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Frequency- and depth-dependent target strength measurements of individual mesopelagic scatterers

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Abstract: Recent estimates based on shipboard echosounders suggest that 50% or more of global fish biomass may reside in the mesopelagic zone (depths of ∼200–1000 m). Nonetheless, little is known about the acoustic target strengths (TS) of mesopelagic animals because ship-based measurements cannot resolve individual targets. As a result, biomass estimates of mesopelagic organisms are poorly constrained. Using an instrumented tow-body, broadband (18–90 kHz) TS measurements were obtained at depths from 70 to 850 m. A comparison between TS measurements at-depth and values used in a recent global estimate of mesopelagic biomass suggests lower target densities at most depths.
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1. Introduction

The mesopelagic zone, an expansive area of the oceans spanning depths from roughly 200–1000 m, is defined by the depths to which light penetrates but is insufficient to support photosynthetic activities. Recent estimates suggest that a majority of global fish biomass inhabits this zone[1,2] and that these animals play an important role in mediating carbon flux to the deep ocean.[3] The majority of this biomass is associated with deep scattering layers detected in shipboard echosounder data. These deep scattering layers have been studied since the 1940s[4,5] and the associated methods have been reviewed in various publications.[6,7] Despite its importance, much remains to be learned about the mesopelagic zone.

Shipboard echosounders are commonly used to survey the mesopelagic zone. The frequencies of these echosounders are typically 18 and 38 kHz. These two frequencies, as well as higher ones, have been successfully used to study the epipelagic zone, which is the top 200 m of the ocean. In this near-surface zone, the acoustic scattering by fishes is generally in the geometric scattering region where there is little dependence of the scattering on frequency. As a result, there exist simple relationships between target strength (TS) and length.[8] Furthermore, fish near the surface are more readily resolved, allowing for direct measurements of TS. These two conditions allow for accurate conversion of acoustic volume backscattering strength (using TS) to abundance.[8]

Because of the depth and diversity of the organisms in the mesopelagic zone, use of these shipboard narrowband echosounders is less effective than in many epipelagic applications. At large ranges individual animals are generally not resolvable using shipboard echosounders, limiting measurements of TS, and high attenuation limits the use of high-frequency signals. Also, the resonance frequencies of fish swimbladders at these deeper depths can be in the 10's of kHz. The pattern of TS versus frequency has a strong peak at the resonance frequency that is both depth- and size-dependent. The proximity of common echosounder frequencies to the resonance frequencies of many mesopelagic organisms makes estimates of abundance sensitive to these resonances. Compounding these challenges are uncertainties in the biodiversity and associated acoustic characteristics of these communities (e.g., the proportion of animals that are non-resonant due to lipid-filled swimbladders[9] or those with no swimbladder). For these reasons, the determination of the TS and estimation of the abundance of mesopelagic populations whose acoustic characteristics span multiple scattering regimes is challenging with narrowband shipboard echosounders.

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Broadband echosounders deployed at deep depths, in combination with rigorous physical sampling, can help to better constrain biomass estimates of the mesopelagic zone. While broadband instruments at relevant frequencies have been applied to epipelagic species,[10–12] similar approaches have not been applied in the mesopelagic zone. Deploying these systems at short ranges from the organisms allows for the animals to be acoustically resolved so that direct measurements of TS can be made. Through use of broadband sound, the pattern of TS versus frequency can be related to the gross anatomical features of the organisms. Specifically, observation of a resonance, a slope that suggests that the band is near a resonance, or a pattern that is near the transition region between Rayleigh and geometric scattering will give information on the size of organism and its gas inclusion (if one exists).

To address these needs, the towed instrument platform *Deep-See* has been developed and equipped with a powerful combination of sensing technologies for deployment in the mesopelagic zone.[13] While other profiling or towed packages have been previously used to measure mesopelagic scatterers,[14–16] *Deep-See* has unique sensing capabilities. For example, it contains seven broadband echosounders with split-beam capabilities spanning the frequency range from roughly 1 to 420 kHz. The package, which is rated to a depth of 2000 m, includes a power and telemetry bottle for real-time observations.

This paper presents a preliminary analysis of measurements of TS versus frequency and depth for mesopelagic organisms from the first series of deployments of *Deep-See*. The analysis focuses on frequencies between 18 and 90 kHz given their relevance to traditional survey techniques. Individual targets are processed from tow-body depths of 70 to 800 m during a nighttime deployment. TS histograms, resonance frequencies, classification of TS spectra, and ship-based narrowband measurements are analyzed. Measured TS values are compared to those used in a previous estimate of global mesopelagic biomass and to quantify the impact of the differences on density inferences.

2. Methods

The first at-sea use of *Deep-See* was performed off of the New England continental shelf, USA, between August 12 and 22, 2018. During that period, seven deployments were performed over a range of depths for system testing, calibration, and studies of marine life. Shipboard narrowband echosounders (Simrad EK60) were operated concurrently at 18, 38, 120, and 200 kHz. In sequence with the deployments, physical sampling was performed using pelagic trawls and zooplankton nets. These physical samples are not further discussed as it is outside the scope of this initial analysis.

The seven broadband tranducers on *Deep-See* are operated by two independent systems. Four of the channels are part of a Simrad EK80 (monostatic) echosounder system (45–420 kHz) and the other three are part of a customized system made by Edgetech (1–45 kHz). In this latter system, three source transducers are paired with an adjacent split-beam receiver array constructed of polyvinylidene fluoride (PVDF). The sources are close enough to the receive array in the Edgetech system that for ranges beyond 20 m this source/receiver geometry is a good approximation to a monostatic system. The broadband echoes from each channel were pulse-compressed using matched filter processing.[17–19] The echosounders were calibrated as a function of depth of the tow-body ($\sim$40 to 700 m) using a 20-cm-diameter solid aluminum sphere suspended about 20 m below the transducers. The response of each channel was determined using a combination of partial-wave and full-wave calibration techniques.[10,20] Further information about the PVDF array, Edgetech system processing, and calibration is available as supplementary material.[21] A Seabird 25plus sensor was mounted on *Deep-See* to measure conductivity, temperature, and depth (CTD).

This analysis focuses on one deployment during which data were collected at depths from 70 to 850 m over a three-hour period overnight (after the diel migration). The deployment took place on 17–18 August 2018 at approximately 39°12′ N, 70°43′ W. Data from two echosounder channels, with nominal center frequencies of 30 and 70 kHz, are analyzed in terms of various characteristics of target strength from individual scatterers. These sub-systems are referred to here as the "30 kHz BB" and "70 kHz BB" channels, where the "BB" refers to broadband. The subsystems transmitted linear frequency modulated signals (i.e., chirps) with pulse durations and frequency ranges of 10 ms/18–45 kHz and 1 ms/45–90 kHz, and with beamwidths of 4.6° and 7° at their center frequencies, respectively. Both sub-systems transmitted at a ping rate of 1 Hz, but operated asynchronously. In post-processing, a quadrant in the 70 kHz BB channel was found to not be operating as expected. Further analysis suggested that the channel performance was suitable for inclusions here despite the increase in uncertainty associated with the data (see supplemental material).[21]

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Echoes from individual targets were manually selected in 0.5 m analysis windows at ranges of 20–50 m from the tow-body. Acceptance for further processing of echoes from individual targets varied across channels due to differences in beamwidth and signal-to-noise ratios. Targets from the 70 kHz BB channel were only considered for further processing if they were detected in at least three pings where the off-axis angle (θ) was less than 3°, the target spectra were structurally similar, and individual pings agreed to within 3 dB of the mean with the exception of nulls that were smoothed over by averaging. In contrast, targets with a few as one echo where $\theta < 2.5°$ were accepted in the 30 kHz BB channel. However, single ping targets were retained only if the target had been observed in additional pings where $\theta > 2.5°$, but still agreed with the accepted ping to within 2 dB below 30 kHz (75% of the targets retained had two or more pings where $\theta < 2.5°$).

The TS spectrum was calculated for each accepted target by taking the linear average of the spectra of its echoes. "Narrowband" values of TS were calculated from the spectra by taking linear averages in the sub-bands of 20–22 kHz, 37–39 kHz, and 69–71 kHz for comparison to shipboard narrowband frequencies and previously published literature. The 20–22 kHz band is the closest approximation of the commonly used 18 kHz channel that could be reliably obtained given the roll-off near the edge of the transceiver band.

Target strength spectra were visually examined and categorized by their shape into the following five classes: flat (F), resonant (R), near-resonance (N), below-resonance/Rayleigh scattering (B), and complex (C). These classifications correspond to portions of modeled TS spectra associated with organisms whose bodies are gas-bearing or fluid-like. These anatomical groups are distinguished acoustically as having a resonance or no resonance, respectively[10,22] [Fig. 1(a)]. *In situ* echo data corresponding to these classifications are shown for comparison [Fig. 1(b)]. Since the channels are not synchronized, the position and orientation of individual targets relative to *Deep-See* are not necessarily consistent between channels. Therefore, instead of directly comparing targets, broader trends and differences between channels for all targets are analyzed. For example, if the targets are generally resonant in the 30 kHz BB channel, then the expectation is that their spectra would be flat in the 70 kHz BB channel.

3. Results and discussion

Observed target strength distributions and their means, echo classification, and resonance frequencies vary as a function of depth (Fig. 2). Trends in scattering observed as a function of frequency in *Deep-See* data are consistent with volume backscattering measurements from the shipboard narrowband echosounders at 18 and 38 kHz (see supplementary material[21]). Important observations as a function of target depth are summarized below:

- 82–120 m: TS spectral classifications included flat, resonant, and near resonance (30 kHz BB) in contrast to flat and complex (70 kHz BB). Observed resonance peaks were limited to 20–25 kHz and the mean narrowband TS value was highest at 20 kHz. Targets at this depth likely included a mix of mesopelagic and epipelagic species.
- 241–278 m: Approximately 81% of targets (30 kHz BB) were resonant, of which 92% had resonance peaks from 33 to 35 kHz. In the 70 kHz BB channel most TS spectra were classified as flat,

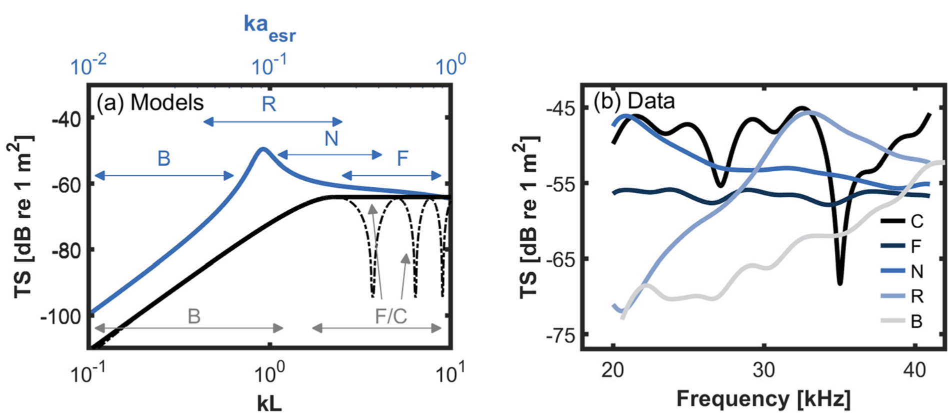

Fig. 1. (Color online) (a) Scattering models for prolate spheroids, one gas (Ref. 24) and one weakly scattering (Ref. 25). Material properties are consistent with those of marine organisms and high ambient pressures. The y axes are presented on a relative scale to focus on the form of the curve and not the amplitude of the scattering. (b) Classification examples for 30 kHz BB channel TS spectra.

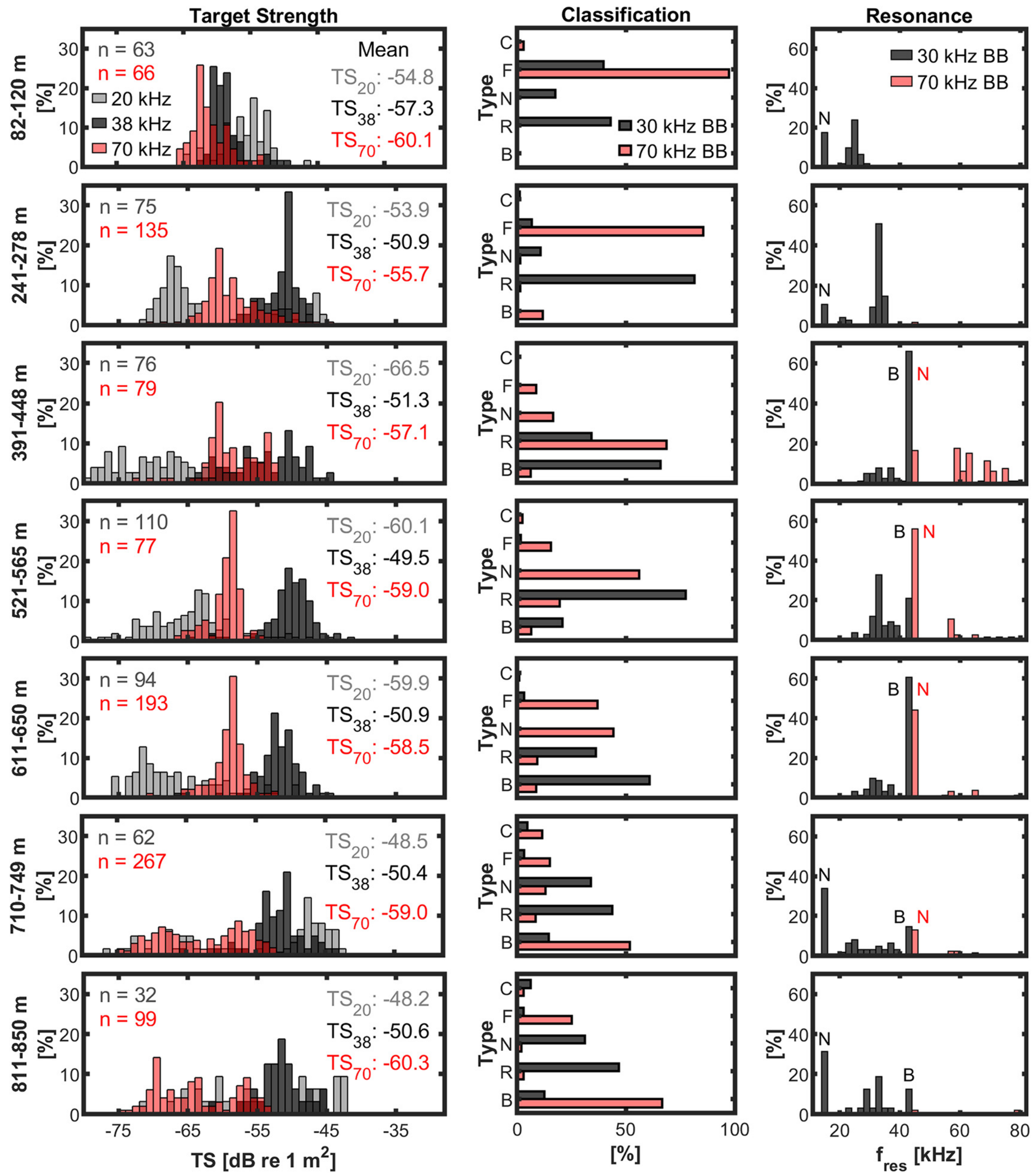

Fig. 2. (Color online) Distributions of TS, spectral classification, and resonance frequencies. The number of targets (n) in the first column applies to the entire row and the colors correspond to the 30 kHz BB (black/grey) and 70 kHz BB channels (red). Mean TS values are given in each panel in the left column. The spectral classifications are (C) complex, (F) flat, (N) near resonance, (R) resonant, (B) below resonance/Rayleigh. Annotations in the right column refer to the spectral classifications. Resonance peaks on these frequency ranges are not resolved.

although some were classified as below-resonance/Rayleigh. No below-resonance/Rayleigh targets were observed with the 30 kHz BB channel, suggesting these echoes were below the noise floor.

- 391–448 m: Approximately 60% of the echoes (30 kHz BB) were below-resonance/Rayleigh while the 70 kHz BB channel includes all classifications except complex spectra. This suggests that many targets may have been resonant between 40 and 50 kHz. Due to different target classifications, TS distributions are wider than at shallower depths. Fewer targets are measured in the 70 kHz BB channel due to a relatively high target density that made resolving individual targets more difficult.
- 521–749 m: Larger proportions of targets near-resonance (70 kHz BB) or below-resonance/Rayleigh (30 kHz BB) are present at these depths and the relative proportion of targets suitable for processing using the 30 kHz BB channel decreases. Resonant targets with peaks near 38 kHz were dominant (∼60% of targets in the 30 kHz BB channel) from 521 to 565 m. From 611 to

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650 m, results suggest unresolved resonance between 40 and 50 kHz, in addition to targets resonant in the 30–40 kHz range. A wide distribution of resonance peaks (30 kHz BB) is observed from 710 to 749 m.

- 811–850 m: Both channels include all spectral classifications. At this depth many more targets were observed in the 70 kHz BB channel and most were below-resonance/Rayleigh. These targets are under-counted by both ship-based echosounders and in the 30 kHz BB channel data due to the system's noise floor. Although the type of these targets is unknown, the 70 kHz TS values and below-resonance/Rayleigh classification are consistent with the targets being gas-bearing organisms.

Using measured TS values, a comparison is made to a recent study[1] based on 38 kHz shipboard echosounder measurements that suggests mesopelagic biomass considerably exceeds estimates based on physical sampling. TS values cannot be converted to biomass without physical sampling to establish TS-weight relationships and apportionment of scattering to different taxa. However, relative comparisons between densities of scatterers based on TS values are possible. Irigoien *et al.*[1] used a TS value of -60.6 dB re 1 m^2, a geometric mean of TS measured in other studies. The 38 kHz TS values within the mesopelagic zone (depth >200 m) presented here range from -51.3 to -49.5 dB re 1 m^2. Applied to volume backscattering measurements, these TS values would result in ∼90% fewer individuals than Irigoien *et al.* Even using the linear mean of the TS values from Irigoien *et al.* (-55.1 dB re 1 m^2), these differences are large (75% to 58% fewer scatterers). In contrast, measurements of targets from 811 to 850 m in our study suggest many animals are under-counted by ship-based echosounders due to their low TS at 38 kHz. The implication is clear: biomass estimates are subject to large uncertainties without well-constrained TS distributions and TS-weight relationships representative of a particular location and depth. These uncertainties are compounded by the reported non-linearity bias from EK60 echosounders (the primary acoustic data source in previous biomass estimates), which may result in overestimates of volume backscattering by 10% or more in this context.[23]

To our knowledge, these are the first broadband TS measurements at these depths with frequencies that overlap with those of ship-based echosounders. These measurements reveal the complexity of mesopelagic backscatter as a function of depth, with changes in the spectral classifications and TS distributions belying the stability in the mean TS values at 38 kHz below 200 m. Furthermore, many scatterers were detected at depth that contribute little to observations using ship-based echosounders. The use of TS values previously applied in global mesopelagic biomass estimates to measurements at this site would result in inferred target densities as much as ten times higher than those be obtained using TS measurements. These measurements are limited to one location over a short period of time and the results should not be assumed to apply throughout the mesopelagic zone or in different regions. New data sets, improved system characterization, refined processing techniques, and larger sample sizes will make future measurements more suitable for broader application. Other sensors and physical samples (trawls) will further contribute to our understanding of the acoustic observations and the mesopelagic zone.

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References and links

[1]X. Irigoien, T. Klevjer, A. Røstad, U. Martinez, G. Boyra, J. Acuña, A. Bode, F. Echovarria, J. Gonzalez-Gordillo, S. Hernandez-Leon, S. Agusti, D. Aksnes, C. Duarte, and S. Kaartvedt, "Large mesopelagic fishes biomass and trophic efficiency in the open ocean," Nat. Commun. **5**, 1–10 (2014).
[2]R. Proud, N. Handegard, R. Kloser, M. Cox, and A. Brierley, "From siphonophores to deep scattering layers: Uncertainty ranges for the estimation of global mesopelagic biomass," ICES J. Mar. Sci. **76**(8), 718–733 (2019).
[3]P. Davison, D. Checkley, Jr., J. Koslow, and J. Barlow, "Carbon export mediated by mesopelagic fishes in the northeast Pacific Ocean," Prog. Ocean. **116**, 14–30 (2013).
[4]R. S. Dietz, "Deep scattering layer in the Pacific and Antarctic Oceans," J. Mar. Sci. **7**, 430–442 (1948).
[5]J. Hersey, R. Backus, and J. Hellwig, "Sound-scattering spectra of deep scattering layers in the western North Atlantic Ocean," Deep Sea Res. **9**, 196–210 (1962).
[6]G. B. Farquhar, *Proceedings of an International Symposium on Biological Sound Scattering in the Ocean*, Warrenton, VA (31 March–2 April, 1970), Rep. 005.
[7]T. Stanton, "30 years of advances in active bioacoustics: A personal perspective," Methods Ocean. **1–2**, 49–77 (2012).
[8]E. Simmonds and D. MacLennan, *Fisheries Acoustics*, 2nd ed. (Blackwell Science, Oxford, UK, 2005).
[9]T. Dornan, S. Fielding, R. Saunders, and M. Genner, "Swimbladder morphology masks southern ocean mesopelagic fish biomass," Proc. R. Soc. B. **283**, 1–9 (2019).

[10]T. Stanton, D. Chu, J. Jech, and J. Irish, "New broadband methods for resonance classification and high-resolution imagery of fish with swimbladders using a modified commercial broadband echosounder," ICES J. Mar. Sci. **67**, 365–378 (2010).
[11]J. Jech, G. Lawson, and A. Lavery, "Wideband (15–260 kHz) acoustic volume backscattering spectra of Northern krill (*Meganyctiphanes norvegica*) and butterfish (*Oeorilus triacanthus*)," ICES J. Mar. Sci. **74**, 2249–2261 (2017).
[12]C. Bassett, A. De Robertis, and C. Wilson, "Broadband echosounder measurements of the frequency response of fishes and euphausiids in the Gulf of Alaska," ICES J. Mar. Sci. **75**, 1131–1142 (2018).
[13]A. Lavery, T. Stanton, J. Jech, and P. Weibe, "An advanced sensor platform for acoustic quantification of the ocean twilight zone," J. Acoust. Soc. Am. **145**, 1653 (2019).
[14]T. Knutsen, W. Melle, M. Mjanger, E. Strand, A. Fuglestad, C. Broms, E. Bagøien, H. Fitje, O. Ørjansen, and T. Vedeler, "Messor—A towed underwater vehicle for quantifying and describing the distribution of pelagic organisms and their physical environment," in *2013 MTS/IEEE OCEANS*, Bergen (2013), pp. 1–12.
[15]R. Kloser, T. Ryan, G. Keith, and L. Gershwin, "Deep-scattering layer, gas-bladder density, and size estimates using a two-frequency acoustic and optical probe," ICES J. Mar. Sci. **73**, 2037–2048 (2016).
[16]I. D. Bernardes, E. Ona, and H. Gjøæter, "Study of the Arctic mesopelagic layer with vessel and profiling multifrequency acoustics," Prog. Ocean. **182**, 102260 (2020).
[17]G. Turin, "An introduction to matched filters," IRE Trans. Inf. Theory **6**(3), 311–329 (1960).
[18]D. Chu and T. Stanton, "Application of pulse compression techniques to broadband acoustic scattering by live individual zooplankton," J. Acoust. Soc. Am. **104**, 39–55 (2013).
[19]D. A. Demer, L. N. Andersen, C. Bassett, L. Berger, D. Chu, J. Condiotty, G. R. Cutter Jr., B. Hutton, R. Korneliussen, N. Le Bouffant, G. Macaulay, W. L. Michaels, D. Murfin, A. Pobitzer, J. S. Renfree, T. S. Sessions, K. L. Stierhoff, and C. H. Thompson, "2016 USA–Norway EK80 workshop report: Evaluation of a wideband echosounder for fisheries and marine ecosystem science," ICES Cooperative Research Report No. 336 (2017).
[20]T. Stanton and D. Chu, "Calibration of broadband active systems using a single standard spherical target," J. Acoust. Soc. Am. **124**(1), 128–136 (2019).
[21]See supplementary material at http://dx.doi.org/10.1121/10.0001745 for topics that include the PVDF receiver array, acoustic data processing, calibration, narrowband 18 and 38 kHz shipboard echosounder data, and broadband transducer performance.
[22]A. Lavery, D. Chu, and J. Moum,"Measurements of acoustic scattering from zooplankton and oceanic microstructure using a broadband echosounder," ICES J. Mar. Sci. **67**, 379–392 (2010).
[23]A. D. Robertis, C. Bassett, L. N. Andersen, I. Wangen, S. Furnish, and M. Levine, "Amplifier linearity accounts for discrepancies in echo-integration measurements from two widely used echosounders," ICES J. Mar. Sci. **76**, 1882–1892 (2019).
[24]R. Love, "Resonant acoustic scattering by swimbladder-bearing fish," J. Acoust. Soc. Am. **64**, 571–580 (1978).
[25]W. Lee, A. Lavery, and T. Stanton, "Orientation dependence of broadband acoustic backscattering from live squid," J. Acoust. Soc. Am. **131**, 4461–4475 (2012).