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Studies on Continuous Transmission Frequency Modulated Sonar

FRANK J. HESTER, Editor

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Sonar Target Classification Experiments with a Continuous-Transmission Doppler Sonar

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ABSTRACT

A continuous-transmission sonar with very fine echo frequency discrimination was designed and constructed to study Doppler effects caused by the motion of fish as they relate to fish size and swimming characteristics. Although the equipment performed as theory predicted, difficulties with sea noise and trouble in maintaining contact with fish schools showed that commercial application of this approach is unsuitable without considerable additional development work. These problems and some results are discussed, and notes on target-strength measurements of several species of fishes are included in this report.

INTRODUCTION

In 1961 the Inter-American Tropical Tuna Commission recognized that the stock of yellowfin tuna in the eastern tropical Pacific was in danger of being overfished and proposed a catch quota to conserve the resource. This quota could be increased if fishing for small yellowfin tuna (fish less than 20 to 25 pounds [10 kg.]) could be controlled (Inter-American Tropical Tuna Commission, 1960). It is difficult however to determine the size of the fish before it is caught, and the attempt has never been made. In addition, it is of value to the fishermen to know approximately the size of the fish before setting their nets. This information decreases the chance of catching fish so small that they "gill" in the net meshes.

Recognizing the economic and management benefits to be gained from determining the size of a fish before it is caught, the Tuna Resources Laboratory of the Bureau of Commercial Fisheries began a study to develop a shipboard sonar that could locate and classify fish schools. This study began in 1963 and ended in 1968. The work was done chiefly through contracts with industry. Straza Industries,[1] now Ametek/Straza, was the prime contractor, and the bulk of this report is taken from their statements of progress. For that reason Frank Hester has preferred to be listed as Editor.

[1] Use of a trade name does not imply endorsement by the Bureau of Commercial Fisheries.

FISH ECHOES IN RELATION TO SONAR DETECTION

One of the first items of concern was what general categories could be used to classify fish. Table 1 gives the general categories for the various means that might be used to detect and identify various single fish specimens. This table does not represent all of the possible means but does include the obvious techniques that might be used for the detection and identification of fish. The visual observations column of the table includes movement in two categories: velocity and body motion, i.e. with respect to the medium and with respect to the body of the fish. The acoustic observations column is included only to show that many categories of noise may be produced in the sea from animal life. These sounds can interfere with acoustic observations, even with ultrasonic equipment. In the frequency range 50 to 60 kHz (kilo Hertz); this problem is not serious but sea organisms can produce certain noises that interfere with measurements.

Table 1 indicates three separate categories under the active acoustic heading. The first of these categories, the static echo return or target strength of a fish, were measured on a limited number of specimens at the U.S. NTCF (Navy Transducer Calibration Facility) at Sweetwater Dam, San Diego, Calif., to determine the target strength and directivity patterns from various specimens. This work, which was necessary for specifying the design

Table 1.--Methods of identifying single fish by visual and acoustic observations.

Visual observations	Acoustic observations			
	Passive acoustic	Active acoustic		
		Static echo return[1]	Dynamic echo return	
			Motion in the medium[2]	Body motion[3]
Direct observations				
a. color	a. swimming noise			
b. shape	b. vocal sounds	a. function of aspect		
c. movement	c. strumming, beating, or scratching noises produced internal to fish			
1. velocity		b. function of depth	a. function of aspect	a. body flexure
				(1) amplitude
2. body motion		c. with or without air bladder	b. function of depth	(2) frequency
d. light output	d. noise produced by contact with external objects			
e. size		d. size	c. velocity/medium	b. propulsion scheme
		e. shape		
f. location (geographic, depth)			d. course	
		f. body material (surface)	e. acceleration	
Indirect observation (wake, surface activity, etc.)		g. composition		

[1] a, c, d, e, f, g, determine target strength and directivity.
[2] c, d, e, determine Doppler motion.
[3] a, determine Doppler motion.

of the fish-detecting sonar, is discussed by Volberg.[2]

Acoustic information that can be used to classify fish targets is listed in the next two columns. A subheading, called dynamic echo return, is broken into two columns: one, motion in the medium, and the other, body motion. The motion in the medium column is best determined by using a CTFM sonar (described below) in the scanning mode that paints a picture of the range and bearing of the specimen at any instant. For normal sonar work the Doppler effect produced by the velocity of the fish is small enough to be neglected for any ranges of interest. The normal CTFM sonar cannot resolve the body motion column outlined under the motion of the fish, with coordinates referenced to the body of the fish. It is therefore necessary to use a Doppler technique wherein the body of the fish produces a frequency change proportional to the velocity of portions of the body of the fish. Unfortunately, the body motion of the fish cannot be removed from the displacement motion in the medium. That is, the velocity of the fish in the medium produces an additional Doppler frequency term which cannot be separated from the Doppler effect produced by body flexure. The items that determine Doppler motion can be found at the bottom of table 1. The steps to be followed in studying Doppler as a means of classifying fish targets follow from the table: (1) determine the target strengths of the subject fish species; (2) design a CTFM sonar system to these standards; (3) obtain Doppler information from fish body motions; and (4) examine the Doppler data for characteristics that can be used for target classification.

[2] H. W. Volberg. 1970. Acoustic target strength of several species of fish. This publication, pp. 21-26.

OPERATING PRINCIPLES OF A CTFM SONAR FOR FISHERY WORK

The best known sonar, the pulsed sonar, gets target range information from the time elapsing between pulse transmission and echo reception. The CTFM sonar has the advantage of transmitting and receiving continuously and simultaneously and gets range information by comparing the frequencies of the transmitted and echo frequencies. Both get target bearing information by using directional receiver hydrophones.

In the simplified block diagram of a CTFM sonar (fig. 1) the transmitted frequency is modulated in a sawtooth manner between f_2 and f_1 shown in figure 2 by the solid lines. For illustrative purposes, f_2 can be 45 kHz and f_1 can be 59 kHz. An echo returning a time Δ_t later is received by the hydrophone. The frequency Δ_f of the beat note between the frequency f_t, being transmitted, and the frequency f_r, of

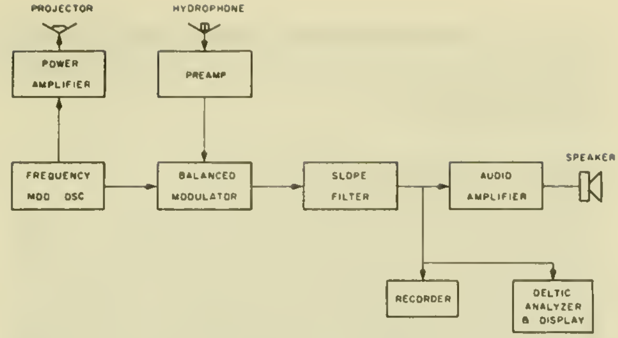

Figure 1.--Block diagram of fishery CTFM sonar system.

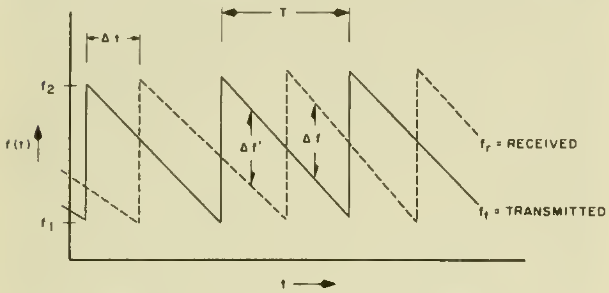

Figure 2.--CTFM frequency and time.

the echo, is $\Delta_t\, df/dt = \Delta_f$, except for the period of time Δ_t immediately after the recycle of the sawtooth frequency variation which is discussed later. This expression also neglects Doppler effects.

The beat note Δ_f is obtained at the output of the balanced modulator and made available for aural observation by the operator as well as fed to a DELTIC (Delay Line Time Compression) frequency analyzer (discussed below) for visual observation. The output of the frequency analyzer is displayed on a CRT (Cathode Ray Tube) as an "A" scan (i.e., target strength versus range) frequency versus time, or a combination of both. This analyzer performs the operation of a group of bandpass filters with adjacent filter characteristics intersecting at the 3 db points. The effective filter bandwidth $\Delta_F \cong 40$ Hz and represents a typical number of filters of 100 running from the lowest center frequency of 500 Hz to the maximum range Δ_f for this system of 4,500 Hz. A sloping response is included in the sonar receiver to accentuate the high-frequency beat notes, since the beat note frequency is proportional to range for the type of transmission shown in figure 2. The attenuation due to range (spreading loss) follows the inverse fourth power law (R^{-4}).

Controlling Relationships

If R_{max} is the maximum range and F_{max} is the effective center frequency of the highest frequency capability of the DELTIC filter that corresponds to this range, then the slope of the frequency-time plot in figure 2 is given by,

$$\frac{df_t}{dt} = -\frac{F_{max}c}{2R_{max}}$$

where c is the propagation velocity of sound in water and f_t is the projected frequency.

Practical limits exist for the generation of sawtooth frequency functions, and therefore the frequency sweep period T and end point frequencies f_1 and f_2 must be considered as design limitations in any CTFM sonar. The time dependence of f_t can be shown to be,

$$f_t = f_2 - \frac{F_{max}c}{2R_{max}}\, t, \quad 0 \leq t \leq T$$

or, written in terms of the frequency sweep period, T,

$$T = \frac{2(f_1 - f_2)}{c\,F_{max}}\, R_{max}.$$

The minimum range, R_{min}, which is now determined by previous parameters, is expressed by,

$$R_{min} = \frac{F_{min}\; R_{max}}{F_{max}}$$

where F_{min} is the center frequency of the lowest effective frequency bandpass filter of the DELTIC analyzer. Table 2 lists values used for the fishery sonar in target analysis.

Doppler System in Block Diagram

According to classical physics, any sound source that moves with respect to the observer changes pitch as its velocity changes with respect to the observer. The same is true in a

Table 2.--Sonar parameters

Typical parameters for a fishery sonar
f_2 = 45 kHz
f_1 = 59 kHz
T = 50 msec.
R_{max} = 40 ft. (12.2 m.)
R_{min} = 4 ft. (1.2 m.)
Range to target 30 ft. (9.1 m.)--typical

sonar system, if the sound is reflected from a moving object and the receiver is stationary. In table 1, column 4, items c, d, and e determine the character of a Doppler signal returned from a fish moving with respect to the medium. These parameters are concerned with the fish's position and velocity components with respect to the hydrophone and projector. Superimposed on the total or average velocity of the body of the fish would be the minute Doppler changes produced by body flexure. These body flexures are necessary for propulsion of the fish or are a result of the propulsion or respiratory mechanisms. Item a in column 5 of the table lists this characteristic. The relation of tail beat to velocity is one of the factors that influence Doppler effects.

Figure 3 shows the block diagram for the Doppler system constructed as a part of this program. Many of the parameters for this Doppler system were adjusted to be compatible with the hydrophone projector and receiver of the fishery sonar. The sensitivity of such a system is the same as the sensitivity of the sonar itself. One difference is that range determination can no longer be made. Since the system is only a velocity-measuring device it is valuable only in determining whether or not motion with sufficient target strength is generated. Because only a portion of the fish produces Doppler effects due to the swimming motion, the information content is weaker than that in a normal sonar return. The theoretical voltages present in the Doppler receiver are noted in figure 3.

Target Strengths of Single Fish

From the work done at the NTCF, Straza determined that the target strength on a beam aspect for individual fish was about -25 db, on the average. Some of the specimens tested indicated target strengths as low as -34 db. Since the target strength for a fish without a gas bladder apparently is a function of the projected area of the fish, it is important that the fish be of reasonable size for the evaluation of the signal returns. In all the experiments the returns from the fish were large enough for the sonar to detect and give information on its range. The Doppler unit is concerned only with that fraction of the fish that is moving at the velocity that can best identify the motion of the species. The signal level for the Doppler unit is therefore less than the signal for the sonar. Enough information was gained in these tests to indicate that with larger fish the Doppler signal would be great enough to permit acquisition of Doppler data. Furthermore, an increased number of fishes, such as a school, would increase the signal-to-noise ratio of the system and permit rapid evaluation of the data.

VALUES OF SIGNAL LEVEL IN DOPPLER RECEIVER

SIG. IN 0.1 μv.	10 μv.	7.0 μv	0.39 v	0.079 v.
CROSS TALK 10 mv	1 v.	"0" BEAT 0.25 v.d.c.	——	——
MIX. INJ FEED THRU	——	300 μv.	——	100 mv.
GAIN/VOLTAGE db	+ 40 db	− 3 db	+ 95 db	− 14 db
TOTAL VOLTAGE GAIN A_{v1}	790,000			

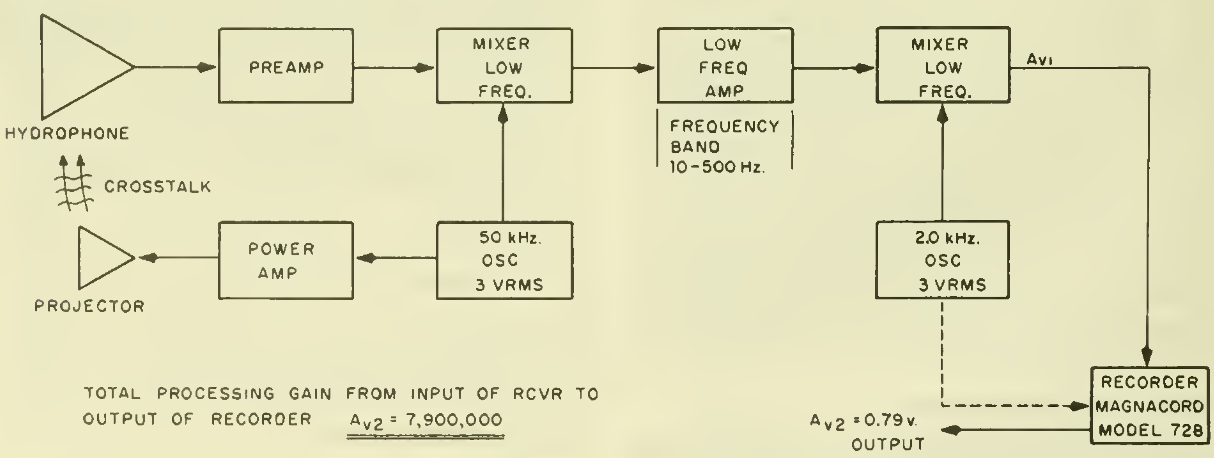

Figure 3.--Doppler sonar block diagram.

School Targets and Their Acoustic Properties

The theory applied here with regard to fish schools is very similar to the general approach used for measuring the scattering and absorption of sound in wakes. No dependence is placed on gas bladders within the fish, however, and the target characteristics for the individual fish targets are those obtained by both dynamic and static tests at the NTCF. For lack of additional information regarding the acoustic properties of the fish, the effective absorption cross section, σ_0, is assumed to be about equal to the scattering across section, σ, obtained from these tests.

The assumption is made that the fish school is dispersed so that the distance between neighboring fish is significant. The whole school contains many fish, and some of these fish will not be in the sound beam. Only those fish in the intersection of the sound beam and the school contribute to the acoustic effects. The total number of fish that are effective in producing an echo depends on the width of the school, the angle between the school and the axis of the sound beam, and the area of the sound beam that the school intercepts.

The calculations involving wide schools are different from those which involve narrow schools. In a sonic view of a narrow school, the relative total number of fish in the active reflective volume is small, so that the projected areas of individual fish overlap only rarely. When this condition is fulfilled the school is considered to be narrow. On the other hand, when there are so many fish that their projected areas usually overlap, the school is considered to be wide.

To obtain a useful approximation for the school target strength the beam pattern of the sonar set must be included in the calculation; involved is the area, A, of the sound beam intercepted by the school. The accurate calculation of A is complicated, and the values of many of the quantities entering into it are uncertain. Therefore, a very rough calculation will suffice for the present discussion. If the angular half-width of the sound beam is $\emptyset$ radians in a given plane, then the width of the beam at a range of R yards from the sonar will be 2 R $\emptyset$ yards.[3] If the school has a vertical dimension of Δ_D yards which is less than the vertical width of the beam at the school, an approximate expression for A is

$$2 R \emptyset \Delta_D$$

[3] Note: Because the contractors involved in this study habitually use the English system of measurement in sonar work this notation will be used throughout. The metric equivalent will be given in parentheses when appropriate.

The above expression may be substituted into the general target strength expression for the school, which is given as

$$T_s = 10 \log \left(\frac{N \sigma\ Aw}{4 \pi \cos \theta}\right),$$

where N = average number of fish in a unit volume of the school (1/yards^3),
σ = scattering cross section of one fish (yards^2) constant for angle θ,
A = 2 R $\emptyset \Delta_D$ (yards^2),
w = geometric width of the school (yards),
θ = angle between axis of sound beam and perpendicular to the axis of the school.

Introduction of the area expression into the above equation and separation of the expression into two terms give the resulting approximate target strength for the narrow school

$$T_s = 10 \log \left(\frac{N \sigma w \Delta_D}{4 \pi}\right) + 10 \log \left(\frac{2 R \theta}{\cos \theta}\right).$$

The first expression contains only the quantities characteristic of the school whereas the second involves quantities describing the position of the sonar and the bearing and width of the sonar beam. The first term in the expression can be referred to as the strength of the school and may be interpreted as the target strength of the school for 1 yard (0.9 m.) of the school.

In wide schools, the total number of fish in the active volume is so great that overlapping of the projected areas is extensive. If the foregoing equations were used to calculate the power removed from the sound beam, the end result would be that the school removed more power than was incident upon it. This obvious impossibility results from the neglect of the overlapping projected areas in the previous equations.

The overlapping can be accounted for by assuming that the fish nearest the source casts shadows on those farther away, removing power from the incident sound beam or in the returning echoes. A rough approximation for the foregoing considerations results in an equation for the target strength of the wide school.

$$T = 10 \log \left\{ \frac{A \sigma}{8 \pi \sigma_0} \left[1 - e^{-(2N\sigma_0 w / \cos \theta)} \right] \right\}$$

The foregoing expression is still somewhat rough in that smaller fish would not cast sharp shadows (depending upon the wavelength). Furthermore, second-degree scattering from one fish to another is ignored and only sound scattered once is considered.

The above equation can be used with the following assumptions: R = 1,600 yards,

σ = 0.04 yard^2, $\theta°$, 2ϕ = 0.1 radian horizontal by 0.2 radian vertical, Δ_D = 20 yards and N = 1/yard^3. By use of the foregoing, the target strength for the school appears to be about 19 db. This approach also considers the fact that the vertical dimension of the beam is wider than the depth of the school. Δ_D, thus the vertical dimension is 20 yards. Also, an incremental width, δw, of 16 yards is taken to agree with a typical CTFM sonar resolution. Checking this result with the summation of fish targets as determined from the target-strength work at NTCF we obtain a target strength in the order of 16 db. From this rough check and the above solution to the equation a typical school target strength of about 15 db appears to be a very conservative value, for the parameters selected.

To examine what the foregoing school target strength represents in terms of a CTFM sonar set of the same beam pattern as selected in the foregoing expressions, we can use the sonar equations as follows:

$2N_w$	= 40 log R + 2aR		
R	= 1600 yards		
a	= 10 db/kiloyard at 50 kHz		
2aR	= 20 X 1.6 = 32 db		
40 lob R	= 128 db		
$2N_w$	= 160 db	$2N_w$ =	160 db
Assume S	= 110 db	S =	110 db
DI	= 26 db for a 6° X 15° beam	DI =	26 db

Assume a recognition differential of 6 db $\quad R_D$ = 6 db

Next, for a 50 Hz analyzer filter of which 100 are used, the bandwidth contribution would be

B_w = 10 log 50 = 17 db $\quad B_w$ = 17 db

The sonar equation given below can now be used.

$$2N_w = S + T + DI - N - R_D - B_w$$

in which T = target strength

N = noise level per Hertz bandwidth.

By substituting tne foregoing values we obtain

T - N = 47 db

If the assumed school target strength of T = 15 db is used in N = T - 47, then N = 32 db/Hz. If the signal from the school is to be seen, the foregoing requires certain limitations on the noise such as maximum sea state of about six or a ship noise of about -35 db at the sonar operating frequency. This requirement represents a fairly quiet ship with a velocity of some 3 knots. If the calculations had been based on a range of 1,000 yards then the permissible ship noise would be about -20 db, which is about 5 to 8 knots for a ship. For the same performance parameters, but with a pulse system of equivalent bandwidth, the pulse system would suffer some 3 db disadvantage. In addition, the pulse system would be totally inadequate owing to the much slower rate of data caused by the roundtrip time between pulses.

FEASIBILITY STUDY

Target classification from theory to practice followed a series of phases. The first phase was to determine some likely values for the target strengths of fishes. This work was done at the NTCF (Volberg, 1970).[4] From these approximations it was possible to specify certain sonar design parameters necessary for the construction of a sonar capable of detecting single fish at ranges up to 100 m.

The second phase was to construct this sonar and use it in tank and field tests to measure sonar returns from fish and to record fish Doppler signals to find out the best way or processing them. If the results from this second phase were encouraging, the next phase would be to modify and package the sonar for shipboard use and to design and construct a suitable unit to process Doppler signals for the sonar.

For the second phase of the program, portions of the sonar system were gathered together and the system layout, system frequencies, sweep rates, beam widths, and other important parameters for the sonar were established. Whenever possible, off-the-shelf components were used. Early in this step we saw that working at close range with such a weak target would impose special problems upon the sonar. Particular emphasis was placed, therefore, on reducing the noise of the sonar receiver to the minimum threshold level dictated by thermal and ocean noise.

The sonar system that evolved from the effort had unique design and capability. Straza Industries at this time possessed a small test tank, 4 by 4 by 20 feet (1.2 by 1.2 by 6.1 m.), which was used to determine some of the water parameters of the sonar system. These tests yielded sufficient information to indicate that open-water, or tank tests, were necessary to evaluate properly the performance of the receiver. This work required a suitable test site to which the instrumentation and equipment could be transported for evaluation of the sonar equipment. Several sites were selected and used.

Lake Murray Equipment Tests

The first tests in a large body of water were intended to determine the smallest signal that the sonar receiver could resolve and to

[4] See footnote 2.

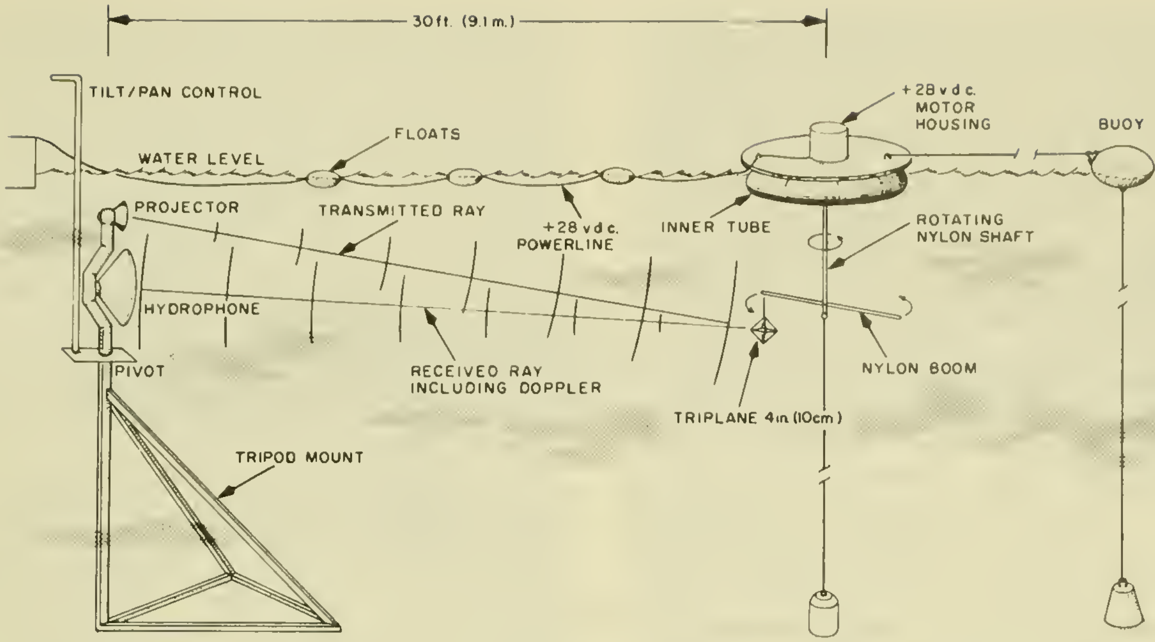

Figure 4.--Test arrangements at Lake Murray.

find the best method for removing weak target information from the recorded data. Although water tests had been made in the very small tank at Straza Industries, it was not possible to project sufficient radiated power into the water for proper evaluation of the operating performance of the equipment. A tank would not have been suitable for this series of tests because reverberations would influence the receiver performance. Lake Murray, a reservoir within 7 miles (11.3 km.) of Straza Industries, was made available for a test through the cooperation of the San Diego County Fish and Game Service. This enclosed body of water was free of manmade noise on 2 days of the week while closed to the public. Lake Murray seemed to meet the evaluation requirements. The equipment was transported to the site, and recordings were made of various inanimate objects.

To evaluate the performance of the equipment appropriately at Lake Murray required a target of a known signal strength. Such a target, a triplane 4 inches (10 cm.) on the side, was built. Equipment was built to support the triplane and also to permit it to rotate in a 4-foot (1.2 m.) circle (fig. 4).

The first returns from the small targets used in the Lake Murray tests indicated that the receiver was not performing with the required sensitivity. The receiver was therefore redesigned on the basis of the information gained in these tests. Actually, the receiver performed well but not to the required specifications. The receiver did respond marginally to small fish swimming near the transducers.

A second test at Lake Murray indicated that the receiver was performing with the desired sensitivity and could respond to extremely small targets. This finding, however, did not necessarily mean that the sonar equipment would perform well on fish in small contained bodies of water. After the second test the next step was use of the equipment on live fish of the desired dimensions and species that were to be studied in the program.

Swimming Pool Tests

Before tests were started with live fish in a large body of water, a series of tests were made to evaluate various enclosed sites. One test was carried out in a kidney-shaped swimming pool to evaluate the crosstalk or reverberation produced by the walls of the pool. The level of crosstalk was found literally to overwhelm the receiver. The reverberation level was so high that it nearly blotted out large signal returns produced by an 18-inch (46 cm.) square flat reflector of aluminum. It was impossible to detect the small triplanes that had been used in the Lake Murray tests. This first indication that the pool would produce substantial reflections from its walls was not totally unexpected, but the level of the reverberation was surprisingly high. Before a test site could be decided upon, it clearly was necessary to transport the equipment to the site and determine the reverberation level of the tank. Since this test had been in a kidney-shaped pool it was possible that a pool with a different shape might produce reverberation levels which did not prevent the detection of the fish. The best possible shape for the operation of the sonar would be a tank similar to the USNEL Transdec transducer test facility but this tank was not available. Therefore, the next possibility was a tank which would scatter the sound and prevent direct reflection from the walls into the hydrophone and sonar. The only shape that was available and could possibly perform this function was that of the circular holding tanks at Sea World, an oceanarium located on Mission Bay in San Diego.

Evaluation at Sea World

Permission was granted by M. Shedd, the Sea World Director, for an evaluation test to be made in one of the circular concrete holding tanks, 40 feet (12.2 m.) in diameter and 10 feet (3.0 m.) deep. We checked the holding tank for reverberation at all angles of incidence and depth of the transducer-projector array. The reverberation level was found to be exceedingly high and of such a character as to mask small targets completely. Using the tank for the evaluation of signal returns from fish was therefore impossible. This problem, even though learned early in the program, raised considerable difficulties because now it forced operation to an open-water environment. The problem of containing a fish at some point in the sonar beam in open-water tests is more difficult.

Mission Bay Yacht Club Pier

For open salt-water experiments a site was selected in Mission Bay, a shallow bay north of San Diego. A series of tests was made at the Mission Bay Yacht Club pier to evaluate the signal return from various materials that could be used for containment of fish specimens in open-water tests. Mission Bay was selected because during a normal week day the boat activity within a radius of 1 mile (1.6 km.) is very low. Tests could be suspended during the infrequent and brief passage of motor launches. The tests were made to determine the reflection capability or target strength of several materials. The materials tested included: 4-inch-mesh (10 cm.) nylon net; 1-3/8-inch-mesh (3.5 cm.) nylon net; and sheets of polyvinyl, 0.002-inch (0.05 mm.) and 0.007-inch (0.18 mm.) thick. In all tests, the net material gave signal reflections high enough to mask small targets viewed through the net. The sheets of polyvinyl material passed the test with only small reflected signals. Most of the reflections were due to clinging air bubbles, which give extremely strong sonar returns. A 4-foot (1.2 m.) diameter cylindrical, polyvinyl bag 15 feet (4.6 m.) long and suitable for operation in the water adjacent to the floating pier at the Mission Bay Yacht Club was constructed. This bag was perforated with several thousand 3/8-inch (9.5 mm.) diameter holes to allow oxygenated water to enter the bag during tests. A boom was constructed to hold the polyvinyl bag at the necessary distance from the pier. Figure 5 shows the top view of the test site and indicates the location and distances in the test on several fish specimens. The problem of obtaining test specimens was very difficult because the waters off and near San Diego had a red tide that repelled fish. Therefore, the polyvinyl enclosure was evaluated in a series of tests with fish that were not necessarily those of greatest interest in this program. The fish that were used did give sufficient information for the equipment and data-processing techniques to be further developed.

During the first of these tests a SCUBA diver observed the position of two fish--kelp bass (Paralabrax clathratus)--within the enclosure. The procedure was as follows: a specimen was placed in the enclosure; the enclosure was moved into the sonar beam by rotation of the boom at its pivot point; the diver entered the water, observed the fish's position, attitude, and behavior; the diver left the water. A data run was taken; the diver reentered the water and observed the location of the fish; it was assumed that the behavior was reasonably consistent during the two observations. The actual location of the fish within the enclosure during a test was never determined owing to the poor visibility under the red tide condition. The fish tended to go directly to the bottom of the bag; when they did they were no longer in the major beam of the sonar. In subsequent tests a 6-foot-diameter (1.8 m.) bag was constructed with a "false" bottom heat-sealed into the walls of the polyvinyl cylinder. This arrangement limited the range of the fish in the bag to about 8 feet (2.4 m.) and ensured retention of the fish in the major lobe of the sonar beam.

The results of the fish tests with the diver indicated a problem in reverberation, not with the walls of the enclosure as had been determined in the previous tests, but between the surface and bottom reflections in the shallow water, which was 15 feet (4.6 m.) deep at high tide. This problem manifests itself in the output of the equipment as multiple returns from a single target. The tape output for example showed two strong returns from one SCUBA diver. Rather than move the operation to deep water, we attempted to determine the signature of fish within the enclosure in the presence of the surface and bottom reflections. Unfortunately, the returns were confused to such a degree that suitable presentation of the motion of the fish was impossible. The tape recordings carried indications of fish motion, but certainty as to the behavior of the specimen in the sonar was not possible. Further tests of the CTFM sonar were abandoned and work was

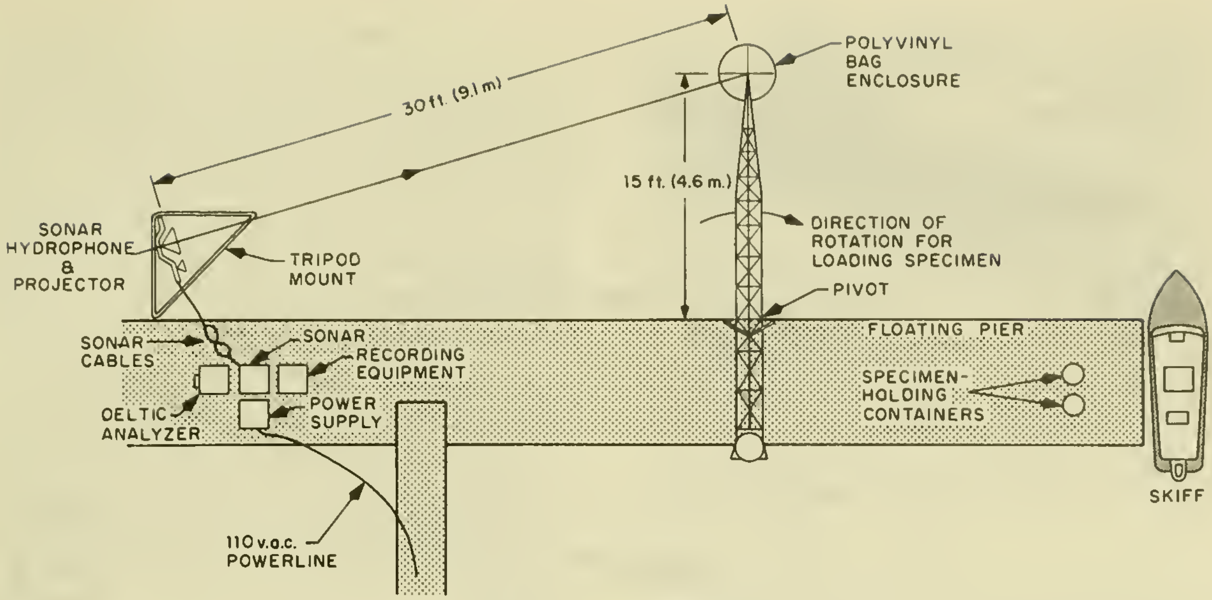

Figure 5.--Top view of test site Mission Bay Yacht Club pier.

limited to the technique of presenting information on the Doppler effect of the fish, a process by which the signal return could be removed in the presence of the surface and bottom reflections.

Preliminary tests in air and pools of the Doppler portion of the sonar equipment had been made at the Straza sonar laboratory. The operation was found to be extremely good; the low-frequency presentation which was possible with the Doppler technique went to at least 2 Hz, and was capable of operation in the 10th's of Hz of Doppler information. A live, 76-cm. yellowtail (Seriola dorsalis) was purchased from one of the commercial fishing boats and brought to the Mission Bay Yacht Club pier. This fish was placed in the new 6-foot-diameter (1.8 m.) bag. During this test, the Doppler unit was used to determine the feasibility of operation in the shallow water. The tape recordings made at this test were observed visually on a Tektronix oscilloscope and aurally. The information that a fish was in the enclosure showed up as differences in the appearance of the waveforms and changes in pitch of the aural signals.

Sophisticated techniques for data reduction were required to extract from the taped information the signals from the fish and those from the surface motion of the water. This point is covered in a separate section--Data Evaluation and Reduction. The tests at the Mission Bay Yacht Club pier were concluded and preparations for a deep, open-water test were begun. Deep water was required because ripples on the surface of the water and the reflection from surface and bottom caused too great problems. The intent was to make a test in water deeper than 50 feet (15.2 m.) and thus eliminate the problem of surface and bottom return and at the same time permit the operation of both the CTFM sonar and the Doppler equipment.

Catalina Tests

A test site at Catalina Island was selected for several reasons: (1) clarity of the water that would permit films to be made of the fish during the test; (2) availability of a large number of fish in the size range of interest in the area; (3) depth of the water sufficiently great to eliminate most of the problems from surface and bottom reflections.

Both the CTFM and Doppler sonar equipment were taken to Catalina. These tests had many operational difficulties owing to the operation of breadboard equipment on the 45-foot (13.7 m.) charter boat Duchess which was used at Catalina Island (and engineer's mal de mer). Three SCUBA divers set up the equipment on the bottom. The arrangement of the equipment and the checkout and operation went smoothly--all systems checked perfectly and on the second day the television equipment offered by the U.S. Naval Ordnance Test Station, Pasadena, and all the sonar equipment were functioning perfectly. During the second day the divers obtained abalone and placed them on the chumming platforms so that fish would accumulate in the beam of the sonar as depicted in figure 6. The sonar returns were recorded on one track of a Magnecord tape recorder. Data runs were taken for 1-1/2 days with both the CTFM sonar and the Doppler sonar equipment. A series of 14 film

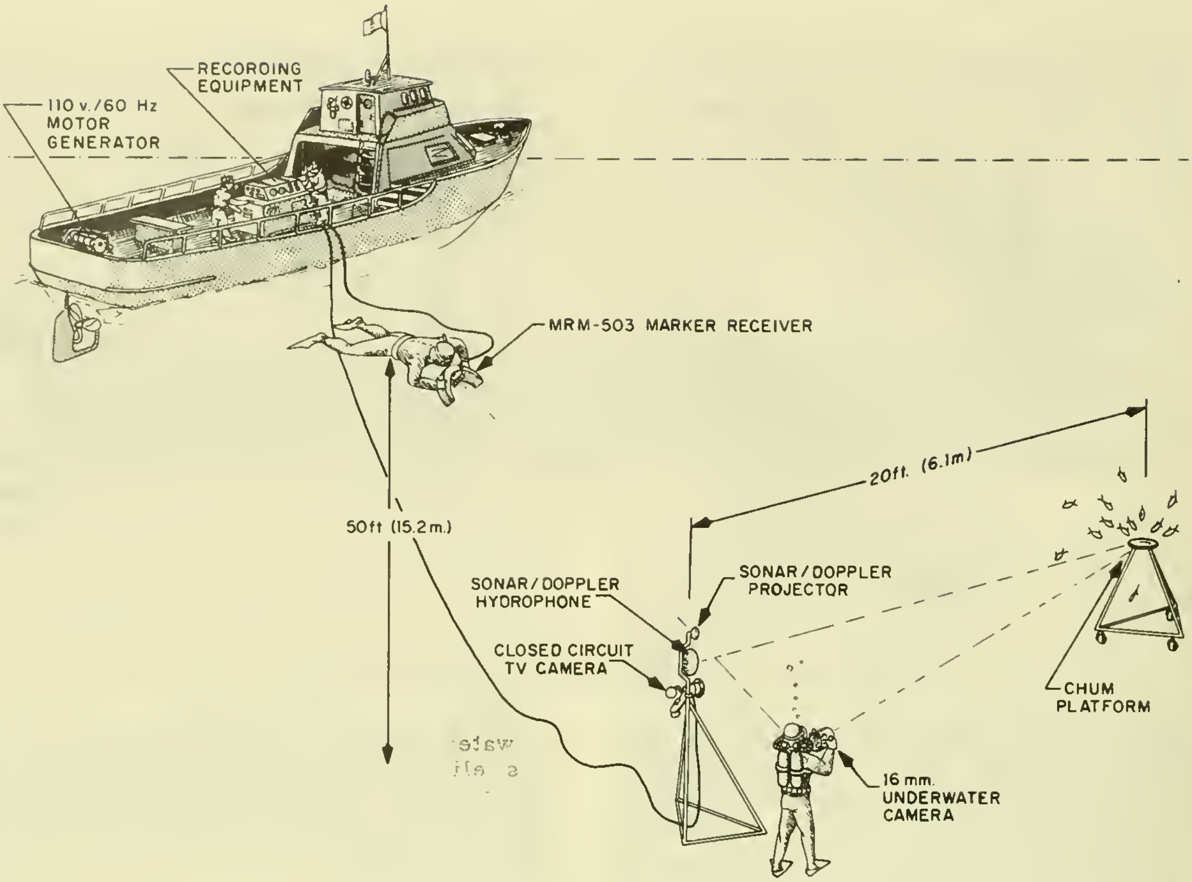

Figure 6.--Test arrangements at Catalina Island.

takes of 10 to 15 seconds duration were made through the use of a diver-operated 16-mm. Bell and Howell camera. Attempts at photographing the television monitor screen were unsuccessful owing to lack of synchronization between the frame rate of the monitor. To provide time synchronization between the tape recordings and the motion picture film, a crude but effective technique was employed: a Straza Industries MRM-503 Marker Receiver was used for listening to the noise the cameraman made when he tapped a screwdriver against the face plate of the camera. The motion picture shows clearly the screwdriver striking the face plate of the camera housing, and the resulting click was recorded on the second track of the tape recorder. The distance from the diver cameraman to the hydrophone was 60 feet (18.3 m.). The time lag between the arrival of the pulse and the occurrence of the event was therefore constant and less than one camera frame (24 frames/second). The conclusions from the Catalina tests are given below. After the processed 16-mm. film from the Catalina tests was viewed, the various fish species of interest were identified as California sheephead (Pimelometopon pulchrum), kelp bass (Paralabrax clathratus), senorita (Oxyjulis californica), and halfmoon (Medialuna californiensis).

FEASIBILITY TESTS OF METHODS OF DATA EVALUATION AND REDUCTION

The following paragraphs delineate the various techniques that were used to extract the data from the tape-recorded tests from Mission Bay and Catalina Island. The associated block diagrams and setups of each method are included. Several techniques were used in an effort to find the best way of removing the information. In all of the presentations except one, that of the DELTIC (Delay Line Time Compression), the time that was necessary for the evaluation is indicated. The reason for this exception is that DELTIC operates in real time when processing information. At this stage in the program, however, the DELTIC had to be used in conjunction with some other analyzer. Most of the other techniques are very slow and the outputs are sometimes difficult to interpret. In all of these techniques the problem of wow and flutter of the recorder was the limiting feature.

The DELTIC Spectrum Analyzer

DELTIC is a new data-processing technique for the analysis of CTFM sonar returns. The DELTIC equipment performs frequency analysis by a sampling procedure and presents an output which is equivalent to the 100-channel filter bank analyzer typically used in CTFM sonar equipment. The DELTIC technique is particularly advantageous for low-frequency, high-resolution analysis in real time. The analyzer has an interesting and useful feature of storage and repeated analysis of data, either automatically or by operator selection.

The conventional 100-channel, multifilter analyzer is generally designed with detectors and envelope filters following each of the 100 filters. The purpose of the envelope filters is to improve the signal-to-reverberation ratio normally encountered in sonar equipment. The time constants involved in the envelope network depend on the scan rate of the sonar hydrophone as it passes a point reflector. Envelope filtering should not be used in searching for potential fish target signatures because no restriction should be placed upon the naturalness of the processed target signals and the fish motion with respect to the scanning rate of the sonar set. To eliminate such restrictions a multichannel analyzer without envelope filters would be required, and, therefore, no provision could be made for minimizing the unwanted reverberation. A multichannel analyzer without envelope filtering would pass a considerable degree of background noise or reverberation that would be presented on the visual display and degrade the presentation.

The DELTIC spectrum analyzer operates on a totally different principle and can cope with the variations in time responses expected for the fish-type targets. The mechanism of the reduction of the reverberation in such an analyzer is considerably different from that used in the conventional multichannel filter analyzer and the equipment therefore can be used to examine fish-type spectra signatures without compromising performance. The DELTIC equipment operates with a wider frequency or range gate than that used for ultimate analysis to sense the level of background reverberation and apply appropriate compensation to the analysis capability of the DELTIC. The DELTIC also provides a "holding" feature by which interesting data can be retained, as desired, for repeated display. In addition, the DELTIC analyzer has been designed to be directly interchangeable with the conventional 100-channel, multifilter analyzer in Straza sonar systems. This arrangement permits a system to be used interchangeably as a sonar or as a Doppler analyzer.

Kay Vibralyzer and DELTIC

The Kay vibralyzer was used for the analysis of selected portions of the CTFM data where permanent records were needed. It was the permanent output of the Kay vibralyzer that first provided measurable proof of the surface and bottom reflections which were indicated in the DELTIC display.

About 5 minutes are required for the analysis of 20 seconds of taped information. This relation indicates the tremendous amount of time required for analyzing test recordings; therefore, a technique had to be found which could be used for searching rapidly to isolate portions of the tape for later analysis with the Kay vibralyzer. The DELTIC was used for the search, and excerpt tapes were then produced for fine analysis and permanent record with the vibralyzer. Figure 7 indicates a typical

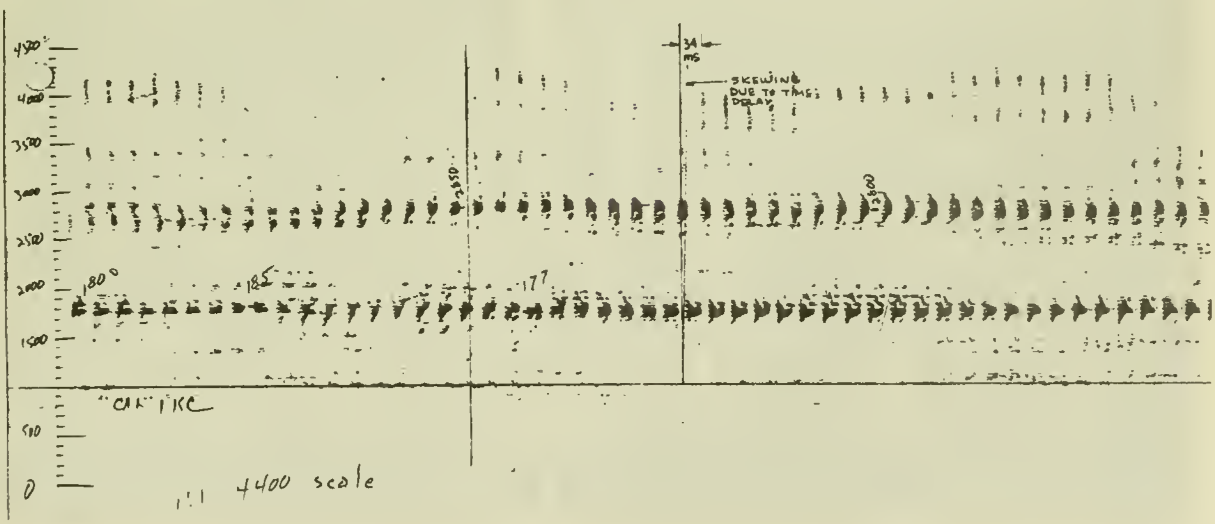

Figure 7.--Sample output from Kay vibralyzer showing double return from SCUBA diver at Mission Bay Yacht Club site.

spectrum output from the Kay vibralyzer. The high sweep rate of the CTFM sonar operating at short range indicates clearly the rate of bursts of data. It is possible that Δ_f and $\Delta_{f'}$ could produce double signals such as those indicated, but for the sweep rate of 34 ms. and the range of the diver, this double signal is impossible. The first return at 1,800 Hz occurs for the diver at a range of 14 feet (4.3 m.) which agrees with his observed position. The second signal can only be accounted for by reverberation between surface and bottom.

U.S. Naval Ordnance Test Station

A trip to USNOTS, Pasadena, at the invitation of J. Vetter and R. Davis, resulted in an analysis of a portion of one of the Doppler tape recordings made at the Mission Bay Yacht Club pier. A lengthy discussion with the personnel at USNOTS indicated that extractions of signals from the returns would not be easy and would require considerable process analysis. A day was spent at USNOTS using their playback equipment and recordings of fish returns from Mission Bay. The time required to analyze these portions of the tape became uneconomical.

Slow Scan Analysis Technique

A rapid means of analysis therefore was attempted with a narrow band Hewlett-Packard low-frequency wave analyzer and the test configuration indicated in figure 8. This technique made use of intensity modulation of a CRT (Cathode Ray Tube) and produced an image suitable for photographic integration. For the first time intensity-modulated signals were integrated to improve the signal-to-noise ratio of the recorded data. The dynamic range of this technique was limited by the CRT, and therefore the output was confused by large noise impulses. A sample of a typical photographic output is included in figure 9 to indicate

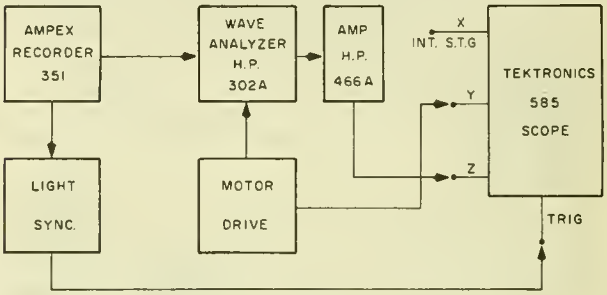

Figure 8.--Slow scan panoramic spectrum analysis block diagram.

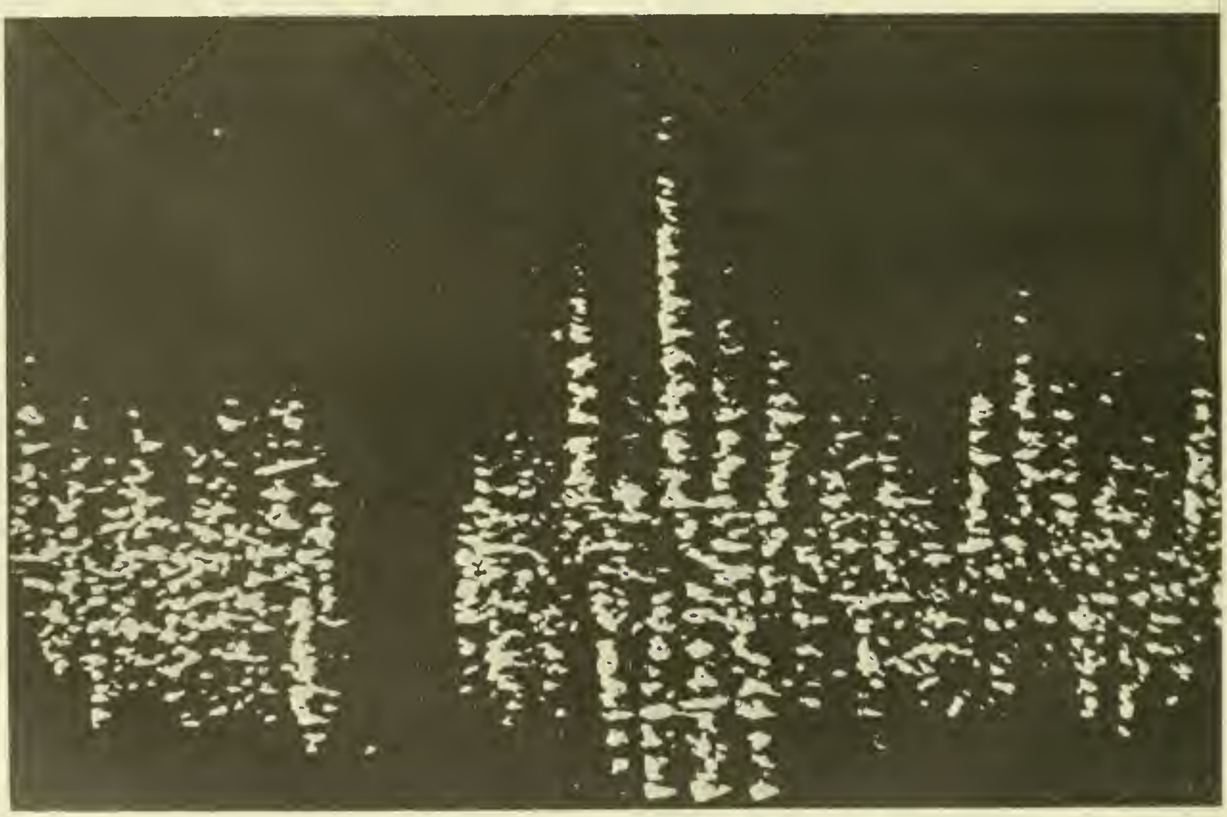

Figure 9.--Slow scan panoramic spectrum analysis from tape loop input.

the output obtained by this particular technique. This technique requires 30 minutes to generate a completed presentation. Although the time seems long for analyzing only 5 seconds of a tape recording, it was short compared to the time necessary for hand reducing the tape information obtained from USNOTS. The amount of tape that could be analyzed in this fashion was certainly limited, and a quick search method was still needed for locating sections of tape of interest. In the photographs obtained with this technique, certain indicated anomalies were later shown to be produced by the wow and flutter of the tape recorder in both the recording and playback mode. Steps were taken to remove the playback wow and flutter and to reduce the wow and flutter produced in recording. Careful observation of the figure shows faint sinusoidal curves passing through the noise. These signals appear to correlate with the motion of the yellowtail specimen used in the Mission Bay Yacht Club tests.

3-D Technique

The final technique that was used for the production of individual photographs necessary for the construction of a three-dimensional model is shown in block diagram (fig. 10) and indicates the simplicity of the test setup.

The technique is reasonably good, but, as before, the time required is 15 seconds per picture. Figure 11 shows a sample of one of the photographs produced from the CRT used in this approach.

The model, composed of 25 individual photographs such as that in figure 11, is shown in figure 12. This model of one film "take" at Catalina contains information on the activity of the fish in the area of the chumming platform. The correlation between the activity of fish in the test photographs and the model is reasonable. The density of activity was too great to isolate individual specimens as in the Mission Bay tests, but some individual correlations could be seen in the model constructed.

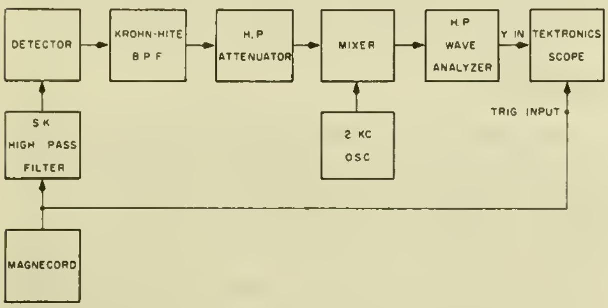

Figure 10.--Spectrum-analysis block diagram used for 3-D model.

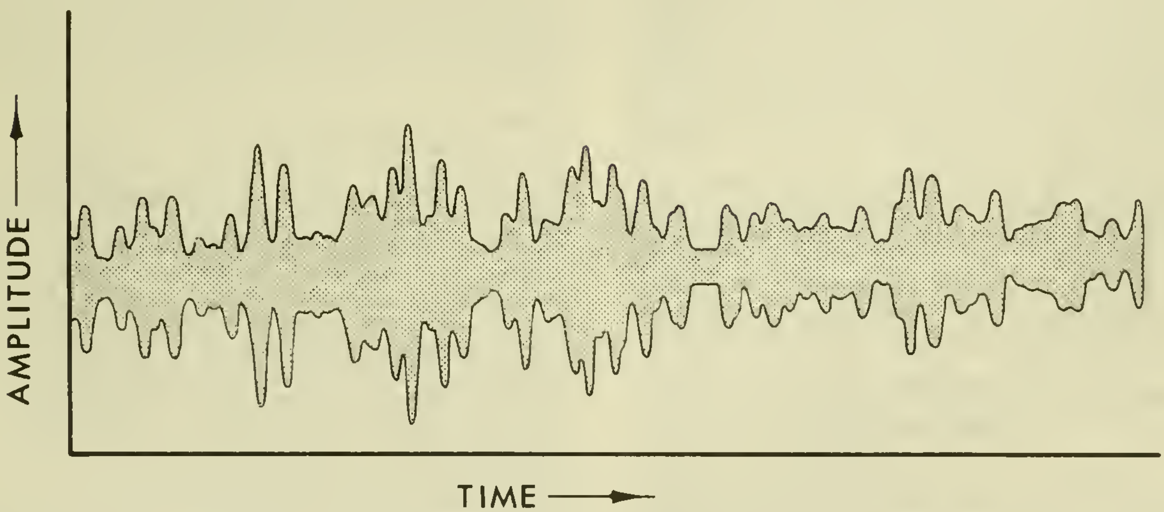

Figure 11.--Representative output from narrow-band analysis technique.

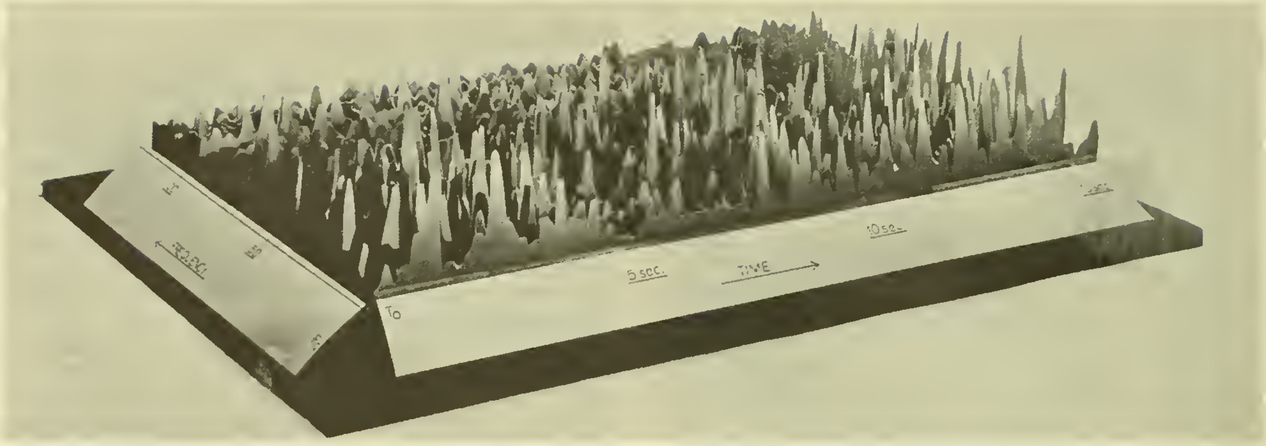

Figure 12.--Photograph of 3-dimensional model used to establish correlation between motion pictures and recorded data.

Three models were constructed to demonstrate the Doppler correlation characteristics between data and the motion pictures.

CONCLUSIONS FROM FEASIBILITY STUDY

The results of the work accomplished clearly indicate the suitability of CTFM sonar for ranging on fish specimens. This fact was determined early in the program.

The remainder of the effort and time was given to generation of techniques for presentation of the weak Doppler return from individual fish targets. The results obtained were not decisive but indicated that with a greater number of specimens the signal-to-noise ratio improved and the data extraction techniques relaxed. The application of a low-frequency DELTIC to the analysis of the Doppler returns produced a simple presentation. The techniques and circuitry that were developed overcame many difficult problems.

In view of the higher target strengths of schools of fish, it is clear that reasonable ranges of detection can be achieved with this type of sonar (e.g., 1,000 yards--914.4 m.). The coherence of the dynamics of the school and increased signal strength provide additional significant analysis information.

SHIPBOARD TARGET CLASSIFICATION EXPERIMENTS

The initial attempts to detect Doppler effects caused by fish showed that the technical problems could be solved. How well theory could be reduced to practice was to be tested in the next, the at-sea, phase. The equipment used in Phase II was modified and packaged for shipboard use. We decided that "real time" signal analysis was necessary and incorporated a DELTIC analyzer in the system; however, we also provided an instrumentation recorder capable of storing target echo signals for laboratory analysis should the need arise.

Equipment

Our target-classification sonar system was a modification of a Straza Electronics 500 series CTFM sonar (table 3). CTFM sonar has several desirable features for use on pelagic fishes. A wide-beam projector continuously fills a large volume of water with sound, the frequency of which is repeatedly varied from high to low in a saw-tooth manner. A narrow-beam hydrophone rapidly scans the insonified volume (25°/second in our sonar). All targets in the projector beam return echoes at a frequency that differs with time (or range) from the projected frequency. Mixing of the transmitted and received frequencies produces a difference frequency corresponding to a range. This continuous process gives a much faster information rate than is possible with a conventional pulsed sonar system. This high information rate makes it possible to maintain contact with fast-moving schools. Each target is a source of continuously reflected sound. The hydrophone scans each target for a time equivalent to several pulse lengths of a pulsed sonar; as a result the target returns are averaged. Such signal-averaging of short-term fluctuations in echo strength increases the likelihood of detection of any particular target.

Because range information was obtained from a difference frequency, CTFM sonar already has some of the circuit design that was required for resolution of the Doppler effect. An addition of a second mode of operation CTD (Continuous Transmission Doppler), that used most of the CTFM circuits plus a

Table 3.--Specifications of SM506 sonar system

Projector	
Source frequency	60-75 kHz, 70 kHz in CTD mode
Source level	+95 db re μ bar/volt 1 yd.
Horizontal beam width	20^0
Vertical beam width	20^0
Receiving hydrophone	
Horizontal beam width	4^0
Vertical beam width	10^0, 20^0
Open circuit sensitivy	- 75 db re 1 volt/μ bar
CTFM ranges	100, 200, 400, and 800 yds.
Horizontal scan rate	25^0/second on 100, 200, and 400 yds. 10^0/second on 800 yds.
Presentation CTFM	
7-inch plan position indicator scope	
5-inch "A" type display on CRT	
Audio	
Presentation CTD	
7-inch relative bearing display	
5-inch frequency spectrum display	
Audio	
Data storage	
Video, audio, range, servo, and mode information to multiplexer and Ampex Model SP-300 tape recorder. Playback through system.	

frequency analyzer of higher resolution, permitted our sonar to be used to locate and also classify a target. The system components were packaged to mount on vessels of convenience; the underwater unit was mounted on an over-the-side column.

Methods

When a fish school was located, the CTFM mode was used to position the boat 100 to 200 yards (91.4 to 182.9 m.) from the school. If the school was moving we tried to match its velocity and direction of movement with the vessel. When the school was positioned, the sonar scan was locked and the system placed in the CTD mode. In this mode a continuous 70 kHz tone was transmitted from the sonar projector. The echo of this tone plus Doppler information was received by the hydrophone, mixed and filtered to remove the portion corresponding to 70 kHz, and fed to the spectrum analyzer. The spectrum analyzer had a DELTIC to raise the Doppler-frequency information by factors of 2 or 4 by 10^3 and allow frequency resolutions of 3.33 Hz or 1.67 Hz over a band of ± 600 Hz or ± 300 Hz. The Doppler spectrum could be displayed on a CRT and photographed or recorded on magnetic tape, or the same information could be stored and displayed repeatedly on the CRT by locking the DELTIC.

The incoming signal was sampled by logic circuitry to convert Doppler-frequency information into digital form. This digital information was loaded into the delay line at the rate of 100 μ sec./bit when the ± 600 Hz Doppler band was used and at 200 μ sec./bit when the ± 300 Hz band was used. Since the DELTIC could store 3,000 bits of information, the initial loading time of the analyzer was 0.3 sec. or 0.6 sec., depending on the resolution selected. After the line was loaded, new Doppler information could be added and old information dropped at the rate of about one bit/150 μ sec. The output of the analyzer then was analogous to a photographic time exposure of the Doppler data received in a 0.3- or 0.6-sec. interval. The analyzed Doppler information was presented as video on the CRT at 5 sweeps per second. Frequency was displayed along the horizontal time line with center frequency (no Doppler) at the center of the scope, up-Doppler to the left, and down-Doppler to the right (fig. 13). Vertical deflection depends on the number of times a particular frequency was present during the load time of the delay line. A single frequency was shown as a single high spike, whereas multiple

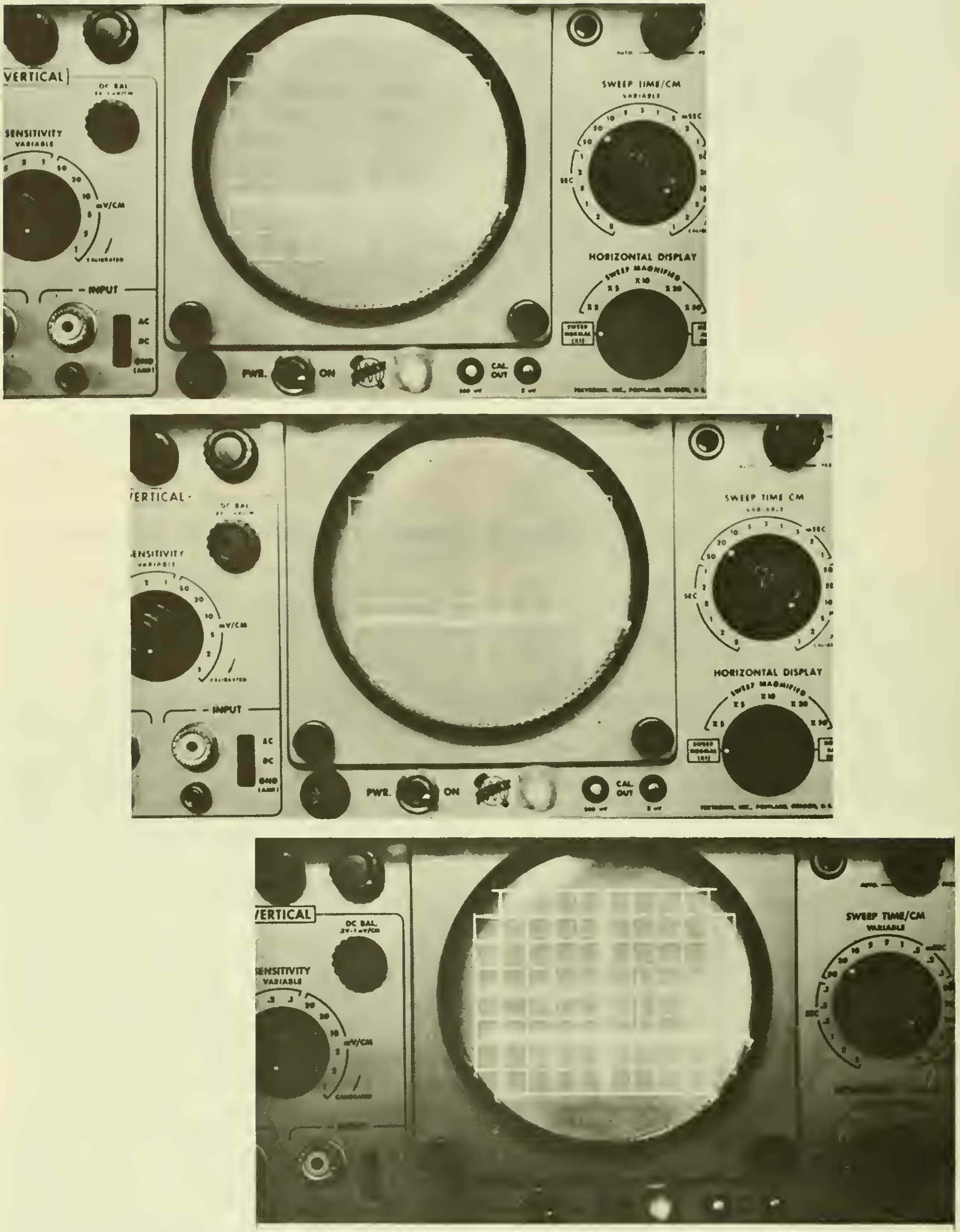

Figure 13(a).--Typical narrow-band Doppler from a small metal triplane at 10 yards (9.1 m.): no motion, large spike at 0 Doppler, horizontal scale 60 Hz/div, vertical scale relative; (b) motion of triplane toward hydrophone, spike displaced to left; (c) motion away from hydrophone, spike displaced to right.

frequencies were displayed as many spikes of lower amplitude.

In practice we felt that the sonar information--fish swimming speed from matching the ship speed to the speed of the school and Doppler shifts caused by tail beats and body motion--would result in some approximation of fish size and type. (For more detailed analysis of these relations and some more examples of results see Hester, 1967.)

Results of Shipboard Tests

Over a 2-year period we tested our equipment under a variety of conditions on several species of fish. We encountered two major difficulties to the obtaining of Doppler records from fish schools.

The first difficulty was sea-noise Doppler effect from surface reflections. The over-the-side transducer array was 10 feet (3.0 m.) below the surface. This shallow depth combined with the 10° vertical beam width of the hydrophone allows surface reflections to be detected readily. To receive a Doppler record from fish, sea conditions must be extremely favorable--no wind ripples or short-period swell. Such conditions do occur, particularly in the early morning, off the Pacific coast, but the occurrence of fish schools and "workable" conditions together are rare. It was soon apparent that commercial applications of Doppler equipment would require a more complex signal-processing procedure than was originally expected.

The second major difficulty arose from the irregular behavior of the large schooling fishes such as tunas. These fishes, because of their streamlined shape, are detectable with our sonar only when viewed from the side (fig. 14). When schooling, scombroids usually travel at a good rate (3 to 5 knots)

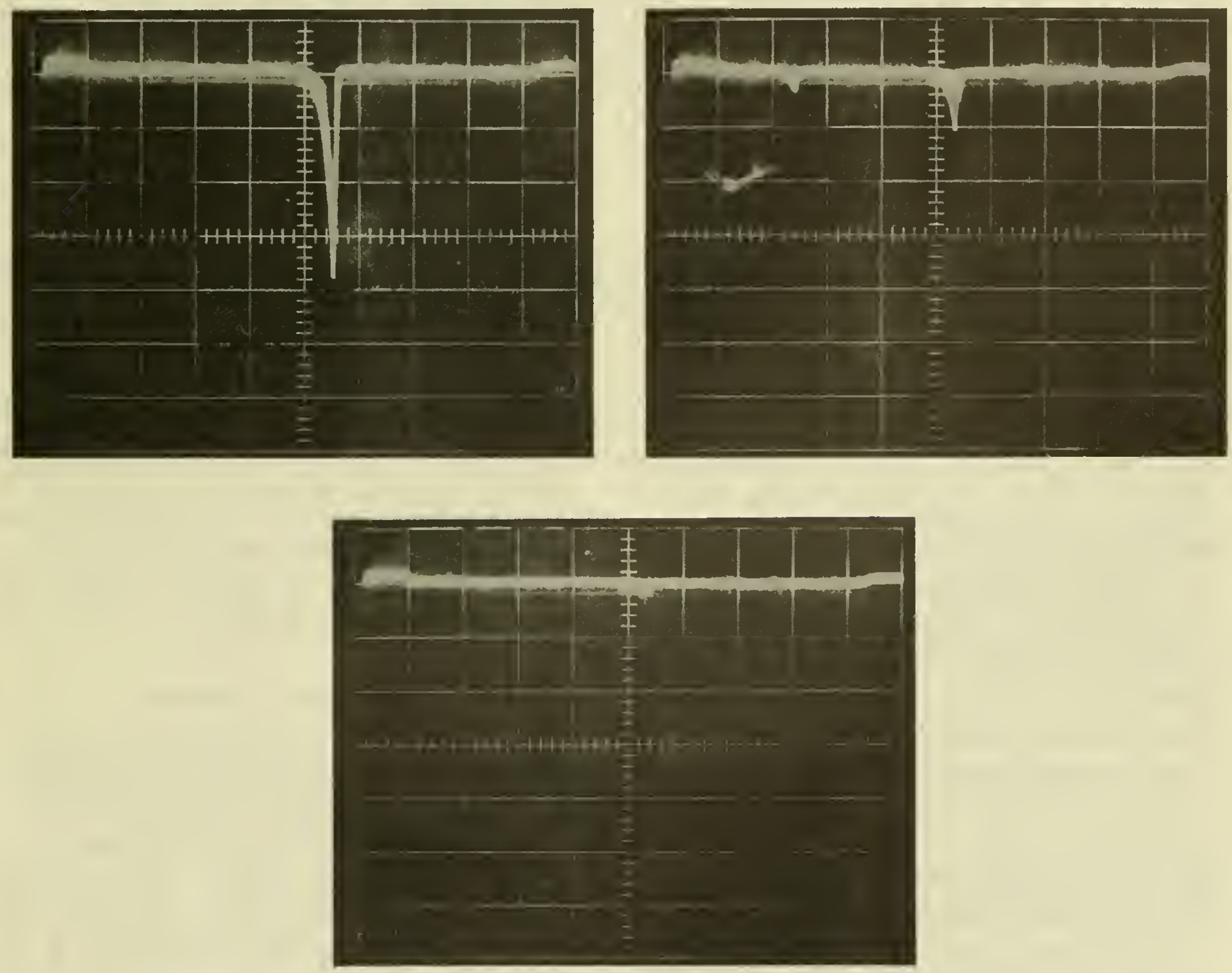

Figure 14.--Target echo video from a fresh 492-mm. black skipjack (Euthynnus lineatus) suspended 5 m. from the sonar dome. The sonar gain was set to saturate the receiver for the target's side aspect (a). The echo video is markedly reduced when the target is rotated head (b) or tail (c) to the beam.

and make capricious course changes. We found it exceedingly difficult to maintain contact with these schools. Even if contact was not broken the schools had to be kept within 100 yards (91.4 m.) of the vessel for Doppler detection, and at these close ranges they usually outmaneuvered us.

Because of these difficulties we decided to see if the complete target signal, noise Doppler effect and target Doppler effect could be classified by computer. A contract was made with Scope Inc., Falls Church, Va., to explore acoustic methods of classifying characteristics of schooling fish. Specifically, the work was concerned with establishing the feasibility of using adaptive pattern-recognition processes in the automatic classification of Straza CTFM/CTD sonar returns.

Data were collected aboard the Bureau of Commercial Fisheries vessel, Miss Behavior, off the coast of southern California. The audio outputs of the CTFM and CTD receivers, as selected in the DELTIC analyzer, were recorded on one channel of the associated Ampex SP300 magnetic tape recorder; a voice annotation was recorded on another channel. When a target searched for in the 200-yard (182.9 m.) and 400-yard (365.8 m.) CTFM mode was located, it was recorded with voice annotation of estimated target size, species, approximate geographical location of the vessel, range-to-target, and sonar mode of operation. Upon target detection, the "Scan Rev" control was manually activated to reduce the scan from $\pm 45^\circ$ or 22.5° to about $\pm$ one-half of the angle subtended by the target. This procedure allowed more nearly constant contact with the target while permitting it to be tracked in azimuth.

The recordings thus made were subsequently dubbed twice to make them compatible with SCOPE's magnetic-tape reproduction facilities. The resulting tape contained six targets and five ambient recordings, totaling about 18 minutes of usable data. Table 4 shows a detailed breakdown of the data.

It became apparent after the initial processing of the magnetic tapes that the limited data base obtained was insufficient for the analysis required to determine the feasibility of using pattern-recognition processes in the automatic classification of sonar returns. We did undertake analysis, however, with the data available to ascertain whether the sonar echo received when a target is present contains anomalies that are not in the echoes received during the recording of ambient conditions. Further, it was intended that, if such anomalies were found, the analysis would reveal whether they have characteristics that might be used in classifying the target as to size and species.

The decision to analyze for spectral content the data available in the initial study was dictated by two factors. The first consideration was that the difference frequency in the CTFM mode is the only expression of the information available in that mode--target range and relative target motion. The latter produces a Doppler shift of the FM signal, resulting in a modulation of the difference frequency. The second consideration was that (as indicated by an examination of the physics of the situation) the information present should be in the form of spectral/time distributions. Furthermore, this analysis could fortunately be produced by instrumentation readily available.

Sonagrams were made of the data on a Sonagraph 6061A manufactured by the Kay Electric Company. This spectrum analyzer produces a frequency versus time versus amplitude (intensity) plot in the 85 Hz to 8 kHz range. When a target was known to be present, a signal occasionally appeared at a frequency corresponding to a range approximating that of the target--when the target range was known. Targets never appeared in more than one-third of the sweeps because of the sector-scanning technique of the sonar.

In both the CTFM and CTD modes and at all ranges of the CTFM mode a signal appears continuously in the 5 to 5.5 kHz range. Attempts to correlate the signal with a known target or a natural obstruction such as the ocean floor proved fruitless.

Further analysis was made on a General Radio Wave Analyzer Model 1900A and recorded on a General Radio Graphic Level Recorder Model 1521B. The frequency-versus-amplitude plot produced disclosed a different frequency signal with a value approximating that of the range of the target. Once again, the unidentified signal appeared, this time at 5.3 kHz.

Signals were detected with both the sonagraph and wave analyzer at frequencies approximating those of target range. The signals also appeared at the times when a target was believed to be present, but the detected signal and the target could not be correlated other than in range and time. Classification of the target by species was impossible, and it does not appear practical to look for more informative features until we obtain a larger and more comprehensive data base.

RECOMMENDATIONS

To date the sonar experiments have given interesting but inconclusive results. The editor believes that the prospects for commercial-fishing applications of Doppler target classification are at this time financially impractical. The usefulness of the Doppler work in research is less clear. The problem of identifying subsurface sonar contacts for population and behavior studies is yet unsolved. It is too early to say whether acoustic methods--high-resolution, resonant studies or Doppler effects--alone or in combination will prove more satisfactory than other methods such as

Table 4.--Log of targets observed

Target no. and length of observation	Mode	Remarks (as noted from voice track on tape)	Data-analysis results
1 3 min., 12 sec.	CTFM - 200 yds. CTD - 600~BW CTFM CTD CTFM	 Target obscured by wake. Target dispersed or lost in wake.	Target observed sporadically in CTFM. No target observed in CTD.
2 4 min., 12 sec.	CTFM - 200 yds. CTD - 600~BW CTFM CTFM - 100 yds. CTD CTFM CTD CTFM	Seals and fish; birds on surface. Two large targets separated, one tracked. Two targets at 50 yds. Largest target subtends 60^0. Target lost.	Target observed sporadically in CTFM 200 yds. Signal appears at 2300 Hz about 50 yds. on 100-yd. CTFM; however, the intensity is less than that observed on the 200-yd. CTFM. No target observed in CTD.
3 2 min., 32 sec.	CTFM - 800 yds. CTD - 600~BW CTFM CTD CTFM CTD - 300~BW CTFM	Target at 320 yds.; recording at anchor in small cove. Target lost.	No target observed in either mode.
4 36 sec.	CTFM - 200 yds. CTD - 300~BW CTFM	Target believed to be school of anchovy. Target lost.	No target observed in either mode.
5 3 min., 36 sec.	CTFM - 200 yds. CTD - 300~BW CTFM CTD CTFM CTD CTFM CTD	Target believed to be jack mackerel at 80 yds., ship in small cove. Two targets; one at 60 yds., one at 80 yds. Target lost.	Target observed sporadically in CTFM. Frequency observed approximates the range of 80 yds. in the tape voice annotation. No target observed in CTD.
6 1 min., 30 sec.	CTD - 300~BW	Target at 10 yds., target lost.	No target observed.
Ambient 1. 24 sec. 2. 26 sec. 3. 30 sec. 4. 32 sec. 5. 20 sec.	 CTFM - 100 yds. CTFM - 200 yds. CTFM - 400 yds. CTFM - 800 yds. CTD - 300~BW		Inexplicable 500 - 5500 Hz signal appears in every instance here also, however, no targets appeared.

trawling or optics. Work is progressing in all of these fields but this Straza unit is apparently the only sea-going Doppler unit under investigation. Soundness of its continued use on surface targets is questionable. Experience suggests that the direction of the research be changed. The difficulties caused by sea return suggest that the sonar should concentrate on deeper targets. Since body-motion Doppler effect is aspect-dependent, that is, it is strong only on the horizontal plane, the transducer array must be mounted on a subsurface vehicle so that it can operate at the same depth as the target. The problems arising from trying to maintain contact with rapidly moving surface schools may not be as great with deep targets since some studies show that these targets generally are nearly stationary. It is most likely, however, that these deep targets are small organisms--which means that work on the big scombroids, the original goal of these experiments, will have to be deemphasized. In addition we should have a combination of laboratory studies of fish locomotion along with the future Doppler work.

SUMMARY

Three phases in the development of a Doppler target classification sonar are reported:

1. Target strengths of subject species were determined to permit the estimation of target-classification sonar equipment: frequency, source level, hydrophone and receiver sensitivity, and scan rate.
2. Feasibility studies were made to determine whether or not Doppler effects from fish body-motion could be detected. These studies were sufficiently promising that a shipboard CTFM/Doppler sonar was constructed.
3. The at-sea experiments showed that under certain conditions, Doppler information could be obtained from near-surface fish schools. This information was not successfully used in target classification, however. The major difficulties with the at-sea phase were caused by sea return and the erratic behavior of near-surface schools. Recommendations for further studies are aimed at overcoming these difficulties. The recommendations include mounting the sonar transducers on an underwater vehicle and working with deeper, slow-moving targets.

ACKNOWLEDGMENTS

The editor acknowledges the cooperation of the U.S. Navy for the loan and subsequent transfer of our sonar boat, the engineering staffs of the contractors for their outstanding performance and reports, and the Direccion General de Pesca e Industrias Conexas, Departmento de Estudios Biologicos Pesqueros, for permission to enter and work in the territorial waters of Mexico.

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Acoustic Target Strength of Several Species of Fish[1]

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ABSTRACT

To design fish-finding sonar equipment it is necessary to have information about target strengths of fish. This study was made principally to determine the target strength of tunas at several acoustic frequencies. In addition, measurements were made on other living, dead, fresh, and frozen fresh-water and salt-water fishes, some without swim bladders.

INTRODUCTION

The use of sound waves to locate objects in the sea has been refined over the last few decades. Most of the impetus for the development of equipment and techniques came from the military. Peaceful application, especially of scanning sonar equipment, often lagged far behind the potential of the military capabilities. Many of the features necessary for sonar system design are available from the military; however, the most important one for fishery work, the target strength of a fish, was not available from the military.

The problems involved in fishery work are complicated by such variables as the presence or absence of a swim bladder in the fish, the behavior of the species (schooling or solitary), the size of the individuals, the expected orientation of the fish to the sound beam (vertical or horizontal echo ranging), and the relation of fish target strength to the sound frequency used. Recently, European experiments have yielded data on several species. These investigations (Harden-Jones and Pearce, 1958; Midttun and Hoff, 1962) were chiefly concerned with determining size/target strength relation and the contribution of the swim bladder to target strength. Cushing (1964) combined the other European data with his to illustrate a fish length-target strength relation applicable for middle frequencies (near 30 kHz). The species reported have swim bladders; some of Cushing's fish had artificial swim bladders placed inside their bodies.

The primary demand in American fishery sonar work comes from the groups working on the fast-swimming, often pelagic species such as scombroids and salmonoids. Differences in target strength between side and dorsal aspect are of interest as is, for example, the difference in target strength between a yellowfin tuna (Thunnus albacares), a species with a swin bladder, and a skipjack tuna (Katsuwonus pelamis), a species without one.

In 1963, Straza Electronics was invited to submit a proposal for a high-resolution sonar system for fishery research. To calculate energy requirements and receiver sensitivity values for the proposed system it was necessary to know something about the target characteristics of the species to be studied (chiefly tunas). Also, the system envisioned would be multifrequency, using frequency modulated bands, one of several tens of kilo Hertz and one of several hundreds of kilo Hertz. This report summarizes the tests made to determine target strengths for several species of fish at various frequencies and for various positions of orientation. Differences of target strength between living, fresh, and frozen specimens and the contribution of the swim bladder to the sound reflective properties of some fishes also were investigated.

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FACILITIES, EQUIPMENT, AND METHODS

The equipment and facilities of the U.S. Navy Electronics Laboratory, Sweetwater Dam facility, San Diego, Calif., were used to determine the target strength of the various fishes. Target strength is defined as 10 log the ratio of the acoustic reflectance of the specimen referred to a perfectly reflecting sphere of 4 m. diameter at a range of 1 m. It is expressed in db (decibels). Figure 1 shows a block diagram of the test setup used to make our measurements of target strength. The fish target was placed appropriately at either 6 or 12 m., depending on the frequency, from the trasmit-receive transducer so that near-field effects were not evident. A 1-millisecond pulse was transmitted at the carrier frequencies of 20, 40, 50 or 280 kHz. At an appropriate time, the receiver gate was opened, to permit the echo pulse to be recorded in amplitude on the polar plot equipment. The pulse repetition rate was adjusted to minimize the interference in the water. The fish target was mounted on monofilament rigging which was rotated by means of a servo system at about 1°/second. The recorder response was capable of 50 db/second, 20 db/half second, and 10 db/third of a second.

To support the fish specimen properly, the rigging took the shape of an inverted "A" with a weight at the bottom (fig. 2). Wire gave

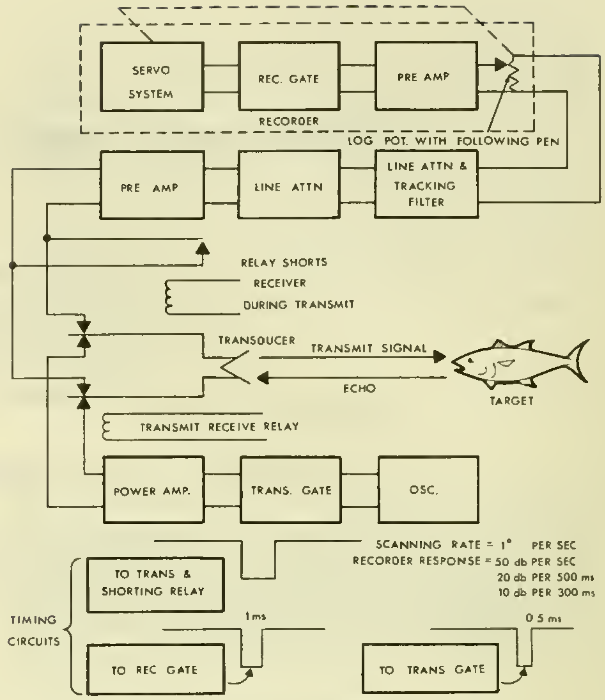

Figure 1.--Block diagram of the test setup used to measure the target strengths of fish.

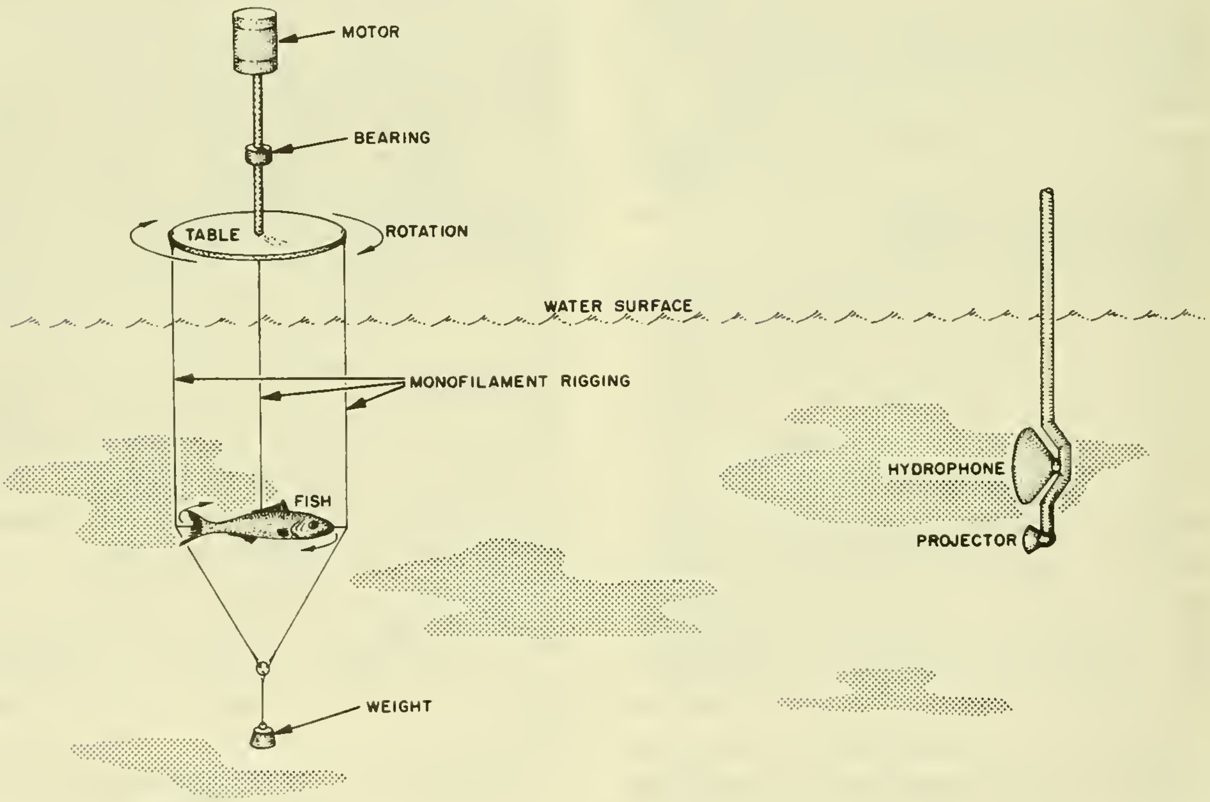

Figure 2.--Diagram of the apparatus used to hold and rotate the fish for target strength measurements.

acoustic reflections which had too great amplitude, especially at 280 kHz, for the types of tests anticipated. Monofilament nylon afforded an improvement of some 15 db over the wire rigging at 280 kHz and was used throughout the tests.

TESTS

Previous studies (Harden-Jones and Pearce, 1958; Midttun and Hoff, 1962) show that the swim bladder in fishes is an important contributor to their acoustic cross-section. Since skipjack tuna (Katsuwonus pelamis) lack a swim bladder yet are of considerable commercial importance, they were tested for comparison with fishes such as the yellowtail (Seriola dorsalis) that have swim bladders.

Fish Without Swim Bladders

To illustrate the nature of the directivity patterns obtained, two figures are shown for a skipjack tuna. This tuna was 60 cm. long, weighed 5.5 kg., and initially had been chilled but not frozen for 48 hours. Measurements were made at two frequencies--40 kHz and 280 kHz. Figures 3 and 4 show patterns obtained when the dorsal fin was in the vertical plane and the body rotated in the horizontal plane. These observations indicated that the target strengths of the skipjack tuna tested were essentially the same at the frequencies used. The structure of the beam patterns became more spiked at the higher frequency.

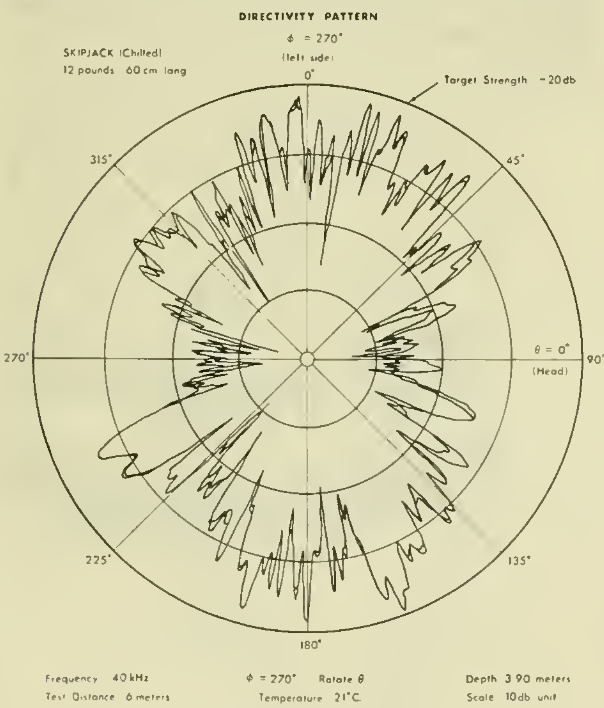

Figure 3.--Directivity pattern for a 60 cm. skipjack tuna rotated in the horizontal plane. The test frequency was 40 kHz. For this and following figures the target range was 6 m., the temperature 21° C., and the test depth 3.9 m. Each ring represents a 10 db decrement from the outer -20 db ring.

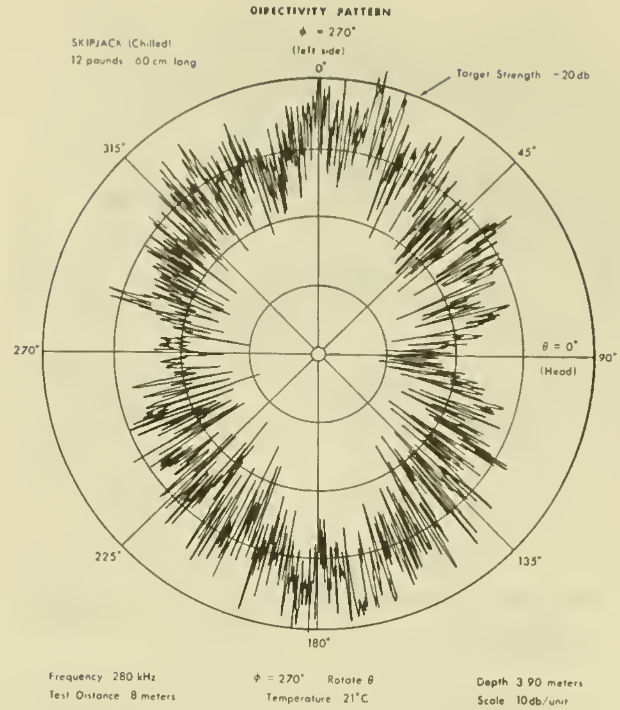

Figure 4.--Directivity pattern for a 60 cm. skipjack tuna rotated in the horizontal plane. The test frequency was 280 kHz. For this and following figures the target range was 6 m., the temperature 21° C., and the test depths 3.9 m. Each ring represents a 10 db decrement from the outer -20 db ring.

One can calculate the target strength of the fish when viewed from the side by assuming its effective acoustic target area to be equal to its projected area. Using $T_s = 10 \log (\frac{A}{4\pi})$ in which A = the scattering cross-section or effective target area, the calculated target strength is about -23 db at the beam aspect. This value is of the same order of magnitude as the value of about -20 db obtained by the measurements.

Figure 5 shows several measurements of different skipjack tuna at a frequency of 40 kHz orientated and rotated as before. Only the left side is shown. The 66- and 72-cm. fish were frozen. Their patterns indicate a greater amount of directivity, perhaps because they were stiffer than the 60- and 70-cm. fish.

Figure 6 shows the target strengths of the skipjack tuna when each fish was supported nose up, tail down, and rotated about its long axis. The figure gives the directivity patterns in views of the back and sides of the fish. Measurements were made at 40 kHz and 280 kHz. A slight increase in target strength is seen for the larger fish.

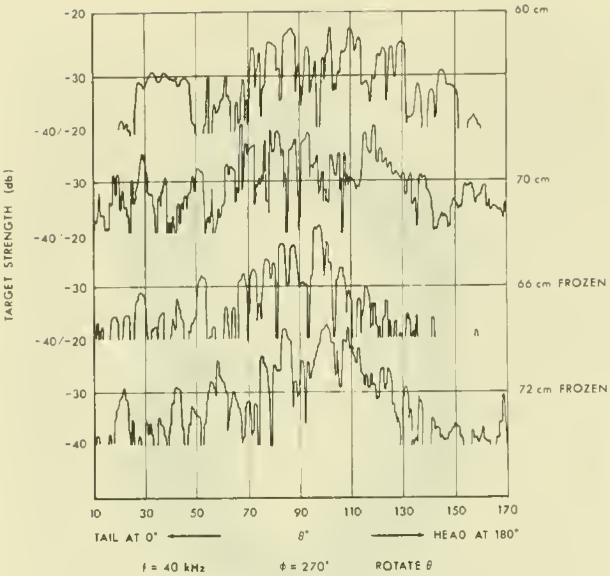

Figure 5.--Rectilinear plot of directivity patterns of 40 kHz (left side only) of four skipjack tuna. See text for explanation.

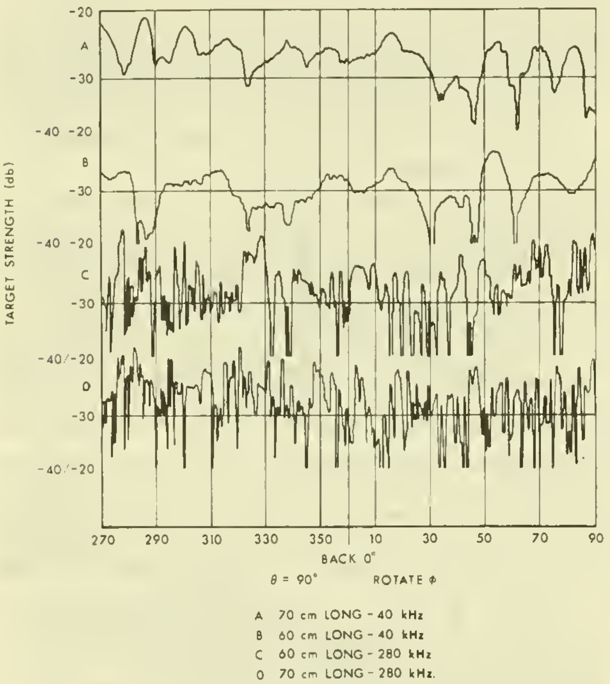

Figure 6.--Directivity patterns for two skipjack tuna suspended nose up, tail down and rotated about the long axis.

The irregular nature of the directivity patterns showed the fish to be a highly complex acoustic target. The surface of a fish and various internal structures both are believed to contribute to the reflectivity of the whole animal. The relative contribution of various anatomical parts of a skipjack tuna were estimated by the progressive dissection of a 72-cm. specimen. First a reference pattern was run; then patterns with the opercle and preopercle removed from one side--from both sides--the corselet removed--pectoral and pelvic gridles removed--head, tail, and viscera removed--flesh from one side removed--and flesh from both sides removed. These tests indicated that any large cross-sectional area of any part of the fish showed a substantial echo with respect to the target strength of the intact fish. At 280 kHz no significant difference existed in the beam aspect target strength when only the skeleton of the skipjack tuna was used minus head and tail, compared to an intact fish.

Fish With Swim Bladders

A frozen yellowtail, 80 cm. long, was used in a series of tests on fish with swim bladders. Figure 7 shows a series of directivity patterns from the 80-cm.-long yellowtail suspended nose up, tail down, so that the back and sides of the fish could be examined. The top two directivity patterns are for 50 kHz--first with the fish intact and second with the swim bladder punctured and flooded. The bottom two patterns are for 280 kHz under like conditions. The 50 kHz frequency was selected because the effect of the swim bladder for this specimen appeared more pronounced there than at any other frequency.

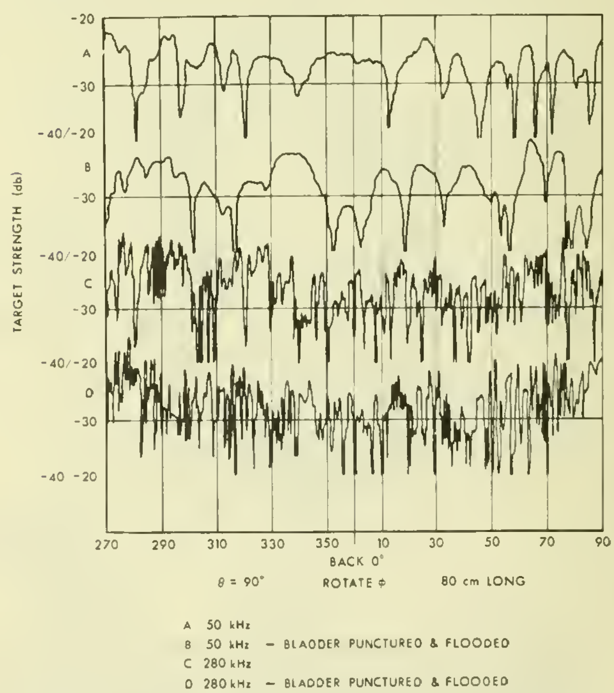

Figure 7.--Directivity pattern for a yellowtail suspended nose up, tail down and rotated about the long axis. Tests were made with and without the swim bladder intact.

The plot in part (A) of figure 7 shows a -27 db target strength near the back portion of the fish. This area is located along the abscissa of the graph at about 0°. In the same area, the return in part (B) was markedly reduced when the bladder was punctured and flooded. By way of comparison, the higher frequency patterns in parts (C) and (D) show no appreciable differences. The influence of the swim bladder at the lower frequencies might be due to lessened attenuation by the flesh at those frequencies and a consequent increase in the response from the swim bladder. For fish of the size of the yellowtail tested, and assuming typical flesh attenuation to be in the order of 0.6 db/cm. at 280 kHz, a difference of some 7 db can be attributed to flesh attenuation (Goldman and Heuter, 1957). This increased attenuation at the higher frequencies could mask the influence of the swim bladder. It is also conceivable that some misalignment occurred during the repeated aspect angles at this high frequency.

A similar experiment was run with yellowfin tuna (Thunnus albacares) at a frequency of 40 kHz. In this test, the fish was suspended both in normal swimming position and nose up, tail down. A typical pattern for the yellowfin tuna is given in figure 8. Figure 9 shows a series of directivity patterns for the 73-cm.-long yellowfin tuna for 20 kHz and 40 kHz. A comparison is made between an intact fish and the same fish with its swim bladder punctured and flooded. For this observation (head up, tail down) the back portion of the fish was

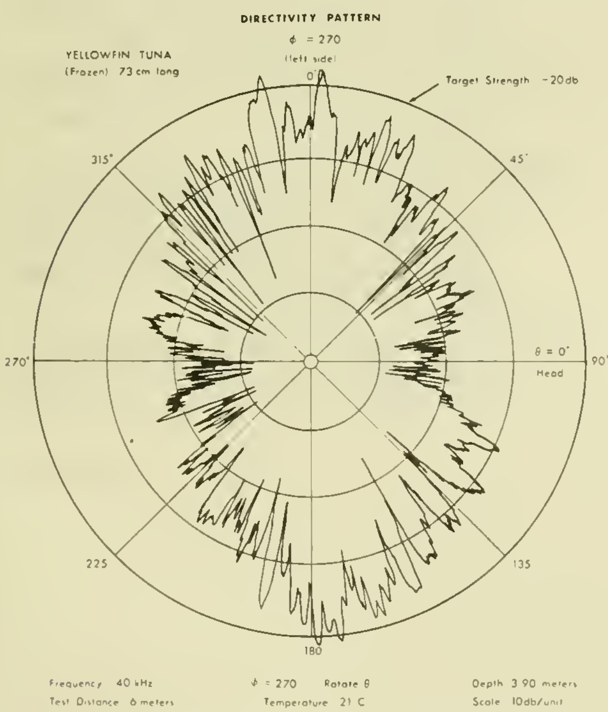

Figure 8.--Typical 40 kHz directivity pattern for a yellowfin tuna suspended in the normal swimming position.

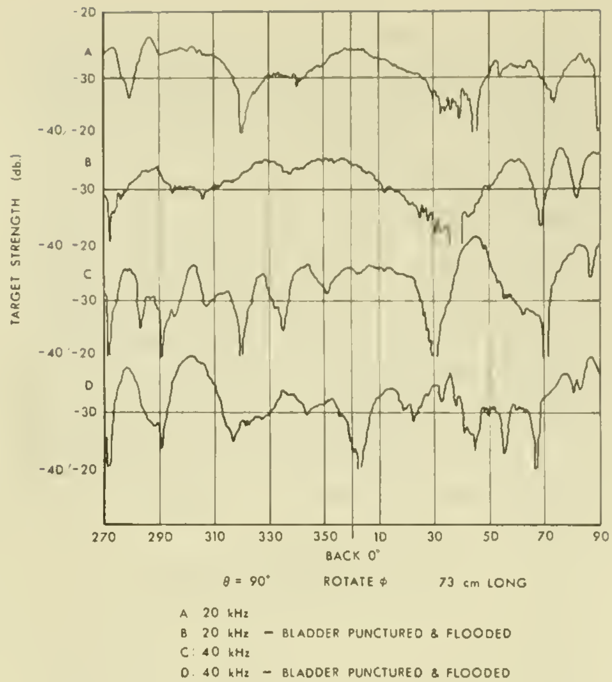

Figure 9.--Directivity pattern for a yellowfin tuna suspended nose up, tail down and rotated about the long axis. Tests were made with and without the swim bladder intact.

viewed. At 20 kHz, difference in response between the intact fish and the fish after the swim bladder had been flooded was not appreciable. At 40 kHz, however, the return decreased significantly when the swim bladder was flooded. With the above exceptions, all the tests showed that in general the target strength of yellowfin tuna was comparable to that of skipjack tuna and yellowtail of approximately the same size.

Additional test were made with largemouth bass (Micropterus salmoides) and white crappie (Pomoxis annularis), both alive and dead. When the bass and crappie were alive, the gill movement was readily observable on the plots of the directivity pattern. Difference between target strength in live and dead fish was scant or nil. The target strengths were 15 db lower than those of the larger tunas due to the smaller size of the fish (largemouth bass 40 cm., white crappie 32 cm.). Deflating the bladders decreased the target strength 3 to 7 db.

RELATION OF PRESENT TO EARLIER FINDINGS

It is evident that the target strength of a fish depends largely on its size. Only in some aspects, especially when the fish is viewed from above, does the swim bladder contribute significantly to the strength of the echo. The contribution of the swim bladder rapidly decreases with increased frequency, apparently because of an increase in attenuation by flesh with rise in frequency. The observations of Harden-Jones and Pearce (1958) and Midttun and Hoff (1962) showed an increase in target strength and directionally with fish size up to about 70 cm. At this point the thickness of the tissue between the swim bladder and the surface of the back of the fish is sufficiently great to begin to mask the contribution of the bladder. The earlier results are combined with some of ours in figure 10. The abscissa is in units of 20 log fish length to put the contribution of size into logarithmic units. Target strengths of both side and back aspect are given for our larger fishes. In open water these species will usually be detected at some slant range and their target strength will lie somewhere between the values given for side and top. The decreases in target strength due to flooding of the swim bladder are indicated by the vertical arrows.

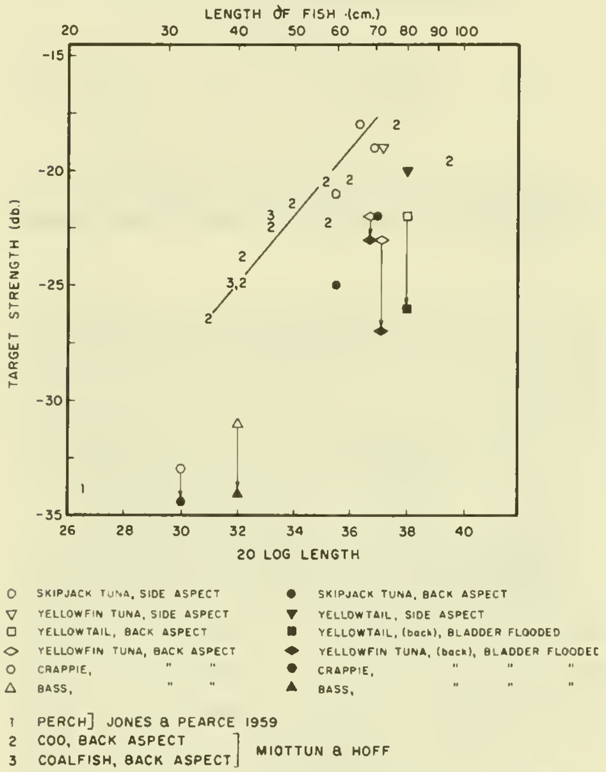

Figure 10.--Comparison of target strength measurements made in this experiment with those obtained by other investigators. All measurements were made between 20 and 40 kHz.

SUMMARY

1. The acoustic target strength for skipjack and yellowfin tunas, yellowtail, white crappie, and largemouth bass were measured for different orientations of the fish at frequencies from 20 kHz to 280 kHz.

2. The differences in target strength among living, dead, chilled, and frozen fish were negligible.

3. The contribution of the swim bladder to target strength decreased as size of the fish and test frequency increased.

4. With the exception of the contribution of the swim bladder, target strength was independent of frequency.

ACKNOWLEDGMENTS

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