FILE COPY

Lamont Geological Observatory
of
Columbia University
PALISADES, NEW YORK

SOME TOWED LINE HYDROPHONE ARRAYS FOR SEISMIC REFLECTION PROFILING

by

C. C. Windisch and J. I. Ewing

Technical Report No. 2

CU-2-67 Nonr 266 (79)

Technical Report No. 9

CU-9-67 Nobsr 85077

Technical Report No. 1

CU-1-67 NAVSHIPS N000-24-67-C1186

MAY 1967

Distribution of this document is unlimited

LAMONT GEOLOGICAL OBSERVATORY OF COLUMBIA UNIVERSITY
PALISADES, NEW YORK

SOME TOWED LINE HYDROPHONE ARRAYS
FOR SEISMIC REFLECTION PROFILING

by

C. C. Windisch and J. I. Ewing

Technical Report No. 2
CU-2-67 Nonr 266 (79)

Technical Report No. 9
CU-9-67 Nobsr 85077

Technical Report No. 1
CU-1-67 NAVSHIPS N000-24-67-C1186

May 1967

Distribution of this document is unlimited

SOME TOWED LINE HYDROPHONE ARRAYS
FOR SEISMIC REFLECTION PROFILING

by

C. C. Windisch and J. I. Ewing

Ship-towed line hydrophone arrays have been used in offshore geophysical prospecting for many years. More recently their use has been expanded to deep-ocean seismic reflection and refraction studies carried out by various universities, private companies and government agencies. Unfortunately, the types of towed line hydrophones most commonly employed for offshore seismic work are not well suited to deep ocean techniques for many reasons. Noteworthy among these are their great size and cost and their inability to operate effectively at the normal cruising speeds (8-12 knots) of oceanographic vessels. The initiation of a continuous deep-ocean seismic reflection profiling program at Lamont in 1960 precipitated an investigation, albeit a rather empirical one, of towed hydrophone arrays suitable for this type of work. During the subsequent six years more than five hundred thousand miles of seismic reflection data have been gathered with these devices. This report summarizes the several types of line hydrophones that have been used or evaluated in the Lamont marine seismological programs and offers some general comment about their performance.

General Statement

The important aspect of any towed line hydrophone array is that it exhibits directional characteristics over some specific range of frequencies. A marine geophysical array is designed to have a maximum sensitivity to sound received from directions normal to its towing axis. In this way output resulting from noise that is received from angles of less than 90° to the axis of the array is reduced relative to the output resulting from seismic energy that is normally reflected from the sea bottom and sub-bottom. The frequency range of interest in most marine geophysical studies usually lies below 200 Hz.

Most of Lamont's towed hydrophone arrays, or "eels" - as they have been called - contain from four to twenty hydrophones spaced uniformly inside a length of hose or plastic tubing. The tubing is filled with an appropriate fluid to provide acoustical coupling between hydrophones and sea water. A fluid-filled section of tubing without hydrophones and approximately equal to one-half the length of the phone string is added to each end of the sensing section in orderto isolate the hydrophones from end disturbances. The "eel" is towed behind the ship with a length of negatively buoyant multi-conductor cable which is fastened by a length of shock cord to the end of an 18-20 foot boom located at the stern of the ship. The boom keeps the array out of the ship's wake and the shock cord serves to reduce the effects of ship surge and cable strumming. Cable depressors have not been used and therefore the towing depth of the eel has been a function of cable length and ship's speed. Except in foul weather, ship's speed is maintained at 10-12 knots and the length of tow cable adjusted to give the best signal-to-noise ratio. Usually 300-1000 feet of cable is sufficient.

Speeds around 10 knots are somewhat higher than usual for marine geophysical work but they have been restricting only as a result of the self noise of the array, which increases markedly with towing speed in the range of seismic reflection frequencies. While attention to the theories of array design is important, the greatest signal-to-noise ratio improvement has been realized by minimizing short period accelerations and by using hydrophones with acoustic sensitivies that are very high relative to their acceleration sensitivity.

General Theory

The theories of linear array design have been well covered in underwater acoustics handbooks and will not be elaborated upon here. The following relationship is fundamental:

$$P(\theta) = \frac{\sin\left(\frac{nd\pi}{\lambda}\sin\theta\right)}{n\sin\left(\frac{\pi d}{\lambda}\sin\theta\right)}$$

where P (θ) is the sensivitity of the array at some angle θ relative to a direction normal to the axis of the array, n is the number of detectors or hydrophones, d is the distance between hydrophones, and λ

the wavelength. Thus the sensitivity of an array to sounds of a given wavelength may be plotted as a function of their direction of propagation relative to the orientation of the array. (Some theoretical directivity patterns are shown in Figure 2.)

It is evident from the equation that the low-frequency directionality of a linear array depends upon its acoustical length (nd) and that its high-frequency directionality depends upon detector spacing (d). In general, very long towed arrays are well suited to low-freqency broad-band geophysical applications and the spacing of detectors in these arrays should be considerably less than the wavelength of the highest frequency of interest. Unfortunately, great array length is often impractical with respect to cost, construction, or handling aboard ship. For these reasons the acoustical length of Lamont"eels" has usually been made to equal the wavelength of the lowest frequency within some particularly useful range of the sound source.

The spacing of detectors depends upon both the desired high-frequency characteristics of the array and the unit cost of the hydrophones. Densely spaced detectors are useful in approximating a continuously sensitive line and in controlling random noise. A large number of hydrophones has a further advantage in compensating for the variable aging characteristics of certain types of elements that depend upon air as an acoustical coupling or pressure release medium. A maximum hydrophone spacing equal to one-quarter wavelength of the highest frequency of interest has been found to give adequate air gun profiles and an even closer spacing is preferred for short arrays (50 ft. or less).

Practice

Since the use of towed hydrophone arrays is intended to improve signal strength with respect to noise, it is useful to know something about the parameters of both. It has been convenient to choose the number and spacing of hydrophones to suit some useful part of the sound source output that lies within the range of seismic reflection profiling frequencies. For most deep-ocean work this range is thought to be from about 15 to 200 Hz. In theory and in practice, the lowest frequencies in the range are particularly important because they penetrate the sea floor more readily and therefore provide more information in areas covered with thick sediments. However, there may be little to gain from the low frequencies if the sediments are particularly thin and/or acoustically transparent. The higher frequencies are more useful for the detailed resolution of reflectors but often at some sacrifice in penetration. Generally speaking, frequencies in the neighborhood of 100 Hz have offered a good compromise between penetration and resolution.

While sound sources have included sparkers, boomers, and gas exploders, most of the Lamont profiles have been gained with explosives or air guns. Explosives are typical high-energy broad-band sources, whose low-frequency content is a function of explosives weight and shot depth. Small charges, such as half-pound blocks of TNT, are capable of providing useful seismic reflections throughout the range of interest. Eels designed for explosives profiling were made fairly long - 100 to 200 ft. - in order to take advantage of low frequencies. The high signal strengths available with explosives were equally useful in offsetting the higher noise levels experienced in early eel designs. Low energy sources tend to be more limited and more selective in frequency content. The air guns which have provided most of Lamont's recent seismic reflection data produce a major portion of their output between 18-150 Hz, and an eel with an acoustical length of 50 ft has been found to give good results within this range. The same array has also given reasonably good results in the 20-30 Hz range but it is essentially non-directional below about 45 Hz.

Ambient noise as it is interpreted by a seismic array is both acoustical and mechanical in origin and increases with ship's speed and at the lower frequencies. It is safe to say that improvement in the towing stability of an array will reduce all aspects of ambient noise which result from the towing process. Neutral buoyancy, uniform mass distribution, smooth outer configuration, small array diameter and controlled tail movement are several factors considered important in reducing towing noise. In practice it is found that the acceleration sensitivity of the average hydrophone is too high to allow its use in most towed hydrophone arrays. In fact it appears that the success of an eel depends to the greatest extent upon maintaining a high ratio of acoustical sensitivity to acceleration sensitivity. No quantitative measure of this ratio is offered. Another important factor is the use of very sensitive hydrophones to maintain acoustic signal levels well above the threshold of electrical noise.

Hardware

With few exceptions, the components which have gone into the various eel designs have been readily available commercial items. This is important because it is not economically feasible to carry large inventories of specialty items to support continuous seismic reflection programs on two or three ships. On the other hand, the availability of suitable and reasonably priced commercial hydrophones has been very limited. It is acknowledged that certain hydrophone designs were not as carefully explored as those that initially gave good results.

Hydrophones

Hydrophones have been divided into two basic categories - piezoelectric ceramic crystals and variable reluctance marsh-type hydrophones. The crystal group can be further divided into cylinders and bimorphs.

Radially polarized crystal cylinders were used in the earliest attempts to build seismic profiling arrays. These cylinders have the advantage of an ideal physical symmetry and they are available in units that are small enough to fit in almost any size tubing. They are also capable of withstanding fairly high ambient pressures, depending upon their physical dimensions, with little loss in overall sensitivity. On the negative sideare the low sensitivity and capacitanceof the smaller units. Furthermore, the process of constructing a sensitive, durable and dynamically balanced phone from the cylinders was difficult and the end result often inadequate or unpredictable.

Crystal bimorphs are presently in use in all Lamont-sponsored seismic reflection programs. This type of unit has also been used for several years by offshore oil prospecting groups and is commercially available in several forms. Hall Sears MP-6, MP-7 and Electrotechnical Laboratories EVP-9 types have been tried at Lamont. These units all contain a single crystal plate working in a bending mode. The plates are stoppered to prevent injury from high pressure transients or excessive ambient pressure. The advantages of the bimorph are its high sensitivity and capacitance, its small size and good low-frequency response. A bimorph also exhibits a very low order of sensitivity to accelerations in directions parallel to the crystal plate, and these directions are most conveniently oriented parallel to the towing axis of the array. While all crystal hydrophones initially gave good results, it was found that a higher degree of acceleration cancelling was achieved by pairing bimorphs back-to-back, permitting satisfactory operation at speeds of 10-12 knots and in all water depths. A similar but improved back-to-back unit designated the EVP-23 is now available. Mark Products dual element P-24 hydrophones are currently being evaluated.

All bimorphs have the same disadvantage; the crystal plates are backed with a small volume of air whose compression restricts their maximum operating depth to around 60 ft.or less. Furthermore, in most designs, air volume decreases with use until the crystal plate is held firmly against its backing plate by the ambient pressure and sensitivity is lost. The air loss has been attributed in part to the slight gas permeability of elastomers used in hydrophone construction. While sensitivity can be restored, the prospect of disassembling an array aboard ship is never attractive.

Variable reluctance hydrophones used include Hall Sears types MP-1 and MP-4. The MP-1 is a dynamically balanced, low impedance unit with a moderately high sensitivity and of a size small enough to permit its use in relatively small diameter tubing. It is also most conveniently oriented with its axis of minimum acceleration sensitivity parallel to the physical axis of the array. The MP-1 provided good data and reasonably reliable service but like a bimorph its operation depends on a pressure release which deteriorates with use. Furthermore, the ability of the phone to withstand continuous immersion is unpredictable.

The MP-4 is a hybrid-type hydrophone which contains two diaphragm-and-moving-coil-type sensors which face a single air chamber. Acoustic signals are transmitted to the air chamber through the walls of a length of rubber tubing which serves as the outer jacket of the hydrophone. While the nonlinear frequency response and high acceleration sensitivity of the MP-4 are incompatible with low-energy sound sources, its high sensitivity and low impedance were useful in early array designs. Its dependence upon air as both a coupling and release medium is ill-suited to any routine requiring continuous immersion.

Array Casings

High axial and radial strength, good flexibility at all working temperatures, and a smooth, abrasion-resistant exterior are considered desirable characteristics for an array (eel) casing. The acoustic impedance of the material relative to sea water or to the coupling fluid is not thought to be important at seismic frequencies but its density must be considered in achieving neutral buoyancy. The size of the tubing usually depends upon the dimensions of available hydrophones but in general the smallest diameters seem to offer quieter towing and greater ease of handling. Several different types of array casing have been tried. These include polyvinyl chloride tubing, nylon-reinforced neoprene hose and even fire hose. The nylon-reinforced neoprene is costly but it is very strong and has been useful in Antarctic cold weather applications. The PVC, on the other hand, is strong and cheap and has a naturally smooth non-wetting surface. It also is readily available and has sufficient radial rigidity to prevent tubing distortion and hydrophone damage in most handling situations. The disadvantages of PVC are that it becomes brittle at low temperatures and that it is susceptible to deterioration from prolonged contact with most oil-base coupling fluids. The towing stability of cloth-covered fire hose seemed excellent but its acoustical value was never ascertained.

Polyurethane tubing is presently being evaluated. Excepting its somewhat higher cost and elasticity, it should be superior to PVC in many respects and particularly in cold weather operation.

Coupling Fluids

Various types of liquids have been used to provide acoustical coupling between the array casing and the hydrophones. These include petroleum derivatives, silicones, vegetable oil, alcohol and water. Certain advantages can be attributed to each with respect to specific gravity, volume resistivity, or chemical compatability with the various components of the array. Water, while chemically the most compatible, is the least desirable in all other respects. Silicones are expensive but because the volume of fluid involved is small their cost is only a small percentage of that of the completed array. But silicones, like petroleum derivatives, also have harmful effects on certain plastics, elastomers, and adhesives. Vegetable oil, specifically castor oil, is moderately costly but has generally given the best results. However, eel tubing must still be replaced after six to ten months of use because of deterioration.

While the density of the coupling fluid is important in controlling the buoyancy characteristics of an array, no obvious improvement in data can be attributed to neutral buoyancy at towing speeds above 7-8 knots.

Preamplifiers

The impedance of the hydrophones used in the early explosives arrays was low and their sensitivity was sufficiently high so as not to require any form of preamplification in the array itself. The preamplifier with about 20 db of gain was included in the crystal bimorph eels used for sparker and air gun profiling. While the preamplifier was used primarily as an impedance reducing device, its additional gain has been useful in maintaining a signal strength well above the anticipated threshold of electrical noise. The input impedance of this unit is 1.5 megohms and the output impedance about 50 ohms.

Accessories

The various towing plugs, coupling bulkheads, and tail plugs of Lamont arrays have been made of hard or unplasticized polyvinyl chloride. This material is very strong and relatively cheap. It has a low specific gravity, permitting a uniform mass distribution along the length of the array.

Punch-lok clamps are used to join the lengths of tubing to the bulkheads and end fittings. This type of clamp has the advantage of a very low non-turbulent profile.

Towing cables are shielded multi-conductor types with copperweld members. Cable jacketing is usually neoprene although polyurethane has also been tried. Because no depressors are used, the depth of the array is primarily a function of the length and the physical properties of the towing cable. The practical limit of cable length is usually held to about 1000 ft. and therefore cable must be chosen for properties that will take the array to maximum desirable depth at the maximum cruising speed of the ship. This depth should be equal to one-quarter wavelength of some frequency of interest in order to permit a constructive interference between the directly received seismic energy with that portion of the energy which is re-reflected from the air-water interface. In practice the need and the ability to maintain one-quarter wavelength depth in all conditions is questionable and particularly with broad-band sound sources.

The following list is a summary of the various towed hydrophone arrays which have been used in the Lamont geophysical programs. Several of these arrays and particularly those made with crystal cylinders were not as carefully evaluated as the crystal bimorph types which initially gave better results. The evaluations were made entirely upon the basis of the quality of the seismic reflection data as compared to that obtained with a single slacked hydrophone. While this method may appear to be in violation of engineering philosophy, its efficacy has been proven by the large body of data obtained and at a relatively low cost.

The MK-IX array described herein is currently in use and has been the most successful basic design to date.

MK-VIII

Hydrophone	Hall Sears MP-1, variable reluctance
Unit impedance	230, 1800, 5000 ohms
Number of hydrophones	8-12
Spacing of hydrophones	2-5 ft depending upon number of phones available
Electrical hookup	Series-parallel, depending upon unit impedance
Type of tubing	Clear, plasticized, polyvinyl chloride, 1.5-1.75" I.D., 0.25" wall thickness
Physical length of array	25 ft, 50 ft
Operating sensitivity (EST)	-97 db re 1 volt/dyne/cm^2 at 100 Hz
Operating impedance	Approximately 500-1000 ohms
Coupling fluid	Castor oil, water, kerosene
Towing cable	Three-conductor, shielded; copperweld conductors, neoprene cable jacket

In spite of its nonlinear response which increases at about 6 db per octave from 20-200 Hz, the MP-1 is a versatile and moderately sensitive hydrophone which has given good service with low energy sound sources such as sparkers and air guns. Its acceleration sensitivity is low and it is most conveniently oriented in an eel in the preferred manner, i.e., with its axis of pressure sensitivity normal to the towing direction. Its life expectancy in eel applications was found to be limited mostly by its inability to withstand continued immersion in any of the coupling fluids employed. Castor oil was invariably found to give the best results with respect to materials compatability and volume resistivity. In later designs, lengths of refrigeration hose insulation were included inside the eel tubing to improve the buoyancy characteristics, but this change did not appear to improve data -- at least at normal profiling speeds.

MK-II, III

Hydrophone	Radially polarized crystal cylinders PZT 5 composition a) 0.5 O.D. x 1.00" long x 0.125" wall thickness. b) 1.5 O.D. x 1.00" long x 0.125" wall thickness
Unit impedance	a) 3300 pf b)11000 pf
Number of hydrophones	a) 8 b)16
Spacing of hydrophones	a) 6 ft b) 12 ft
Electrical hookup	Single phones consisting of two cylinders bolted and glued together to form a capped and dynamically balanced pair separated by a rigid bulkhead. All units are in electrical parallel.
Type of tubing	Clear polyvinyl chloride a) 0.75 I.D. x 1.0" O.D. b) 2.0 I.D. x 2.50" O.D.
Physical length of array	a) 50 ft b) 200 ft
Operating sensitivity	a) -104 db re 1 dyne/cm^2 b) -92 db re 1 dyne/cm^2
Operating impedance	a) 500 ohms; preamplifier used in array for impedance matching b) 500 ohms; transformer in array for impedance matching

Coupling fluid	a) Castor oil b) Diesel oil
Towing cable	Three conductor shielded; copperweld conductors, neoprene cable jacket.

The crystal cylinder arrays did not work well initially and for this reason their true potential may not have been appreciated. For the most part their signal-to-noise ratios seemed low and their overall sensitivity was marginal in spite of their seemingly adequate sensitivity ratings. A further disadvantage of the cylinder eels has been the time-consuming process of constructing acceleration-balanced hydrophones with pairs of cylinders. It is possible, however, that the accelerations encountered with small diameter eels are low enough in magnitude so as not to require a dynamically balanced phone for most geophysical applications. The ability of the crystal cylinder to retain most of its sensitivity at moderate pressures (depths) is a significant factor in its favor.

<u>MK-V</u>

Hydrophone	Hall Sears MP-4
Unit impedance	500 ohms
Number of hydrophones	8
Spacing of hydrophones	12.5 ft
Electrical hookup	All in parallel or led to the ship individually for array shading
Type of tubing	Clear polyvinyl chloride 1.75" I.D. x 0.25" thickness B. F. Goodrich Sonar hose, nylon reinforced neoprene 1.75" I.D. x 0.125" wall thickness

Physical length of array	100-150 ft
Operating sensitivity	-84 db re 1 volt/dyne/cm^2 at 125 Hz
Operating impedance	75 ohms
Coupling fluids	Water, castor oil, silicones, diesel fuel
Towing cable	Three conductor, shielded; 14 conductor shielded; copperweld conductors, neoprene cable jacket

The MP-4 is a hybrid variable reluctance hydrophone whose operation depends upon air as an acoustical link between the hydrophone jacket and the moving coil sensors within. Even at modest confining pressures, it was found that the air inside the hydrophone would permeate the outer hydrophone jacket (diaphragm) until the diaphragm collapsed and sensitivity was lost. It is now apparent that this permeability problem was not unique with the MP-4 but seems inherent to hydrophones that depend upon air as a pressure coupling or release medium.

The undamped frequency response of the MP-4 is strongly peaked and slopes off at nearly 12 db per octave above and below 125 Hz. This is a partial advantage in that the latter frequency is generally well suited to deep-ocean seismic profiling. The MP-4 was used extensively in the later stages of explosives profiling but its acceleration sensitivity was too high for low energy sound sources. The life expectancy of the MP-4 rarely exceeded 1-2 months of use.

MK-VI

Hydrophone	Hall Sears MP-6
Unit impedance	560 ohms
Unit sensitivity	-114 db re 1 volt/dyne/cm^2 when properly damped

All aspects of the MK-VI eels were identical to the MK-V, except for the hydrophones. The MP-6 is a crystal bimorph type of phone which also contains a matching transformer. When properly damped the MP-6 operating sensitivity was found to be impractically low. Also its tendency to become insensitive with use and confining pressure was similar to the MP-4. When properly damped, its frequency response, however, was far superior to any of the earlier Hall Sears designs.

MK-VII

Hydrophone	Hall Sears MP-7, crystal bimorph
Unit impedance	.007 uf
Unit sensitivity	-92 db re 1 volt/dyne/cm^2
Number of hydrophones	20
Hydrophone spacing	2.5 ft
Electrical hookup	Series parallel. Five parallel groups of hydrophones with four series phones in each group.
Preamplifier	Darlington type circuit. Input impedance 1.5 megohms; output impedance 50 ohms; gain 18-20 db
Array operating sensitivity	-60 db re 1 volt/dyne/cm^2
Operating impedance	50 ohms

Type of tubing	Clear polyvinyl chloride; 1.75" I.D. x 0.25" wall thickness
Physical length of array	75-100 ft
Towing cable	Three conductor shielded; copperweld conductors, neoprene cable jacket.

The small size of the MP-7 is well suited to array applications and particularly with small tubing diameters. The initial performance of the phone was outstanding with low energy sources. However, its signal-to-noise ratio varied markedly with changes in towing conditions. As with most hydrophones whose operation depends on air, the MP-7 would become insensitive after a short period of use. This problem was simpler to deal with in the MP-7 than in variable reluctance hydrophones but it happened all too frequently.

MK-IX

Hydrophone	Back-to-back series pair of Electrotechnical Laboratories EVP-9 crystal bimorphs
Unit impedance	.007 uf
Unit sensitivity	-86 to -84 db re 1 volt/dyne/cm^2
Number of hydrophones	8, 16
Hydrophone spacing	6 ft, 3 ft
Electrical hookup	Four parallel groups with four hydrophones in series in each group.
Preamplifier	Darlington type circuit; input impedance 1.5 megohms; output impedance 50 ohms; gain 18-20 db
Operating sensitivity	-54 to -52 db re 1 volt/dyne/cm^2

Type of tubing	a) clear polyvinyl chloride; 1.75" I.D. x 0.25" wall thickness
	b) clear polyvinyl chloride; 1.125" I.D. x .1875 wall thickness
Physical length of array	75-100 ft

The initial performance of the MK-IX eels was outstanding particularly in that they seemed less sensitive to variations in towing conditions. This advantage was attributed to the lower degree of acceleration sensitivity of the elements. The 16-element arrays have given the best results. Due to a fairly wide range in EVP-9 sensitivity, it is advantageous to match the hydrophones in each array. While the individual EVP-9 elements tend to collapse and lose sensitivity after two to three months of use, this represents a somewhat longer period of service than experienced with other units but the process of restoring the original unit sensitivity is equally unpleasant. The EVP-23, a new commercial version of the paired EVP-9 detectors, represents a vast improvement in uniformity, serviceability and probable dependability.

A long and fairly small diameter eel (1.5 O.D.) also constructed from pairs of EVP-9 elements was found to give a quieter performance in following seas than the standard arrays. This apparent improvement in signal-to-noise ratio has been attributed in part to reduced tow cable vibration resulting from the lower drag forces involved with smaller diameter tubing. Unfortunately, the closer fit of the hydrophone spring inside the eel tubing created maintenance difficulties and the small-diameter projects were temporarily abandoned.

MK-X

Hydrophone	Clevite type CH-13E, ceramic crystal rings
Unit sensitivity	-92 db re 1 volt/dyne/cm^2
Number of hydrophones	8
Hydrophone spacing	6 ft
Electrical hookup	Two parallel groups of four series hydrophones
Preamplifier	Darlington type circuit 1.5 megohm input impedance; 50 ohms output impedance; 18-20 db gain
Operating sensitivity	-60 db re 1 volt/dyne/cm^2
Operating impedance	50 ohms
Type of tubing	Clear, polyvinyl chloride; 2.0" I.D. x 0.25" wall thickness
Physical array length	100 ft

The MK-X array gave satisfactory results. The greatest virtues of the CH-13E are its uniform hydrophone sensitivity, wide depth-range of operation, low acceleration sensitivity, and freedom from desensitization with use. Unfortunately, it is relatively large and costly for eel applications and its location inside an array requires care to prevent its pistons from coming into contact with the eel casing. The performance of the MK-X eel is roughly comparable to a MK-IX eel with eight matched elements. The trouble-free operation of the CH-13E hydrophone is well worth considering.

Conclusions

The preceding discussion has presented the basic designs of the line hydrophone arrays used in the Lamont marine geophysical programs over the past six years. Minor ramifications of these designs are not included for purposes of clarity. All arrays or eels have been required to provide satisfactory and continuous seismic reflection data at speeds of 10-12 knots and in all deep ocean areas. This aim was easily achieved with high energy sound sources such as explosives, but lower energy sources such as sparkers, boomers and air guns have required the development and use of more sensitive detectors with very low acceleration sensitivities. While Lamont has found that certain types of crystal bimorph detectors are well suited to low-energy profiling, other types of hydrophones may be equally useful and particularly those using crystal cylinders. This seems particularly important when one considers that all the evaluated bimorphs have had depth limitations and a restricted life span. The latter problem is easily treated but no permanent cure is anticipated.

The most successful array construction to date has been the MK-IX variety which is currently in use in seismic reflection work aboard the research vessels, VEMA, ROBERT D. CONRAD, and ELTANIN. Further effort is being made to evaluate very long, small diameter eels in anticipation of a growing need for more detailed seismic investigation.

Acknowledgments

This work has been supported by U. S. Navy Office of Naval Research contract Nonr 266 (79), and by the Bureau of Ships contract Nobsr 85077. The preparation of this report was partially supported by NAVSHIPS Contract N000-24-67-C1186.

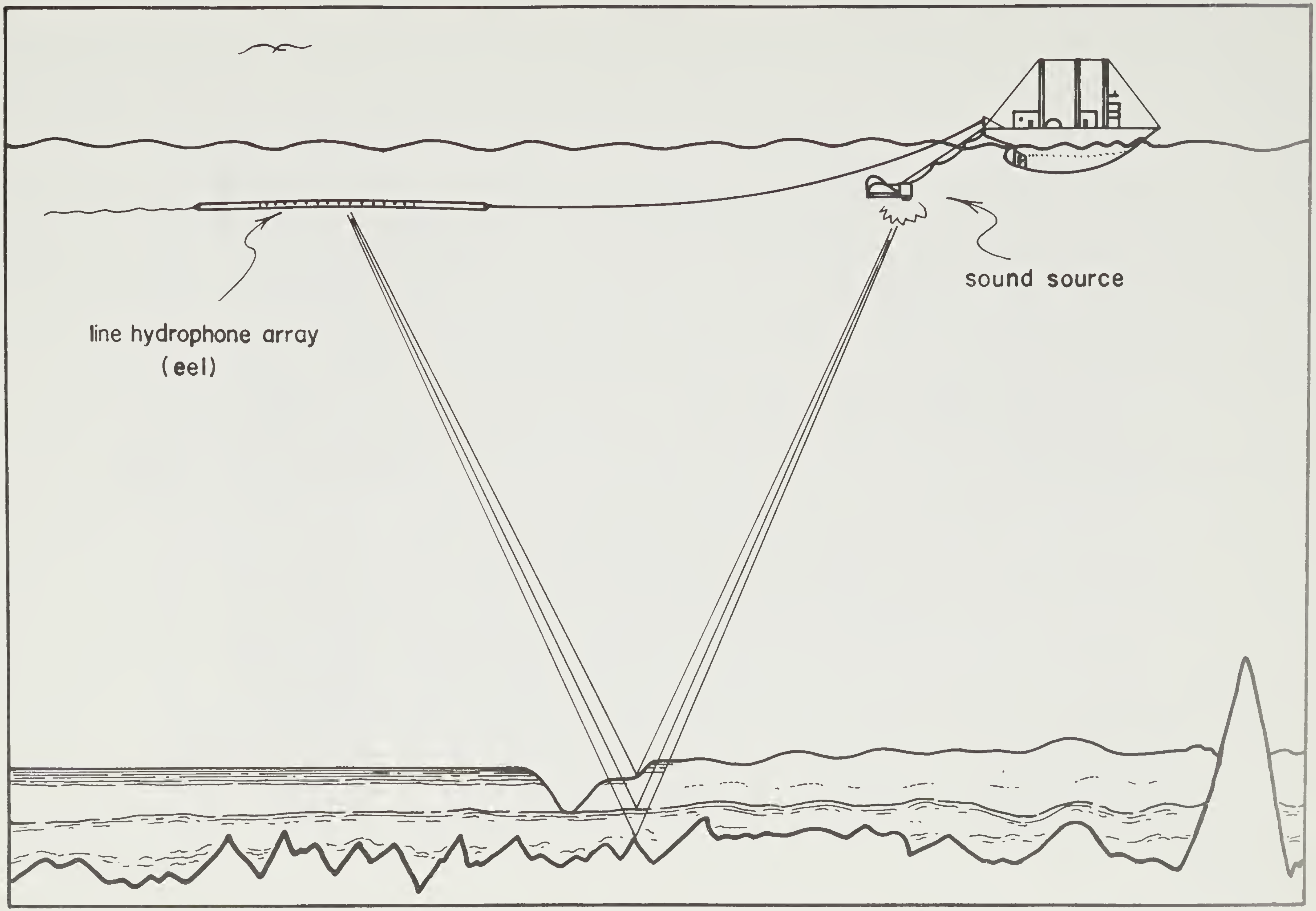
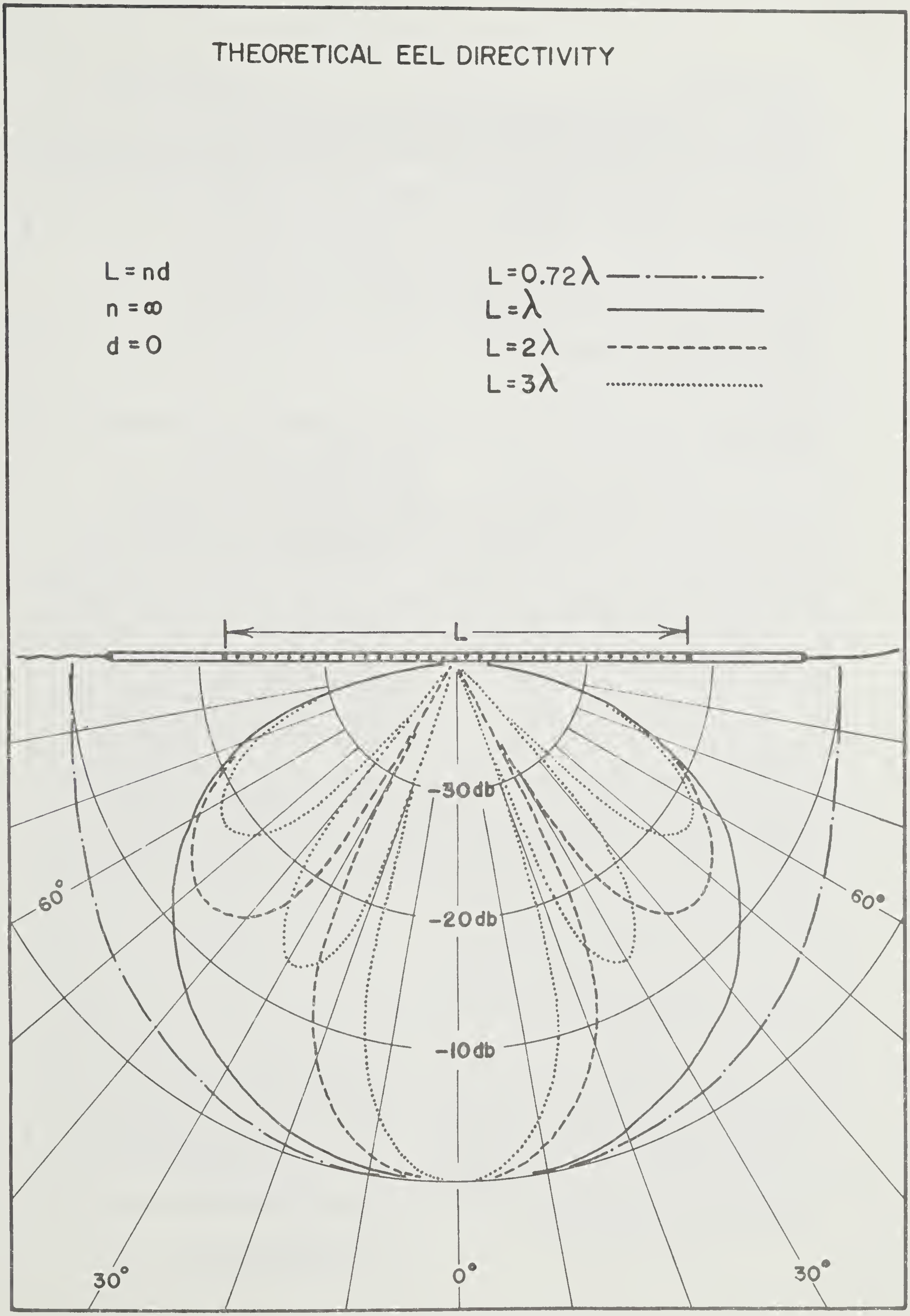


FIGURE 1



THEORETICAL EEL DIRECTIVITY
L = nd
n = ∞
d = 0
L = 0.72λ
L = λ
L = 2λ
L = 3λ
L
-30db
-20db
-10db
60°
60°
30°
0°
30°

FIGURE 2

Unclassified
Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Lamont Geological Observatory of Columbia Univ. Palisades, New York 10964	2a. REPORT SECURITY CLASSIFICATION 2b. GROUP

3. REPORT TITLE

SOME TOWED LINE HYDROPHONE ARRAYS FOR SEISMIC REFLECTION PROFILING

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*
Technical Report

5. AUTHOR(S) *(Last name, first name, initial)*
Windisch, C. C.
Ewing, J. I.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
May 1967	23	-

8a. CONTRACT OR GRANT NO. Nonr 266 (79) b. PROJECT AND TASK NO. Nobsr 85077 NAVSHIPS)N000-24-67 c. DOD ELEMENT)C1186 d. DOD SUBELEMENT	9a. ORIGINATOR'S REPORT NUMBER(S) Tech. Report No. 2- CU-2-67 Tech. Report No. 9- CU-9-67 Tech. Report No. 1- CU-1-67 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*

10. AVAILABILITY/LIMITATION NOTICES

Distribution of this document is unlimited

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Department of the Navy Office of Naval Research and NAVSHIPS, Washington, D. C.

13. ABSTRACT

This report reviews briefly developments of ship-towed line hydrophone arrays used by the Lamont Geological Observatory in its deep-ocean geophysical programs. These arrays have been used with explosives and lower energy sound sources to gather seismic reflection data at ship's speed averaging 10-12 knots.

DD FORM 1 JAN 64 1473

Unclassified
Security Classification

Unclassified

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Ship towed hydrophone arrays						

INSTRUCTIONS

1. ORIGINATING ACTIVITY: Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization *(corporate author)* issuing the report.

2a. REPORT SECURITY CLASSIFICATION: Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2b. GROUP: Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. REPORT TITLE: Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. DESCRIPTIVE NOTES: If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. AUTHOR(S): Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. REPORT DATE: Enter the date of the report as day, month, year, or month, year. If more than one date appears on the report, use date of publication.

7a. TOTAL NUMBER OF PAGES: The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7b. NUMBER OF REFERENCES: Enter the total number of references cited in the report.

8a. CONTRACT OR GRANT NUMBER: If appropriate, enter the applicable number of the contract or grant under which the report was written.

8b, 8c, & 8d. PROJECT NUMBER: Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

9a. ORIGINATOR'S REPORT NUMBER(S): Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9b. OTHER REPORT NUMBER(S): If the report has been assigned any other report numbers *(either by the originator or by the sponsor)*, also enter this number(s).

10. AVAILABILITY/LIMITATION NOTICES: Enter any limitations on further dissemination of the report, other than those imposed by security classification, using standard statements such as:

(1) "Qualified requesters may obtain copies of this report from DDC."

(2) "Foreign announcement and dissemination of this report by DDC is not authorized."

(3) "U. S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through ________________."

(4) "U. S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through ________________."

(5) "All distribution of this report is controlled. Qualified DDC users shall request through ________________."

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. SUPPLEMENTARY NOTES: Use for additional explanatory notes.

12. SPONSORING MILITARY ACTIVITY: Enter the name of the departmental project office or laboratory sponsoring *(paying for)* the research and development. Include address.

13. ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as *(TS), (S), (C), or (U)*.

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, rules, and weights is optional.

Unclassified

Security Classification

LAMONT GEOLOGICAL OBSERVATORY
Columbia University
Palisades, New York

Distribution List on Contract Nobsr 85077

U. S. Navy Underwater Sound Laboratory
New London, Conn. 1

U. S. Navy Electronics Laboratory
Point Loma, San Diego, Calif. 1

Marine Physical Laboratory
Univ. of California
San Diego, Calif. 1

Scripps Inst. of Oceanography
La Jolla, Calif. 1

Woods Hole Oceanographic Inst.
Woods Hole, Mass. 1

Naval Ship Systems Command
Washington, D. C. 20360
Code 1622 K 1

Naval Ship Systems Command
Washington, D. C. 20360
Code 2021 3

Commander,
Submarine Development Group Two
via: CDR. Submarine Force
U. S. Atlantic Fleet
c/o Fleet Postoffice
New York, N. Y. 1

Commander,
Submarine Force
U. S. Pacific Fleet
c/o Fleet Postoffice
San Francisco, Calif. 1

Chief of Naval Research
Navy Department
Washington, D. C.
Code 468 1
Code 416 1
Code 418 1
Code 466 1

Defense Research Laboratory
University of Texas
Austin, Texas
Via: ONR Resident Repr. 1

Office of Naval Research
346 Broadway
New York 13, N. Y. 1

U. S. Naval Oceanographic Office
Navy Department
Washington 25, D. C. 2

Chief, Bureau of Naval Weapons
Code Ru 222
Navy Department
Washington 25, D. C. 1

Bell Telephone Laboratories, Inc.
Whippany, New Jersey
Att: Dr. W. A. Tyrrell

Commander
Naval Ordnance Laboratory
Silver Spring, Maryland 1

Security Officer
Marine Laboratory
University of Miami
#1 Rickenbacker Causeway
Miami 49, Florida 1

Director
U. S. Naval Research Laboratory
Washington 25, D. C.
Code 5500 1

Director
Applied Physics Laboratory
University of Washington
Seattle, Washington 1

Director
Department of Oceanography
Texas A&M College
College Station, Texas 1

Director
Arctic Research Laboratory
P. O. Box 1070
Fairbanks, Alaska 1

Resident Rep.
Office of Naval Research
Hudson Laboratories
145 Palisade Street
Dobbs Ferry, New York 1

Committee on Undersea Warfare
National Academy of Science
2101 Constitution Ave., N.W.
Washington, D.C. 1

UNCLASSIFIED TECHNICAL REPORTS DISTRIBUTION LIST
FOR OCEANOGRAPHIC CONTRACTORS
OF THE OCEAN SCIENCE & TECHNOLOGY GROUP
OF THE OFFICE OF NAVAL RESEARCH
(Revised April 1967)

DEPARTMENT OF DEFENSE

Director of Defense Research and Engineering
Office of the Secretary of Defense
Washington, D. C. 20301
1 Attn: Office, Assistant Director (Research)

Navy

2 Office of Naval Research
Ocean Science & Technology Group
Department of the Navy
Washington, D. C. 20360
1 Attn: Surface & Amphibious Programs (Code 463)
1 Attn: Undersea Programs (Code 466)
1 Attn: Field Projects (Code 418)
1 Attn: Geography Branch (Code 414)

1 Commanding Officer
Office of Naval Research Branch Office
495 Summer Street
Boston, Massachusetts 02210

1 Commanding Officer
Office of Naval Research Branch Office
219 South Dearborn Street
Chicago, Illinois 60604

1 Commanding Officer
Office of Naval Research Branch Office
1030 East Green Street
Pasadena, California 91101

5 Commanding Officer
Office of Naval Research Branch Office
Navy #100, Fleet Post Office
New York, New York 09510

6 Director
Naval Research Laboratory
Washington, D. C. 20390
Attn: Code 5500

2 Commander
U. S. Naval Oceanographic Office
Washington, D. C. 20390
1 Attn: Code 1640 (Library)
1 Attn: Code 031
1 Attn: Code 70
1 Attn: Code 90

1 West Coast Support Group
U. S. Naval Oceanographic Office
c/o U. S. Navy Electronics Laboratory
San Diego, California 92152

1 U. S. Naval Oceanographic Office Liaison Officer (Code 332)
Anti-Submarine Warfare Force
U. S. Atlantic Fleet
Norfolk, Virginia 23511

1 U. S. Naval Oceanographic Office Liaison Officer
Anti-Submarine Warfare Force Pacific
Fleet Post Office
San Francisco, California 96610

1 Commander-in-Chief
Submarine Force Pacific Fleet
Fleet Post Office
San Francisco, California 96610

1 Commander-in-Chief
Pacific Fleet
Fleet Post Office
San Francisco, California 96610

1 Chief
Naval Ordnance Systems Command
Department of the Navy
Washington, D. C. 20360

1 Chief
Naval Air Systems Command
Department of the Navy
Washington, D. C. 20360
1 Attn: AIR 370E

1 Office of the U. S. Naval Weather Service
Washington Navy Yard
Washington, D. C. 20390

1 Chief
Naval Facilities Engineering Command
Department of the Navy
Washington, D. C. 20390
1 Attn: Code 70

U. S. Navy Electronics Laboratory
San Diego, California 92152
1 Attn: Code 3102
1 Attn: Code 3060C

1 Commanding Officer and Director
U. S. Naval Civil Engineering Laboratory
Hueneme, California 93041

1 Commanding Officer
Pacific Missile Range
Pt. Mugu, Hueneme, California 93041

1 Commander, Naval Ordnance Laboratory
White Oak
Silver Spring, Maryland 20910

1 Commanding Officer
Naval Ordnance Test Station
China Lake, California 93557

1 Commanding Officer
Naval Radiological Defense Laboratory
San Francisco, California 94135

1 Commanding Officer
U. S. Naval Underwater Ordnance Station
Newport, Rhode Island 02884

1 Chief
Naval Ship Systems Command
Department of the Navy
Washington, D. C. 20360
1 Attn: Code 1622B

1 Officer-in-Charge
U. S. Navy Weather Research Facility
Naval Air Station, Bldg. R-48
Norfolk, Virginia 23511

1 Commanding Officer
U. S. Navy Air Development Center
Warminster, Pennsylvania 18974
1 Attn: NADC Library

1 U. S. Fleet Weather Central
Joint Typhoon Warning Center
COMNAVMARIANAS Box 12
San Francisco, California 94101

1 Superintendent
U. S. Naval Academy
Annapolis, Maryland 21402

2 Department of Meteorology & Oceanography
U. S. Naval Postgraduate School
Monterey, California 93940

1 Commanding Officer
U. S. Navy Mine Defense Laboratory
Panama City, Florida 32402

1 Commanding Officer
U. S. Naval Underwater Sound Laboratory
New London, Connecticut 06321

1 Officer-in-Charge
U. S. Fleet Numerical Weather Facility
U. S. Naval Postgraduate School
Monterey, California 93940

Air Force

1 Headquarters, Air Weather Service
(AWSS/TIPD)
U. S. Air Force
Scott Air Force Base, Illinois 62225

1 AFCRL (CRZF)
L. G. Hanscom Field
Bedford, Massachusetts 01730

Army

1 Coastal Engineering Research Center
Corps of Engineers
Department of the Army
Washington, D. C. 20310

1 Army Research Office
Office of the Chief of R&D
Department of the Army
Washington, D. C. 20310

1 U. S. Army Beach Erosion Board
5201 Little Falls Road, N. W.
Washington, D. C. 20016

1 Director
U. S. Army Engineers Waterways
Experiment Station
Vicksburg, Mississippi 49097
1 Attn: Research Center Library

OTHER GOVERNMENT AGENCIES

20 Defense Documentation Center
Cameron Station
Alexandria, Virginia 20305

2 National Research Council
2101 Constitution Avenue, N. W.
Washington, D. C. 20418
Attn: Committee on Undersea Warfare
Attn: Committee on Oceanography

1 Laboratory Director
California Current Resources Laboratory
Bureau of Commercial Fisheries
P. O. Box 271
La Jolla, California 92038

1 Director
Coast & Geodetic Survey - U.S. ESSA
Attn: Office of Hydrography &
Oceanography
Washington Science Center
Rockville, Maryland 20852

1 Director
Atlantic Marine Center
Coast & Geodetic Survey - U.S. ESSA
439 West York Street
Norfolk, Virginia 23510

1 Director
Institute for Oceanography
U. S. ESSA
Gramax Building
Silver Spring, Maryland 20910

1 U. S. ESSA
Geophysical Sciences Library (AD 712)
Washington Science Center
Rockville, Maryland 20852

1 Commanding Officer
Coast Guard Oceanographic Unit
Bldg. 159, Navy Yard Annex
Washington, D. C. 20390

1 Chief, Office of Marine Geology &
Hydrology
U. S. Geological Survey
Menlo Park, California 94025

1 Director
Pacific Marine Center
Coast and Geodetic Survey - U.S. ESSA
1801 Fairview Avenue, East
Seattle, Washington 98102

1 Geological Division
Marine Geology Unit
U. S. Geological Survey
Washington, D. C. 20240

1 National Science Foundation
Office of Sea Grant Programs
1800 G Street, N. W.
Washington, D. C. 20550

1 Laboratory Director
Bureau of Commercial Fisheries
Biological Laboratory
450-B Jordon Hall
Stanford, California 94035

1 Bureau of Commercial Fisheries
U. S. Fish & Wildlife Service
P. O. Box 3830
Honolulu, Hawaii 96812

1 Laboratory Director
Biological Laboratory
Bureau of Commercial Fisheries
P. O. Box 3098, Fort Crockett
Galveston, Texas 77552

1 Laboratory Director
Biological Laboratory
Bureau of Commercial Fisheries
P. O. Box 1155
Juneau, Alaska 99801

1 Laboratory Director
Biological Laboratory
Bureau of Commercial Fisheries
P. O. Box 6
Woods Hole, Massachusetts 02543

1 Laboratory Director
Biological Laboratory
Bureau of Commercial Fisheries
P. O. Box 280
Brunswick, Georgia 31521

1 Laboratory Director
Tuna Resources Laboratory
Bureau of Commercial Fisheries
P. O. Box 271
La Jolla, California 92038

1 Bureau of Commercial Fisheries & Wildlife
U. S. Fish and Wildlife Service
Librarian
Sandy Hook Marine Laboratory
P. O. Box 428
Highlands, New Jersey 07732

1 Director
National Oceanographic Data Center
Washington, D. C. 20390

1 Laboratory Director
Biological Laboratory
Bureau of Commercial Fisheries
#75 Virginia Beach Drive
Miami, Florida 33149

1 Director, Bureau of Commercial Fisheries
U. S. Fish & Wildlife Service
Department of the Interior
Washington, D. C. 20240

1 Bureau of Commercial Fisheries
Biological Laboratory, Oceanography
2725 Montlake Boulevard, East
Seattle, Washington 98102

1 Dr. Gene A. Rusnak
U. S. Geological Survey
Marine Geology & Hydrology
345 Middlefield Road
Menlo Park, California 94025

1 Assistant Director
Oceanography Museum of Natural History
Smithsonian Institution
Washington, D. C. 20560

1 Advanced Research Projects Agency
The Pentagon
Washington, D. C. 20310
Attn: Nuclear Test Detection Office

RESEARCH LABORATORIES

2 Director
Woods Hole Oceanographic Institution
Woods Hole, Massachusetts 02543

1 Director
Narragansett Marine Laboratory
University of Rhode Island
Kingston, Rhode Island 02881

1 Gulf Coast Research Laboratory
Ocean Springs, Mississippi 39564
Attn: Librarian

1 Chairman, Department of
Meteorology & Oceanography
New York University
New York, New York 10453

1 Director
Lamont Geological Observatory
Columbia University
Palisades, New York 10964

1 Director
Hudson Laboratories
145 Palisade Street
Dobbs Ferry, New York 10522

1 Great Lakes Research Division
Institute of Science & Technology
University of Michigan
Ann Arbor, Michigan 48105

1 Department of Physics
Northern Michigan University
Marquette, Michigan 49855

1 Director
Chesapeake Bay Institute
Johns Hopkins University
Baltimore, Maryland 21218

1 Director, Marine Laboratory
University of Miami
#1 Rickenbacker Causeway
Miami, Florida 33149

2 Head, Department of Oceanography &
Meteorology
Texas A&M University
College Station, Texas 77843

1 Director
Scripps Institution of Oceanography
La Jolla, California 92038

1 Allan Hancock Foundation
University Park
Los Angeles, California 90007

1 Head, Department of Oceanography
Oregon State University
Corvallis, Oregon 97331

1 Head, Department of Oceanography
University of Washington
Seattle, Washington 98105

1 Director, Arctic Research Laboratory
Pt. Barrow, Alaska 99723

1 Director
Bermuda Biological Station for
Research
St. Georges, Bermuda

1 Director
Hawaiian Marine Laboratory
University of Hawaii
Honolulu, Hawaii 96825

1 President
Osservatorio Geofisico Sperimentale
Trieste, Italy

1 Department of Engineering
University of California
Berkeley, California 94720

1 Applied Physics Laboratory
University of Washington
1013 N. E. Fortieth Street
Seattle, Washington 98105

1 Physical Oceanographic Laboratory
Nova University
1786 S. E. Fifteenth Avenue
Fort Lauderdale, Florida 33316

1 Director
Ocean Research Institute
University of Tokyo
Tokyo, Japan

1 Marine Biological Association
of the United Kingdom
The Laboratory
Citadel Hill
Plymouth, England

1 Serials Department
University of Illinois Library
Urbana, Illinois 61801

1 New Zealand Oceanographic Institute
Department of Scientific and
Industrial Research
P. O. Box 8009
Wellington, New Zealand
Attn: Librarian

1 Director
Instituto Nacional de Oceanographia
Rivadavia 1917-R25
Buenos Aires, Argentina

1 Lieutenant Nestor C. L. Granelli
Head, Geophysics Branch
Montevideo 459, 4° "A"
Buenos Aires, Argentina

1 Oceanographische Forschungsantalt
der Bundeswehr
Lornsenstrasse 7
Kiel, Federal Republic of Germany

1 Underwater Warfare Division
of the Norwegian Defense Research
Establishment
Karljohansvern, Horten, Norway

1 Department of Geodesy & Geophysics
Columbia University
Cambridge, England

1 Institute of Oceanography
University of British Columbia
Vancouver, B. C., Canada

1 Department of the Geophysical Sciences
University of Chicago
Chicago, Illinois 60637

1 Coastal Engineering Laboratory
University of Florida
Gainesville, Florida 32601

1 Marine Science Center
Lehigh University
Bethlehem, Pennsylvania 18015

1 Institute of Geophysics
University of Hawaii
Honolulu, Hawaii 96825

1 Mr. J. A. Gast
Wildlife Building
Humboldt State College
Arcata, California 95521

1 Department of Geology & Geophysics
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

1 Division of Engineering and
Applied Physics
Harvard University
Cambridge, Massachusetts 02138

1 Department of Geology
Yale University
New Haven, Connecticut 06520

1 Westinghouse Electric Corporation
1625 K Street, N. W.
Washington, D. C. 20006

Director
Institute of Marine Sciences
University of Alaska
College, Alaska 99735

COLUMBIA LIBRARIES OFFSITE
CU90641965