Bioacoustic Attenuation Spectroscopy: A New Approach to Monitoring Fish at Sea

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Introduction

How does one find fishes in the sea? For millennia, catching fish has depended on luck for a fisherman out for a day of recreation and both luck and knowledge of fish behavior and ecological preferences for those seeking larger catches. Still, in many ways, finding fish, especially in large quantities, was a "shot in the dark." However, this started to change when fisheries biologists started to apply acoustics to the hunt for fishes. The various approaches that have been used and that continue to evolve now enable fishers not only to find large groups of fish more efficiently and effectively but also to enable fishery biologists to quantify the number of fish in areas of interest, their migration patterns, and how their numbers evolve over time as well as other aspects of their behavior.

The purpose of this article is to provide a brief historical review of acoustic approaches to fishery biology, discuss the limitations of these approaches, and describe bioacoustic attenuation spectroscopy (BAS), a new and promising acoustic approach that has the potential to revolutionize fishery biology. The BAS approach is essentially noninvasive, provides measures of fish abundance and the number of fish in a region, and can even estimate the number of fishes of different lengths in the ensonified region.

The most important practical application of research in fisheries acoustics is the estimation of the abundance of species that are of commercial interest. This information is used by government agencies to set limits on commercial fishing.

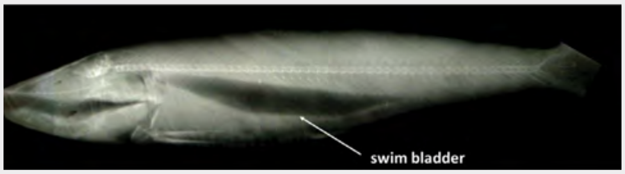
Interactions Between Fish and Sound

Before reviewing the history of sonar methods to detect fish, first I review the basic physics of sound interaction with fish. The majority of species of bony fishes that occur in large numbers have a swim bladder, which is an elongated, air-filled chamber located in the abdominal cavity. Swim bladders provide buoyancy and enable fish to be neutrally buoyant at their preferred depth between bouts of vigorous swimming (Helfman et al., 2009). The size of the swim bladder varies by species and is often related to the size of the species. Although the swim bladder probably evolved to provide buoyancy to the fish, it is also involved in other functions such as hearing and sound production in many species (e.g., Popper and Hawkins, 2019).

Figure 1 shows an X-ray image of a side view of the swim bladder of a pilchard sardine (*Sardinops ocellatus*). Because swim bladders are generally filled with air, they scatter sound in various directions and are the primary cause of backscattering and the echoes detected by fisheries sonars. Fisheries scientists employ a concept called target strength (TS) to describe how much energy is reflected in the backscattered direction by an individual fish. TS increases with the size of the swim bladder.

As sound propagates through an aggregation of fish, each encounter with a fish within the aggregation causes some of the energy to be scattered in various directions, including sound that is backscattered, as illustrated in **Figure 2**. As a result, each encounter with each fish within the aggregation diminishes the energy of the sound propagating in the forward direction (**Figure 2**, *red arrows*).

Figure 1. *X-ray image of the of the swim bladder of a pilchard sardine (*Sardinops ocellatus*). Anterior is to the left. Image courtesy of John Horne, University of Washington, Seattle.*



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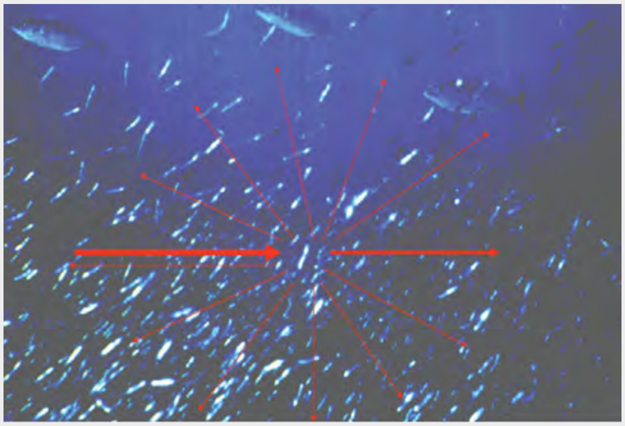


Figure 2. *Sound from a source at the left incident (**thick red arrow**) on a fish is scattered in various directions (**thin red arrows**). Note that the energy level of sound propagating in the forward direction at the right (**thick red arrow**) is diminished.*

Scattering and attenuation are manifestations of the same process. The loss in acoustic signal level versus range is called biological attenuation. The physics-based concept of attenuation coefficient, which may be expressed in decibels per meter, describes the magnitude of this effect. As a result of biological attenuation, interpretation of back-scattered energy (echoes) from an aggregation of fish is complicated by the fact that echo levels are controlled not only by the TS of the fish at a specified range but also by the attenuation coefficient due to all the fish between the echo sounder and the specified range.

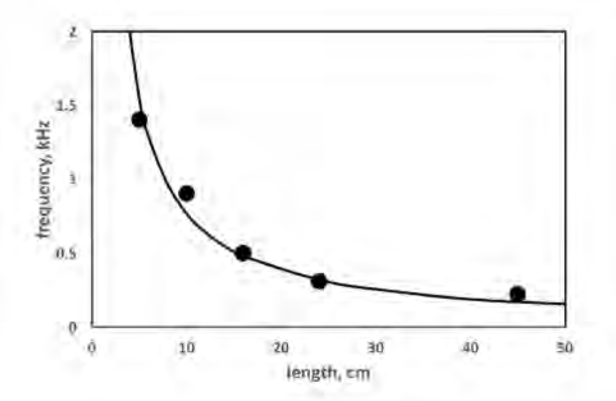
It is ironic that the BAS method, described here as a new approach to fish monitoring, has its roots in the first documented successful demonstration of the use of sound to detect fish (Kimura, 1929). Kimura installed a sound transmitter and a hydrophone on opposite ends of a pond. The distance between the transmitter and receiving hydrophone was 43 m. The pond was sufficiently shallow, less than 4.5 m, so that he was able to observe the movements of schools of fish. He transmitted a continuous signal at one frequency for long periods of time. When there were no fish between the transmitter and hydrophone, he heard a continuous hum. When a school of fish passed through the acoustic path between the transmitter and hydrophone, the acoustic signal fluctuated as a result of time variable attenuation.

Swim Bladder Resonance

Swim bladders, being air-filled bubbles, resonate at frequencies (f_0).that are controlled primarily by the effective radius (r; the radius of a spherical bubble with the same volume as the swim bladder) and to a small extent by the eccentricity (e; the ratio of the major and minor axes) of the swim bladder. To a good approximation, $r = 0.044L$, where L is the fish length in centimeters. **Figure 3** illustrates how f_0 varies as a function of fish length and provides experimental measures of f_0 at the surface, which were extrapolated from at-sea measurements of f_0 at other depths at sites where the dominant species and their depths were known. The three highest values of f_0 were derived from attenuation measurements, whereas the two lowest values of f_0 were derived from backscatter measurements (Nero et al., 1998; Stanton et al., 2010). The depth dependence of f_0 is discussed in **A Brief Historical Review of Fisheries Sonar**.

The relationship between fish length and f_0 illustrated in **Figure 3** is valid only when fish are far apart (many fish lengths) and each fish is free to resonate. When fish are in schools in which the separation between fish is less than two fish lengths (Pitcher and Parrish,1993), then the close proximity between fish dampens the resonances of each fish and causes the school to act as a "bubble cloud" that resonates at a lower frequency (F; Diachok, 1999; Raveneau and Feuillade, 2015). F decreases as the average separation between fish decreases and, in the (admittedly unrealistic) limit of zero separation, approaches the resonance frequency of a large bubble formed by the swim bladders of all of the fish within the school.

Figure 3. *Measurements (**circles**) and calculations (**line**) of the resonance frequency of fish swim bladders at the surface versus fish length.*



TS and biological attenuation, which are much greater at f_0 than at other frequencies, are controlled by the magnitudes of r, f_0, and the number of fish per cubic meter, known as the number density. Consequently, measurement of f_0 and the magnitude of the attenuation coefficient at f_0 permits calculation of the number density versus fish length. This is possible using the well-established theory for when fish are far apart (Medwin and Clay, 1997). A more sophisticated theory, however, is required to infer the number densities when fish are in close proximity in schools (Raveneau and Feuillade, 2015).

A Brief Historical Review of Fisheries Sonar

Sonar as Fish Finder

The development of transducers, which was driven by the need to detect and track submarines near the end of World War I, paved the way for the development of fisheries sonar. The feasibility of the sonar detection of fish was first reported by Sund (1935), who detected the presence of Atlantic cod (*Gadus morhua*) in the wild. Developments in sonar technology during and after World War II also led to an increased sophistication of fisheries sonar. By the 1970s, echo sounders were widely employed by fishers and fisheries scientists to find fish (MacLennan and Simmonds, 1991). It was, no doubt, apparent that large fish produce strong echoes and small fish produce weak echoes when both are at the same range. However, the lack of quantitative knowledge of the TS of fish precluded an estimation of abundance.

Target Strength of Individual Fish: The Basis for Estimation of Abundance

Subsequently, new instruments, called split beam echo sounders, which were developed in the late 1970s, permitted measurement of the TS of individual fish in the wild (Ehrenberg, 1979). Split beam sonars have four crystals that permit measurement of the TS of fish as function of their orientation. At frequencies of echo sounders, the TS of swim bladders is extremely sensitive to fish orientation. Because they are horizontally elongated, swim bladders act almost like small mirrors, which cause reflected echoes to be very strong only when the swim bladders are nearly perpendicular to the direction of the sonar beam. This technological development transformed echo sounders from being merely fish finders to a tool for abundance estimation.

Knowledge of TS is a prerequisite for the estimation of fish abundance. As a result, the swim bladder and how it affects the TS have received much attention by the fisheries science community (Stanton, 2012). Extensive measurements have revealed that TS is species dependent. In particular, the TS of species that cannot control the amount of gas in their swim bladders (known as physostomes), such as sardines and anchovies, decreases with the depth of the animal. Because this change is understood, it is possible to predict how the resonance frequency changes with depth. In contrast, the TS of species that can control the amount of gas in their swim bladders (known as physoclists), such as cod and hake, is independent of depth. These species are able to adjust the amount of gas in their swim bladders through special secretory mechanisms, but the process is slow. Thus, when a physoclist changes depth, its swim bladder requires hours to adjust to the new depth. As a result of the long timescale of this process, the TS of physoclists may not be readily predictable, especially after changes in depth (see Helfman et al., 2009, for a discussion of swim bladder filling mechanisms).

Effect of Biological Attenuation on Echo Level

Because measured echo levels are controlled not only by the TS of fish at a specified depth but also by the attenuation due to all the fish between the sonar and the specified depth, initial estimates of fish abundance were biased by disregarding this effect. Biological attenuation due to fish was measured and theoretical corrections for the effect of sound attenuation on echo level were developed by Foote (1990). The magnitude of this effect is species dependent and increases with the size and number density of the fish at each depth that are generally not known because concurrent trawls generally provide information on species composition usually at only one depth.

Estimation of fish abundance assumes that echo sounders are capable of detecting the species of interest, independent of their depth. Fisheries echo sounders, being hull mounted, cannot detect fish near the surface. Commercially important species, such as sardines and anchovies, that are generally assumed to reside at depths far from the surface have in fact been observed in large numbers near the surface (Scalabrin et al., 2007). Hull-mounted echo sounders are also ineffective at discriminating between echoes from fish that are near the bottom and those at the bottom. As a result, they are not capable of monitoring bottom-dwelling species, such as flatfish (e.g., flounder).

Ship Avoidance and Sonar

Estimation of fish abundance also assumes that echo sounder measurements do not affect the behavior of the species being measured. Unfortunately, hull-mounted echo sounder measurements are plagued by the problem of ship avoidance. As a ship approaches, fish dive to greater depths and to the left and right of the track of the ship, thereby reducing the number of fish beneath the echo sounder. This phenomenon biases estimates of fish abundance (Scalabrin et al., 2007).

In recognition of the severity of the avoidance problem, an international committee of fisheries scientists conducted a comprehensive review of the literature on ship avoidance, concluded that its main cause is acoustic noise from the engines of the ship, and recommended construction of quiet ships. Many quiet ships were built for use by fisheries biologists. Unfortunately, ship avoidance of the new quiet ships was just as severe as ship avoidance of the older, noisy vessels (Ona et al., 2007). A possible explanation is that fish respond to the pressure wave of approaching vessels rather than to the acoustic noise of engines.

In view of this apparently unsolvable problem, recent research has focused on removing echo sounders from ships and placing them on autonomous underwater vehicles (AUVs; Scalabrin et al., 2007) and wave glider-based systems (Greene et al., 2014). These approaches will improve the quality of echo sounder measurements because they will not be affected by the ship avoidance phenomenon and will permit measurements of fish near the surface.

Another approach for eliminating the ship avoidance problem is to deploy echo sounders in an upward-looking mode on the bottom. This approach provides unbiased data of scientific interest (Kaltenberg and Benoit-Bird, 2009) but is not suitable for estimating fish abundance in large areas of commercial interest because these devices only detect fish in specific locations.

Bioacoustic Backscatter Spectroscopy

Early Impulsive Source Measurements

During the 1960s and 1970s, extensive research on swim bladder resonance was conducted in support of new, low-frequency naval sonars. This research was motivated by need of the United States and other navies to understand the effects of echoes from fish aggregations on the detection of submarines and was focused on the bioacoustics of myctophids, a group of species that reside primarily in the deep ocean during the day but that move toward the surface at night (Farquhar, 1970). The scientific measurements utilized impulsive devices (usually explosives) to generate broadband sound at frequencies between about 100 Hz and several kilohertz and an array of hydrophones to determine the depth of fish-reflected echoes. Measured resonance frequencies were consistent with the theoretical calculations of the resonance frequencies of myctophids (Chapman et al., 1974).

Modern Directional Sonar Measurements

In recent years, impulsive devices were replaced by directional, broadband transducers (Nero et al., 1998; Stanton et al., 2010). Stanton et al. (2010) adapted a commercial, highly directional subbottom profiler with a source level (SL) of about 197 dB re 1 μPa root-mean-square (rms) to measure the frequency dependence of echoes from fish at resonance frequencies. The SL is defined as the level of sound at 1 m from the source. As a result of its high directionality, this source is unlikely to affect marine mammal behavior unless the animal is directly beneath the beam. Stanton et al. (2010) measured the resonance frequency of 25-cm-long herring *Clupea harengus*, the dominant species at their measurement site, and demonstrated consistency with theoretical calculations. Because the source is towed behind a ship, this configuration is limited to the detection of fish that are below the wake of the ship. The resultant measurements may be biased by changes in fish behavior in response to high-level acoustic signals, particularly at their resonance frequencies, at short distances from the source.

Long-Range Sonar Measurements

Much more powerful broadband sonars, which operate at low frequencies, have been employed to measure the frequency dependence of backscattered echoes from fish in the vicinity of their resonance frequencies at ranges of about 100 km. A major benefit of this approach is that it provides a synoptic view of the synchronized changes in fish behavior over areas as large as about 100 km (Makris et al., 2006). Interpretation of the resultant measurements, however, is limited by uncertainties in sound propagation, the inability to estimate the depths of fish aggregations, and the lack of corroborating biological data. This approach requires a very high SL, about 230 dB re 1 μPa rms, that may affect the behavior of both marine mammals and fish at long ranges from the source.

Interpretation of Bioacoustic Backscatter Spectroscopy Measurements and Biological Attenuation

As mentioned in the **Introduction**, interpretation of bioacoustic backscatter spectroscopy (BBS) data is complicated by the fact that echo levels are affected not only by the TS of fish at a specified range but also by the effect of biological attenuation due to fish between the sonar and the specified range (Weston and Andrews, 1990), except when there are no fish between the sonar and fish at the specified range. The two lowest resonance frequencies, shown in **Figure 3** (Nero et al., 1998; Stanton et al., 2010), were derived from BBS measurements at sites where there were no fish between the sonar and the targeted layers of fish. Duane et al.'s (2019) experiment at the resonance frequency of a species (possibly herring) showed that a spatially well-defined aggregation of fish at short range, which moved in front of a spatially well-defined aggregation of fish at long range, dramatically reduced the magnitude of the echoes from the more distant aggregation. Qiu et al. (1999) conducted the only known concurrent measurements of attenuation and backscattering from fish at the resonance frequency of the fish. The attenuation coefficient peaked at the resonance frequency of dispersed Japanese anchovies (*Engraulis japonicus*), consistent with theoretical calculations (Diachok and Wales, 2005), whereas backscattered levels exhibited a minimum, instead of the theoretically expected maximum, at the resonance frequency as a result of biological attenuation.

Bioacoustic Attenuation Spectroscopy

Experimental Approach

The alternate approach to exploit swim bladder resonance is to measure attenuation due to the presence of fish between a source and a receiving hydrophone. The geometrical configuration for this approach, bioacoustic attenuation spectroscopy (BAS), is illustrated in **Figure 4**. A broadband source is suspended from a ship, and a hydrophone array is deployed between a near-surface float and an anchor at a range of between 1 and 10 km from the source. The vertical array permits measurement of how the layer of fish affects attenuation as a function of hydrophone depth. This information may be used to infer the depth of the fish layer (Diachok and Wales, 2005). The acoustic source must cover the frequency band that includes the resonance frequencies of the species that are expected to be present at the measurement site, ideally between 100 Hz and 10 kHz. The level of the received signal is affected by the number and size of the fishes that come between the source and receiver. Proper analysis of the received signal can tell us a great deal about the fish.

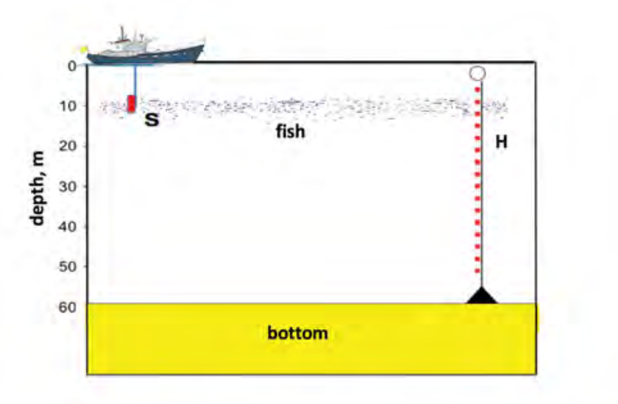


Figure 4. *Geometrical configuration for measurement of biological attenuation due to a layer of fish, including a broadband source (S;* ***red rectangle****) deployed from a ship and a fixed hydrophone array (H;* ***red circles****).*

Because all fishes hear low frequencies and some may hear above 3 kHz, they may react to some sounds if the sounds are sufficiently loud (Doksæter et al., 2009; Popper and Hawkins, 2019). To minimize the effects of acoustic signals on fish behavior, sources used in BAS experiments were programmed to generate a sequence of 1-second-long continuous-wave (CW) signals, with very low SLs (Diachok, 1999, 2005). These are similar to the sequence of tones one hears during a hearing test. By contrast with conventional and low-frequency sonars, BAS measurements may be conducted with a SL as low as 170 dB re 1 μPa rms at ranges less than 10 km. At this SL, only those fishes that are in very close proximity to the source may detect or react to the sounds and change their behavior. This effect is unlikely to bias BAS measurements, which provide information about fish over a much greater distance. As a consequence, the BAS method is not likely to alter fish behavior.

Why can BAS measurements be conducted with such a low SL, whereas BBS measurements require such a high SL? BAS measurements are subject to one-way transmission loss (TL) between the source and the hydrophone. TL is defined as the loss in signal level between one meter and another range. One-way TL is 60 dB at 1 km (due to spherical spreading), whereas BBS measurements are subject to two-way TL between the source to the fish and then from the fish to the sonar. The resultant TL is twice as large, 120 dB at 1 km. So, detection of fish with BBS at 1 km requires a SL, which is 60 dB louder than with BAS.

If there are no fish present between the source and the receiving array, then signal levels recorded by the hydrophone array will be relatively loud and measured levels will be in accord with theoretical levels derived from TL models. TL models account for geometrical spreading loss, chemical absorption loss, and loss in signal level due to sound transmission into the bottom.

If a large number of fish are present between the source and the hydrophone array, then the fish will cause excess (biological) attenuation. Biological attenuation will be maximum at the resonance frequency of the fish. The biological attenuation coefficient (A), in decibels per kilometer, may be derived from measurements of signal level versus range by towing the source. If the source is fixed, then biological attenuation coefficients may be calculated by comparing measured levels with calculated levels of received levels that account for all causes of attenuation except biological attenuation.

Discovery of Biological Attenuation at Resonance Frequencies

David Weston (1967) discovered that biological attenuation peaks at the resonance frequencies of fish fortuitously as a result of routine measurements of TL in support of engineering tests of an experimental Navy sonar. To his surprise, sound attenuation was generally much higher at night than during the day and that transitions occurred during morning and evening twilight throughout the year (Ching and Weston, 1971). During months when sardines were present, differences in TL between night and day were generally about 15 dB and occasionally as high as 40 dB at some frequencies. During months when sardines were absent, the difference between night and day was essentially zero at all frequencies.

Ching and Weston (1971) attributed the diurnal variability in attenuation to diurnal changes in fish behavior. Pilchard sardines, the dominant species in the Bristol Channel where he worked, generally disperse at night and school during the day. Weston speculated that the low levels of attenuation during the day may be due to interference between reflections from nearby fish in schools, a phenomenon that would dampen the resonance of individual fish. Attenuation at night tended to peak at frequencies of 0.7 and 3.5 kHz. Weston attributed the resonance at 0.7 kHz to pilchard sardines with a mean length of 24 cm and the resonance at 3.5 kHz, which was mostly evident a few months after the spawning season, to juvenile sardines (Ching and Weston, 1971).

Biological Attenuation: Day Versus Night

Inspired by Weston's (1967) compelling acoustic observations, Diachok (1999) conducted a BAS experiment. The objectives were to demonstrate that resonance frequencies of dispersed fish at night were due to the dominant species at the measurement site and to determine the cause(s) of the difference in biological attenuation during night and day. Concurrent trawls revealed that the 16-cm European pilchard (*Sardina pilchardus*) was the dominant species at this site. A ship-mounted echo sounder provided measurements of the depths and schooling behavior of this species. Concurrent echo sounder data showed that fish were dispersed at night at a depth of 20 m, descended to 65 m during dawn, and formed schools at 65 m a few minutes after sunrise.

TL measurements were made at many frequencies between 0.7 and 5 kHz along a track with constant depth, parallel to the shoreline, to simplify data interpretation and modeling.

Figure 5 shows measurements and theoretical calculations of resonance frequencies of dispersed European pilchard (f_0), and schools (F). The diameter of the data points is proportional to the magnitude of biological attenuation at the resonance frequencies. Measurements of resonance frequencies at night of 1.2 kHz at 20 m and at sunrise of 2.7 kHz at 65 m are consistent with theoretical calculations of the resonance frequencies of dispersed 16-cm sardines. The increase in frequency from 1.2 kHz at night to 2.7 kHz at sunrise is driven by the decrease in the effective radius of European pilchard swim bladders as they descend from 20 to 65 m. The measurement of the resonance frequency at 1.6 kHz at

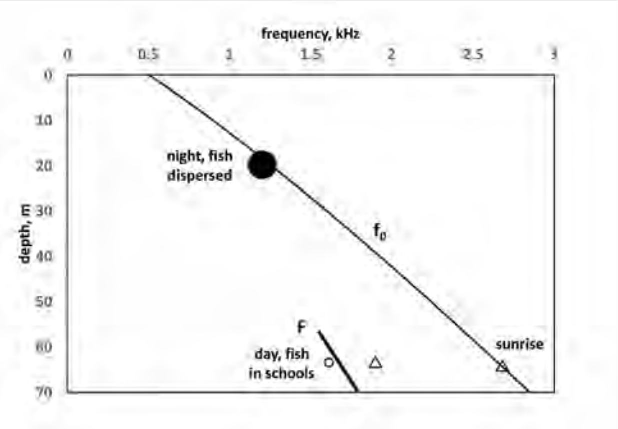


Figure 5. *Measurements of resonance frequencies of 16-cm sardines in dispersed* (f_0) *and school* (F) *modes during night* (***solid circle***)*, sunrise* (***open triangles***) *and day* (***open circle***)*. The diameters of the symbols are proportional to the magnitudes of the attenuation coefficients at* f_0 *and* F*. Theoretical calculations of* F *are from Raveneau and Feuillade, 2015.*

65 m during the day is consistent with Raveneau and Feuillade's (2015) theoretical calculations of the resonance frequency of European pilchard schools.

Figure 5 also shows that biological attenuation was highest during night when the fish were dispersed and lowest during the day when the fish were in schools. The transition occurred during sunrise when some of the fish were dispersed and some were in schools. Why is attenuation due to fish in schools during the day much lower than attenuation due to dispersed fish at night? Theoretical calculations indicate that Ching and Weston's (1971) speculation was essentially correct. The difference in biological attenuation between night and day is driven primarily by the difference in the separation between fish in dispersed and school modes and, to a lesser extent, by the difference in the effective radius of swim bladders (Diachok, 1999; Raveneau and Feuillade, 2015).

Possible Practical Applications of Bioacoustic Attenuation Spectroscopy

The measurement approach, illustrated in **Figure 4**, is well-suited to test scientific hypotheses but is too cumbersome for practical applications. In particular, a vertical array that spans most of the water column is difficult and time consuming to deploy and recover. Furthermore, such an array is not needed for practical applications. Diachok and Wales (2005) showed that the bioacoustic parameters of an aggregation of fish may be inferred from TL measurements with hydrophones at two depths. There are several technologically mature approaches that would permit BAS measurements with a small number of hydrophones. Consideration of the relative merits of these approaches is beyond the scope of this article.

Because TL is affected not only by bioattenuation but also by the geoacoustic properties of the bottom, the latter would have to be measured in areas of interest. The geoacoustic properties of the bottom could be measured with direct methods (e.g., Turgut, 1990), inverted (derived) from TL data in the absence of fish or inverted from the application of the concurrent inversion method (Diachok and Wales, 2005) in the presence of fish. The usefulness of information derived from BAS measurements would probably have to be initially demonstrated by fisheries scientists charged with estimating fish abundance and could eventually be employed by fishers to reduce the vast bycatch (unwanted species) that fishers routinely catch and discard daily throughout our oceans.

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About the Author

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Orest Diachok has made significant contributions to arctic acoustics, geoacoustics of the upper crust, and matched-field processing, a powerful acoustical method for studying the ocean. During his tour as chief scientist at the NATO Undersea Research Centre (1970–1975), he met David Weston and, as a result of numerous discussions, became a convert to marine bioacoustics and designed the first interdisciplinary bioattenuation experiment. Orest enjoys traveling, hiking in national parks, and playing billiards. He loves Puccini arias, BB King laments, and Ukrainian and American folk songs. He is happily married to Olha and has two sons, Mateo and Mark.