

COUNTING CRITTERS IN THE SEA USING ACTIVE ACOUSTICS

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Introduction

A few years after I finished graduate school, I was a contestant on the TV game show “Jeopardy,” where my performance could generously be described as terrible. During the between-rounds Question and Answer (Q&A) segment with host Alex Trebek, we talked about my research on Antarctic krill and he asked me a simple question. “How many krill does a whale eat when it opens its mouth and takes a gulp?” I froze and realized I had no idea what the answer was to his question. Having attended a few scientific conferences at this point in my career, I knew how to respond to a question like this: sound knowledgeable, speak confidently, and answer a different question. So I told him that each gulp is about the size of a small car like a Volkswagen bug. A decade later, I still can’t answer Trebek’s question, but I can at least make an educated estimate based on field-collected data from my research. And it’s all because of underwater acoustics.

Terrestrial acousticians (my name for those whose research doesn’t occasionally involve seasickness) may be unfamiliar with the properties of sound in the marine environment. It travels faster (by a factor of 5) and more efficiently (with less energy dissipation) than in air. As a result, while visual systems are limited to ranges of a few hundred meters (at best); acoustic transmission and detection systems can reach halfway around the globe (literally) (Munk *et al.*, 1994; Baggeroer *et al.*, 1994). The term “active acoustics” is often used to describe those who both transmit and receive acoustic signals in the ocean; whereas “passive acoustics” refers to those who just listen to sounds. As acoustic waves propagate through the ocean, they are scattered by inhomogeneities in the water column. The seafloor and sea surface are very strong reflectors due to differences in acoustic impedance between seawater, sediment, and air. By transmitting a short acoustic pulse downward, detecting the echo reflection from the seafloor, and tracking the time delay, one can calculate the distance from the transmitter to the seafloor. This is how the depth-sounder on a boat can tell you how deep the water is underneath the vessel. For more detailed information on underwater acoustics, see Urick (1983), Medwin and Clay (1998), or Simmonds and MacLennan (2005). Similarly, biological organisms (as well as many other inhomogeneities in the water column) can reflect acoustic energy. Thus many of those depth-finders on the boat will also work as fish-finding sonars. When speaking to a non-scientist, I often describe my research as using a

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“fancy fish-finder.” While this is true in a very broad sense, there are significant differences between scientific echosounders and the fish-finders on most fishing boats.

The first recorded incident (that I am aware of) of active acoustic detection of biological organisms was in the “deep scattering layer” (DSL) (Dietz, 1948; Johnson, 1948). Early depth-measuring systems used paper-charts to record the strength of the echoes that were detected. The seafloor produced a very strong echo, however the chart-recorder also showed weaker reflections occurring several hundred meters deep in the ocean that were definitely not the seafloor. The cause of the DSL was correctly hypothesized to be biological in origin, but it was not until the first submersible traveled to these depths that the specific sources (small fish and zooplankton) were identified. (Marshall, 1951; Hersey and Backus, 1954; Barham, 1963, 1966; Bary, 1966; Bary and Pieper, 1971; Hansen and Dunbar, 1971; Castile, 1975). If you are trying to create bathymetric maps using acoustic methods, non-seafloor reflections (like the DSL) are noise or unwanted signals. However, as many people have said, one person’s noise can be another person’s signal. Those of us who are interested in the biological organisms in the ocean have found this “noise” to be one of the best methods possible to study these animals in their natural habitat.

Nekton and zooplankton are the names given to two broad categories of animals in the marine environment. Nekton are animals that typically are actively moving within the marine environment, whereas zooplankton are usually passively advected or moved by ocean currents. These definitions are somewhat crude as many organisms called zooplankton can actively move. Some do so regularly, traveling hundreds of meters up and down in the water column every day—a process called diel vertical migration (Miyashita, 2003; Benoit-Bird *et al.*, 2009; Kaltenberg and Benoit-Bird, 2009). On the other hand, numerous nekton species (including most fish) have larval or juvenile forms that can be considered zooplankton as they are unable to move against a current until they reach a later life stage. Regardless of whether we are discussing nekton or zooplankton, both types of animals are incredibly important both economically (as commercial or recreational fisheries) and ecologically. Humans and many other higher-trophic levels rely on nekton and zooplankton as their primary energy source (Sinclair, 1994; Honkalehto *et al.*, 2009). Zooplankton are, in most oceanic environments, the link between the primary producers (phy-

toplankton) and the higher levels of the food web (e.g., fish, many marine mammals, seabirds, pinnipeds) (Croll and Tershy, 1998; Lang *et al.*, 2005).

Why is counting fish important?

To properly manage a fishery and sustain fish populations, accurate knowledge of the standing stock is necessary. Historically (and presently in some cases), net tows are conducted to collect fish which are measured (and their gender identified) to produce year-class (or cohort) data. By conducting multiple tows at multiple sites and times, fishery scientists can estimate how many adult and juvenile fish are present in an ecosystem and predict how many will be there over the next few years. Similarly, net tows are also used to measure the abundance and distribution of zooplankton species in many areas. In some cases, zooplankton are commercially fished; whereas in other areas, ecologists are interested in knowing how many and what kind of animals are present to study and model the marine ecosystem.

One limitation of using net or trawl collected data is that most marine ecosystems are very large (100s–10,000s) of km² and nets sample a very, very small fraction of that environment. The smaller the area that is surveyed, the more uncertainty there will be in estimates of fish abundance and distribution. Since most marine ecosystems are already a very difficult place to accurately sample due to their size and dynamic nature, sampling systems that can increase the volume of water surveyed to produce population estimates are needed. Optical systems, such as underwater cameras, are also used to survey fish and zooplankton stocks; however, they suffer from the same limitations as net sampling in that the volume surveyed by these methods is very small compared to the overall ecosystem (Benfield *et al.*, 1996).

Active acoustic methods allow scientists to sample a much larger volume of water than either net or optical methods. In a few seconds, a typical scientific echosounder can collect data from a volume of water that is comparable to typical net tows (~ 1000 m³). In addition, the acoustic data has a very fine vertical resolution of approximately a meter or smaller. If acoustic echosounders are used during a ship-based survey, they allow for continuous measurements of the scattering below the vessel. How deep the acoustic systems “hear” is dependent on their frequency but most systems used for surveys cover at least several hundred meters in depth. These systems “ping” every few seconds so the horizontal resolution of these data is on the order of 1–10s of meters depending on ship speed. These fishery systems have even been used in non-fishery survey situations where the increased sampling abilities provided information regarding the Gulf of Mexico Deepwater Horizon Oil spill (Weber *et al.*, 2011).

While these are substantial advantages compared to other ways of measuring marine life, acoustic systems have a major disadvantage best summarized by the quote on a tee shirt from a bioacoustics course I took in graduate school. “We only measure voltage and time.”

Converting voltage (pressure) and time information into something that is biologically-meaningful (such as an esti-

mate of fish abundance for the survey area) can be incredibly difficult and sometimes impossible. So a primary challenge in our field is to transform the acoustic information to biological data. The errors and uncertainties in this conversion process are dependent on many things: the acoustic systems used, the survey methods, and the number, behavior, fitness; and type of fish, zooplankton, or other scatterers that are present.

The inverse problem

This conversion process is called the “inverse problem” and is best explained using a simple example. Acoustic surveys collect volume backscatter strength (S_v) data which is a measure of how much acoustic energy was scattered back to the transmitter on the ship in a volume of water. If we assume that all the scatterers in this volume of water are identical and the target strength (TS) of a single organism is known, we can use the difference to calculate the number (N) of these targets that are in the volume of water. For a more detailed explanation of this see: Beamish, 1971; Foote and Stanton, 2000; or Warren and Wiebe, 2008.

If a scientific echosounder is properly calibrated (Foote *et al.*, 1987), accurate volume backscatter data can be collected. The target strength value of a scatterer can be measured (either in situ or in a laboratory), predicted using physics-based scattering models (Anderson, 1950; Stanton *et al.*, 1993; Stanton *et al.*, 1998b; Stanton and Chu, 2000; Demer and Conti, 2005; Conti and Demer, 2006), or found in the literature (Amakasu and Furusawa, 2006; Benoit-Bird *et al.*, 2008). If these two values are known, then numerical density (# of animals per volume) can be calculated. Unfortunately, there are often numerous complications that occur which transform this simple equation into a much more complex equation. If multiple types of scatterers such as different species or size classes, non-biological scatterers such as bubbles, suspended sediments, or turbulence (Woods, 1977; Stanton *et al.*, 1994b) are present in a given volume, then there are multiple contributors to the measured scattering and the equation no longer has a unique solution (i.e., you can’t determine if the measured scattering is due to a single strong scatterer or multiple weaker scatterers) (Stepnowski and Moszynski, 2000).

There are several ways this equation can be constrained. Ground-truthing of acoustic data via net, video, or literature data is a necessity and can determine what potential scattering types and size classes are present in the region (Sameoto *et al.*, 1993; Greene *et al.*, 1998; Kasatkina *et al.*, 2004; Wiebe *et al.*, 1996; Wiebe *et al.*, 1997; Ressler *et al.*, 2012). Physical oceanographic data can also be used to determine if some non-biological sources are important and need to be considered (Goodman, 1990; Seim, 1999; Seim *et al.*, 1995). The “forward problem” uses ground-truthing data to provide information on the number and type of scatterers present which are combined with target strength models to produce an estimate of expected acoustic scattering. If there is good agreement with the expected and measured backscatter data, then the solutions to the inverse problem are likely to be more accurate. However this assumes that there are not

major differences in the marine environment between the locations where the forward and inverse problems are used (Warren and Wiebe, 2008).

Many of these complications and difficulties are beyond our control as scientists. The ocean is a dynamic environment; nekton and zooplankton occur in patches so their abundances can vary over several orders of magnitude over very short time and space scales (minutes, 10s of meters); using ship-based platforms makes it difficult to make synoptic measurements (unlike satellites); and there are many factors which can affect the target strength of a particular species (size, orientation, health/fitness). So uncertainties in acoustic estimates can be quite large. However despite these issues, inversion of acoustic data for biological information is done accurately over both large and small scales throughout the world. Many fisheries throughout the world use acoustic methods accompanied by net and trawl sampling to produce a stock assessment for management purposes including several of the largest in terms of landings such as pollock, hake, herring, sardine, and anchovy. Historically, there have been technological reasons (as opposed to our general ignorance about how the natural world works) that limited our ability to accurately measure these systems; however that is changing.

Mo' beams; mo' bandwidth; mo' data

Traditional fishery echosounders operate at a single acoustic frequency between 10 and 200 kHz with narrow bandwidth (< 10%) and beamwidths between 7 deg and 30 deg, and are hull-mounted pointing downward. Thus as ship moves around, data are collected in a cone beneath the ship producing a ribbon-like plot of acoustic backscatter (Fig. 1). Many fishery survey vessels travel ~ 10 kts so covering a large habitat area will take several weeks or months at sea and produces transect lines that are widely spaced often several km apart. While a great improvement in terms of spatial and temporal coverage relative to other sampling systems, these sur-

veys still cover a relatively small volume of the marine habitat. When a fish school is measured by a traditional echosounder, we know the vertical dimension (height) of the school along the ship's path; however we do not have any information as to the cross-track dimension of the school. One can make assumptions as to whether fish schools are isotropic or not, but our picture of the size of a fish school is incomplete.

Multibeam acoustic systems, originally developed for high-resolution bathymetric mapping, have changed our data collection from being a 2-D system (depth, distance along the ship's path) to a 3-D system (depth, along- and cross-path distance) greatly increasing the volume covered in an acoustic survey (McGehee and Jaffe, 1996; Jaffe, 1999). Unlike traditional echosounders, multibeam systems provide cross-track information as to fish school dimensions and in some cases entire fish or zooplankton schools can be ensonified. (Weber *et al.*, 2009; Cox *et al.*, 2009; Cox *et al.*, 2010). Studies have even been able to show feeding interactions between groups of air-breathing predators whose lungs scatter significant amounts of energy and schools of their prey (Benoit-Bird and Au, 2009; Benoit-Bird, 2009b). Many countries that regularly conduct fishery surveys are equipping their fleets with these systems, along with the traditional echosounders, to take advantage of the increase in sampling volume. However, there are some new problems that have arisen with these systems. Calibration of a multibeam system can be challenging (Foote *et al.*, 2005) and some animals will scatter sound differently depending on their orientation relative to the acoustic transducer. Two identical scatterers (size, species, orientation) may have different target strengths depending on whether they are ensonified by a beam directly above them or from a beam off to their side (Roberts and Jaffe, 2008).

Shifting from using a single frequency to multiple frequencies of sound to survey the ocean is analogous to viewing a picture in black and white and then adding additional colors to the image (Gareth Lawson was the first person I

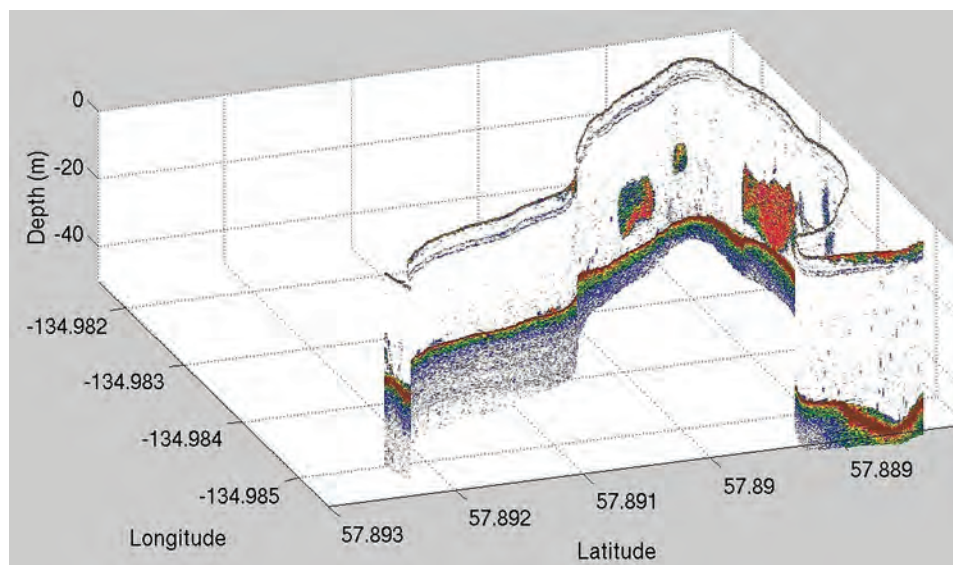


Fig. 1. A 200 kHz echogram recorded in the coastal waters of Alaska showing a school of Pacific herring. Colors represent strong (brown and red) and weak (blue and green) scattering regions with white representing scattering below an arbitrary threshold. The ribbon-plot is made up of thousands of echosounder "pings" which measure the backscatter in the water column beneath the boat. The strong red and brown layer at approximately 50 m depth is the seafloor. As our vessel moved we appear to have gone over a herring school (likely a single school given that the area shown is roughly 100 m by 150 m, although it is possible that they were distinct schools).

heard use this great analogy). Animals in the ocean (depending on their anatomy, composition, and physiology) scatter sound with different efficiencies at different frequencies (Chu *et al.*, 1992; Horne and Jech, 1999; Benoit-Bird, 2009a;). Using different acoustic frequencies provides us with the ability to identify and discriminate between different sizes such as year classes of a long-lived species or different types, and in some cases even species, of nekton and zooplankton. In general, with more frequencies one has a greater ability to identify and discriminate different scatterers (Holliday, 1977; Foote and Stanton, 2000).

Discrete broadband systems have been around for decades (Napp *et al.*, 1993; Holliday and Pieper, 1995; Holliday *et al.*, 1989; Au and Benoit-Bird, 2008;) using multiple single-frequency or narrowband transducers to span several decades in frequency. The use of multiple acoustic frequencies with ground truthing have allowed scientists to use acoustic backscatter data to identify and discriminate scattering from multiple size classes (Greenlaw, 1979; Kristensen and Dalen, 1986; Warren *et al.*, 2003) or types of scatterers (Pieper *et al.*, 1990; Martin *et al.*, 1996) and even scattering from biological and physical sources (Warren *et al.*, 2003). A thorough review of acoustic species identification is provided by Horne (2000). Recently however, we have begun to see the development of new systems that allow broadband data to be collected and studied providing insights into predator foraging (Stanton *et al.*, 2010; Lavery *et al.*, 2010). As these technologies continue to develop, the data collected during acoustic studies will continue to increase our ability to interpret acoustic backscatter data.

Sampling platforms for the assessment of fish and zooplankton have traditionally been ship-based allowing scientists to cover large areas over the course of several weeks, but limiting the temporal duration of these studies. The development of autonomous underwater vehicles (AUV) and Glider-based samplers allows scientists to cover much larger areas although there are power and engineering constraints which will limit the number and types of frequencies of echosounders used in these systems (Brierley *et al.*, 1998). Observatory and moored systems while limited in spatial coverage can provide unique insights into daily, seasonal, or annual changes in the ecosystem that cannot always be observed during shorter-term surveys occurring once a year. A very different application of underwater sound (compared to echosounder surveys) for biological assessment has been the use of the ocean water column as a wave guide with lower frequency sources and receiver arrays. These large-scale experiments cover 100s of square kms which can ensound multiple schools of fish nearly instantaneously (Makris *et al.*, 2006).

At the other spatial scale extreme, some scientists like myself have become interested in ecological interactions between nekton and zooplankton and their predators which occur at very small space (10–100 m²) and time scales (seconds to minutes) (Warren *et al.*, 2009; Hazen *et al.*, 2011). If answering the very simple question “How many krill does a whale swallow at a time?” can’t be answered currently without very large uncertainties, the calculated estimate may not be useful for ecological studies. Collecting co-located (in both

time and space) data on marine predators and their prey is challenging (and in some cases involves being very close to very large animals in boats that are substantially smaller than the predators). Baleen whale and odontocetes can be tracked underwater using instrumented tags. Concurrent measurements of these animals’ prey from nearby vessels can provide insights into predator behavior and prey availability (Hazen *et al.*, 2009; Parks *et al.*, 2011).

These engineering advances have greatly increased our ability to collect vast amounts of data covering greater volumes of water and acoustic bandwidths. Thus our volume backscatter measurements cover more regions and provide more information about the scatterers in the water column. However, to convert the acoustic data into biological information, there are still many unknowns on the biological side of things when we try to predict how much sound specific organisms will scatter in the ocean.

One fish, two fish, big fish, tilted fish

If all fish were identical biologically (e.g., their size, shape, internal organs, etc.) and their position and orientation in the water column were constant, acousticians would have a much easier time counting them in the ocean. Fortunately (particularly if you enjoy eating seafood), fish and other animals in the ocean are very diverse spanning many different types and sizes (and tastes).

Animal size has one of the strongest impacts on the amount of acoustic energy they scatter. Specifically the ratio of the acoustic wavelength to the size of the scatterer determines whether the scattering follows Rayleigh or geometric scattering theory (Greenlaw, 1977; Holliday, 1977). In the Rayleigh regime (where scatterers are much smaller than a wavelength), scattering is primarily a function of animal size, with larger animals scattering more energy than smaller ones. However in the geometric regime (where the acoustic wavelength is much smaller than the scatterer), there are strong frequency dependencies on the scattered energy and animal characteristics like shape and orientation play an important role. In general, lower frequencies allow scientists to look deeper into the water column, but often limit the minimum size of scatterer that can be observed. But there are other factors that need to be considered. Two fish of similar size can have different scattering efficiencies depending on their taxonomic identity. Many fish (but not all) have a swim bladder. These are gas-filled organs that help animals regulate their buoyancy and position in the water column. Acoustically, these organs are extremely strong scatterers (often more important than the rest of the animal) of sound due to the acoustic impedance difference between seawater and the gas-filled bladder. Some species of fish can control or adjust the volume of gas in their bladder while others cannot. Thus, a fish that changes depth may adjust its swim-bladder volume accordingly which can cause a shift in its scattering spectra.

In a very simplistic sense, acoustic scattering from fish and zooplankton could be divided into two approaches. For animals with a swim-bladder or an elastic-shell, the scattering from the animal can be described by modeling the scattering from the structure which typically dominates the backscatter

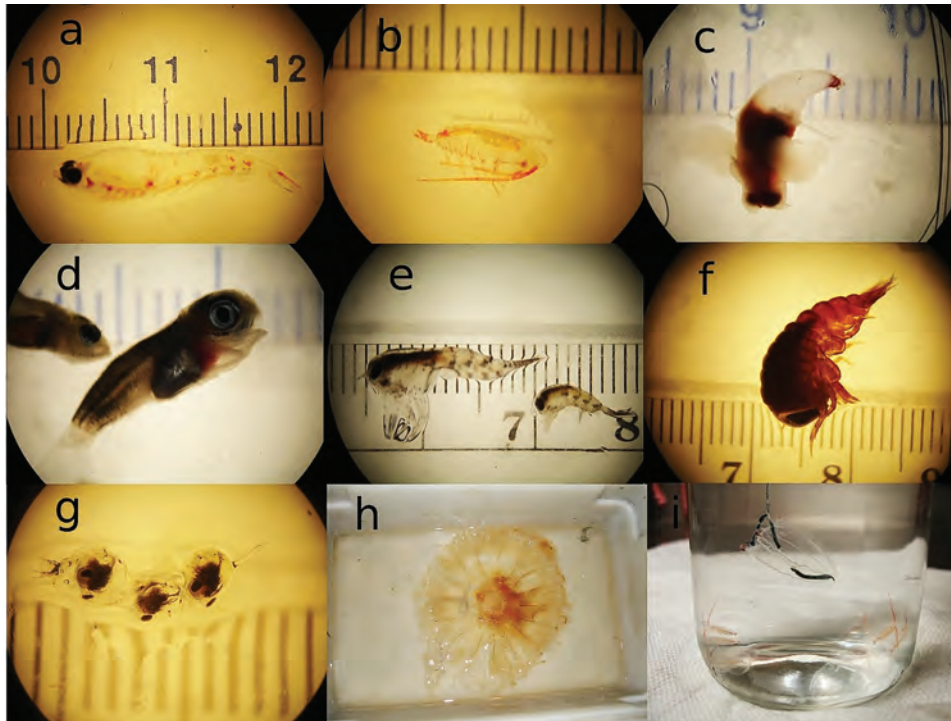


Fig. 2. A photo album of just a few types of zooplankton from the Bering Sea including: euphausiid (a), copepod (b), gastropod (c), larval pollock (d), two types of amphipods (e, f), crab zoea (g), jellyfish (h), and a siphonophore (i). The ruler shown in a-g is in cm whereas the jellyfish and siphonophore are approximately 20 and 3 cm in diameter respectively.

from the animal. For other fish and zooplankton, the scattering from the animal can be modeled as a fluid-like object where the animal is represented by a geometric shape containing a fluid with different acoustic impedance than the surrounding seawater (Stanton, 1998; Stanton, 1990). Many of these models are not perfect as they have a uniform composition within the body volume which we know is not true since muscle, bone, and other organs and tissues are different. Simple geometric shapes (e.g., spheres and spheroids) of these structures produce the simplest mathematical scattering models. However, these shapes may not accurately represent the actual scatterer shape. Thus a variety of more accurate but complex shapes have been used ranging from cylinders (Chu *et al.*, 1993; Stanton *et al.*, 1998c) to high-resolution (mm) computerized tomographic measurements (Lavery *et al.*, 2002). Much work has been done recently in detailed adjustments to many of these scattering models (Demer and Conti, 2003a,b). Despite these approximations, these models have been tested with measurements from animals (Gorska *et al.*, 2005; Ianelli *et al.*, 2009;) and have been found to be accurate enough for use in stock assessment purposes.

Although fish can be considered a diverse group of animals with different body shapes, sizes, and composition; they appear to be relatively uniform when compared to the diversity of the zooplankton. The groups represented with the word zooplankton represent many different phyla, ranging from crustaceans to mollusks to cnidarians to fish (Fig. 2). If you exclude the microzooplankton and only include mesozooplankton (those you can see without a microscope), their size ranges over four orders of magnitude from small mm-long copepods to siphonophores which can be 10 m in length. In addition to the size differences within this group,

there are a large variety of body morphologies from fish larvae to crustaceans (the most abundant zooplankton group) to snails with and without shells to the gelatinous organisms which may or may not contain a gas-inclusion. Siphonophores are a particularly fascinating zooplankton (Biggs, 1977; Rogers *et al.*, 1978; Gould, 1984; Mackie *et al.*, 1987;). These are gelatinous zooplankton related to coral polyps which are often described as jellyfish, but they are morphologically and phylogenetically distinct from the more common moon jellies, ctenophores, or blobs of goo you may see washed up on the beach. These animals have a structure called a pneumatophore which contains a small volume (often spherical with a diameter of a few mm) of gas (Pickwell *et al.*, 1964). Like fish, siphonophores use this body part to control their position in the water column (Warren *et al.*, 2001). Several of these animals, specifically pteropods containing a calcium carbonate snail-like shell and the aforementioned siphonophores, can be very strong acoustic scatterers (Stanton *et al.*, 1998a). So strong that the scattering from a single pteropod or siphonophore can be equivalent to that from tens of thousands of crustacean (fluid-like) zooplankton (Stanton *et al.*, 1994a; Stanton *et al.*, 1998c).

So to make sense of acoustic survey data, one must have a good handle on the types of animals that lie beneath the surface. Using ground truthing data such as net or video tows, one can calculate the relative abundance of the various scatterer types and by applying theoretical scattering models, one can estimate how much of each taxa would contribute to the total backscatter that the survey measures (Warren and Wiebe, 2008). Ideally one size or type of animal would dominate the scattering in a region. And in that case, it is fairly straightforward to estimate biological information from



Fig 3. Time to go fishing as a National Marine Fisheries Service vessel deploys a net trawl to capture fish as part of an acoustic and trawl stock assessment survey in the Bering Sea.



Fig. 4. What comes up in the net are Alaskan pollock which may not look familiar to you, but you've likely eaten it as fish sticks, fish sandwiches, or imitation crabmeat. Despite its small size relative to other commercially fished species such as halibut, salmon, or cod, more pounds of pollock are landed in the United States every year than any other fish species.

acoustic data. Antarctic krill surveys have been conducted acoustically for several decades by several nations (Reiss *et al.*, 2008; Kasatkina *et al.*, 2004). Krill dominate the ecosystem in terms of scatterer biomass in many locations in Antarctica and elsewhere, and they can be discriminated from larger fish scatterers by measuring the difference in scattered energy at two or more acoustic frequencies (David *et al.*, 1999; Miyashita and Aoki, 1999; Lawson *et al.*, 2006, 2008; De Robertis *et al.*, 2010). However, many other regions in the world have multiple types or sizes of animals that are contributing to the overall scattering signal which makes this process much more difficult, or in some cases impossible.

Differences in animal behavior which might seem insignificant to a biologist can be very important to an acoustician. The

angle (or tilt) of a scatterer can cause very large differences in scattered energy at frequencies in the geometric scattering regime (McGehee *et al.*, 1998; Warren *et al.*, 2002). Surprisingly we know very little about how fish and zooplankton orient themselves in the water column, and how their orientations vary during regular behaviors such as vertical migration, schooling, dispersion, predator avoidance, feeding, or reproduction. In practice, assumptions must be made about the orientation distributions of these organisms which are very rarely species and site specific due to a paucity of information about these animal characteristics and the difficulty in making these measurements. Optical sampling methods can provide this information (Davis *et al.*, 1992; Endo, 1993; Benfield *et al.*, 2000) so combining them with acoustical sampling systems is a productive method (Sameoto, 1980;

Miyashita *et al.*, 1996; Wiebe *et al.*, 2002).

Other important parameters needed to properly model the scattering from fish and zooplankton are the material properties of the organism. These values describe the acoustic impedance of the organism and how it differs from the surrounding seawater, which has a very large impact on the amount of energy these animals scatter. The importance of these properties has been known from the very early stages of acoustic modeling (Smith, 1954; Greenlaw and Johnson, 1982), however most studies do not make these measurements, as they can be time-consuming and occasionally difficult to make at sea. In practice, scientists (including myself) use material property values from the literature which may be based on different species or groups of animals in a different part of the world. One of the most frequently-cited studies is Foote (1990) which described the material properties of Antarctic krill. The values from this study have been applied by other scientists to model the scattering from animals ranging from gelatinous zooplankton to almost every type of crustacean in habitats ranging all over the world. Again the paucity of information about these parameters is a severe limitation in accurately describing the scattering from zooplankton as very small differences in these values (a few percent or less) can cause order of magnitude differences in the scattered energy (Chu and Wiebe, 2005). Recently, several research groups (including my own) have been making more measurements of this type on many different types of animals including: coastal crustacean (Forman and Warren, 2010) and gelatinous zooplankton (Warren and Smith, 2007), larval fish (Chu *et al.*, 2000), Antarctic krill (Chu and Wiebe, 2005 done in situ!) and salps (Wiebe *et al.*, 2010), and several types of zooplankton from the Bering Sea (Køgeler *et al.*, 1987; Smith *et al.*, 2010).

An interesting discovery of our work in the Bering Sea was that we did not observe differences in material properties (or target strength) for the three different species of krill that we captured and studied. What did cause a difference in the

animal's material properties was where they were caught. We believe this is the result of differences in food (phytoplankton) abundance for the krill and that well-fed animals (presumably with larger lipid reserves) differed physically from krill in regions with less food. The differences that we measured in these animals are important when trying to interpret acoustic survey data. Colleagues at the National Marine Fisheries Service who conduct acoustic surveys to measure pollock (the largest US fishery in terms of landing biomass) stocks in the Bering Sea (Figs. 3 and 4) have also used the acoustic survey data to develop a measure of euphausiid biomass in this region (Ressler *et al.*, 2012). The krill biomass estimate is very important in understanding the ecosystem dynamics of this region as pollock's preferred prey are euphausiids. The results from our work (Smith *et al.*, 2010) showed that regional differences in the euphausiid's physical state (and thus their acoustic scattering efficiency) would lead to a doubling (or halving) of the krill biomass estimate. The results of this study are currently being applied to acoustic data collected at a mooring site in the Bering Sea which may allow us to monitor seasonal differences in the zooplankton and fish components of the ecosystem over annual cycles which may provide opportunities to examine how climate change (and the changes in sea ice in this region) will affect the fish and zooplankton.

The future?

In many marine systems, the ability to use acoustics to remotely monitor over long time periods and identify key components of the ecosystem is a distant goal. However in some locations, at certain times, and under certain conditions, acoustic techniques provide a remarkable ability to collect information about the fish and zooplankton in the ocean that cannot be collected in any other way. The spatial and temporal resolution of acoustic systems combined with the ability to ensonify large volumes of water rapidly allows acoustic data to provide insights into different aspects of marine ecology in addition to just producing abundance and distribution data for different species of animals. Recent advances in technology will increase our capabilities and help us to reduce the uncertainties in our indirect measurements of biology. However, the constant confounding factor will be our lack of knowledge about the biological organisms in their natural state. These data are the key to improving our ability to study marine life using active acoustic systems. A decade later, I think I finally may have an answer for Alex Trebek (several thousand Antarctic krill in a gulp).**AT**

References

Amakasu, K., and Furusawa, M. (2006). "The target strength of Antarctic krill (*Euphausia superba*) measured by the split-beam method in a small tank at 70 kHz," ICES J. Marine Sci. **63**, 36–45.

Anderson, V. C. (1950). "Sound scattering from a fluid sphere," J. Acoust. Soc. Am. **22**, 426–431.

Au, W. W. L., and Benoit-Bird, K. J. (2008). "Broadband backscatter from individual Hawaiian mesopelagic boundary community animals with implications for spinner dolphin foraging," J. Acoust. Soc. Am. **123**, 2884–2894.

Baggeroer, A. B., Sperry, B., Lashkari, K., Chiu, C. S., Miller, J. H.,

Mikhalevsky, P. N., and von Der Heydt, K. (1994). "Vertical array receptions of the Heard Island transmissions," J. Acoust. Soc. Am. **96**, 2395–2413.

Barham, E. G. (1963). "Siphonophores and the deep scattering layer," Science **140**, 826–828.

Barham, E. G. (1966). "Deep scattering layer migration and composition: Observations from a diving saucer," Science **151**, 1399–1403.

Bary, B. M. (1966). "Backscattering at 12 kc/s in relation to biomass and number of zooplankton organisms in Saanich Inlet, British Columbia," Deep-Sea Research I **13**, 655–666.

Bary, B. M., and Pieper, R. E. (1971). *Sonic-scattering studies in Saanich Inlet, British Columbia: A preliminary report*. (Dept. of the Navy, Maury Center for Ocean Science, Report No. MC-005).

Beamish, P. (1971). "Quantitative measurements of acoustic scattering from zooplanktonic organisms," Deep-Sea Research I **18**, 811–822.

Benfield, M. C., Davis, C. S., Wiebe, P. H., Gallager, S. M., Lough, R. G., and Copley, N. J. (1996). "Video plankton recorder estimates of copepod, pteropod and larvacean distributions from a stratified region of Georges Bank with comparative measurements from a MOCNESS sampler," Deep-Sea Research II **43**, 1925–1945.

Benfield, M. C., Davis, C. S., and Gallager, S. M. (2000). "Estimating the in-situ orientation of *Calanus finmarchicus* on Georges Bank using the video plankton recorder," Plankton Biol. and Ecol. **47**, 69–72.

Benoit-Bird, K. J., Gilly, W. F., Au, W. W. L., and Mate, B. (2008). "Controlled and in situ target strengths of the jumbo squid *Doedicus gigas* and identification of potential acoustic scattering sources," J. Acoust. Soc. Am. **123**, 1318–1328.

Benoit-Bird, K. J. (2009a). "Effects of scattering layer composition, animal size, and numerical density on the frequency response of volume backscatter," ICES J. Marine Sci. **66**, 582–593.

Benoit-Bird, K. J. (2009b). "Dynamic three-dimensional structure of zooplankton thin layers is affected by foraging fish," Marine Ecol. Progress Series **396**, 61–76.

Benoit-Bird, K. J., and Au, W. W. L. (2009). "Cooperative prey herding by a pelagic dolphin, *Stenella longirostris*," J. Acoust. Soc. Am. **125**, 125–137.

Benoit-Bird, K. J., Au, W. W. L., Wisdom, D. W. (2009). "Nocturnal light and lunar cycle effects on diel migration of micronekton," Limnology and Oceanography **54**, 1789–1800.

Biggs, D. C. (1977). "Field studies of fishing, feeding and digestion in Siphonophores," Marine Behaviour and Physiol. **4**, 261–274.

Brierley, A. S., Brandon, M. A., and Watkins, J. L. (1998). "An assessment of the utility of an acoustic Doppler current profiler for biomass estimation," Deep-Sea Research I **45**, 1555–1573.

Castile, B. D. (1975). "Reverberation from plankton at 330 kHz in the western Pacific," J. Acoust. Soc. Am. **58**, 972–976.

Chu, D., Stanton, T. K., and Wiebe, P. H. (1992). "Frequency dependence of sound backscattering from live individual zooplankton," ICES J. Marine Sci. **49**, 97–106.

Chu, D., Foote, K. G., and Stanton, T. K. (1993). "Further analysis of target strength measurements of Antarctic krill at 38 and 120 kHz: Comparison with deformed cylinder model and inference of orientation distribution," J. Acoust. Soc. Am. **93**, 2985–2988.

Chu, D., Wiebe, P. H., and Copley, N. (2000). "Inference of material properties of zooplankton from acoustic and resistivity measurements," ICES J. Marine Sci. **57**, 1128–1142.

Chu, D., and Wiebe, P. H. (2005). "Measurements of sound-speed and density contrasts of zooplankton in Antarctic waters," ICES J. Marine Sci. **62**, 818–831.

- Conti, S.G., and Demer, D. A. (2006). "Improved parameterization of the SDWBA for estimating krill target strength," ICES J. Marine Sci. **63**, 928–935.
- Cox, M. J., Demer, D. A., Warren, J. D., Cutter, G. R., and Brierley, A. S. (2009). "Multibeam echosounder observations of Antarctic krill (*Euphausia superba*) swarms and interactions between krill and air breathing predators," Marine Ecol. Progress Series **378**, 199–209. doi: 10.3354/meps07795.
- Cox, M. J., Warren, J. D., Demer, D. A., Cutter, G. R., and Brierley, A. S. (2010). "Three dimensional observations of Antarctic krill (*Euphausia superba*) swarms using a multi-beam echosounder," Deep-Sea Res. II **57**, 508–518. doi: 10.1016/j.dsr2.2009.10.003.
- Croll, D. A., and Tershy, B. R. (1998). "Penguins, fur seals, and fishing: Prey requirements and potential competition in the South Shetland Islands, Antarctica," Polar Biol. **19**, 365–374.
- David, P. M., Guerin-Ancey, O., and Cuyck, J. P. V. (1999). "Acoustic discrimination of two zooplankton species (mysid) at 38 and 120 kHz," Deep-Sea Research I **46**, 319–333.
- Davis, C. S., Gallager, S. M., Berman, M. S., Haury, L. R., and Strickler, J. R. (1992). "The Video Plankton Recorder (VPR): Design and initial results," Archiv für Hydrobiologie **36**, 67–81.
- Demer, D. A., and Conti, S. G. (2003a). "Reconciling theoretical versus empirical target strengths of krill: Effects of phase variability on the distorted-wave Born approximation," ICES J. Marine Sci. **60**, 429–434.
- Demer, D. A., and Conti, S. G. (2003b). "Validation of the stochastic distorted-wave Born approximation model with broad bandwidth total target strength measurements of Antarctic krill," ICES J. Marine Sci. **60**, 625–635.
- Demer, D. A., and Conti, S. G. (2005). "New target-strength model indicates more krill in the Southern Ocean," ICES J. Marine Sci. **62**, 25–32.
- DeRobertis, A., McKelvey, D. R., and Ressler, P. H. (2010). "Development and application of an empirical multifrequency method for backscatter classification," Can. J. Fish. and Aqu. Sci. **67**(9), 1459–1474.
- Dietz, R. S. (1948). "Deep scattering layer in the Pacific and Antarctic oceans," J. Marine Res. **7**, 430–442.
- Endo, Y. (1993). "Orientation of Antarctic krill in an aquarium," Nippon Suisan Gakkaishi, **59**(3): 465–468.
- Foote, K. G., Knudsen, H. P., Vestnes, G., MacLennan, D. N., and Simmonds, E. J. (1987). *Calibration of acoustic instruments for fish density estimates: A practical guide*. ICES Cooperative Res. Report 144.
- Foote, K. G. (1990). "Speed of sound in *Euphausia superba*," J. Acoust. Soc. Am. **87**, 1405–1408.
- Foote, K. G., and Stanton, T. K. (2000). "Acoustical Methods" (Ch. 6) in ICES *Zooplankton Methodology Manual* edited by R. Harris, P. H. Wiebe, J. Lenz, H. R. Skjoldal, and M. Huntley, (Academic Press, London), pp. 223–258.
- Foote, K. G., Chu, D., Hammar, T. R., Baldwin, K. C., Mayer, L. A., Hufnagle, L. C., Jr., and Jech, J. M. (2005). "Protocols for calibrating multibeam sonar," J. Acoust. Soc. Am. **117**(4), 2013–2027.
- Forman, K. A., and Warren, J. D. (2010). "Variability in the density and sound-speed of coastal zooplankton and nekton," ICES J. Marine Sci. **67**(1), 10–18. doi:10.1093/icesjms/fsp217.
- Goodman, L. (1990). "Acoustic scattering from ocean microstructure," J. Geophys. Res. **95**, 11557–11573.
- Gorska, N., Ona, E., and Korneliussen, R. (2005). "Acoustic backscattering by Atlantic mackerel as being representative of fish that lack a swimbladder. Backscattering by individual fish," ICES J. Marine Sci. **62**, 984–995.
- Gould, S. J. (1984). "A most ingenious paradox," Natural History **12**, 20–30.
- Greene, C. H., Wiebe, P. H., Pershing, A. J., Gal, G., Popp, J. M., Copley, N. J., Austin, T. C., Bradley, A. M., Goldsborough, R. G., Dawson, J., Hendershott, R., and Kaartvedt, S. (1998). "Assessing the distribution and abundance of zooplankton: A comparison of acoustic and net-sampling methods with D-BAD MOC-NESS," Deep-Sea Research II **45**, 1219–1237.
- Greenlaw, C. F. (1977). "Backscattering spectra of preserved zooplankton," J. Acoust. Soc. Am. **62**, 44–52.
- Greenlaw, C. F. (1979). "Acoustical estimation of zooplankton populations," Limnology and Oceanography **24**, 226–242.
- Greenlaw, C. F., and Johnson, R. K. (1982). "Physical and acoustical properties of zooplankton," J. Acoust. Soc. Am. **72**(6), 1706–1710.
- Hansen, W. J., and Dunbar, M. J. (1971). *Biological causes of scattering layers in the Arctic Ocean*. (Dept. of the Navy, Maury Center for Ocean Science, Report No. MC-005).
- Hazen, E. L., Friedlaender, A. S., Thompson, M. A., Ware, C. R., Weinrich, M. T., Halpin, P. N., Wiley, D. N. (2009). "Fine-scale prey aggregations and foraging ecology of humpback whales *Megaptera novaeangliae*," Marine Ecol. Program Series **395**, 75–89.
- Hazen, E. L., Nowacek, D. P., St. Laurent, L., Halpin, P. N., Moretti, D. J. (2011). "The relationship among oceanography, prey fields, and beaked whale foraging habitat in the Tongue of the Ocean." PLoS ONE **6**(4), e19269. doi:10.1371/journal.pone.0019269.
- Hersey, J. B., and Backus, R. H. (1954). "New evidence that migrating gas bubbles, probably the swimbladders of fish, are largely responsible for scattering layers on the continental rise south of New England," Deep-Sea Res. I **1**, 190–191.
- Holliday, D. V. (1977). "Extracting Bio-physical Information from the Acoustic Signatures of Marine Organisms" in *Oceanic Sound Scattering Prediction* edited by N. R. Andersen and B. J. Zahuranec, (Plenum Press), pp. 619–624.
- Holliday, D. V., Pieper, R. E., and Kleppel, G. S. (1989). "Determination of zooplankton size and distribution with multifrequency acoustic technology," ICES J. Marine Sci. **46**, 52–61.
- Holliday, D. V., and Pieper, R. E. (1995). "Bioacoustical oceanography at high frequencies," ICES J. Marine Sci. **52**, 279–296.
- Honkalehto, T., Jones, D., McCarthy, A., McKelvey, D., Guttormsen, M., Williams, K., and Williamson, N. (2009). "Results of the Echo Integration-Trawl Survey of Walleye Pollock (*Theragra chalcogramma*) on the U.S. and Russian Bering Sea Shelf in June and July 2008," U.S. Department of Commerce, NOAA Technical Memorandum NMFS-AFSC-194, 56 p. <http://www.afsc.noaa.gov/Publications/AFSC-TM/NOAA-TM-AFSC-194.pdf>
- Horne, J. K., and Jech, J. M. (1999). "Multi-frequency estimates of fish abundance: Constraints of rather high frequencies," ICES J. Marine Sci. **56**(2):184–99. doi:10.1006/jmsc.1998.0432.
- Horne, J. K. (2000). "Acoustic approaches to remote species identification: A review," Fisheries Oceanog. **9**(4): 356–371.
- Ianelli, J. N., Barbeaux, S., Honkalehto, T., Kotwicki, S., Aydin, K., and Williamson, N. (2009). "Assessment of the walleye pollock stock in the eastern Bering Sea," p. 47–136 in *Stock Assessment (NPFMC Bering Sea and Aleutian Islands Stock Assessment and Fishery Evaluation (SAFE) document*. 605 W. 4th Ave., Anchorage, AK 99501.
- Jaffe, J. S. (1999). "Target localization for a three-dimensional multi-beam sonar imaging system" J. Acoust. Soc. Am. **105**(6): 3168–3175.
- Johnson, M. W. (1948). "Sound as a tool in marine ecology, from data on biological noises and the deep scattering layer," J. Marine Res. **7**, 443–458.
- Kaltenberg, A. M., and Benoit-Bird, K. J. (2009). "Diel behavior of sardine and anchovy schools in the California Current System."

- Marine Ecol. Progress Series **394**, 247–262.
- Kasatkina, S. M., Gross, C., Emery, J. H., Takao, Y., Litvinov, F. F., Malyshko, A., Shnar, V. N., and Berezinsky, O. A. (2004). “A comparison of net and acoustic estimates of krill density in the Scotia Sea during the CCAMLR 2000 Survey,” *Deep-Sea Research II*, **51**, 1289–1300.
- Køgelier, J. W., Falk-Petersen, S., Kristensen, Å., Pettersen, F., and Dalen, J. (1987). “Density- and sound speed contrasts in sub-Arctic zooplankton” *Polar Biol.* **7**, 231–235.
- Kristensen, A., and Dalen, J. (1986). “Acoustic estimation of size distribution and abundance of zooplankton,” *J. Acoust. Soc.* **80**(2), 601–611.
- Lang, G. M., Livingston, P. A., and Dodd, K. A. (2005). *Groundfish food habits and predation on commercially important prey species in the eastern Bering Sea from 1997 through 2001*. U.S. Dept. of Commerce, NOAA Tech. Memo. NMFS-AFSC-158, 230p.
- Lavery, A. C., Stanton, T. K., McGehee, D. E., and Chu, D. (2002). “Three-dimensional modeling of acoustic backscattering from fluid-like zooplankton,” *J. Acoust. Soc. Am.* **111**(3), 1197–1210.
- Lavery, A. C., Chu, D., and Moum, J. N. (2010). “Measurements of acoustic scattering from zooplankton and oceanic microstructure using a broadband echosounder” *ICES J. Marine Sci.* **67**, 379–394.
- Lawson, G. L., Wiebe, P. H., Ashjian, C. J., Chu, D., and Stanton, T. K. (2006). “Improved parameterization of Antarctic krill target strength models,” *J. Acoust. Soc. Am.* **119**(1), 232–242.
- Lawson, G. L., Wiebe, P. H., Stanton, T. K., and Ashjian, C. J. (2008). “Euphausiid distribution along the Western Antarctic Peninsula—Part A: Development of robust multi-frequency acoustic techniques to identify euphausiid aggregates and quantify euphausiid size, abundance, and biomass,” *Deep-Sea Res. Part 2. Topical studies in oceanography* **55**, 412–431.
- Mackie, G. O., Pugh, P. R., and Purcell, J. E. (1987). “Siphonophore biology,” *Advances in Marine Biol.* **24**, 97–262.
- Makris, N. C., Ratital, P., Symonds, D. T., Jagannathan, S., Lee, S., and Nero, R. W. (2006). “Fish population and behavior revealed by instantaneous continental shelf-scale imaging,” *Science*. **311**(5761), 660–663.
- Marshall, N. B. (1951). “Bathypelagic fishes as sound scatterers in the ocean,” *J. Marine Res.* **10**, 1–17.
- Martin, L. V., Stanton, T. K., Wiebe, P. H., and Lynch, J. F. (1996). “Acoustic classification of zooplankton,” *ICES J. Marine Sci.* **53**, 217–224.
- McGehee, D., and Jaffe, J. S. (1996). “Three-dimensional swimming behavior of individual zooplankters: Observations using the acoustical imaging system FishTV,” *ICES J. Marine Sci.* **53**(2), 363–369.
- McGehee, D. E., O’Driscoll, R. L., and Martin-Traykovski, L. V. (1998). “Effects of orientation on acoustic scattering from Antarctic krill at 120 kHz,” *Deep-Sea Research II* **45**, 1273–1294.
- Medwin, H., and Clay, C. S. (1998). *Fundamentals of Acoustical Oceanography* (Academic Press, Boston, MA).
- Miyashita, K., Aoki, I., and Inagaki, T. (1996). “Swimming behaviour and target strength of isada krill (*Euphausia pacifica*),” *ICES J. Marine Sci.* **53**, 303–308.
- Miyashita, K., and Aoki, I. (1999). “Acoustic measurements of zooplankton using a dual frequency echo sounder,” *Marine Ecol. Progress Series* **180**, 105–109.
- Miyashita, K. (2003). “Diurnal changes in the acoustic-frequency characteristics of Japanese anchovy (*Eugraulis japonicus*) post-larvae “shirasu” inferred from theoretical scattering models,” *ICES J. Marine Sci.* **60**, 532–537.
- Munk, W. H., Spindel, R. C., Baggeroer, A., and Birdsall, T. G. (1994). “The Heard Island Feasibility Test,” *J. Acoust. Soc. Am.* **96**, 2330–2342.
- Napp, J. M., Ortner, P. B., Pieper, R. E., and Holliday, D. V. (1993). “Biovolume-size spectra of epipelagic zooplankton using a multi-frequency acoustic profiling system (MAPS),” *Deep-Sea Research I* **40**, 445–459.
- Parks, S. E., Warren, J. D., Stamieszkin, K., Mayo, C. A., and Wiley, D. (2011). “Dangerous dining: Surface foraging of North Atlantic right whales increases risk of vessel collisions,” *Biol. Lett.* doi: 10.1098/rsbl.2011.0578.
- Pickwell, G. V., Barham, E. G., and Wilton, J. W. (1964). “Carbon monoxide production by a bathypelagic siphonophore,” *Science* **144**, 860–862.
- Pieper, R. E., Holliday, D. V., and Kleppel, G. S. (1990). “Quantitative zooplankton distributions from multifrequency acoustics,” *J. Plankton Res.* **12**, 433–441.
- Reiss, C. S., Cossio, A. M., Loeb, V., and Demer, D. A. (2008). “Variations in the biomass of Antarctic krill (*Euphausia superba*) around the South Shetland Islands, 1996–2006,” *ICES J. Marine Sci.* **65**(4), 497–508.
- Ressler, P. H., De Robertis, A., Warren, J. D., Smith, J. N., and Kotwicki, S. (2012). “Developing an acoustic survey of euphausiids to understand trophic interactions in the Bering Sea ecosystem,” *Deep-Sea Research II* **65–70**: 184–195. doi: 10.1016/j.dsr2.2012.02.015.
- Roberts, P. L. D., and Jaffe, J. S. (2008). “Classification of live, unfiltered zooplankton from observations of multiple-angle acoustic scatter,” *J. Acoust. Soc. Am.* **124**(2), 796–802. doi:10.1121/1.2945114.
- Rogers, C. A., Biggs, D. C., and Cooper, R. A. (1978). “Aggregation of the siphonophore *Nanomia cara* in the Gulf of Maine: Observations from a submersible,” *Fishery Bull.* **76**, 281–284.
- Sameoto, D. D. (1980). “Quantitative measurements of Euphausiids using a 120-kHz sounder and their in situ orientation,” *Can. J. Fish. and Aqu. Sci.* **37**, 693–702.
- Sameoto, D., Cochrane, N., and Herman, A., (1993). “Convergence of acoustic, optical, and net-catch estimates of euphausiid abundance: Use of artificial light to reduce net avoidance,” *Can. J. Fish. and Aqu. Sci.* **50**, 334–346.
- Seim, H. E., Gregg, M. C., and Miyamoto, R. T. (1995). “Acoustic backscatter from turbulent microstructure,” *J. Atmos. and Oceanic Technol.* **12**, 367–380.
- Seim, H. E. (1999). “Acoustic backscatter from salinity microstructure,” *J. Atmos. and Oceanic Technol.* **16**, 1491–1498.
- Simmonds, J., and MacLennan, D. (2005). *Fisheries Acoustics: Theory and Practice*, 2nd ed. (Blackwell Science Ltd., Oxford, UK, 437 p.).
- Sinclair, E. (1994). Prey selection by northern fur seals (*Callorhinus ursinus*) in the eastern Bering Sea. *Fisheries Bulletin*, **92**(1): 144–156.
- Smith, P. F. (1954). “Further measurements of the sound scattering properties of several marine organisms,” *Deep-Sea Research I* **2**, 71–79.
- Smith, J. N., Ressler, P. H., and Warren, J. D. (2010). “Material properties of euphausiids and other zooplankton from the Bering Sea,” *J. Acoust. Soc. Am.* **128**(5), 2664–2680.
- Stanton, T. K. (1988). “Sound scattering by cylinders of finite length I: Fluid cylinders,” *J. Acoust. Soc. Am.* **83**, 55–63.
- Stanton, T. K. (1990). “Sound scattering by spherical and elongated shelled bodies,” *J. Acoust. Soc. Am.* **88**, 1619–1633.
- Stanton, T. K., Clay, C. S., and Chu, D. (1993). “Ray representation of sound scattering by weakly scattering deformed fluid cylinders: Simple physics and application to zooplankton,” *J. Acoust. Soc. Am.* **94**(6), 3454–3462.
- Stanton, T. K., Wiebe, P. H., Chu, D., Benfield, M. C., Scanlon, L.,

- Martin, L., and Eastwood, R. L. (1994a). "On acoustic estimates of zooplankton biomass," *ICES J. Marine Sci.* **51**, 505–512.
- Stanton, T. K., Wiebe, P. H., Chu, D., and Goodman, L. (1994b). "Acoustic characterization and discrimination of marine zooplankton and turbulence," *ICES J. Marine Sci.* **51**, 469–479.
- Stanton, T. K., Wiebe, P. H., and Chu, D. (1998a). "Differences between sound scattering by weakly scattering spheres and finite-length cylinders with applications to sound scattering by zooplankton," *J. Acoust. Soc. Am.* **103**(1), 254–264.
- Stanton, T. K., Chu, D., and Wiebe, P. H. (1998b). "Sound scattering by several zooplankton groups. II. Scattering models," *J. Acoust. Soc. Am.* **103**(1), 236–253.
- Stanton, T. K., Wiebe, P. H., and Chu, D. (1998c). "Differences between sound scattering by weakly scattering spheres and finite-length cylinders with applications to sound scattering by zooplankton," *J. Acoust. Soc. Am.* **103**, 254–264.
- Stanton, T. K., and Chu, D. (2000). "Review and recommendations for the modeling of acoustic scattering by fluid-like elongated zooplankton: Euphausiids and copepods," *ICES J. Marine Sci.* **57**, 793–807.
- Stanton, T. K., Chu, D., Jech, J. M., and Irish, J. D. (2010). "New broadband methods for resonance classification and high-resolution imagery of fish with swimbladders using a modified commercial broadband echosounder," *ICES J. Marine Sci.* **67**, 365–378.
- Stepnowski, A., and Moszynski, M. (2000). "Inverse problem solution techniques as applied to indirect in situ estimation of fish target strength," *J. Acoust. Soc. Am.* **107**, 2554–2562.
- Urick, R. J. (1983). *Principles of Underwater Sound*, 3rd edition. (McGraw-Hill, Inc. Peninsula Publishing, Los Altos, CA).
- Warren, J. D., Stanton, T. K., Benfield, M. C., Wiebe, P. H., Chu, D., and Sutor, M. (2001). "In situ measurements of acoustic target strengths of gas-bearing siphonophores," *ICES J. Marine Sci.* **58**(4), 740–749.
- Warren, J. D., Stanton, T. K., McGehee, D. E., and Chu, D. (2002). "Effect of animal orientation on acoustic estimates of zooplankton properties," *IEEE J. Ocean. Eng.* **27**(1), 130–138.
- Warren, J. D., Stanton, T. K., Wiebe, P. H., and Seim, H. E. (2003). "Inference of biological and physical parameters in an internal wave using multiple frequency acoustic scattering data," *ICES J. Marine Sci.* **60**, 1033–1046.
- Warren, J. D., and Smith, J. N. (2007). "Density and sound speed of two gelatinous zooplankton: Ctenophore (*Mnemiopsis leidyi*) and lion's mane jellyfish (*Cyanea capillata*)," *J. Acoust. Soc. Am.* **122**(1), 574–580.
- Warren, J. D., and Wiebe, P. H. (2008). "Accounting for biological and physical sources of acoustic scattering improves estimates of zooplankton biomass," *Can. J. Fish. and Aqu. Sci.* **65**, 1321–1333. doi:10.1139/F08-047.
- Warren, J. D., Santora, J. A., and Demer, D. A. (2009). "Submesoscale distribution of Antarctic krill and its avian and pinniped predators before and after a near gale," *Marine Biol.* **156**, 479–491. doi: 10.1007/s00227-008-1102-0.
- Weber, T. C., Pena, H., and Jech, J. M. (2009). "Consecutive acoustic observations of an Atlantic herring school in the Northwest Atlantic," *ICES J. Marine Sci.* **66**(6), 1270–1277.
- Weber, T. C., De Robertis, A., Greenaway, S. F., Smith, S., Mayer, L., and Rice, G. (2011). Estimating oil concentration and flow rate with calibrated vessel-mounted acoustic echo sounders. *Proc. Nat. Acad. Sci.* doi: 10.1073/pnas.1108771108.
- Wiebe, P. H., Mountain, D. G., Stanton, T. K., Greene, C. H., Lough, G., Kaartvedt, S., Dawson, J., and Copley, N. (1996). "Acoustical study of the spatial distribution of plankton on Georges Bank and the relationship between volume backscattering strength and the taxonomic composition of the plankton," *Deep-Sea Research II* **43**, 1971–2001.
- Wiebe, P. H., Stanton, T. K., Benfield, M. C., Mountain, D. G., and Greene, C. H. (1997). "High-frequency acoustic volume backscattering in the Georges Bank coastal region and its interpretation using scattering models," *IEEE J. Oceanic Eng.* **22**, 445–464.
- Wiebe, P. H., Stanton, T. K., Greene, C. H., Benfield, M. C., Sosik, H. M., Austin, T., Warren, J. D., and Hammer, T. (2002). "BIO-MAPER II: An integrated instrument platform for coupled biological and physical measurements in coastal and oceanic regimes," *IEEE J. Oceanic Eng.* **27**(3), 700–716.
- Wiebe, P. H., Chu, D., Kaartvedt, S., Hundt, A., Melle, W., Ona, E., and Batta-Lona, P. (2010). "The acoustic properties of *Salpa thompsoni*," *ICES J. Marine Sci.* **67**(3), 583–593.
- Woods, J. D. (1977). "Turbulence as a factor in sound scattering in the upper ocean," in *Oceanic Sound Scattering Prediction* edited by N. R. Andersen and B. J. Zahuranec (Plenum Press), pp. 129–145.



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