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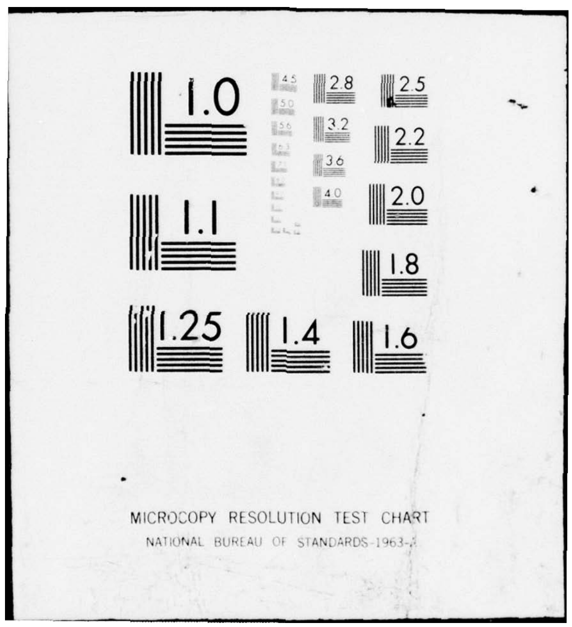
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REQUIREMENTS OF A METHOD FOR LOCATING UNDERWATER BIO-ACOUSTIC SOURCES.

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San Diego, California

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REQUIREMENTS OF A METHOD FOR LOCATING UNDERWATER BIO-ACOUSTIC SOURCES[1,2]

William C. Cummings

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Introduction

On 10 May 1967, a meeting was called in Washington, D.C. by the American Institute of Biological Sciences, Advisory Committee on Hydrobiology to the Office of Naval Research, Oceanic Biology Programs. One aim of this meeting was for attending bio-acousticians to acquaint the Committee with the problems which limit our knowledge of bio-acoustics in the sea. Another aim was to suggest directions of future research. This author stressed the need for estimating the location of underwater biological signals, for without very special instrumentation underwater sounds appear to come from everywhere. Discussion from the floor included numerous suggestions covering a wide spectrum of ideas from directional receivers to sonic tags. However, it appeared that a practical solution was not readily available.

The purpose of this report is to recommend the requirements of a technique which would enable bio-acousticians to estimate the locality of the source of underwater biological signals in the natural environment. These recommendations

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2 This work was supported by the Naval Ship Systems Command, SR 1040301, Task 0531 and by special project NUWC Z148.

were partly based upon consultations with numerous other persons including engineers and physicists inside and outside of NUWC, as well as 20 other bio-acousticians. A working model system, or precise specifications, were beyond the present undertaking. Hopefully, the ideas set forth here will lead towards completion of an adequate system which can be made available to bio-acousticians who are involved with studying underwater biological signals in the natural environment.

Need for Locating Biological Signals

There are at least three basic needs for an adequate method to estimate the field location of acoustic signals in bio-acoustic studies.

1. Identification When a hydrophone is placed in the vicinity of a dense underwater fauna, the listener is almost invariably confronted with an abundance of acoustic signals, most of which he cannot identify. The same frustrating experience may also occur in moderately or sparsely populated areas. Unenlightened observers facing this problem are often tempted into associating sound and source on the basis of anecdotal or anthropomorphic evidence that is misleading. Examples of this may be found in the literature. In contrast, considerable information may be inherent in the identification of bio-acoustic signals. To illustrate, general behavior that is already known about the species or family may often be used to infer spatial or temporal predictions of the sound's occurrence. Identification of the signal is a virtual requisite for most bio-acoustic investigations. More often than not, the identification will require some knowledge of where the sound is coming from, and hence a method of location. It is relatively easy for an investigator, aided by a rapidly-advancing technology, to extend his acoustic observations into the ocean. The commonest problem is that he frequently does not know what he is listening to.

2. Source Levels The availability of sonagraphic instruments has made it possible, on a routine basis, to include frequency spectrum analyses in the

physical descriptions of underwater biological signals. However, one rarely encounters data on sound pressure level at the source. A review of 94 papers on sound production of fishes showed that source levels were available for just 21 signal types of about 200 kinds of signals from 158 species.[1] Underwater animals apparently can generate large sound pressures that are detectable at relatively long distances.[2,3,4,5] Investigators can estimate the sound pressure level at a given distance from the source (ie, 1 yd) by determining the absolute received sound pressure level and the distance of the source from the hydrophone. Other requirements include a calibrated hydrophone system and local knowledge of sound spreading and attenuation losses. It is usually necessary to locate the source to determine its distance from the receiving hydrophone. Since the spreading loss of sound pressure is an inverse power function of distance, closer sources require more accurate estimates of their distance than do more remote sources.

3. Behavioral Information Movements of underwater acoustic sources can be described if one has the capability to locate their sounds. Moreover, tracks of underwater signals may offer clues to their identity. Movements of underwater soniferous organisms are not only of inherent interest, but they may help to explain some of the rhythmic occurrences of bio-acoustic sources. There are many examples of marine animal sounds occuring on a periodic basis, such as at sunrise, sunset, midnight, or at a predictable time during the month or season.[4,6,7] However, without some method of estimating their location, it may be difficult to distinguish between actual rhythmic sound production and rhythmic movements of the causative species in and out of hydrophone range.[7]

Basic Requirements

The following basic requirements were based upon the author's experience and the thoughtful comments of other bio-acousticians who were asked for suggestions.

1. Portability Any proposed system for localizing bio-acoustic signals in

the field should be portable enough to operate from a boat as small as a 16-ft skiff. Over-the-side components must be easily and quickly set in place without the aid of a diver.

2. Power All components requiring electrical power should run on small, rechargeable storage batteries.

3. Hydrophones Hydrophone sensitivity should be approximately -85 dB re $1v/dyn/cm^2$ or greater, and its capacity should be about 500 pF. Frequency response should be essentially constant from 20 Hz to 10 kHz if the system is used primarily for fish sounds. The detection of high frequency cetacean sounds will require a hydrophone with sufficient response to signals up to about 100 kHz, depending upon the objectives of the investigation. A locating system capable of operating at high frequencies could also be used to locate sonic tags that are placed on organisms to determine their movements. A low impedance system with a preamplifier near the hydrophone probably would be more satisfactory for field use than one with just an inboard preamplifier. The latter systems usually have more unwanted noise, relative to the signal, from stresses on the cable during field use. Hydrophone size will depend upon the kind of method, ie, bottom array, suspended binaural system, or bi-gradient system. In any case, the hydrophone should be as small as is practical since the operation will usually be carried out from small boats without lifting devices.

4. Simplicity Most bio-acousticians do not have sufficient funding or engineering and technical assistance to use and maintain complex systems. This is especially applicable when investigations are undertaken in remote areas. These limitations and the requirement of portability necessitate relatively simple instrumentation which can be checked out and repaired in the field. The equipment must be capable of withstanding the rough handling involved in field work.

5. Water Depth Bio-acousticians do most of their field work with animal sounds in shallow areas, generally less than 75 ft deep. However, those who work

with marine mammals frequently operate over areas as deep as 6000 ft. Preferably, an all-round system should be suspended in order to meet the requirements of most investigators. A bottom-mounted system would be satisfactory only under special circumstances.

One of the reasons why bio-acousticians historically have concentrated on shallow water investigations is that their visual observations from television, the surface, or while diving with SCUBA, were necessarily limited to shallow areas. However, this requirement will probably change as deep submersibles and other habitats become more available to bio-acousticians. It would be advantageous to use hydrophones which operate at equivalent pressures from the surface to about 500 ft, although attempts to record biological signals have been undertaken from submersibles down to 6500 ft.[8,9]

6. Accuracy The degree of accuracy required of any locating system depends on the objectives of the investigation. To illustrate, a bio-acoustician, who wants to know if the signals he hears are from the whales he sees, requires much less accuracy in locating signals than one who is trying to locate the source of a given signal in the vicinity of a highly populated reef. Much more accuracy is required of a locating system that is used to determine the source level of a signal from a nearby animal than one that is used for more distant sources. Finally, it would be easier to locate a group of chorusing animals than it would be to locate an individual. Azimuth errors generally should be less than 3 deg.

7. Calibration Depending upon the area, species, or season, underwater bio-acoustic signals may mask other underwater signals. Bio-acoustic signals are often a predominant feature of the ambient noise,[10] because of their number, proximity to the hydrophone, or high source levels. Any attempt to evaluate bio-acoustic signal level at the source or the receiver will require a calibrated hydrophone system. It is unfortunate that few bio-acousticians have a calibrated system to determine absolute levels. A calibrated hydrophone system can either

be integrated into the locating system, or it may be separate.[11]

Employed Methods of Location

The mean of principal frequencies reported for 125 fish sounds was 911 Hz in a range of frequencies from 50 Hz to 5 kHz.[1] These data did not include a reported sound from a shark, Squalus acanthius, which had a principal frequency of 20.5 kHz.[12] Although a general indication of directionality was noted by W. A. Watkins, using a partially-shielded hydrophone in studies of cetacean sounds (personal communication), single transducers usually are not very directional at the principal frequencies reported for most sounds of underwater animals. Exceptions occur among the cetaceans whose echo-ranging clicks extend as high as 150 kHz.

A successful method for localizing bio-acoustic sources has been to use a hydrophone array of three or more sensors and calculations based upon time differences of sound arrivals between hydrophones. To illustrate, this technique[13] was used by the author in bio-acoustic investigations in the Bahamas. Others have used similar techniques, some of which were highly refined.[2,14,15,16] The use of a hydrophone array and arrival time differences worked quite well for the author, although the following limitations should be noted. In part, these limitations can be applied to the general concept of using large hydrophone arrays as a field method to locate bio-acoustic sources.

1. The system lacked portability imposed by long heavy cabling which was terminated in a shore-based laboratory with bulky instrumentation.

2. Hyperbolae describing regions of equal arrival time differences became nearly tangential outside the triangle of hydrophones. This considerably increased the magnitude of error in locating distant sources.

3. The instrumentation required substantial maintenance which demanded a relatively large work force when combined with the labor involved in determining

sound locations. The actual determinations, even when aided by a plotting board, were cumbersome and time-consuming; and they were not established until long after the event.

The general method described above is based upon the concept of triangulation wherein location depends on the solution of three simultaneous equations.

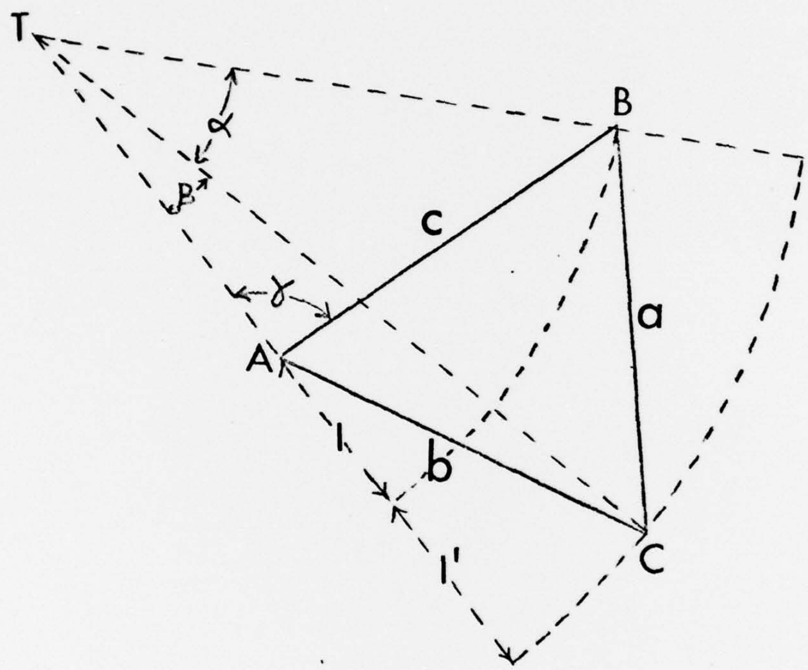


Figure 1

Given: hydrophone locations A,B,C; hydrophone separations a,b,c; distance TA (range from nearest hydrophone A to source T = x), l (arrival time difference between hydrophones A and B converted to distance), l' (arrival time difference between hydrophones B and C converted to distance); angles α, β, γ.

Find: distance TA and angle γ. Based on the law of cosines, the three equations are:

$$a^2 = (x + l)^2 + (x + l + l')^2 - 2(x + l)(x + l + l') \cos \alpha$$

$$b^2 = (x + l + l')^2 + x^2 - 2x(x + l + l') \cos \beta$$

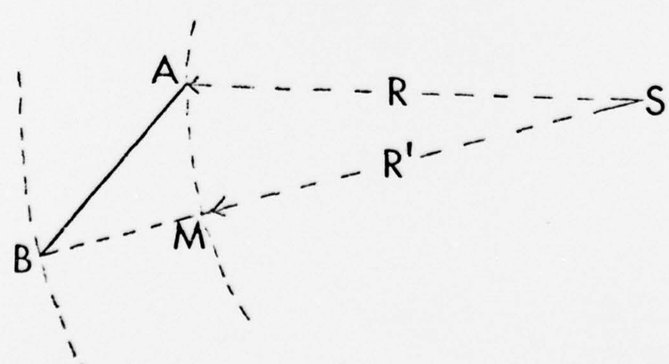
$$c^2 = (x + l)^2 + x^2 - 2x(x + l) \cos (\alpha + \beta)$$

These equations are generally solved simultaneously with a computer; otherwise, the solution is too cumbersome.

Location by triangulation may also be determined on a plotting board by finding the intersection of two hyperbolae, each of which represents a region of equal arrival time difference between two of the hydrophones in a triangular array. Interpolations are made between hyperbolic guides already drawn on the plotting board.

A two-hydrophone system was used for determining source level and localizing the sounds of gray whales, Eschrichtius glaucus (= gibbosus), during recent investigations off San Diego, California.[17] This method required absolute received sound pressure levels of a signal at each of the two hydrophone locations and the sound arrival time difference between hydrophones. Even with the assumption that the source is in the same plane as the hydrophones, ie, on the bottom, the two-hydrophone system offers 180-deg ambiguity unless there are extenuating environmental circumstances,[17] such as a location so near shore that all sources are known to be seaward.

The basic equation used to derive the two-hydrophone method was modified from that given by Johnson et al.[18] The modified equation states that a signal which has traveled less than 10 nautical miles experiences a pressure loss (Δ dB) equivalent to $20 \log_{10} R$, where R is the distance from the source to the hydrophone in yds.



Given: hydrophones A,B; sound source location S; sound pressure level at A = LA; sound pressure level at B = LB; sound pressure level at the source = LS; LA - LB = Δ dB; sound arrival time difference between A and B = Δt; distance from A to S in yds = R = R' = MS; distance between B and M in yds = Δt(1600), where 1600 = sound velocity in yds/sec.

Find: S, assuming spherical apreading loss, negligible attenuation, and single plane.

$$LA = LS - 20 \log_{10} R$$

$$LB = LS - 20 \log_{10} (R' + \Delta t\ 1600)$$

simultaneous solution yields

$$R = \frac{\Delta t\ 1600}{\left[10^{\frac{\Delta dB}{20}}\right] - 1}$$

An improved three-hydrophone system was considered. The improved system (Fig. 3) included a small (16-bit) digital computer to process acoustic data, locate the signal source, and determine the sound pressure level of the source. Three non-colinear hydrophones accurately placed on the bottom would yield three second order equations which could be solved simultaneously on line to determine the source location. Their solution is subject to serious errors from variable parameters in the physical environment which affect sound velocity. An error analysis was accomplished by varying the parameters by as little as 1 percent. These variations produced errors in location as much as several hundred percent, and in some cases there was no real solution. Such a system would require a very accurate survey in the area of investigation. A cross correlation technique would involve a thorough understanding of local acoustic propagation including speed and multi-paths as a function of time and space. It was concluded that such an improved system would not be feasible in the present application. The most apparent objections include time, prohibitive costs, lack of portability, and considerable

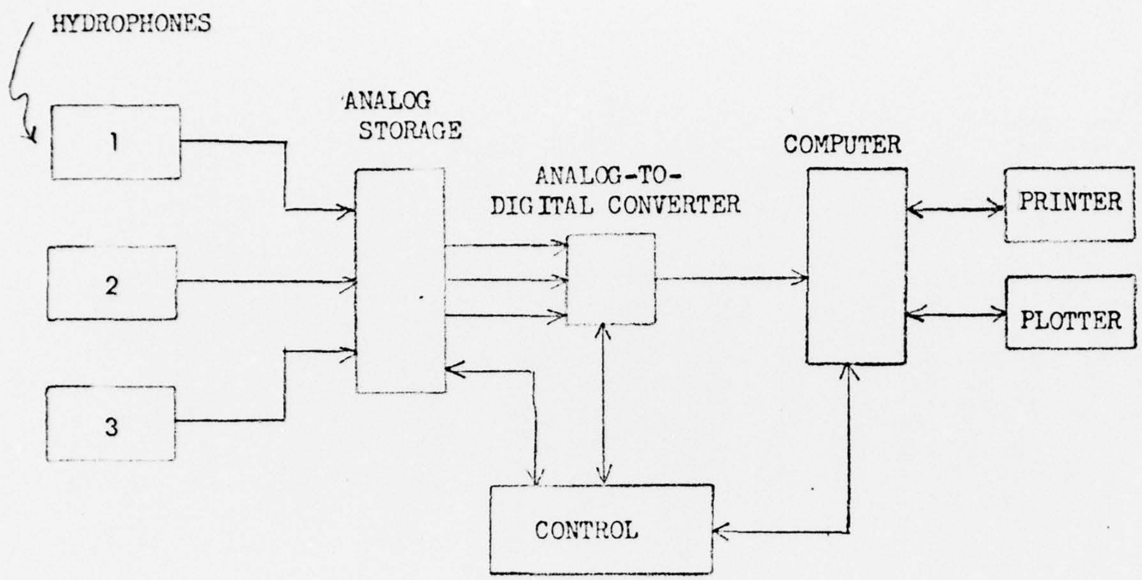


Figure 3. Block diagram of an automatic system for locating underwater signals.

maintenance. The same can be said for any of the larger arrays designed for other purposes.

Shaver *et al.* used a hydrophone system for tracking the movements of sea lions, *Zalophus californianus*, from their phonations in a tank.[19] Shaver's system of location, described in detail, was based upon the relative time of arrival of the signal at four hydrophones in a three-dimensional array. Compared with the previously described planar arrays, the added dimension made it possible to determine the depth of the sea lion, in addition to its horizontal location. Large hydrophone arrays have been used to estimate the depth of apparent biological sound sources in the natural environment.[2,15,20] None of the three-dimensional array methods which have been used appear to meet the present requirements for reasons applied in the preceding discussions of planar arrays. However, W. E. Schevill and W. A. Watkins are contemplating a small three-dimensional, suspended array for use from a ship (personal communication). They propose to trail a surface hydrophone astern of the ship, send a surface hydrophone out to each side, and lower a fourth hydrophone below the ship to obtain depth information.

A notable advancement in the design of hydrophones shows considerable promise for the present needs to locate underwater biological signals. CBS Laboratories, a Division of the Columbia Broadcasting System, Inc., has developed a moving-coil, bi-gradient hydrophone, which is reported to have an accuracy in establishing the exact null of an incoming signal to about 1 deg.[21] Frequency response of this hydrophone is relatively constant from 20 Hz to 500 Hz. Its sensitivity is about -120 dB re 1v/dyn/cm^2. The bi-gradient hydrophone responds to differences in pressure between that part of the matrix element facing the impinging pressure wave and its opposing side. However, effective use of this type of hydrophone to locate bio-acoustic sources would require higher sensitivity and higher frequency response. CBS was made aware of the problems in locating bio-acoustic sources, and they volunteered to re-examine the capabilities of the bi-gradient hydrophone. Consequently, a new type is being developed without commitment, out of sheer interest in our requirements (Dr. B. B. Bauer, personal communication).

Perkins has reported the installation of a directional hydrophone and baffle assembly aboard the research vessel Trident.[22] Despite high self noise components from the ship, he reported that the hydrophone system operated surprisingly well, but no details were given concerning its directional performance.

Man's ability for directional hearing in air depends upon temporal and intensity differences between arrivals of an acoustic signal at each of his ears. The directional aural sensations which result are often called the binaural effect. Humans have excellent abilities for processing acoustic signals, especially the recognition of signals apart from noise and the ability to concentrate upon a desirable signal. All of these attributes emphasize the utility of a binaural listening system for detecting the directivity of a propagated underwater signal.

A binaural listening system was used during World War I for determining the azimuth of underwater signal sources.[23] It consisted of two electroacoustic receivers separated in water at least by a distance equivalent to the effective separation of man's ears in air. This distance in water is approximately 40 in. A simple acoustic delay line consisting of tubes was inserted between the hydrophone and a binaural headset. By altering the distance of the air paths through the tubing, the listener could adjust the time of the separate arrivals to bring them into phase and determine the approximate bearing of the signal source.

The efficiency of a binaural system of localization is considerably improved if the receivers can be rotated. The angular resolution of humans in air is maximal when the source is out between the two ears and minimal when the source is out on the same axis as the two ears. It was found that resolution is best between 250 and 1000 Hz; and that localization up to 1400 Hz primarily depends on interaural temporal differences, while intensity differences are more important in higher frequencies.[24]

In an early paper, Eady and Brady evaluated binaural localization and detection of submarine noise using two hydrophones separated by various distances.[25] The observers rotated the underwater system, or they provided electrical delays, to center the acoustic image inside the listener's head. The average of bearing errors with a 40-in. separation was about 3 deg. The error decreased with increasing hydrophone separation to 0.5 deg at 240 in. Detection thresholds were slightly improved over those of a single channel system, but only by about 2 dB.

Brady and Klumpp[26] used two hydrophone pairs with 20-ft separation to eliminate front-back ambiguity. They concluded that the binaural system offered a simple and reliable means of obtaining accurate sound source bearings in the field. They confirmed the earlier finding that binaural listening did not offer a great detection advantage over a single hydrophone system.

A binaural listening system was installed aboard the Sea-see to obtain an approximate bearing to bio-acoustic sources (W.E. Evans, personal communication). One hydrophone is located on each side of a transparent observation sphere which is suspended between the two hulls of a catamaran. This listening system was said to be generally satisfactory on a left-right basis, although its directionality had not been critically evaluated. Sea-see was recently built for NUWC, primarily to observe cetaceans and other marine organisms off southern California.

A unique underwater binaural listening system, incorporating a scaled-up imitation of the human pinna, has been developed by Listening Inc. under contract with NOTS, China Lake.[27] The system uses stainless steel, 11-in. "ears" which reportedly were used to determine the location of an underwater acoustic source in real time to $\pm$ 8 deg. This company has also reported that the system can be used to determine azimuth, elevation, and range.

In the summer of 1961, the present author rigged an "oyster" hydrophone at each end of a 3.5-ft pole which could be rotated horizontally. A pair of preamplifiers, a binaural headset, and a simple pointer completed the system which was used off a dock at the Institute of Marine Science, University of Miami. It was possible with this simple apparatus to determine the approximate bearing to soniferous toadfish, Opsanus tau, if their signals were repeated a few times. We have recently assembled a similar device which has circular, air-cell baffles and reflecting plates to increase the intensity difference effect and to increase the signal-to-noise ratio by nearly combining the direct with the reflected arrival. A decrease in received ambient noise was accomplished by adding a pair of matched variable filters. In its present form, this device was given only a cursory evaluation, but it appears promising. It is planned to include a two-way, gimbeled mounting bracket for increased stability in the water (Fig. 4). The mounting will include a pelorus. A calibrated hydrophone system, a two-channel tape recorder, and a battery-operated, split screen storage oscilloscope can be added to increase the overall capability.

Dr. Charles M. Breder, Jr successfully used a binaural listening device in the presence of groups and individuals of swimming catfish, Galeichthys felis, at Sarasota, Florida (personal communication). Dr. Breder indicated that his "audiogoniometer" utilized changes in intensity differences as the unit was rotated below, through, and above the azimuth of a concentrated sound source field. By taking bearings from two locations, he was able to calculate the actual position of the sound source. His system will be described in a forthcoming publication of the American Museum of Natural History.

Bauer and Torick[28] used a binaural conversion network to provide phase and intensity differences between each side of a bone-conducting, underwater headset. In a related experiment,[28] they also preserved directionality underwater when topside observers listened through earphones which had a special cross coupling network on the output of two small hydrophones separated underwater by just 4 in. The hydrophones were connected with a symmetrical phase-shift network. These

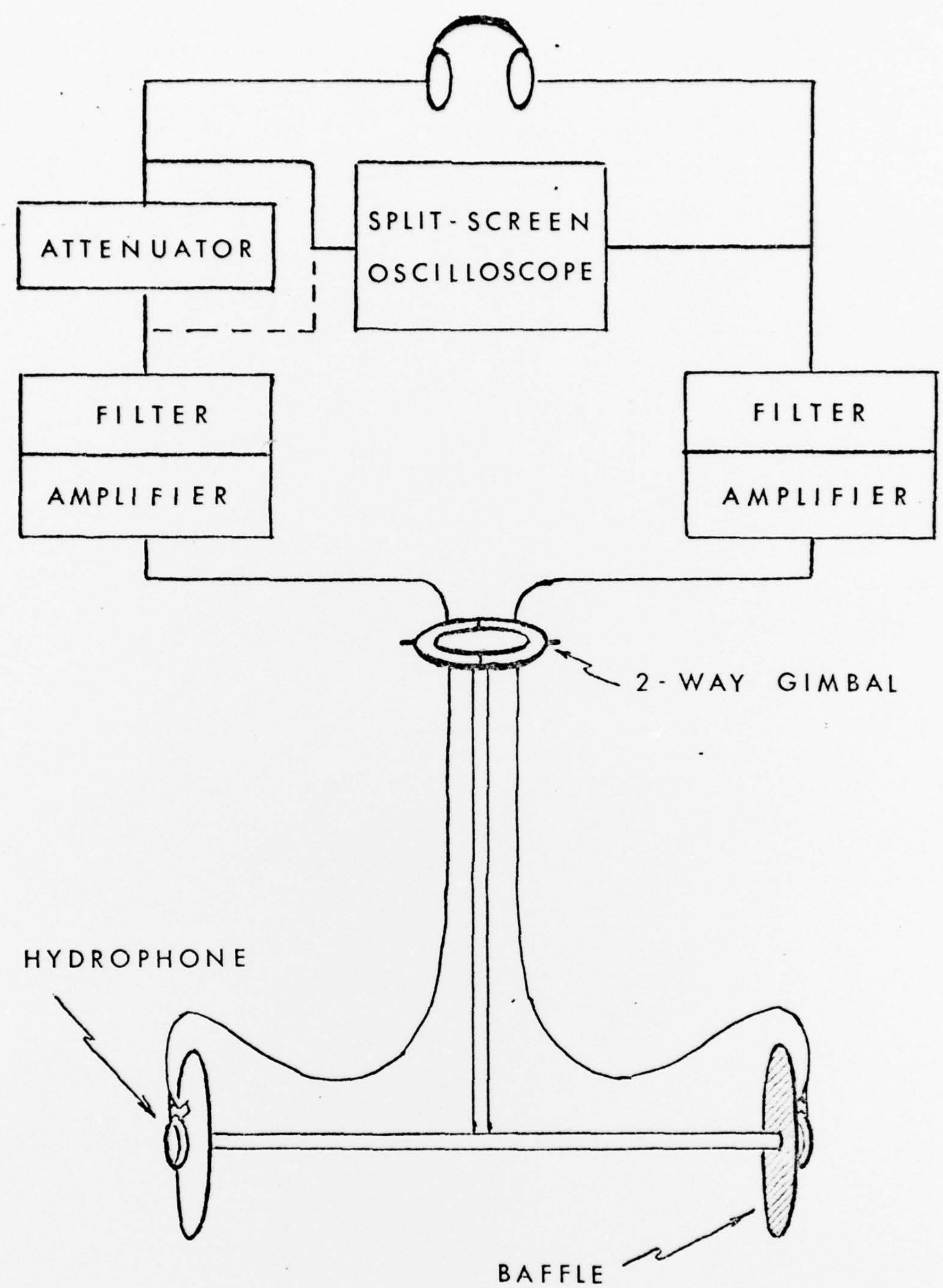


Figure 4. Block diagram of simplified, underwater listening device in use at NUWC.

workers are presently evaluating these techniques in the light of our requirements for locating biological signals.

Conclusions and Recommendations

The techniques for locating underwater signals fall into two general categories. One utilizes some kind of instrumental signal processing followed by computation. The other receives underwater signals in such a way as to use man's naturally-endowed faculties for hearing in air. In view of the requirements already set forth in this report, the latter technique of listening in real time appears to be most satisfactory for the following reasons.

1. Binaural listening devices, even when provided with delay circuitry, can be relatively inexpensive, simple to operate, easy to maintain, and portable enough to use from small boats.

2. Locations are made in situ, providing the investigator with immediate knowledge to pursue his objectives at the site.

3. Binaural listening devices for location make use of man's excellent abilities to discriminate against noise and to recognize a particular signal of interest under conditions of low signal-to-noise ratio. To the author's knowledge, there has been no successful attempt to synthesize a technique of recognizing the existing variety of marine animal sounds. As received, the same basic category of animal sound will usually have many different forms resulting from different physical and behavioral conditions. These forms vary as a function of time, frequency, and amplitude. It would be very difficult to generalize these forms with an instrumental recognizer; and, in all probability, the decision would ultimately lie with the investigator. Moreover, in many instances, the field investigator will be encountering a previously-unknown signal.

4. Human perception is less apt to be misled by interfering reflections and multi-paths of the incoming signal (precedence effect), compared with the problems

inherent with instrumental processing. As previously noted, these problems may cause vast errors in estimating the location of a signal source by instrumental means.

5. Hydrophone-preamplifiers that are suitable for a binaural locator are commercially available. The same applies to a calibration system, bandpass filters, magnetic tape recorder, headset, balance control, and oscilloscope. Bracketing, mounting, and baffle design would require further development; and the prototype would have to be evaluated.

Despite the advantages of a binaural method of underwater localization, it has limitations which should be pointed out. This method will not yield the source range from a single location of the hydrophones. Range can be determined with two setups simultaneously operated by different observers, or by changing one's location in hope that the source will remain in the same general area and that it will repeat its signal. These independent estimates of azimuth should also resolve any front-back ambiguity. In practice, a binaural method for localizing underwater signals, at best, will be no more accurate than the same method used for locating airborne sounds. Both are frequency dependent and both utilize interaural temporal and intensity sensations. The binaural method could be used for estimating depth of the source by turning the system to operate in the vertical plane. Depth also may be determined with a vertical array; or, if horizontal position is also required, a three-dimensional array will be needed.

The concept of binaural listening to locate underwater bio-acoustic signals is recommended in hope that a satisfactory instrument will soon be available. However, a suitable technique is not necessarily limited to binaural listening. Further development of bi-gradient hydrophones is also very encouraging. A simple modification of the rotatable, two-hydrophone system is the combination of the two channels out of phase to produce a null system. This can give quite precise localization of steady state, or frequently recurring signals. It is significant that the lack of directional capabilities has seriously limited our knowledge of sound production by underwater animals, a discipline of increasing importance to passive sonar. The resulting disadvantage to field biologists has been costly in terms of time, funds, and, in some cases, inaccurate information. The necessary technology is available for a practical solution, and it should be applied.

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