SONAR MAPPING IN THE CALIFORNIA CURRENT AREA: A REVIEW OF RECENT DEVELOPMENTS

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ABSTRACT

Some developments in the use of sonar to study pelagic fish schools are reviewed. Techniques for counting the number of fish schools per unit area, measuring their horizontal dimensions, determining their biomass, sizing individual fish within a school, and distinguishing northern anchovy, *Engraulis mordax,* schools from all others are discussed briefly. Acoustic observations of the distribution, behavior, sizes, and packing density of anchovy schools are reviewed.

INTRODUCTION

It is the intent of this paper to review the use of horizontally directed echo ranging devices (sonar) to study pelagic fish schools off the coast of California. Research objectives are reviewed and several papers by biologists at the California Department of Fish and Game (CDFG) and the Southwest Fisheries Center (SWFC) are discussed as they relate to a development of sonar research.

Sonar mapping is the process by which a sample transect of the upper mixed layer of the ocean is insonified by a ship proceeding at 9 to 12 knots. Echo returns are recorded or digitized for detection of aggregations of organisms thought to be mostly fish shoals. The primary measurements are the location of each school in the horizontal plane and the diameter of the school on an axis perpendicular to the direction of travel of the survey vessel (Figure 1). The method was first discussed by Smith (1970) and later by Mais (1974) and Hewitt, Smith and Brown (1976). Collectively the measurements yield the number of fish schools per unit area, the geographical distribution of fish schools within the survey area, and the relative proportions of the fish school sizes.

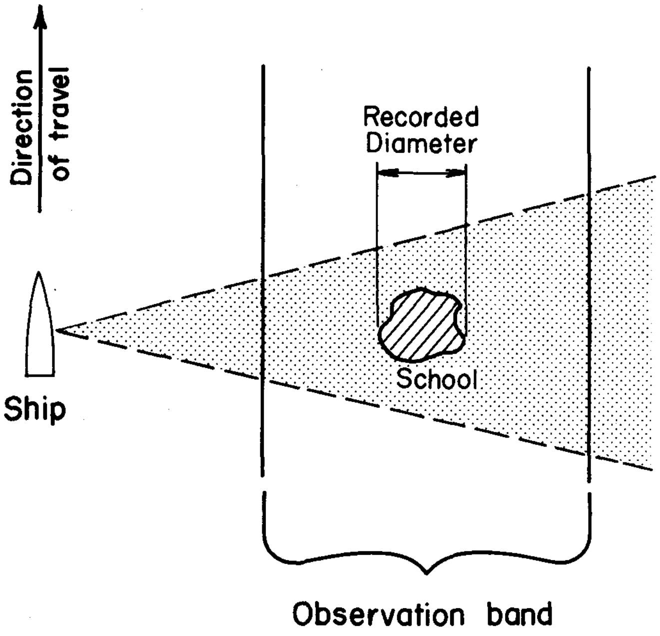

FIGURE 1. Plan view of the sonar mapping technique. Transducer is fixed at 90° to the ship's head rather than swept from side to side as in searching patterns.

Other measurements of the acoustic return have been demonstrated to be of use in estimating the biomass of a school, the size of the fish in a school, and in identifying schools of the northern anchovy, *Engraulis mordax,* in a mixture of fish schools. Unfortunately these measurements have not yet been feasible from a ship underway at full speed.

RESEARCH STRATEGY

The ultimate intention of the program to detect and determine fish schools by sonar is to develop a tool for pelagic fish stock assessment and to describe its precision. A secondary goal is to investigate the nonrandomness (or patchiness) of the spatial distribution of fish schools, particularly its similarity to distributions encountered when studying other life stages of the same group of animals; e.g., pelagic fish eggs and fish larvae.

In 1968, with these goals in mind, the development of the following capabilities were established as objectives of the research program:

1) To count the number of fish schools per unit of sea area,
2) To measure the horizontal dimensions of detected fish schools,
3) To estimate the fish biomass of any detected school,
4) to estimate the size of individuals constituting a school,
5) To distinguish northern anchovy schools from all other aggregations.

Progress toward the accomplishment of these objectives may be most clearly described with the use of a simple matrix which considers the five objectives, in terms of measurement capabilities, and the degree to which these capabilities may be considered practical operations (Table 1).

TABLE 1

Objectives of the Research at the Southwest Fisheries Center and the Degree to Which These Objectives have been Attained, as of 1975.

Objective	Phase I develop theory/ technique	Phase II demonstrate/ test feasibility	Phase III practical operation from a ship underway at 9-12 knots
1. Count fish schools per unit area	Accomplished	Accomplished	Automated and corrected for known biases
2. Measure horizontal school dimensions	Accomplished	Accomplished	Automated and corrected for known biases
3. Determine school biomass	Accomplished	Direct methods shown to be feasible indirect methods currently being calibrated	
4. Determine individual fish size	Accomplished	Acoustic techniques demonstrated as feasible	
5. Distinguish northern anchovy	Accomplished	Acoustic techniques demonstrated as feasible	

Counting Fish Schools and Measuring Their Horizontal Dimensions

The technique for determining the number of fish schools per unit area and their horizontal dimensions has been developed into a practical method and automated with a shipboard computer. All known biases have been investigated and proper corrections applied to the technique (Hewitt, Smith, and Brown, 1976).

A significant source of potential bias, encountered when enumerating schools with sonar, is the variation in effective range caused by internal waves. Temperature and salinity variations, due to internal waves, cause changes in the magnitude of sound velocity. While investigating the expected tidal period of these waves, Smith (1973) noted that variations of equal amplitudes occurred with periods as short as 5 minutes. The implication of short range spatial variations and the infeasibility of collecting coherent sound velocity profiles, led Smith to suggest a statistical approach to the estimation of a probable effective range.

Smith assembled long term hydrographic data for several subregions of the California Current area by month. He then assumed that no fewer than two sound velocity profiles per month-region stratum would be taken and sampling activities were allocated among regions and seasons to reduce the standard error of the mean sound velocity gradient to a uniform value. To illustrate the idea, a portion of his "allocation" table is reproduced here (Table 2).

TABLE 2

An Allocation of Sound Velocity Profiles Among Inshore Areas (0–80 miles from coast) by three regions and 4 months.

	Southern California inshore	Northern Baja California	Southern Baja California
January	2*	2*	3*
April	6	4	5
July	25	14	36
October	23	11	17

* The numbers indicate the number of profiles necessary to equalize the standard error of the mean sound velocity gradient in the upper 30 m.

Table 2 describes the number of sound velocity profiles required to equalize the standard error of the sound velocity gradient among regions and months. It may also be used to determine the optimum time of the year to conduct a sonar mapping survey in a particular region in terms of reducing the variability in effective range caused by thermal changes.

Smith further proposed the construction of a probability diagram to apply corrections to the numbers of targets received at various ranges and depths (Figure 2).

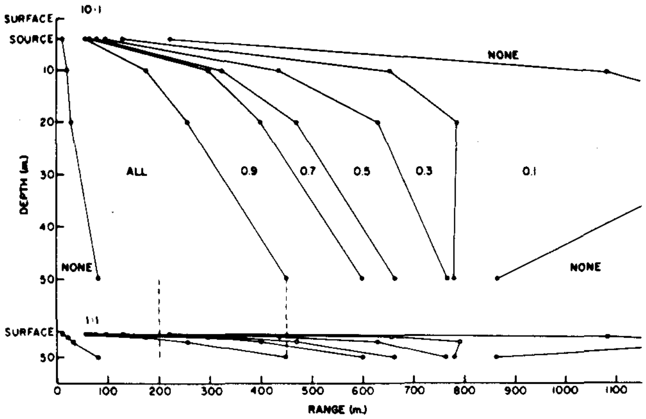

FIGURE 2. A pooled summary of 38 ray trace analyses of limiting range by depth by the probability of detection of −30 db targets (from Smith, 1973). Sound velocity profiles were obtained in October 1972 off the southern California coast.

Mais (1974) discussed, in some detail, his observations from enumerating and measuring fish schools, particularly those composed of northern anchovy. Mais reports the bulk of detected anchovy schools within 50 nautical miles of the coast and the most seaward school ever detected at 165 miles from shore. The north-south range is characterized by an ill-defined limit in northern California to a more abrupt southern limit 100 miles north of the southern tip of Baja California, with the bulk of detected schools off southern California and northern Baja California.

TABLE 3

Summary of Mais' (1974) Observations on Anchovy Schools and Their Constituents by Three Geographic Regions.

	Northern and central California	Southern California and northern Baja California	Central and southern Baja California
Distribution	5% of all detected schools. Bulk of schools within 0.5 miles of shore.	70% of all detected schools. Bulk of schools within 85 miles of shore; largest concentrations within 20 miles of shore.	25% of all detected schools. Bulk of schools within 15 miles of shore.
School types* encountered	I—most common, all seasons III—rare	I—most common, all seasons. II—encountered most frequently in the northern inshore portion of the bight, in the fall. III—encountered most frequently in the southern portion of the bight, in the spring. IV—rare. V—encountered year round in the inshore flats between Santa Barbara and Ventura. VI—encountered rarely in the late summer and fall in the inshore flats between Santa Barbara and Ventura. VII—encountered in the summer.	I—most common, all seasons. V—prevalent school type encountered in the summer and fall. III—encountered in the northern portion of region in the spring.
Age and length	Largest fish—most rapid growth	Slightly smaller fish than north and central California. Moderate growth—larger fish offshore, smaller inshore.	Slowest growth—shortest lived least maximum length.

* See text for explanation of school types.

Mais (1974) also reported a mean vertical school dimension of 12 m and both Mais and Hewitt et al. (1976) reported a median horizontal school diameter of 30 m. Mais further identified and described seven school patterns observed for the northern anchovy. The school types are briefly described below and summarized by region and occurrence (Table 3).

Type I: The most common school type encountered was 5 to 30 m diameter, 4 to 15 m thick (vertical dimension) and 9 to 18 m from the surface. These schools were the dominant type year-round but were detected most frequently during late winter and early spring. The schools were well delinated during the day, dispersing into a thin scattering layer at dusk. This was the only school type found to contain actively spawning fish. These schools were usualy wary and difficult to approach.

Type II: Large schools measuring 25 to 100 m in diameter, 12 to 40 m thick, and 0 to 55 m from the surface were encountered fall through winter over deep water basins and channels adjacent to the coast. These schools dispersed into a coarse scattering layer at dusk and reformed into distinct schools after midnight attaining their densest structures slightly before dawn. Time of schooling reformation occurred progressively later until January or February when it occurred after dawn. These schools were not wary and easy to approach.

Type III: Moderately large and dense schools, highly visible at the surface, and measuring 10 to 100 m in diameter and 12 to 40 m thick were encountered during spring and early summer over basins and channels within 20 miles of the coast. Samples from these schools suggested that the fish were in a postspawning stage.

Type IV: Large and dense schools were infrequently encounted at depths of 120 to 220 m along canyons and excarpments within 5 miles of the coast. These schools were observed to rise to the surface at dusk and form a heavy scattering layer. After midnight, surface schools would reform and submerge to daytime depths at dawn.

Type V: A loose and extensive scattering layer was occasionally observed during all seasons in the shallow flats (<100m) between Santa Barbara and Ventura, California, and in the summer and fall off central Baja California. The scatter was near bottom during daylight hours and formed a thin surface layer at night.

Type VI: Infrequently dense schools were observed in the shallow flats between Santa Barbara and Ventura during the summer and fall. these schools would form a scattering layer at dusk and regroup after midnight.

Type VII: A loose and extensive scattering layer was occasionally observed offshore of southern California during the summer months. Such concentrations were observed during daylight hours and over deep water.

Estimating Biomass

The determination of fish biomass contained in a school cannot at present be considered a practical operation; however, some progress has been made toward developing this capability. Anchovy school biomass is assumed to be a function of schooling densities. A theoretical model of school compaction has been developed to describe the maximum variability one may expect in school densities; two direct methods of sampling school compaction have been employed; and work is continuing with the aim of correlating direct and indirect measures of school compaction.

To gain an idea of school structure and resulting densities, an idealized model may be employed which can be used to compute the space required for a single fish when separated from its neighbors by a specified distance. The inverse of the resulting volume yields the number of fish which may occupy a unit volume for a given interfish spacing.

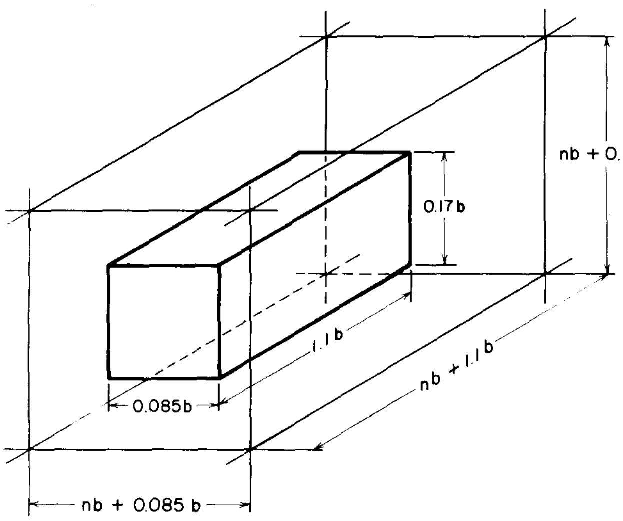

FIGURE 3. Idealized volume required by a single fish of standard length b in a school whose packing density is expressed by an interfish distance of nb.

The standard length, b, of an anchovy is used as the basic measurement. The fish is idealized as a rectangular solid whose dimensions are fractions of b. School structure is idealized by assuming that the fish's six nearest neighbors lie equidistant from the centers of the rectangle's six faces. If the interfish spacing is specified as some multiple of body length, nb, then the required volume for a single fish may be described (Figure 3). The volume, V_n, may be expressed:

$$V_n = (nb + 0.085b) = (nb + 1.1b)(nb + 0.17b)$$
$$= (nb)^3 + 1.355n^2b^3 + 0.2950nb^3 + 0.0159b^3$$

School density, D_n, is the number of fish which may occupy a unit volume for an interfish spacing of nb. D_n may be expressed:

$$D_n = (V_n)^{-1}$$

Using a standard length of 12 cm as typical of anchovy school constituents detected by sonar (Mais, 1974), a range of school densities may be calculated. The minimum spacing which may be attained without interference from the tail beat of adjacent fish is assumed to be 0.2b. The maximum spacing observed to be necessary to retain school integrity under ideal conditions is 10b. Densities have been determined using these maximum and minimum values and three intermediate points (Table 4). A maximum variation in anchovy school compaction of approximately 8,000 fold was estimated using this approach. While the model may be an oversimplification of school structure, it does provide an estimate of the scale of the parameter we are trying to measure.

TABLE 4

Interfish Spacing and Corresponding School Densities as Calculated from an Idealized Model

Interfish spacing in body lengths (nb)	Density fish $(\text{meter})^{-3}$ (D_n)
10	0.51
7	1.41
4	6.66
1	217.08
0.2	4,219.40

Graves (1974) analyzed *in situ* photographs of anchovy schools in order to estimate various schooling parameters, including school density. Three-dimensional analysis of 10 photographs yielded school densities ranging from 50 to 366 fish/m^3. Although this represents only a small portion of the possible range of anchovy school compaction, Graves estimates that the technique may be useful over a range of 1,000 fold, i.e., 0.5 to 500 fish/m^3 (pers. comm.).

Another direct method of sampling school compaction was reported by Hewitt, Smith, and Brown (1976). Horizontal dimensions of 49 anchovy schools were measured acoustically and subsequently captured by commercial purse seiners. Assuming the school vertical dimension to be constant, a horizontal school area to biomass conversion factor was calculated by dividing the weight of the school by its detected area. Hewitt, Smith, and Brown (1976) used the mean of a distribution of this factor (Figure 4) to convert detected horizontal school area to fish biomass on a sonar mapping survey of the Los Angeles Bight. Assuming a vertical school dimension of 12 m and an individual fish weight of 20 g, these factors may be converted to school densities with a range of 0.52 to 533 fish/m^3.

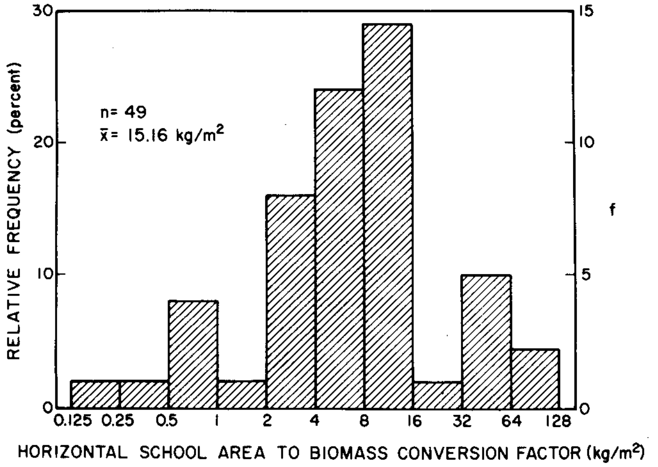

FIGURE 4. Distribution of horizontal school area to biomass conversion factors obtained from the charter boat experiment (from Hewitt, Smith, and Brown, in press).

The ideal method would be to correlate an indirect school measurement, in this case an acoustic parameter, with direct estimates of school compaction and thus establish a remote sensing technique for determining school density. Target strength, the ability of an object to reflect a sound wave, is an acoustic parameter easily measured with proper system calibration and signal digitizing equipment. When recording a peak value of target strength for each school, Hewitt, Smith, and Brown (1976) were able to describe a distribution range of 30 db (1,000 fold).

There are, however, several problems to consider when attempting to relate school target strength with school density. The target strength of a single fish has been shown to vary considerably with aspect by several experimenters (Cushing, 1973). One may expect this condition to exist in an aggregation of fish sharing a common directivity. Secondly, a fish school is neither a solid object nor a point source as considered in classical acoustic theory. Attenuation or absorption of the sound wave in a school must be considered as a complex function of fish aspect, reflection between fish and school density. Lastly, since target strength is measured by sampling a continuous variable (echo power), the calculation of a single value for each school is a function of the sampling frequency and averaging method employed.

Work is ongoing, at the SWFC, with the aim of correlating direct measures of fish school compaction (using camera and capture methods) with indirect measures (target strength). Schools are being insonified from several directions in an attempt to detect school aspect dependence of target strength estimmates. Target strength estimates are being made, using a variety of methods, from echoes which have been digitized at the smallest significant interval. The resulting distributions will be compared in a search to find the most meaningful one. The strategy is not to attempt to describe the interaction of a sound wave and an aggregation of fish, but to define an acoustic measurement, if any, which most accurately represents the school.

Sizing Individual Fish; Distinguishing Northern Anchovy

Holliday (1972, 1973, 1974) approached these related problems from an acoustician's point of view and demonstrated to biologists that meaningful information may be obtained by the application of acoustic theory. He investigated the frequency domain of echoes from pelagic fish schools by examining the resonance structure of echo returns (1972), and by studying the Doppler spread in echo energy (1974).

Using broad-band explosive acoustic sources and narrow-band spectral analysis, Holliday (1972) observed significant resonant structure in five schools. The schools were subsequently sampled and theoretical predictions for the resonant swim bladder response compared with the experimentally observed resonances. Correlation was made (Figure 5), and a method established for remotely determining the presence of swim bladders in an aggregation of pelagic organisms. A relationship between fish size and resonance frequency also was demonstrated. Holliday further suggested that the technique may be used for acoustic determination of weight or length distributions within a species and age determinations within a population.

The resonant frequency technique was modified and extended to underway operation at ship speeds up to 5 knots and described by Holliday in 1973. A towed arcer source, similar to those used for seismic profiling, and a towed hydrophone array were employed to detect significant frequency structure

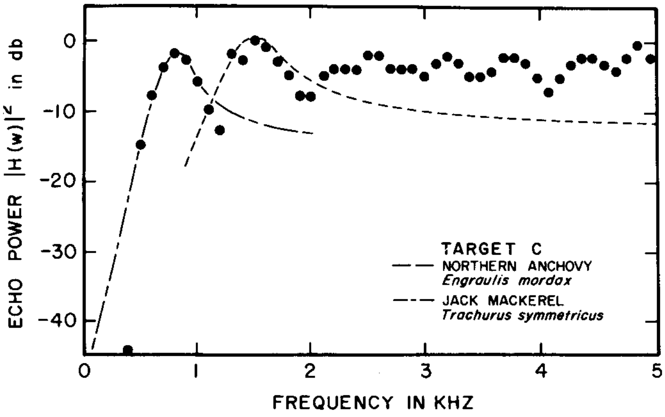

FIGURE 5. An example of the comparison between predicted and observed frequency structure in four echoes from a mixed school of jack mackerel and northern anchovy. The dashed lines represent predicted swim bladder resonance response and the dots represent observed values. The difference between the predicted curve and experimental points above 2 kHz is attributed to scattering from scales, bones, and flesh (Holiday, 1972).

in fish school echo returns (Figure 6). The structure was explained by resonant scattering from fish swim bladders.

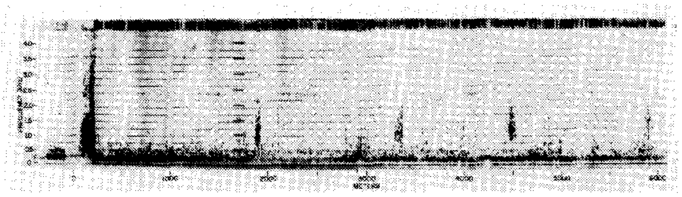

FIGURE 6. Frequency structure in fish schools echoes obtained from an underway survey vessel. Distance along the survey track is displayed on the abscissa; frequency is displayed on the ordinate; and echo energy is displayed as marking intensity (light marks representing less energy than dark marks).

In 1974, Holliday published a study of Doppler energy spread detected in echoes from pelagic fish schools. From the Doppler shift of side aspect echoes, the tail beat velocities of school constituents were calculated. Using Bainbridge's (1960) equation relating swimming speed, length, tail beat amplitude, and tail beat frequency, Holliday calculated the corresponding body lengths. These lengths agreed well with average fish lengths computed from observed school cruising speeds. When examining the Doppler spread from head and tail aspect echoes, Holliday was able to detect swimming behavior characteristics, particularly the accelerate-and-glide swimming behavior associated with northern anchovy and jack mackerel. By knowing the individual fish length and swimming behavior, it may be possible to distinguish northern anchovy from other common pelagic schooling organisms in the California Current area.

The two techniques described above are potentially valuable tools to the fisheries biologist. Additional work must be performed before they can be considered fully developed. In the case of resonance structure, information on the acoustical and physical properties of gas filled swim bladders as a function of depth, season, and geographic location must be obtained. With regard to Doppler structure, additional experimentation and confirmation of results is necessary.

Visual species identification is also possible by examining photographs taken with a free-fall camera* described by Graves (1974). The camera and method for quantifying photographs of fish obtained with it are valuable tools for confirming and calibrating remote sensing techniques.

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* The camera system, commonly called the Isaac-Brown free-fall camera, was designed and built by John Isaacs and Daniel Brown at Scripps Institution of Oceanography.