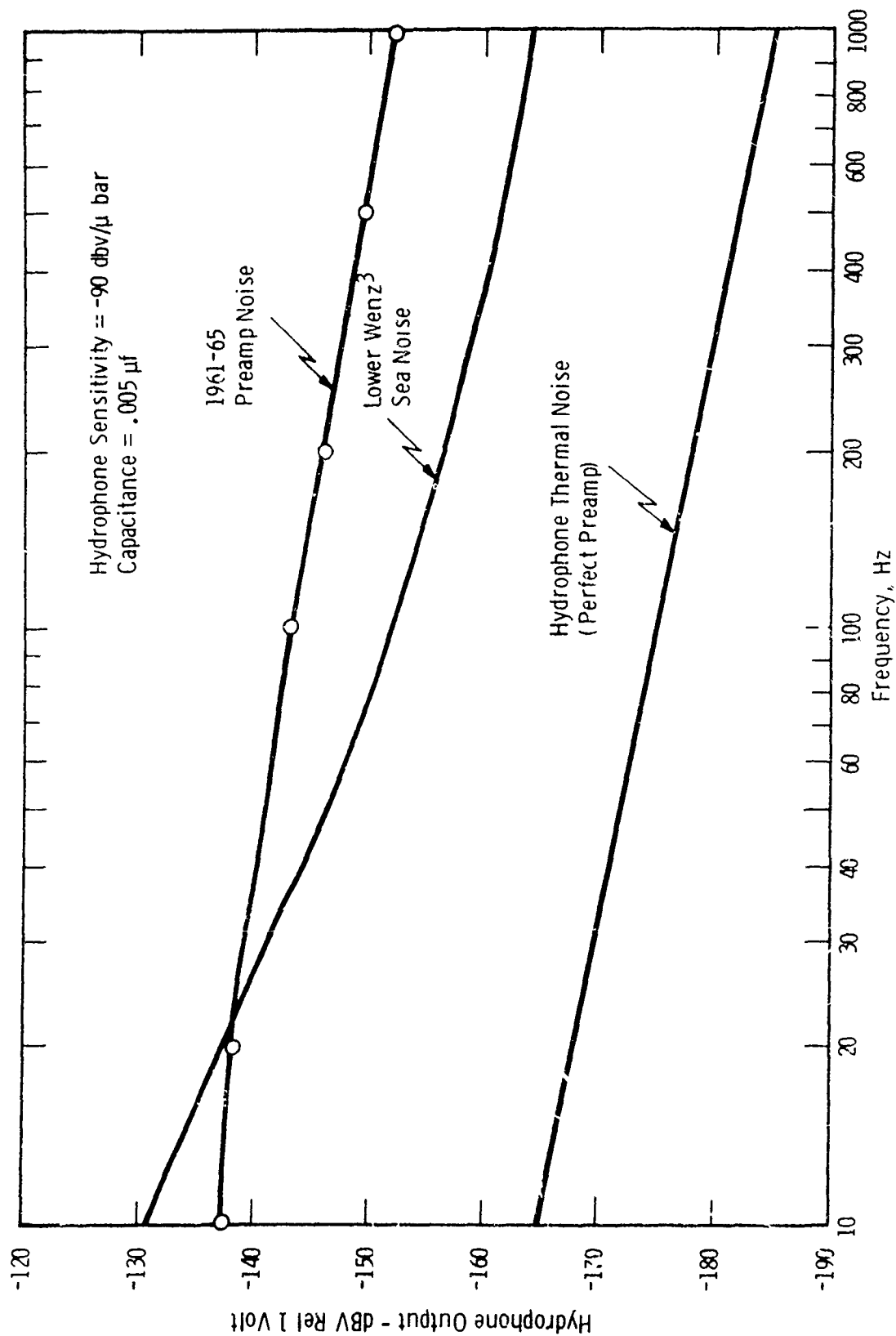


Fig. 7 - (1961-65) Preamplifier noise, minimum Wenz sea noise, hydrophone thermal noise

DWG. 2966A61

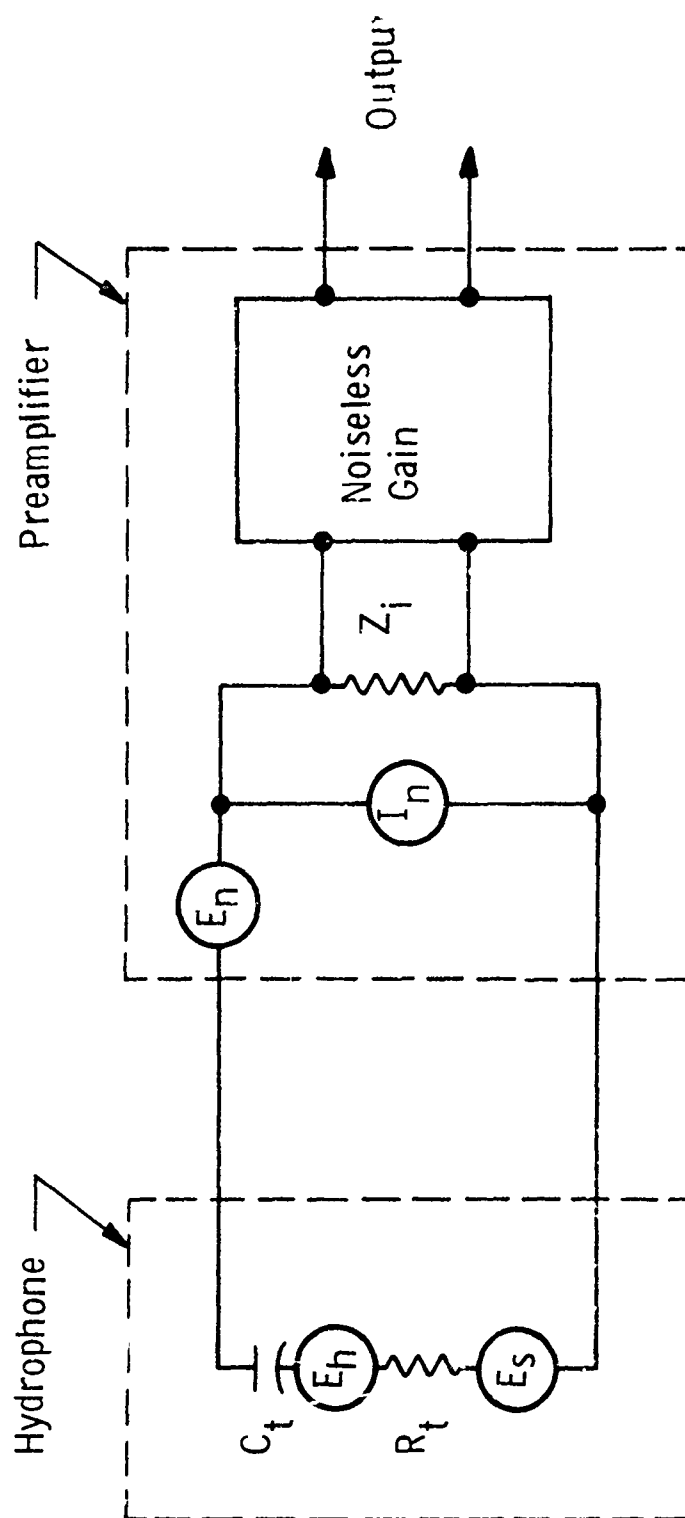


Fig. 8 — Hydrophone and preamplifier with noise sources

Curve 645432-3

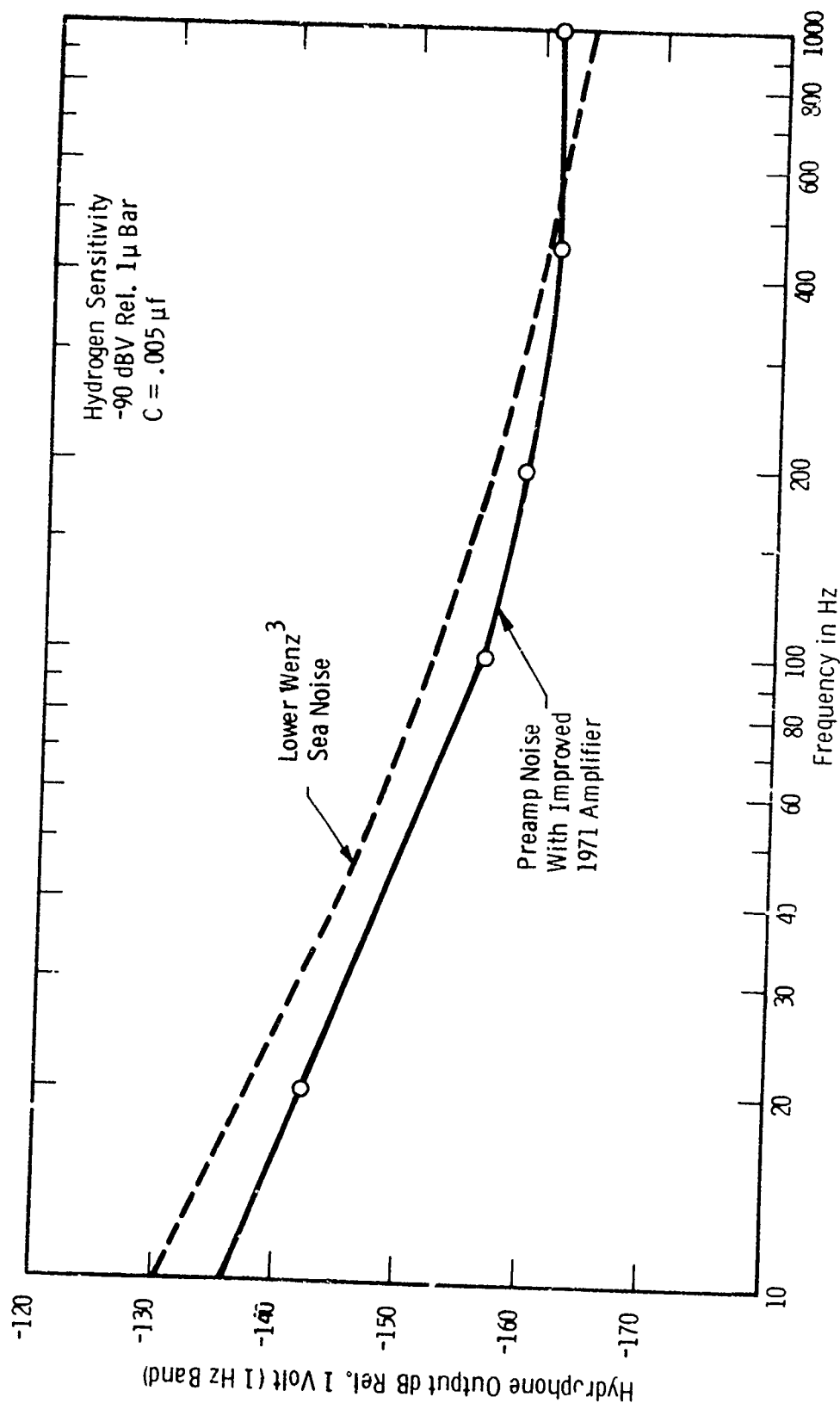


Fig. 9 - Preamplifier noise, minimum Wenz sea noise

TABLE I

Characteristics of Westinghouse Hydrophone with 1971 Amplifier

Acceleration Response:

50 Hz - 52 dB rel 1 volt per g
100 Hz - 50 dB rel 1 volt per g
200 Hz - 51.8 dB rel 1 volt per g

Sensitivity:

100 Hz - 90.8 dB rel 1 volt per microbar

Amplifier:

Gain 40 dB
Stabilizing Feedback 48 dB

Maximum Output Levels:

With a short cable 6 volts rms (1000 feet)
With a long cable ($C \approx 0.2 \mu\text{f}$) 2 volts rms (10,000 feet)

Impedances:

Preamp output $Z \approx 1 \text{ K ohm}$
Amp box input $Z \approx 10 \text{ K ohms}$
Amp box output $Z \approx 100 \text{ ohms}$

DC Supply:

45 volts, 35 mA

PERSONNEL

The following people were involved in the work and as authors of various portions of this report. K. P. Geohegan, R. U. Sims, and K. Wood of (2) Oceanics Division, Bay Bridge, Maryland; E. L. Shaver and P. R. Anderson of (2) Ordnance Systems Division, Defense Center, Baltimore, Maryland; G. R. Douglas, C. H. Jones, A. Nelkin, C. F. Petronio, and J. H. Thompson of (2) Research Laboratories, Pittsburgh, Pa.

These same personnel will be involved in the work on Phase II should it be funded within the next six months.



DEPARTMENT OF THE NAVY

OFFICE OF NAVAL RESEARCH
875 NORTH RANDOLPH STREET
SUITE 1425
ARLINGTON VA 22203-1995

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