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Determination of fish size distributions and areal densities using broadband low-frequency measurements

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Broadband low-frequency measurements have been used in conjunction with a fish swimbladder scattering model to determine size distributions and areal densities of well-known populations of dispersed fishes. The method has also been used to identify and estimate the abundance of deep-dwelling fishes that are generally beyond the range of high-frequency echo-sounders. It can also be used to examine swimbladder behavior. Results on five fish species in three widespread locations are presented to demonstrate the capabilities of the method.

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Key words: low-frequency scattering, scattering from fish, swimbladder resonance.

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Introduction

The Naval Research Laboratory (NRL) has been studying low-frequency (0.5–10 kHz) acoustic scattering from fish, using a method that combines at-sea measurements and modeling. This method has potential fisheries research applications for dispersed fishes.

Swimbladders of many fishes resonate in the 1 to 5 kHz range. Thus, low-frequency broadband measurements can provide data at resonance, as well as below (Rayleigh scattering) and above (geometric scattering) resonance. Resonance frequency is inversely proportional to swimbladder size, which can be related to fish size, and scattering levels are directly proportional to numbers of fish. Hence, these measurements, when used in combination with a swimbladder scattering model and general biological information, allow the estimation of sizes and numbers of dispersed fish. Another advantage of low-frequency measurements is their capability to measure fish concentrations below 1000 m depth. The method can also provide information on swimbladder behavior. This paper presents results demonstrating these capabilities.

Methods

Measurements

NRL's measurement technique uses explosive sources and a downward-looking receiver to measure volume scattering strengths (S_v) versus depth over a wide frequency range. Sources are 0.2 kg blocks of TNT detonated 0.5 m below the surface. The receiver, which is deployed just below the hull of the ship, is a 32-element line hydrophone mounted along the axis of a conical reflector. The hydrophone elements can be grouped to provide near-constant beam widths between 2.5 and 20 kHz. Much below 1 kHz, increasing beam width couples with decreasing sensitivity to make the receiver ineffective.

Shot data are processed to produce color plots of S_v as a function of frequency and depth (Figs 1–3). In these figures, the high levels shown near the surface are caused by the direct blast from the source. The plots are analyzed to determine depth ranges in which volume scattering occurred. Integration of S_v over these depths produces layer-scattering strengths (S_L) which are compared to results from the swimbladder scattering model. A full description of data collection and processing methods is given in Love and Thompson (1992).

Swimbladder model

NRL's swimbladder scattering model models a fish as an air-filled viscous spherical shell (Love, 1978). The model calculates the resonance frequency and acoustic cross-section (σ) of a single swimbladder. When the model is applied, corrections for the non-spherical shape of actual swimbladders are included, as are distributions of swimbladder volume to fish weight and fish weight to length. Application of the model is fully described in Love (1993).

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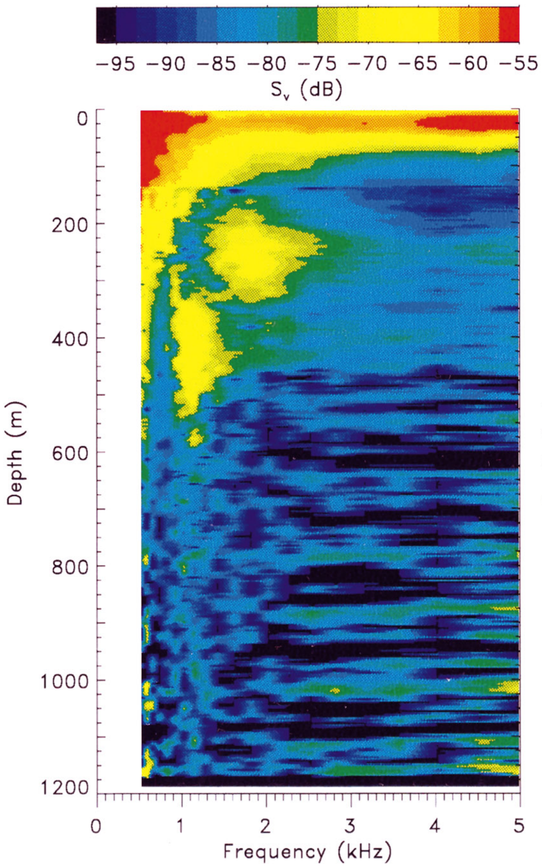

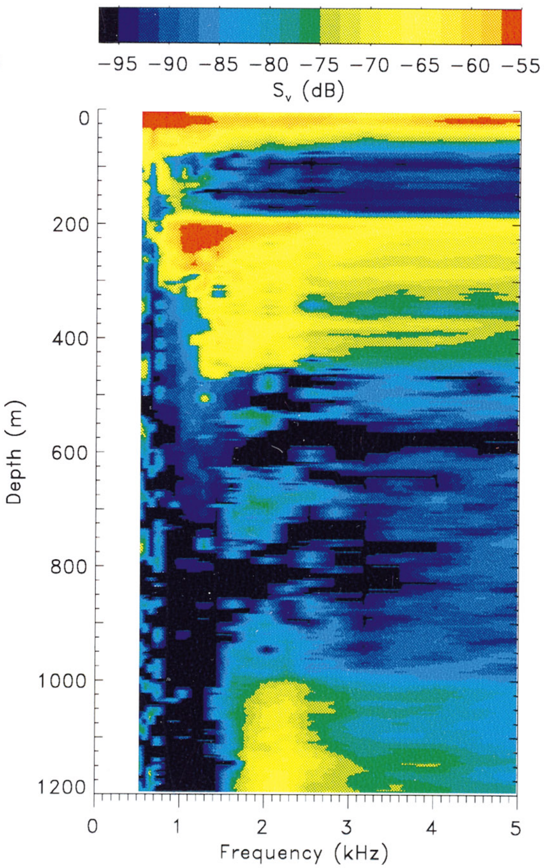

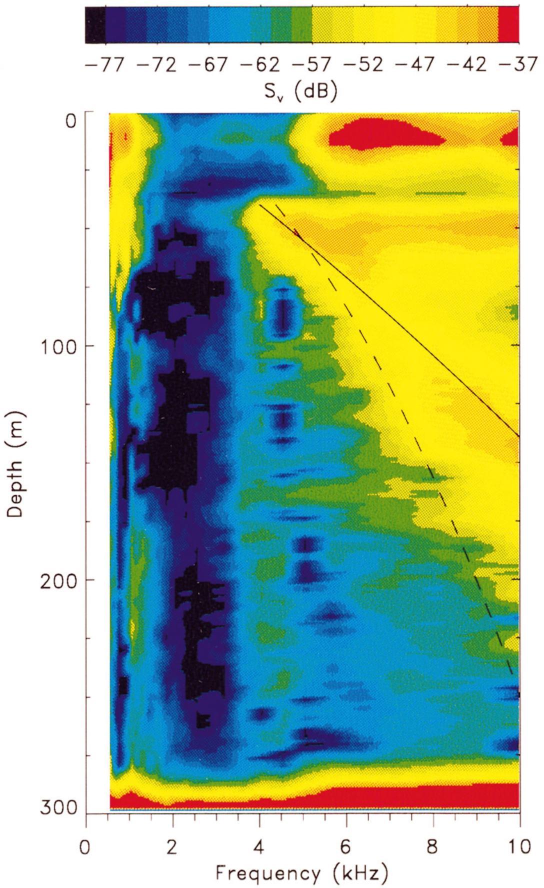

Figure 1 (left). An example of volume scattering strength (S_v) from the central Norwegian Sea.

Figure 2 (middle). An example of volume scattering strength (S_v) from the continental slope off Oregon.

Figure 3 (right). An example of volume scattering strength (S_v) from the western Gulf of Oman. Dotted line = resonance frequency of a swimbladder of constant size as a function of depth. Solid line = resonance frequency of a swimbladder that compresses with depth according to Boyle's Law.

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To compare model results with acoustic data, curves of layer strength versus frequency are calculated. Conceptually, S_L is the logarithm of the sum of σ of each fish within a column of unit area extending through the layer. In practice, S_L is determined by calculating a normalized σ which is multiplied by an areal density of individuals m^{-2}. The model is applicable only to dispersed fish because it assumes that there are no acoustic interactions between fishes.

Fish size and depth distributions determine the shape of the model curve and density controls its overall level. In NRL's work, depths are determined from the acoustic results and sizes are usually obtained from the best available independent fisheries data. Fish density is then the only free parameter; it is adjusted to best match the level of the data curve, providing a quantitative measure of populations of dispersed fish. A different approach is to vary both size and density to obtain the best fit between data and model. This approach can provide both size distributions and numbers of fish but can produce erroneous results because small variations in the acoustic results can cause large changes in calculated size distributions.

Results

Examples of results from three experiments are presented to illustrate the method: one in the Norwegian Sea in July 1991, another off the west coast of the United States in August 1992, and the third in the Gulf of Oman in May–June 1994. The upper frequency limit was 5 kHz for the first two experiments and 10 kHz for the third.

Norwegian Sea

Figure 1 is an S_v plot from a location in the central Norwegian Sea. Two distinct layers can be seen. The shallower layer, between about 150 and 350 m, has a resonance peak between 1.5 and 2 kHz. The deeper layer, between 300 and 550 m, peaks near 1 kHz.

During the 1980s, European fisheries laboratories regularly conducted summertime acoustic assessment surveys of blue whiting (*Micromesistius poutassou* Risso) in the Norwegian Sea. By 1991 these surveys had stopped because the fish were dispersed at depth at such low densities that the 38 kHz echo-sounders then generally in use could not provide accurate assessments (Monstad, 1992). Redfish (*Sebastes* spp.) were also known to occur in limited numbers over deep waters of the Norwegian Sea, but because the redfish fishery is confined to the slope, they had never been assessed in off-slope waters (Nedreaas, 1992).

Length distributions of blue whiting and redfish obtained by the Institute of Marine Research during April and October 1991, respectively, were used in the swimbladder model. The comparison of model results to the data (Fig. 4) showed that blue whiting, at a density of 0.008 individuals m^{-2}, could produce the shallower layer and that redfish, at a density of 0.004 individuals m^{-2}, could produce the deeper layer.

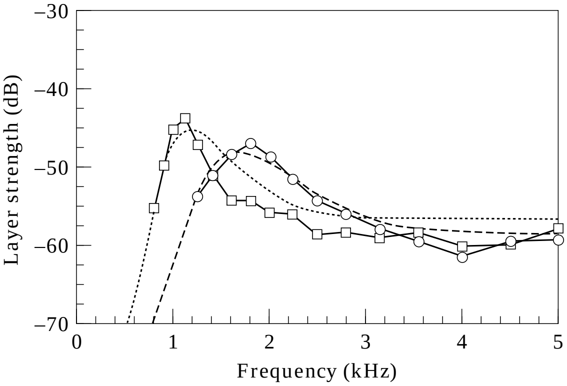

Figure 4. Comparison of measured and modeled layer-scattering strengths from the central Norwegian Sea. Measured data: circles = shallow layer; squares = deep layer. Model results: dashed line = blue whiting at 0.008 individuals m^{-2}; dotted line = redfish at 0.004 individuals m^{-2}.

US West Coast

Figure 2 is an S_v plot from a location on the continental slope off Oregon. The stronger shallower layer, between about 200 and 450 m, peaks between 1 and 1.5 kHz. The weaker, deeper layer, which extends from about 1000 m to the bottom (at 1260 m), peaks near 2 kHz.

National Marine Fisheries Service (NMFS) data had indicated that Pacific hake (*Merluccius productus* Ayres) would be a major contributor to volume scattering in this region. When size distributions obtained from NMFS trawls collected at a nearby location during July 1992 were used in the swimbladder model, the model–data comparison indicated that Pacific hake at a density of 0.08 individuals m^{-2} could produce the shallower layer (Fig. 5).

No fish of present commercial importance exist at the great depths of the deeper layer. Therefore, no fisheries data were available. However, deepwater scientific trawls conducted by Oregon State University (OSU) had caught several adult pelagic grenadiers (*Coryphaenoides* spp.) in the experimental area (Pearcy, 1976). Adult grenadiers are generally considered bottom dwellers, and OSU has conducted a relatively extensive series of bottom trawls to study bottom-dwelling grenadiers (Pearcy *et al.*, 1982). Using grenadier size distributions and densities (0.008 individuals m^{-2}) from OSU bottom trawls in the swimbladder model gave excellent agreement with the acoustic data (Fig. 5), indicating that grenadiers are the likely cause of the deeper layer. Measurements at eight sites along the California,

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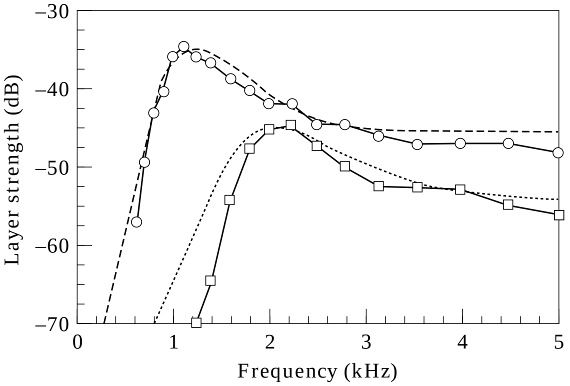

Figure 5. Comparison of measured and modeled layer-scattering strengths off Oregon. Measured data: circles = shallow layer; squares = deep layer. Model results: dashed line = hake at 0.08 individuals m^{-2}; dotted line = grenadiers at 0.008 individuals m^{-2}.

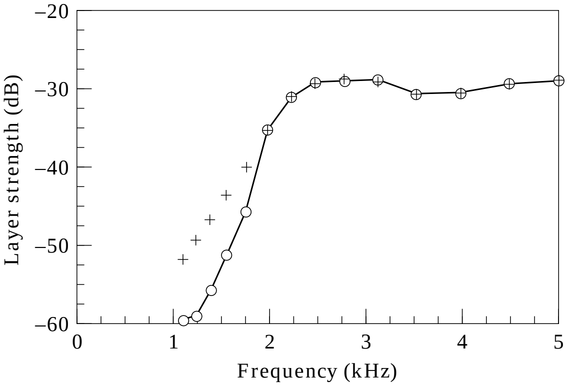

Figure 6. Comparison of measured and modeled layer-scattering strengths from the Gulf of Oman. Measured data: circles. Model results: crosses.

Oregon, and Washington coasts suggest that these fish are widespread in pelagic waters over bottom depths greater than 1000 m, with pelagic densities comparable to bottom densities.

Gulf of Oman

Fishery surveys in the Gulf of Oman have indicated that a small myctophid, *Benthosema pterotum* (Alcock), totally dominates the fish population. Abundance estimates have been made from 38 kHz acoustic surveys (Aglen *et al.*, 1982). However, there has been some question about the state of *B. pterotum* swimbladders throughout the diurnal cycle and how that might affect 38 kHz stock assessments (Sætersdal, 1994).

Broadband measurements and modeling can address this question. Figures 3 is an S_v plot from a location in 290 m of water at the western end of the Gulf of Oman. Two features are notable: the first is the very strong layer between 40 and 65 m, with maximum scattering strengths around 5 kHz; the second is that the frequency of maximum scattering increases rapidly with depth between about 75 and 150 m. This measurement was conducted about 4 h after sunset, well after the upward migration from daytime depths should have been completed.

The first objective was to determine if the scattering was produced by *B. pterotum*. Aglen *et al.* (1982) show a number of length distributions for *B. pterotum* in the Gulf of Oman, with lengths ranging from 10–45 mm. However, no information on weight–length relationships or on swimbladder volumes was available, so data on *Benthosema glaciale* (Reinhardt) in the Mediterranean Sea were used (Gibbs *et al.*, 1972). Rather than attempting to select the proper length distribution from Aglen *et al.* in the direct application of the swimbladder model, Holliday's (1977) inversion technique was combined with the model to determine what length distribution was required to match the S_L curve for the 40–65 m layer (Fig. 6). The results indicate that a distribution of fish between 15 and 45 mm long, with the assumed swimbladder sizes of *B. pterotum*, can match the data quite well, except at low frequencies, where the data decrease more rapidly than Rayleigh scattering. Thus, it is quite likely that the 50 m layer was produced by *B. pterotum*.

If swimbladder volume remains constant with depth, resonance frequency is proportional to the square root of the pressure. However, if swimbladder mass is constant and swimbladders compress according to Boyle's Law, resonance frequency is proportional to pressure to the 5/6 power. These two relationships are shown in Figure 3, each starting with a resonance frequency of 5 kHz at 55 m. The constant mass curve follows the frequency of maximum scattering much better than the constant volume curve.

If the size distribution of *B. pterotum* is constant with depth, then these results indicate that *B. pterotum* swimbladders compress with depth. These results, from one measurement in a rather shallow location, are not definitive proof of *B. pterotum* swimbladder behavior. However, they do illustrate that proper broadband measurements can provide that proof.

Discussion

These three examples demonstrate that the combination of broadband measurements of low-frequency scattering strengths and modeling of swimbladder scattering can have applications in fisheries research. One application of this method is the simultaneous determination of size distributions and abundances of known fish stocks. The method could be particularly useful for fish at great depths. It can also be used to examine swimbladder

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behavior, differentiate between species with different swimbladder characteristics, and, with a little biological information, identify species. In some cases the difficult logistics of making broadband low-frequency measurements can outweigh the advantages, but there will be other cases where the low frequency method is the only alternative.

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