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Acoustic backscattering by deepwater fish measured in situ from a manned submersible

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Abstract

An outstanding problem in fisheries acoustics is the depth dependence of scattering characteristics of swimbladder-bearing fish, and the effects of pressure on the target strength of physoclistous fish remain unresolved. In situ echoes from deepwater snappers were obtained with a sonar transducer mounted on a manned submersible next to a low-light video camera, permitting simultaneous echo recording and identification of species, fish size and orientation. The sonar system, consisting of a transducer, single board computer, hard disk, and analog-to-digital converter, used a 80 μs, broadband signal (bandwidth 35 kHz, center frequency 120 kHz). The observed relationship between fish length and in situ target strength shows no difference from the relationship measured at the surface. No differences in the species-specific temporal echo characteristics were observed between surface and in situ measures. This indicates that the size and shape of the snappers' swimbladders are maintained both at the surface and at depths of up to 250 m. Information obtained through controlled backscatter measurements of tethered, anesthetized fish at the surface can be applied to free-swimming fish at depth. This is the first published account of the use of a manned submersible to measure in situ scattering from identified, individual animals with known orientations. The distinct advantage of this technique compared with other in situ techniques is the ability to observe the target fish, obtaining accurate species, size, and orientation information.

Keywords: Acoustic properties; Active sonar; In situ measurements; Pressure effects; Bottomfish fishery; USA; Hawaiian Islands

1. Introduction

Deepwater snappers in the family Lutjanidae are the most important component of the Hawaiian bottomfish fishery. Catch data collected over the past decade indicate that the populations of two species, the onaga, or long-tailed red snapper (*Etelis coruscans*), and the ehu, or red snapper (*Etelis carbunculus*), are depleted in the main Hawaiian Islands (Western Pacific Regional Fisheries Management Council, 1999). A third species, the opakapaka, or pink snapper (*Pristipomoides filamentosus*), is heavily targeted and is also

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considered at risk. In 1998, a network of 19 restricted fishing areas (RFAs) was created in an effort to protect approximately 20% of the designated essential habitat for onaga and ehu. Without catch data in these areas, the recovery of most of the RFAs has gone unmonitored. However, efforts are now under way to develop non-lethal assessment techniques that can be used for this purpose.

Onaga, ehu, and opakapaka habitats are found between 100 and 400 m depths so are inaccessible to SCUBA divers. Currently, non-lethal observations can be made only from submersibles, ROVs, or drop cameras. Sonar has the potential to provide cost-effective sampling of deepwater fish. However, the application of sonar survey techniques requires acoustic backscattering data for each target species (MacLennan, 1990). A primary measure necessary for the utilization of acoustics is the target strength, or acoustic size, of the target species. Accurate determination of target strength is essential to fisheries acoustics, since it allows conversion of backscattering to fish biomass. The air-filled swimbladder is the most important factor affecting acoustic backscattering in fish that have them (Foote, 1985; Foote and Ona, 1985). However, an outstanding problem in fisheries acoustics is the depth dependence of target strength of swimbladder-bearing fish (Dunn, 1978; Midtunn, 1984; Mukai and Foote, 1997). When these fish dive, their swimbladders are compressed as a result of the increase in pressure at greater depths (Marshall, 1966). Lutjanids are physoclistous, i.e., they have closed swimbladders and can physiologically regulate volume to control their buoyancy when permitted time to acclimatize. In contrast, physostomous fish have open swimbladders, which they cannot regulate. The swimbladder volumes of many physostomous fish have been shown to decrease as fish go deeper, according to Boyle's pressure law (Blaxter et al., 1979). Consequently, the target strength of these fish also decreases (Mukai and Foote, 1997; Mukai and Iida, 1996; Mukai et al., 1988). Experiments with physostomous and some physoclistous fish forced to change depth rapidly have also shown target strength changes that fit Boyle's law (Edwards and Armstrong, 1984; Mukai and Foote, 1997). However, the effects of pressure on the target strength of free-swimming physoclists measured in situ with split or dual beam echosounders remain unresolved and ambiguous (Dunn, 1978; Rose and Porter, 1996; Traynor and Williamson, 1983).

Other acoustic scattering characteristics can also be important for fisheries surveys. The temporal and spectral structure of broadband echoes can be important in species classification (Reeder et al., 2000; Stanton et al., in press). Echo structure is created by differences in the shape of structures causing sound scattering (Stanton et al., in press). Rapid increases in pressure on physoclistous fish have been shown to cause deformation of the shape of the swimbladder as the volume follows Boyle's law but the dorsal area of the bladder does not change as rapidly (Ona, 1990). The change in the volume of the swimbladder is not always concentric (Blaxter et al., 1979), so shape can change with depth, potentially changing echo characteristics that could permit species identification.

Two types of methods have been utilized to measure target strength and other scattering characteristics (MacLennan and Simmonds, 1992). Ex situ methods involve anesthetizing or stunning a fish and measuring its backscattering under controlled conditions, often while the fish is completely immobilized or enclosed in a small cage. The major advantage of ex situ methods is that biological and behavioral characteristics of the fish can be precisely known, including species, size, tilt angle, swimming speed, maturity, and depth adaptation. In situ methods, usually involving split beam or dual beam echosounders, remove the effects of constraining the fish and potential effects of bringing the fish to the surface. However, they also add significant uncertainties in the target's species, size, orientation, and other potentially important factors (MacLennan and Menz, 1996). In asking questions about the effects of pressure, in situ measures are preferable because the fish can normally acclimatize to ambient pressure.

Ex situ measurements have been obtained of the backscattering from snappers brought to the surface. However, the validity of these measures to fish living in their natural, high-pressure environment, at depths of 150–350 m, is uncertain. To directly compare measures taken of fish in situ to measures of fish taken at the surface requires the species, size, and orientation of the animal be known. The simultaneous use of trawling and split beam or dual beam sonar can estimate size and species composition, but cannot elucidate behavior including orientation. An alternative in situ technique is to directly observe the fish while simultaneously obtaining echo data. This was accomplished by simultaneously recording low-light video and acoustic backscatter from deep-water snappers in their natural habitat using a manned submersible. The video allowed individual fish to be identified and sized and their orientation relative to the sonar beam to be determined. The data collected provided a means of validating controlled backscatter measurements from tethered, anesthetized fish at the surface as well as an understanding of the processes affecting sound scattering in physoclistous fish.

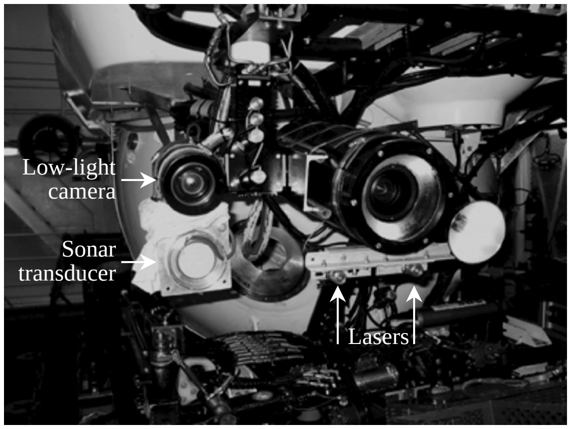

Fig. 1. Photograph of the pan and tilt on the submersible showing the position of the low-light camera, sonar transducer, and parallel lasers.

2. Methods

The Hawaii Undersea Research Laboratory's Pisces IV submersible was utilized during two dives in October 2002 to record simultaneous video and acoustic data from deepwater snappers. The study sites were located between depths of 170 and 253 m, inside the Kaho'olawe Island Reserve near Maui, Hawaii. To obtain in situ data from onaga, ehu, and opakapaka, a sonar transducer and a ROS 20/20 Navigator CCD camera were mounted on the pan and tilt of the submersible (Fig. 1). The sensitivity of the camera enabled the capture of video on a mini digital video recorder using only ambient light. This eliminated the well-known avoidance of submersible lights characteristic of these species and permitted echoes from individual fish to be obtained. The sonar system was composed of a transducer, single board computer, hard disk, analog-to-digital converter, remote interface with gain control, and batteries. The system used a 80 μs, broadband signal, modeled after a dolphin echolocation click, which had a 35 kHz bandwidth and a center frequency of 120 kHz (Fig. 2). Data acquisition was triggered by the outgoing signal, and echoes were digitized at sampling rate 500 kHz with a National Instruments 6062E PCMCIA DAQ card connected to a single board computer. A composite piezo-electric ceramic transducer with a beam width of 12° at the center frequency was used to send and receive acoustic signals. Placement of the transducer next to the camera allowed synchronous recording of both video and acoustic data. Snappers crossing in front of the camera and transducer were ensonified by manually triggering a set of acoustic pulses that fired every 700 ms for 1 min. To synchronize the video with the acoustic data, the tape position and time were recorded precisely at each triggering.

The peak-to-peak target strength of an 8 cm diameter, 2.5 cm tall, cylindrical syntactic foam target was measured with a calibrated hydrophone in a seawater tank. The same cylinder, attached to a lead weight and monofilament line, was deployed from the submersible at 250 m. This incompressible yet buoyant target was chosen because of the difficulties and dangers associated with deploying monofilament line from a submersible. The buoyant target reduced the length of line needed by half. Echoes from the cylinder, floating 1.6 m above the bottom, were recorded with the sonar system (Fig. 3). At both the surface and at depth, the cylinder was centered in the sonar beam horizontally and vertically with the convex sides of the cylinder facing the transducer. The

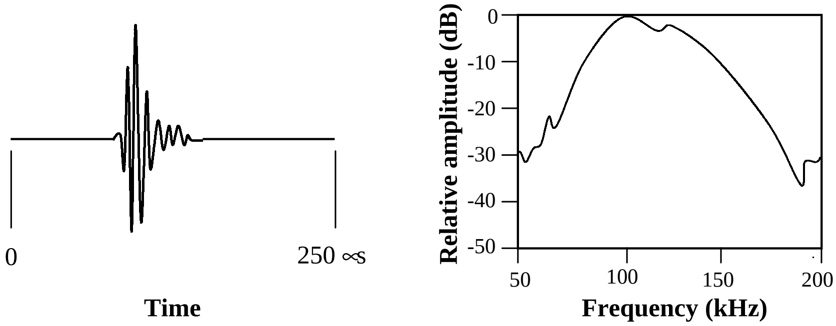

Fig. 2. Waveform (left) and spectrum (right) of the broadband sonar signal used to obtain echoes both at the surface and in situ.

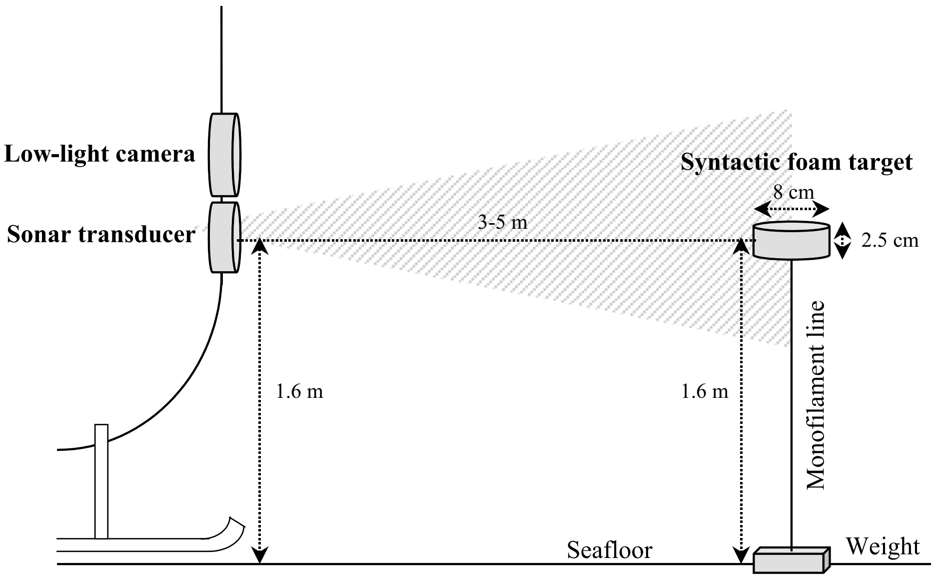

Fig. 3. Setup used for the measurement of the calibration cylinder from the submersible. The transducer and target were the same distance from the substrate and the target was centered in the transducer's beam, represented by the hatched area, both horizontally and vertically. The convex sides of the cylinder faced the transducer. A similar setup was used to measure the target strength of the cylinder at the surface with a calibrated hydrophone.

variability of echoes from the cylinder was within ± 2 dB. To understand the effects of depth on the transducer, the response of the sonar system to the cylinder at depth was compared to echoes obtained with the system at the surface. Peak-to-peak target strengths of fish targets were then determined from the equation

$$\mathrm{TS}_{\mathrm{Fish}} = 20\log(V_{\mathrm{Fish}}/V_{\mathrm{Cylinder}}) + 40\log(R_{\mathrm{Fish}}/R_{\mathrm{Cylinder}}) + \mathrm{TS}_{\mathrm{Cylinder}}, \quad (1)$$

where V is the voltage recorded by the sonar system, R is the range from the transducer to the target, and TS is target strength in dB. Because of difficulties in obtaining echoes in an uncontrolled setting, many in situ signals had a limited dynamic range and their envelopes resembled a decaying exponential. This made determination of the precise duration of the echo impossible in the presence of noise. Consequently, peak-to-peak target strength rather than total energy target strength (see MacLennan and Simmonds, 1992) was measured. From surface measures, both total energy and peak-to-peak target strengths could be calculated. The total energy target strength was consistently 1.0–3.2 dB higher than the peak-to-peak target strength.

Ensonified fish were identified to species from the videotape. The length of each fish was estimated with the beams from two parallel lasers, positioned 15.25 cm apart. The position of the fish, relative to the sonar beam was also recorded. Only fish whose lateral aspects were nearly perpendicular to the axis of the sonar beam were utilized in the analyses.

Surface measures of backscattering were obtained as part of a larger study investigating the effects of fish size, species, and orientation on scattering characteristics. Fish were captured off islands of Oahu and Molokai by standard bottomfishing techniques, and their swimbladders were punctured at the surface to release internal pressure. The fish were maintained for at least 8 days while their swimbladders healed before being measured. Anesthetized fish were tethered to a rotor 6 m from a transducer. The same broadband signal (Fig. 2) and a similar technique were employed but the single board computer was replaced with a portable PC. The incident signal was measured and digitized with a calibrated hydrophone located where a target fish would be. Peak-to-peak target strength was calculated by comparing the reflected signal to the incident signal according to the equation

$$TS_{Fish} = 20\log(V_{Fish}/V_{Incident}) + 20\log R, \qquad (2)$$

where V_{Fish} is the voltage received by the transducer from the fish, $V_{Incident}$ is the voltage recorded by the hydrophone, and R is the distance between the transducer and the target.

To determine the effects of depth on the backscattering strength of the snappers, in situ peak-to-peak target strength measurements were compared to lateral aspect peak-to-peak target strengths of the same species taken at the surface. A single-factor analysis of variance (ANOVA) was used to test the effects of depth, species, and length on the lateral aspect acoustic backscattering cross-section measured both at the surface and in situ. Backscattering cross-section is the linear form of backscattering strength and was chosen for the statistical analysis because the residuals indicated a normal distribution, satisfying the assumptions of ANOVA. Visual comparisons between surface measures and in situ measures of the temporal structure of echoes obtained from each species were also made.

3. Results

In situ, lateral aspect target strengths were obtained for a total of 54 individual fish: 4 opakapaka (*P. filamentosus*), 23 onaga (*E. coruscans*), and 27 ehu (*E. carbunculus*). The target strengths of the three target snapper species ($N_{total} = 31$, 11 opakapaka, 10 onaga, 10 ehu) measured at the surface were compared with target strengths of the same fish species measured in situ (Fig. 4). A single log-linear regression for target strength as a function of fish length was fitted for

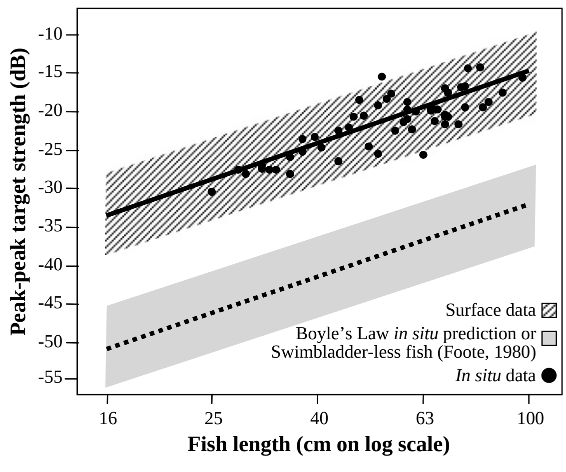

Fig. 4. Best-fit linear regression for the length–target strength relationship of all three snapper species measured at the surface is indicated by the solid line. The dotted line represents the length–target strength relationship predicted for fish at 250 m if their swimbladder volume changes as a function of Boyle's law and the difference in target strength expected for fish without swimbladders (Foote, 1980). The 99% confidence interval for each regression line is indicated by the hatched areas. Scatter points show the target strength for the same fish species measured in situ from the submersible. The in situ measures were not significantly different from those taken at the surface.

all three species measured at the surface ($TS_{p-p} = 23.6 \log SL - 61.9$; $r^2 = 0.62$, where SL is fish standard length in cm). If the fish's swimbladders compressed as a function of Boyle's pressure law, their target strengths would change 0.67 dB for each atmosphere of increased pressure (Mukai et al., 1988), resulting in an average target strength decrease of 16.8 dB. The regression of Foote (1980) for target strength at 120 kHz for swimbladder-bearing fish fits the surface target strength data well ($r^2 = 0.86$). The regression for fish of the size range measured lacking a swimbladder predicts target strengths of an average of 15.8 dB lower (Foote, 1980). The 99% confidence intervals for the target strength–fish length relationship measured at the surface, and the relationship predicted by Boyle's law or swimbladder-less fish, are not overlapping, allowing unambiguous discrimination of the in situ data's fit to the two alternatives. Scatter points of fish length, estimated from the video, versus lateral aspect target strength nearly all fit within the 99% confidence interval for the surface target strength measurements. A log-linear regression of the length, in situ target strength relationship, was similar to the relationship measured at the surface ($TS_{p-p} = 23.9 \log SL - 62.8$; $r^2 = 0.62$). An analysis of variance on the lateral aspect backscattering cross-section showed no significant differences between measures taken at the surface and those taken in situ ($p \gg 0.05$, Table 1). Species also had no significant effect on backscattering cross-section ($p \gg 0.05$) although length significantly affected backscattering strength ($p < 0.05$). No interactions were significant. The overall observed statistical power of the test was 0.81.

Table 1
ANOVA of between subject effects on acoustic backscattering cross-section

Source	SS	df	MS	F	p
Depth (surface or in situ)	0	1	0.002	0.66	ns
Species	0.01	2	0.003	1.12	ns
Length	1.21	57	0.021	6.82	<0.05
Depth × species	0	0			ns
Depth × length	0.01	1	0.008	2.53	ns
Species × length	0.02	10	0.002	0.59	ns
Depth × species × length	0	0			ns
Error	0.01	4	0.003		
Total	2.34	85			

SS = sum of the squared deviations of scores from their mean (a measure of variability or dispersion); df = degrees of freedom (the number of independent pieces of information available in the estimation of population parameters); MS = mean square (a calculated variance estimate); $F = F$ ratio (an index permitting assessment of the statistical significance); p = probability; ns stands for non-significant (Zar, 1999).

Temporal structure of lateral aspect fish echoes measured at the surface varied by species. These differences were conserved in fish measured in situ (Fig. 5). Differences in echo structure between individual fish measured at the surface and those of the same species measured in situ were within the range observed for each species at the surface.

4. Discussion

When fish descend, their swimbladders may or may not become compressed or deformed by increasing pressure. This could result in differences in acoustic backscattering strength and echo structure. The effects of pressure on the acoustic scattering of deepwater snappers under natural conditions were previously uninvestigated. However, this work shows that these physoclistous fish maintain their swimbladder shape and volume both at the surface and at great depths. The relationship observed between snapper length and target strength shows no difference from the relationship measured at the surface. This shows that swimbladder volume, rather than mass of gas, is maintained by snappers at a range of depths, from the surface to 350 m. It also shows that surface measures of backscattering strength made on deepwater snappers, maintained long enough to permit healing of their swimbladders and acclimatization to surface pressure conditions, are valid. The ex situ backscattering strength results, from which more information could be obtained on orientation effects, can be extrapolated to single snappers in the wild.

The conservation of echo temporal structure within species, regardless of depth, indicates that deformation of the swimbladder and the remainder of the fish body with increasing pressure is minimal. These snapper species are maintaining

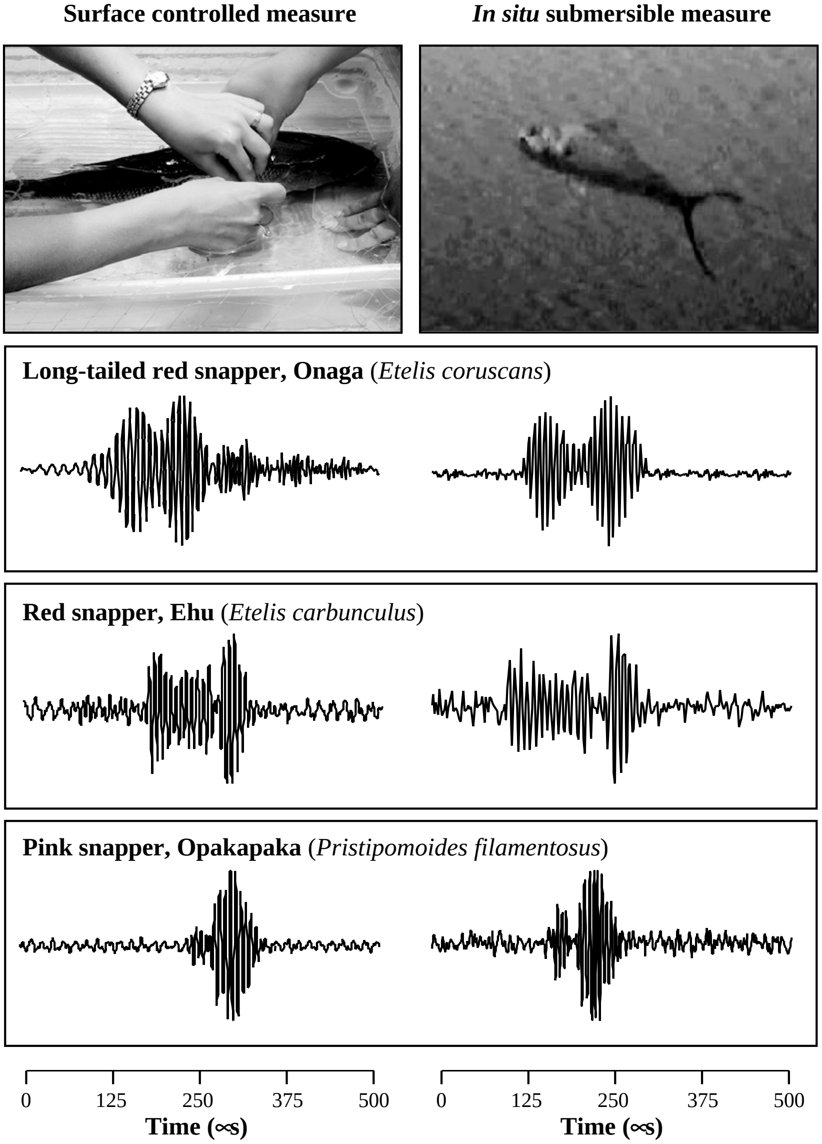

Fig. 5. Representative echoes from the lateral aspect of each Hawaiian snapper species. Echoes on the left were taken from anesthetized fish under controlled conditions at the surface. Echoes on the right were taken from the submersible of free-swimming fish at 250 m deep. Differences in echo structure are observed between species but the differences between fish measured at the surface and those measured in situ are within the variance observed for the species. This indicates that the shape of the structures causing acoustic reflections, primarily the swimbladder, remain the same in an acclimatized fish at the surface and the one at depth.

their swimbladder shape, the primary cause of temporal and spectral differences in broadband echoes that can distinguish species. The conservation of swimbladder shape means that differences between species in broadband echoes measured at the surface, under controlled conditions, can be applied to fish in situ. The difficulties obtaining multiple echoes, from a range of orientations on a single fish in situ, makes the use of surface measures necessary for the development of a sonar system potentially capable of species identification.

A thorough understanding of changes in backscattering strength as a function of pressure is crucial for the evaluation of acoustic data (Olsen, 1987). Previous work on physoclistous fish has not resolved the issue (Dunn, 1978; Rose and Porter, 1996; Traynor and Williamson, 1983), which has led to difficulties interpreting field data and creating predictive acoustic models. For example, differences observed in target strength as a function of depth in cod were explained as the effects of pressure changing swimbladder volume rather than differences in fish size (Rose and Porter, 1996). While this may be correct, it seems unlikely that cod and other physoclistous fish, capable of regulating their swimbladder volume to maintain their buoyancy, would dramatically change their swimbladder volume under natural conditions in the absence of large, vertical migrations. An assessment of the state of acclimatization of fish in the wild is imperative to reduce the uncertainty in utilizing the most appropriate target strength value. Free-swimming lutjanid snappers appear to have been acclimated to the ambient pressure during all measures. Large daytime vertical excursions (i.e., >100 m) in these species are not known.

This is the first published account of the use of a manned submersible to measure acoustic backscatter from identified, individual marine animals with known orientations relative to the sonar signal. Remotely operated vehicles have been employed to measured scattering from relatively slow moving, gelatinous animals (Warren et al., 1999). However, this application shows that it is possible to obtain in situ echo information from highly mobile animals from a deep submergence vehicle fitted with a low-light camera. Using the submersible to obtain in situ echoes had distinct advantages over other methods. Unlike current split-beam and dual-beam echosounder techniques, the species, size and orientation of the target can be determined with relative certainty. This is crucial for comparing echoes from individual fish. The number of fish measured in two submersible dives exceeded by more than 20 the total number of fish measured in a year of working with the same fish at the surface. Deepwater fish are difficult to bring up alive and they must be kept alive while their swimbladder heals from the trauma of rapid depth change during capture and acclimates to surface pressure. The amount of effort required to measure a single fish was significantly reduced using the submersible. The size fish measured at the surface was also limited. Larger fish were difficult to catch, keep alive, and fit into surface measuring equipment. Fish measured at the surface covered a 33 cm length range, but those measured in situ covered 82 cm. The largest fish measured in situ was nearly 60 cm longer than the largest fish measured at the surface. However, much more information on each fish could be obtained at the surface, in particular a much greater range of orientations could be measured. The validity of the surface measures to fish living at their natural depth range allows us to combine the information from both ex situ and in situ methods. The combination of the two methods provides the most information, over the entire range of fish lengths, with the most efficient use of effort.

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