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# Results of Explosive Array Measurements, September 1978

W.R. Hamblen and B.G. Watters

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Prepared for:
Defense Advanced Research Projects Agency

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# RESULTS OF EXPLOSIVE ARRAY MEASUREMENTS, SEPTEMBER 1978

## SUMMARY

As part of a larger active detection exercise a series of measurements was undertaken to ascertain the performance of explosive array sources. The explosive arrays consisted of four types, each having ten charges separated by lengths of fuse. Each array was 100 feet long and detonated by the pressure switch from a SUS charge. Two types of arrays were used predominantly; ten, four-pound charges detonated at a depth of 2500 feet with a primacord fuse (type P), and the same as above but with a mild detonating fuse and boosters (type M). To measure the performance of these arrays, specially modified sonobuoys were placed on the main beam of each array. This technique provided a useful solution to a normally difficult measurement problem. In addition, a hydrophone located near the sea surface directly over the array was monitored. In all tests the geometry, detonation timing, number of detonations per array, pressure levels, energy source levels (ESL) and beamforming performance were measured.

The measurement system performed very well. An independent check of the levels was made possible through the occurrence of array misfires in which only one detonation occurred. The levels for single shots are well known and were compared with the measured values. In all cases the two values differed by only a few dB.

The array performance was quite variable. The type P arrays often misfired and averaged only two detonations per array. The type M arrays performed very well. The measured ESL's for these arrays averaged 246 dB//$\mu$Pa$^2$sec compared with 228.6 dB for single

detonations. This was a 17.4 dB gain. The maximum theoretical gain of 20 dB for an array of 10 simple sources was not achieved due to the less than half-wavelength element spacing at the designed fundamental frequency of 100 Hz. However, the 20 dB gain should be realized at the higher harmonics.

While the fundamental frequency was designed to be 100 Hz for both the type P and M arrays, the actual frequency varied. The average value was 109 Hz. This was due to the slightly greater than expected detonation depths.

The detonation timing intervals showed no detectable jitter, indicating good beamforming ability. This was verified in the frequency domain where on-axis records showed coherence to 1 kHz. However, for some tests the hydrophone was slightly off-axis. This fact was indicated by reduced levels at the higher frequencies. Finally, the timing information indicated that the type M arrays were steered to a slightly greater angle off horizontal than expected.

Several conclusions and points of interest are noted. First, a reasonably reliable and easy measurement technique for high level sources has been developed and shown to be effective at determining source performance. Second, the primacord alone is insufficient to detonate the explosives, a booster should be used. Third, the overall performance of the mild detonating fuse arrays (type M) was good. High ESL's were achieved with good reliability and repeatability. Fourth, considerable detection improvement could be obtained by matching the analysis band to the actual frequency band of the source and, for improved performance at low frequencies, increasing the element spacing to one-half wavelength.

## I.0 INTRODUCTION

This report presents the results of BBN's measurements of several types of explosive arrays. These measurements provide quantitative information about the performance of these arrays as high-level sources for active surveillance. Prior to these measurements, the on-axis performance of explosive arrays had been assumed, not measured. Thus, this effort represented the implementation of a new measurement system.

The explosive arrays were used as part of a larger surveillance experiment. The exercise consisted of both active and passive detection sections. Briefly, the active sections of this experiment consisted of a source ship, a receiver ship and a target. The source and receiver ships were located within 4-10 nm of each other while the target was located at the first, third or fifth convergence zone. This resulted in an essentially mono-static experiment geometry.

The measured arrays were of four different types each with 10 charges 10 feet apart. The four array types were; ten, one-pound blocks supported by burlap(B); ten, four-pound blocks detonated by primacord (P); ten, four-pound blocks detonated by mild detonating fuse (M); and ten, six-pound blocks detonated by primacord (S). Of these four, the vast majority were either type P or type M. The type B arrays were detonated at 800 feet and type P, M, and S arrays where detonated at a nominal 2500 foot depth. All of the arrays were designed to have a fundamental (bubble pulse) frequency near 100 Hz.

To obtain useful measurements of these arrays, specially modified sonobuoys were deployed. In this manner, measurements with the hydrophone far enough away to accurately measure the far-field strength of the arrays and on the main axis of the array beam pattern, could be made from a single ship. In addition to the sonobuoy measurements, measurements of the direct arrivals, off-axis, were made by a hydrophone near the surface directly over the array. The equipment was designed to measure and quantify the following items,

- detonation timing
- pressure levels
- on-axis Energy Source Levels (ESL)
- beamforming characteristics

The ESL in dB//$\mu$Pa$^2$sec @ 1m is defined as the integral over time of the far-field squared signal pressure in the frequency band of interest, referred back to a 1-meter range. In our case, the band is between -3 dB frequencies centered on the fundamental frequency. Knowledge of the above information will allow complete characterization of the array performance.

# II INSTRUMENTATION/PROCEDURE

## 2.1 Equipment

A sketch of the experimental set-up is shown in Figure 1. The sonobuoys were SSQ-41's with the standard hydrophone and preamplifier removed and a special hydrophone-preamplifier package substituted. The hydrophone's were Benthos AQ1's (nominal sensitivity -203 dBv/µPa) and the preamplifiers were designed and built by BBN. The preamplifiers were designed for an FET-input op-amp (AD 540) whose low output impedance was used to reduce cable microphonics. The preamplifier response was flat between about 10 Hz and 1 kHz. The preamplifier gain was set as large as possible (actually less than unity due to the large signal levels) in order to overwhelm cable microphonic signals. The gain of the sonobuoy system was reduced to compensate for these higher voltages and the buoy low frequency response was extended down to about 10 Hz. These modifications were necessary to insure that the shock front arrivals would not overload the sonobuoy system. The gains were carefully set so that the calculated peak pressure levels would almost fill the available dynamic range. This allowed for the greatest possible signal-to-noise ratio.

In all, six sonobuoys were modified, four SSQ 41B's manufactured by Magnavox and two SSQ 41A-XN1's manufactured by Hermes. All had 1000 foot hydrophone cables. Special launching procedures were developed since the hydrophone-preamplifier package was considerably larger than standard. Sheets of water soluble gel were used to hold the hydrophone package and the cable drum in place while the sonobuoy was lowered over the side of the ship. On contact with the water, the gel dissolved, launching the hydrophone.

In addition to the sonobuoy signal, an over-side hydrophone output was also recorded. The hydrophone signal was supplied by NRL, who were engaged in launching and monitoring the arrays. This hydrophone was hung off the source ship, the USNS Hayes, and thus was near the surface directly over the arrays as they detonated. In addition to the NRL hydrophone, a BBN towable hydrophone was also available as a back-up and in the event the arrays were deployed with the ship underway. Deploying arrays with the ship underway was contemplated initially but was never executed.

The output of the sonobuoy receiver and of the NRL hydrophone were recorded on a two channel plus voice Nagra recorder. The data were recorded at 7-1/2 ips on 1/4 inch magnetic tape. Simultaneously the two channels were displayed on a two channel oscilloscope and polaroid pictures taken of the direct arrivals at the hydrophone and sonobuoy.

The sonobuoy receiver was a converted AN/ARR52 supplied by NOSC.

## 2.2 System Calibration

Because of the relative insensitivity of the modified buoys, the measurement system was calibrated in three steps. First, the hydrophones were calibrated against a precision acoustic reference. Next, the voltage gain of the buoy-receiver system (preamplifier input to sonobuoy receiver output) was measured for each buoy. Finally, a reference voltage was recorded in the field to calibrate the gain of the tape recorder analyzer system.

An independent check on our system calibration was available by utilizing the "defective" one-shot P array signals. As an example, ESL's measured for shots 24B, 24C, and 25A using buoy 13A averaged 228.6 $dB//\mu Pa^2 sec$ @ 1m. By comparison, Christian and

Blaik [1] publish empirical formulas which indicate a level of 230.2 dB//$\mu Pa^2$sec @ 1m, a difference of only 1.6 dB.

Also, measured pressure levels of single detonators were compared with theoretical and empirical values. In all cases the values differed by, at most, a few dB.

## 2.3 Procedure

To obtain useful data it was necessary to place the sonobuoy hydrophone on or near the main axis of the arrays. The explosive array types P, M, and S, were initiated at a nominal depth of 2500 feet. Due to the finite speed of the fuse, each of these arrays was effectively ripple fired, thus steering the main axis of the array upwards. The nominal detonation speeds indicated the arrays would be steered either 11 or 15 degrees off horizontal, dependent upon the type of fuse. In the B type arrays the 10 charges were initiated simultaneously at a nominal depth of 800 feet. Thus, to place the sonobuoy hydrophone exactly on-axis for all the arrays it would have been necessary to have the hydrophone at a depth of 800 feet at a horizontal separation of 6300 feet. Actually, due to the finite width of the on-axis beam at the frequencies of interest considerable variation was possible. The sonobuoy deployment depth was fixed at 1000 feet. Calculation showed that at this depth the hydrophone would be on-axis for the fundamental frequency at horizontal ranges of 4000 feet or more.

To achieve these separations the following procedure was followed. At some short (e.g. ten minutes) time before the next cluster of arrays was to be deployed, the ship would be slowed and the sonobuoy launched. The ship would then steam for a nominal 4000 feet, usually 4 knots for 10 minutes. Since the geometry could be reconstructed from the various signal arrival times, precise knowledge of distance was not required. The ship would then stop and as many clusters of arrays as possible would be deployed before the ship was required to move in order to maintain the desired geometry with respect to the receiver ship. Typically during this interval, drifting would cause a steady increase in the sonobuoy-ship separation. Thus shots would occur at ranges varying from the 4000 feet minimum to 6000 feet or more.

## 2.4 Processing

The processing is divisible into three components. The first, completed on the ship, was to examine the arrival instants to reconstruct the geometry at the time of the shot. The second was to examine in more detail the hydrophone and sonobuoy records to determine the major features of the array performance (timing, number of detonations), and to ascertain any trends. The third and final task was to analyze in detail a representative subset of the data to determine the spectral content and beamforming abilities of the arrays.

The geometry of each detonation was reconstructed in the following fashion. The actual shot depth was determined by the interval between the second (one bottom bounce) and third (one surface reflection and one bottom bounce) arrivals at the overhead hydrophone. The path length difference between these two arrivals is twice the depth of the shot. Knowing the depth of the shot gave the shot-instant relative to the direct arrival. The interval between the direct arrival overhead and the direct arrival at the sonobuoy combined with the depth yielded the slant range to the sonobuoy. The slant range to the surface image was obtained from the time to the surface reflection arrival at the sonobuoy. The two slant ranges plus the depth of the shot were then sufficient to solve for the horizontal range and the depth of the sonobuoy hydrophone. Table 1 shows the results of this type of analysis for the shots received by one sonobuoy. The remaining processing was accomplished in the laboratory. The recorded data was played back into a 400 line spectrum analyzer and both the waveform and its spectrum photographed. In addition, the spectral levels were read and recorded. Timing information and the peak pressure levels were read from the photographs. The recorded levels were then corrected for hydrophone sensitivity, transmission loss, external gain, recording sensitivity and in the case of the sonobuoy, radio receiver sensitivity to obtain absolute pressure levels referred back to one meter.

TABLE 1: SONOBUOY GEOMETRY FOR SELECTED SHOTS

| Shot Number | $d_s$ shot depth (feet) | R slant range (feet) | R' image slant range (feet) | d depth of sonobuoy (feet) | A horizontal range (feet) |
|---|---|---|---|---|---|
| 21A | 2650 | 4650 | 5800 | 1133 | 4395 |
| 22B | 2650 | 5350 | 6350 | 1103 | 5120 |
| 24B | 2725 | 5750 | 6650 | 1052 | 5520 |
| 25A | 2625 | 6350 | 7200 | 1086 | 6150 |

## 2.5 Equipment Performance

The technique of on-axis measurements of high level impulsive sources via sonobuoys is, as far as we know, new. Thus, the reliability and performance of the equipment is of interest as a separate issue. The techniques involved are relatively simple, and if reliable, provide a useful tool.

In all, six sonobuoys were modified. Of the six, two appeared to malfunction. One of these failed to transmit a signal, although a strong carrier was present; the other deployed its hydrophone to a depth of 100 feet, instead of the desired 1000 feet. Both of these failures indicate that the electronic assemblies, battery pack, transmitter, etc performed satisfactorily while the lower assembly of hydrophone, preamplifier and cable housing were the site of the failures. These are precisely the assemblies which were extensively modified and where a greater failure rate could be expected. We believe that increased experience will reduce the failure rate. The remaining four units worked perfectly and appeared to give excellent results, although data acquisition was limited on one other unit due to a strong surface current which lifted the hydrophone from its desired depth.

The shots were also monitored on the NRL-supplied overhead hydrophone. Unfortunately these levels were significantly different from the anticipated levels. In Figure 2 the waveform of a single shot received by the NRL phone shows high frequency artifacts uncharacteristic of explosive waveforms (compare with Figure 5). These artifacts are characteristic of poor low frequency response systems. The spectra also show this behavior. Direct comparisons of the BBN hydrophone and the unfiltered NRL hydrophone spectra show poor low frequency response in the NRL hydrophone. A salt water leak in the hydrophone is one possible explanation for this type of response. In any event the NRL hydrophone must be considered useful for timing information only.

The BBN overhead hydrophone performed well but was only deployed on a few shots, primarily to provide for comparison with the NRL hydrophone.

## III RESULTS

### 3.1 Timing

Analysis of the detonation timing as seen by the overhead hydrophone revealed that:

a) The number of charges that actually detonated depended strongly on the array type.

b) There was no significant jitter in the detonation times.

c) The detonation interval as seen overhead was shorter than the design value for type M arrays.

Figures 3 and 4 show typical waveforms for the overhead hydrophone. Figure 3 is a type M array and Figure 4 is a type P.

The most striking feature of Figures 3 and 4 is in the comparison of the number of detonations. The type M array has ten detonations while the type P array shows only two. This trend is generally true. In most cases the primacord failed to detonate the charges. The P type arrays showed predominately two or three detonations per array with several single detonations and a recorded maximum of six. The M type arrays, where a booster was used to help initiate the charge, showed universally good performance with almost all arrays having 10 detonations. The type B and type S arrays had mixed results with an average of five or six detonations per array. A complete list of detonations is given in Table 2.

Next note that the interval between detonations (Fig. 3) is extremely uniform. This indicates that, barring other phenomena, the charges should "stack" very well and that the anticipated array gains should be realized. No variations were found to a resolution

TABLE 2: DETONATIONS PER ARRAY

| Type M | Shot No. | Number of Detonations | Type P | Shot No. | Number of Detonations |
|---|---|---|---|---|---|
| | 21A | 10 | | 10 | 6 |
| | 21B | 8 | | 11A | 3 |
| | 21C | 10 | | 11B | 2 |
| | 22A | 10 | | 20A | 2 |
| | 22B | - | | 20B | 2 |
| | 39C | 10 | | 23A | 2 |
| | 40A | 10 | | 23B | 2 |
| | 40B | - | | 23C | 2 |
| | 40C | - | | 23C | 2 |
| | 41A | - | | 24B | 1 |
| | 41B | 10 | | 24C | 1 |
| | 41C | - | | 25A | 1 |
| | 44A | 10 | | 25B | 5 |
| | | | | 25C | 2 |
| Type B | 7A | 7 | Type S | 46A | 1 |
| | 7B | 8 | | 46B | 6 |
| | 7C | 6 | | 46C | 5 |
| | 8 | 5 | | 48A | 1 |
| | 9 | 6 | | | |

of a few tenths of a millisecond. Thus the arrays should beamform to at least the order of several hundred hertz. This statement is supported by evidence in the frequency domain as well. This will be discussed in section 3.4

Finally, it was noted that the total extent of the arrivals in time was shorter than predicted for the type M arrays. A value of 16.3 msec was predicted while an average of five arrays show a value of 14.3. This difference could be attributable to several items; a) a non-vertical array; b) a slower than estimated detonation velocity; or c) an effectively shorter than expected fuse or array. We do not believe that a) is responsible since array tilt would cause a serious shot-to-shot level variation as the direction of tilt with respect to the sonobuoy varied. We did not observe a variation of this sort. Consequently, we believe that the net effect of the change in the firing interval is to increase the steering angle of the array. The effect on the experiment should be minimal, however, since the design angle was on the order of $10^{\circ}$ and the new angle would be on the order of $14^{\circ}$, still well within the sound channel.

## 3.2 Pressure Levels

As indicated earlier the poor performance of the primacord (P) arrays provided an opportunity for an independent check of the measurement system. For single charges, empirical relations for the peak pressures are well substantiated. For a single four-pound shot at 2500 feet these formulas give 276 dB//μPa @ 1m for the peak (shock) and 261 dB//μPa @ 1m for the first bubble pulse. An average of measured levels for several such shots gave 274.4 dB//μPa @ 1m for the peak pressure and 263.5 dB//μPa @ 1m for the bubble pulse. See for example Figure 5. The indicated peak pressures are somewhat low. However, this is most likely due to the restricted high frequency response of our hydrophone system which was deliberately rolled off above 1 kHz. This would tend to lower the peak of the shock arrival (but would not effect the ESL measurements in the fundamental band). The indicated first bubble pulse pressures are somewhat high.

The peak pressures were also measured on the over-head hydrophone. As stated in section 2.4 the NRL hydrophone levels were not indicative of the true levels. However, the few measurements made with the BBN hydrophone yielded levels of 274.6 dB// μPa @ 1m for the peak pressures, nearly identical to those measured by the sonobuoys. The preamplifier for this hydrophone also had a 1 kHz high frequency roll-off.

## 3.3 Energy Source Level (ESL)

The ESL of a representative sample of arrays is shown in Table 3. These values are calculated by summing the energy spectra in the band around the fundamental frequency. The summation bandwidth was taken as 40 Hz, which for these arrays is essentially the 3 dB down bandwidth. While the arrays were designed for a 100 Hz fundamental frequency, the actual average fundamental was 109 Hz. Individual shot fundamentals ranged from 98 Hz to 120 Hz. This variation is attributable to the variation in actual shot depth, with the average depth some eight percent greater than the nominal 2500 feet (see Table 1).

The average measured ESL for a single detonation was 228.6 dB// $\mu Pa^2$sec @ 1m. This compares to an estimated value of 230.2 dB//$\mu Pa^2$sec. The average measured level for two detonations was 233.9 dB, (up 5.3 dB) and the average level for a full array (ten detonations) was 246.2 dB, up 17.6 dB. The 17.6 dB array gain is compared with the 20 dB theoretical maximum gain. The 2.4 dB

TABLE 3: ESL FOR SELECTED ARRAYS

| Shot | Type | Number of Detonations | ESL dB//$\mu Pa^2$sec@1m |
|---|---|---|---|
| 8 | B | 5 | 235.6 |
| 9 | B | 5 | 238.0 |
| 11A | P | 3 | 238.2 |
| 21A | M | 10 | 246.1 |
| 21B | M | 8 | 245.2 |
| 21C | M | 10 | 246.0 |
| 22A | M | 10 | 246.4 |
| 22B | M | - | 246.8 |
| 23A | P | 2 | 234.2 |
| 23B | P | 2 | 234.4 |
| 23C | P | 2 | 232.8 |
| 24B | P | 1 | 229.0 |
| 24C | P | 1 | 228.6 |
| 25A | P | 1 | 228.1 |
| 25B | P | 5 | 239.1 |
| 25C | P | 2 | 235.5 |

loss is attributable to the less than one-half wavelength spacing at 100 Hz. The directivity index curve for 10 elements shows that at the actual array spacing a DI of only 7 dB is expected, thus, including the 10 dB gain in power, a total of 17 dB is expected. Note that at higher frequencies the spacing criteria is satisfied and a full 20 dB array gain should be achieved. Unfortunately only a few sonobuoys were effectively on-axis for the higher frequencies. However, those that were tend to support this hypothesis. See for example, Figures 6 and 7. Figure 6 is the spectra for a single shot while Figure 7 is the spectra for an array with five detonations. The second harmonic (300 Hz) is 8 dB down from the fundamental on the single shot but only 7 dB down on the array. The difference is attributable to the added gain at the higher frequency.

### 3.4 Beamforming

The evidence indicates that the arrays beamformed very well. Primary evidence is in the lack of timing jitter (Fig. 2, section 3.1) and in comparison of the single and multiple detonation spectra (Figures 6 and 7, section 3.3). The latter figures show not only the ability of the charges to "stack" but also the absence of nonlinear interference effects. The evidence is partially obscured by the fact that at the higher frequencies the sonobuoy hydrophone is not always on the main axis of the array. This is evidenced both in the time domain and in the frequency domain. Figure 8 shows the spectrum of a 10-detonation array. Note that while the energy in the fundamental and first harmonic are coherently added, that in the higher harmonics is not. This is because the sonobuoy is not on the main beam at these higher frequencies. This is seen in the time domain in Figure 9. Note the low frequency events (the bubble pulses) "stack" perfectly but the high frequency events (the shock waves) do not. The reciprocal of the spread of the shock fronts is proportional to the frequency at which the sonobuoy ceases to be on-axis. For most arrays the sonobuoys were on the main axis for frequencies below 300 Hz (a time spread of 3 msec). This interpretation is supported by the geometry analysis. The records with the sonobuoy on axis at the higher frequencies are at the better (longer) ranges.

## IV CONCLUSIONS

Several conclusions and points of interest should be noted. First, a reasonably reliable and easy measurement technique for high level sources has been developed and shown to be effective at determining source performance. Second, it is obvious from Table 2 that primacord alone is insufficient to detonate the explosives, a booster should be used. Third, the overall performance of the mild detonating fuse arrays (type M) was good. High ESL's were achieved with good reliability and repeatability. Fourth, considerable improvement in detections could be obtained by matching the analysis band to the actual frequency band of the source and, for improved performance at low frequencies, increasing the element spacing to one-half wavelength.

## REFERENCE

1. Christian, E.A., and M. Blaik, "Near Surface Measurements of Deep Explosions II: Energy Spectra of Small Charges, *J. Acoust. Soc. Am.*, 38:57 (1965).

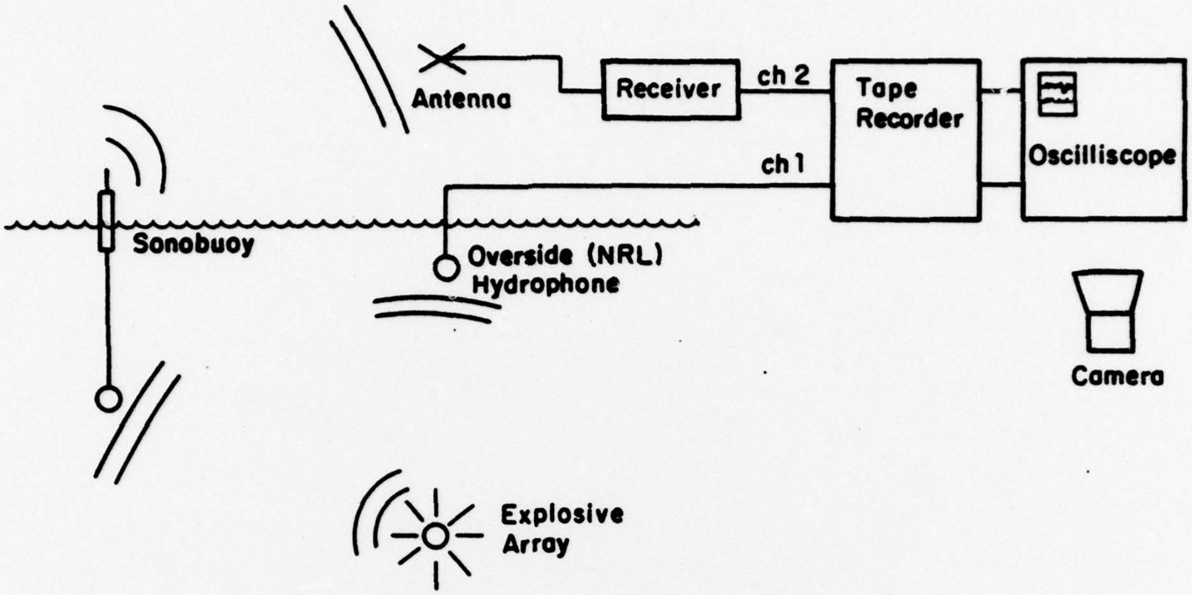

FIGURE 1: EXPERIMENTAL SETUP

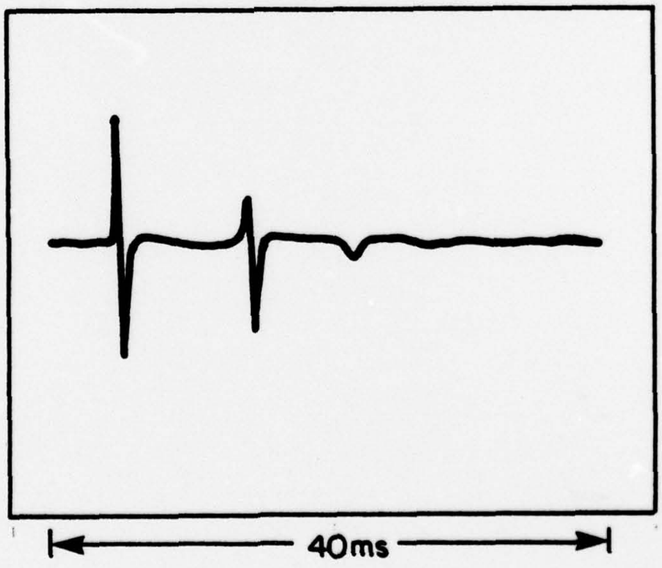

FIGURE 2: SINGLE DETONATION WAVEFORM ON NRL HYDROPHONE

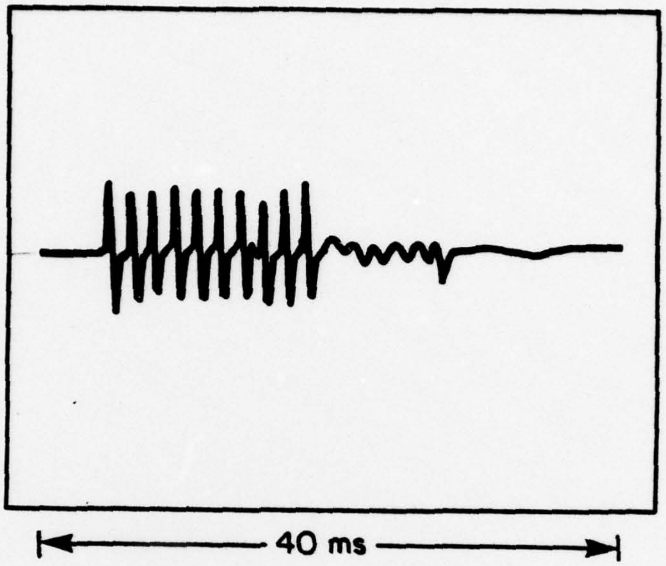

FIGURE 3: M ARRAY WAVEFORM ON NRL HYDROPHONE

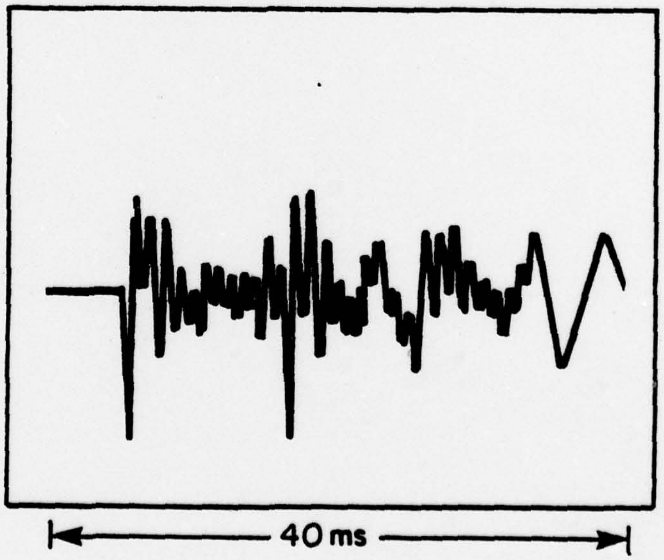

FIGURE 4: TYPICAL P ARRAY WAVEFORM ON NRL HYDROPHONE

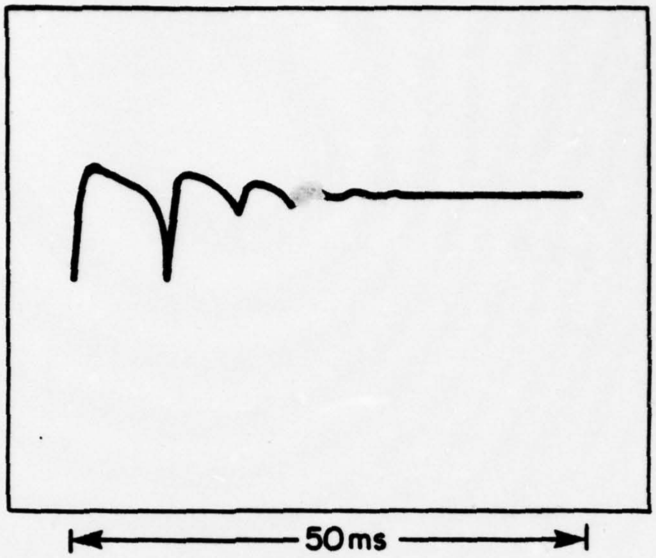

FIGURE 5: SINGLE DETONATION WAVEFORM ON SONOBUOY

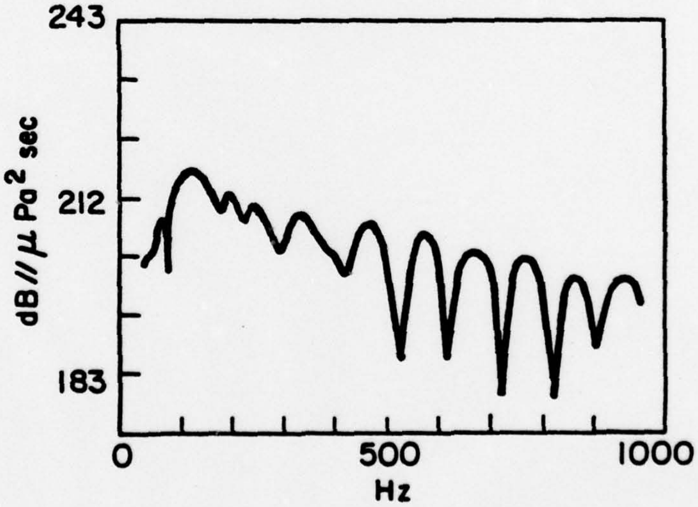

FIGURE 6: SINGLE DETONATION SPECTRA

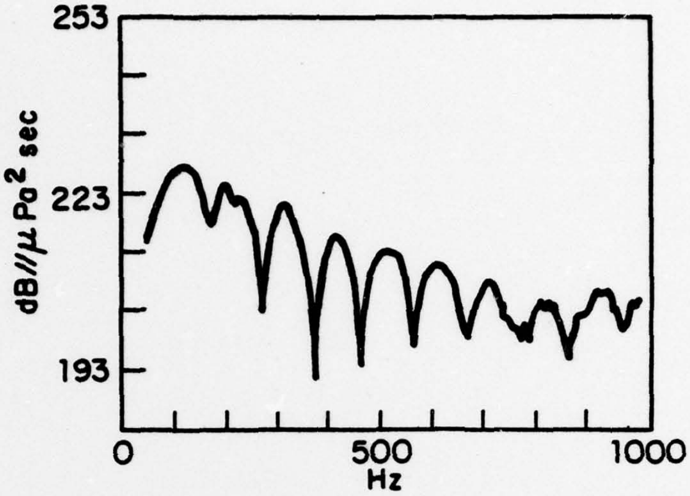

FIGURE 7: ON-AXIS ARRAY SPECTRA (5 DETONATIONS)

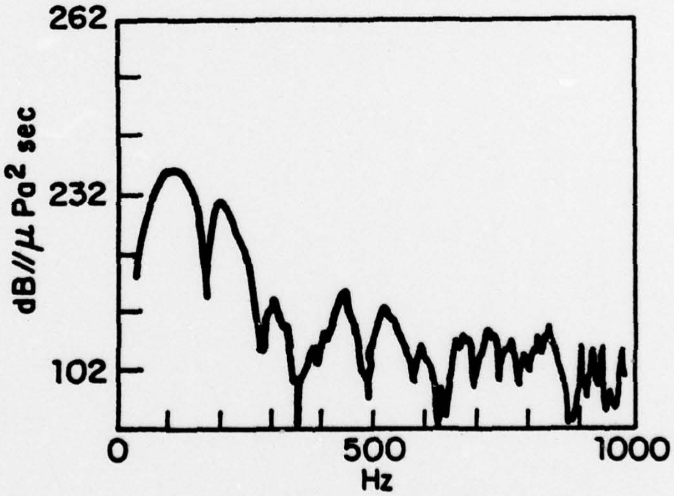

FIGURE 8: SLIGHTLY OFF-AXIS ARRAY SPECTRA (10 DETONATIONS)

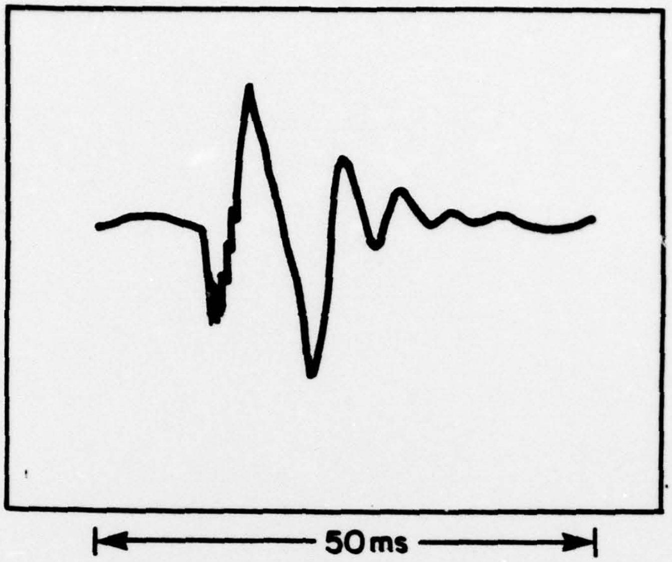

FIGURE 9: SLIGHTLY OFF-AXIS ARRAY WAVEFORM