ACOUSTIC MEASUREMENTS OF A MIGRATING LAYER OF THE MEXICAN LAMPFISH, *TRIPHOTURUS MEXICANUS*, AT 102 KILOHERTZ

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ABSTRACT

Biological sampling in a migrating scattering layer recorded at 102 kilohertz resulted in collections which consisted primarily of juvenile *Triphoturus mexicanus*. The scattering from this layer was quantified. Volume scattering strengths and corresponding target strengths were determined. The rate of migration and the target strength of *T. mexicanus* changed as the layer approached the surface. Target strengths at 102 kilohertz ranged from −60.6 decibels at 284 m to −71.3 decibels at 206 m.

Initial investigations of the deep scattering layer (DSL) emphasized military and hydrographic applications and used relatively low-frequency echo sounders (20-80 kHz). Later, research was directed at the biological organisms responsible for sound scattering in the DSL but was still confined largely to low-frequency studies. Fishes and physonectid siphonophores have been identified as the major scatterers in this frequency range (Barham 1963). In addition to determining the sources of scattering, oceanographers, fishery biologists, and commercial fishermen have been using acoustics to locate and quantify fish schools and shoals. Quantitative studies require the measurement of volume scattering strengths from the water column and knowing (or measuring) the ability of the fishes to scatter sound (acoustic cross section or target strength). Recent compilations of work in these areas can be found in Farquhar (1970) and Andersen and Zahuranec (1977).

The development of high-frequency echo sounders (>50 kHz) during the past 10 yr has progressed to the point where research at frequencies up to 3.0 MHz is now practical (Holliday and Pieper[2]). Working with high frequencies has several advantages over low frequencies. As the frequency is increased, shorter pulses can be used and the resolution is increased. In addition, smaller organisms become better sound scatterers as the frequency is increased. At 102 kHz, for example, shoals of euphausiid shrimp can be detected and quantified at ranges up to 300 m (Bary and Pieper 1970; Pieper 1979).

The present paper reports on two migrating scattering layers recorded only at 12 kHz and a deeper, third layer recorded at both 12 kHz and 102 kHz. Large numbers of a single size class of juvenile Mexican lampfish, *Triphoturus mexicanus* (Gilbert 1890), were collected from the deepest scattering layer. Volume scattering strengths of this layer were measured at 102 kHz and corresponding target strengths of *T. mexicanus* were calculated. Although no directed sampling was completed in the two, shallower, 12 kHz scattering layers, the possible scatterers responsible for these layers are indicated. We discuss the advantage of using acoustic frequencies above swim bladder resonance for biomass studies and recommend the increased usage of high-frequency acoustics for biological studies in the sea.

METHODS

Three 12 kHz scattering layers were observed migrating towards the surface near sunset on an acoustic survey at the northwest end of the San Clemente basin off southern California on 25 and 26 January 1977. The deepest of these 12 kHz layers was recorded as a strong scattering layer on a 102 kHz echo sounder being used to study euphausiid distributions (Pieper 1979). Quantitative acoustic measurements at 102 kHz and biological sampling were completed in this scattering layer on 26 January. Salinity and temperature profiles were taken immediately after the tow

with a submersible salinity, temperature, and depth (STD) recorder.

Acoustic Measurements

A Ross Laboratories[3] 102 kHz echo sounder with its transducer housed in an Endeco V-fin was used in conjunction with a 12 kHz hull mounted Edo transducer triggered by an Edo model 444 transceiver and model 551 recorder. Information from the 12 kHz sounder was recorded only as qualitative echograms. Acoustic data from the 102 kHz echo sounder was recorded qualitatively as echograms, and quantitatively over specific 20 m (26.87 ms) intervals where the scattering was observed. The returned signal for this interval was electronically squared and integrated for each pulse, and the value displayed on a chart recorder. The average scattering level (RL) over this 20 m interval was then calculated and the volume scattering strength (S_v) was determined by the following (Urick 1975):

$$S_v \, (\text{dB/m}^3) = RL - SL + 40 \log r + 2 \alpha r - 10 \log V$$

where RL = average received (scattering)
                level
         SL = source level
         r = mean range of the 20 m interval
         α = absoprtion loss per m³
         V = volume insonified =
                $(c\tau/2)(\Psi r^2)$
                where c = speed of sound
                       τ = pulse length
                       Ψ = solid angle of the
                              ideal   two-way
                              beam pattern.

Volume scattering strengths were determined at various times (and depths) as the layer migrated toward the surface.

Biological Sampling

Biological samples were collected with a 6-ft modified Tucker trawl with an acoustically controlled opening-closing sequence and a continuous depth readout on a Gifft recorder. While sampling in the migrating scattering layer, the net depth was regulated to keep pace with the movement of the layer. The samples were preserved in 10% buffered Formalin in the field and transferred to 70% ethanol in the laboratory. All fishes were identified to species and their standard length measured.

The density of fishes collected was calculated by dividing the number of animals caught by the product of ship speed (meters per minute) times the length of the tow (minutes) times the mouth area (square meters). The mouth area of the net has been calculated to be 2.36 m² assuming a 45° fishing angle (Davies and Barham 1969).

Swim bladders were measured from 12 *T. mexicanus* which represented the range of sizes of this species collected by the trawl in the 102 kHz scattering layer (trawl 25660[4]). Swim bladder measurements were also taken from four *Protomyctophum crockeri*, five *Argyropelecus sladeni*, and five *Vinciguerria lucetia* collected from two earlier trawls (trawls 25657 and 25658). The volume of the swim bladder was calculated by using the formula for a prolate spheroid (Capen[5]).

Calculations

The density of fishes was then used to calculate their average target strength (TS) by applying the formula:

$$TS = S_v \, (\text{fishes}) - 10 \log (\text{fishes m}^{-3})$$

where S_v (fishes) = $10 \log[\log^{-1} 0.1 \, S_v$ (total)
                $- \log^{-1} 0.1 \, S_v$ (plankton)].

The S_v value for plankton was calculated from an average of the two integration values recorded after the fish scattering layer had migrated out of the integration window.

The depth where the swim bladder would resonate at 12 kHz was calculated for the range of swim bladder sizes observed assuming constant swim bladder volume with depth. These calculations were determined by solving for z (depth) in the following simplified formula for resonance of an air bubble in water (Clay and Medwin 1977; equation 6.3.10):

$$f_{FR} = (3.25 \times 10^6/a)(1 + 0.1z)^{\frac{1}{2}}$$

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[4]All trawl numbers mentioned refer to ship's station numbers (*Velero IV*, University of Southern California).
[5]Capen, R. L. 1967. Swimbladder morphology of some mesopelagic fishes in relation to sound scattering. U.S. Navy Electronics Laboratory, San Diego, Calif., Rep. 1447, 25 p.

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[3]Reference to trade names does not imply endorsement by the National Marine Fisheries Service, NOAA.

where f_{FR} = resonant frequency (Hz)
          a = equivalent spherical radius (μm)
          z = depth (m).

In the above formula, f_{FR} is 12 kHz. The a is the radius of a sphere equal in volume to that of the swim bladder at the surface.

RESULTS

The deepest of the three 12 kHz scattering layers (Figure 1) was also recorded at 102 kHz (Figure 2). The calculated volume scattering strengths at 102 kHz and at different times and depths are also shown in Figure 2. The biological sample from this layer was composed almost ex-

TABLE 1.—Biological collection from trawl 25660 taken in the 102 kHz scattering layer of San Clemente basin, southern California, 26 January 1977, 1731-1744 h.

Taxon	Total number caught	Number per 1,000 m³	Mean standard length (mm)	SE
Triphoturus mexicanus	263	114.0	24.5	0.2
Stenobrachius leucopsarus	3	1.3	24.7	1.4
Lampanyctus ritteri	1	0.4	68.5	
Argyropelecus sladeni	2	0.9	10.5	3.0
Sergestids	9	3.9	28.7	2.9
Euphausiids	105	45.0	17.4	0.7

clusively of juvenile *T. mexicanus* (Table 1). The movement of the scattering layer with time showed an increasing rate of migration up to a depth of around 180 m which corresponded to a change in the temperature-salinity characteristics of the water (Figure 3).

Calculated target strengths for *T. mexicanus* (Table 2) were highest at the deepest depth (−60.6 dB at 284 m) and slowly decreased as the layer migrated upwards (−71.3 dB at 206 m). The decrease in calculated target strengths corresponded to the increased migratory rate of the layer (Fig-

TABLE 2.—Volume scattering strengths (S_v) for the 102 kHz scattering layer and calculated target strengths (TS) for *Triphoturus mexicanus*. Data from San Clemente basin, southern California, 26 January 1977.

| Time (PST)	Type of scattering	Depth (m)	S_v (dB/m³)	Fish S_v (dB/m³)	Fish TS (dB)
1719.0	Plankton	257	−76.86	—	—
1735.0	Plankton	244	−77.31	—	—
	Average plankton	—	−77.08	—	—
1716.0	Plankton and fish	284	−69.13	−70.02	−60.6
1726.0	Plankton and fish	257	−71.13	−72.40	−63.0
1726.5	Plankton and fish	257	−71.13	−72.40	−63.0
1730.5	Plankton and fish	244	−72.83	−74.88	−65.4
1731.0	Plankton and fish	244	−73.05	−75.24	−65.8
1736.0	Plankton and fish	226	−74.48	−77.94	−68.5
1736.5	Plankton and fish	226	−74.18	−77.30	−67.9
1740.5	Plankton and fish	206	−75.23	−79.83	−70.4
1741.0	Plankton and fish	206	−75.53	−80.76	−71.3
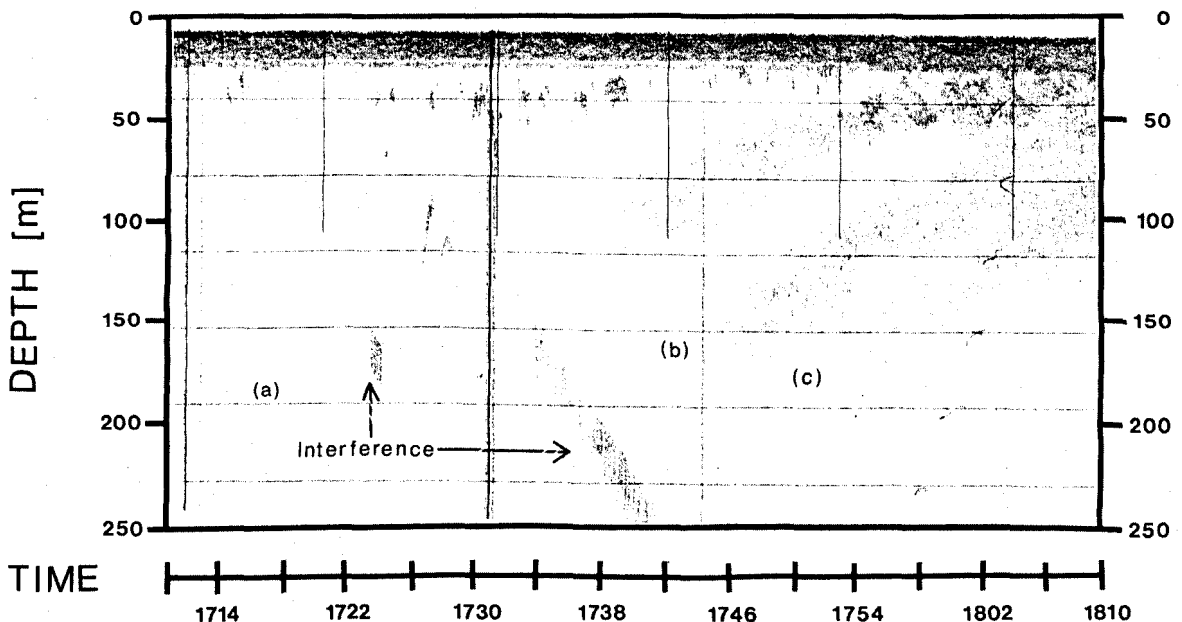
FIGURE 1.—A 12 kHz echogram from the San Clemente basin, southern California, 26 January 1977. Three scattering layers are shown, first appearing at depths around 150 m, and then migrating towards the surface. The first two scattering layers, (a) and (b), to migrate (starting around 1720 and 1745, respectively) were only recorded at 12 kHz. The third scattering layer (c) (starting around 1750) was also recorded on a 102 kHz echo sounder. The echogram also shows scattering from single fish or small fish schools between 50 m and the surface. The interference indicated is from the ship's echo sounder.
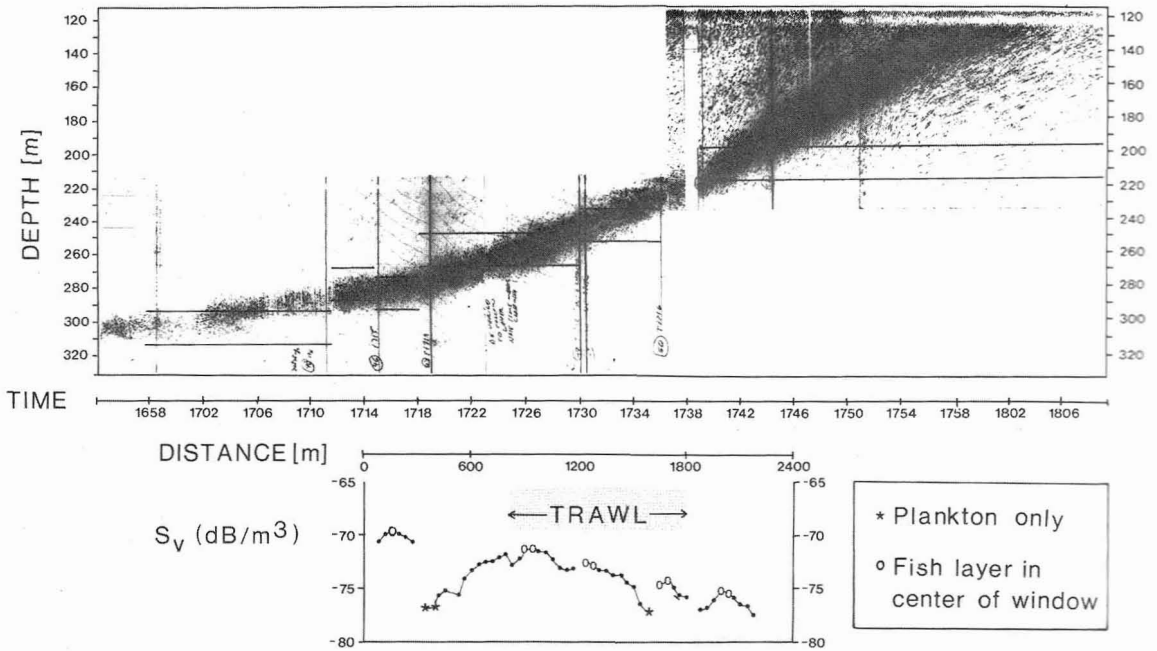
FIGURE 2.—A qualitative 102 kHz echogram showing a migrating scattering layer in San Clemente basin, southern California, 26 January 1977, and calculated volume scattering strengths (S_v) at 102 kHz for selected 20 m depth intervals (horizontal solid lines on echogram). The volume scattering strengths are shown when the scattering layer is in the center of the integration window (open circle), partially in the window (solid circle), and absent from the window (asterisk). The towing period for trawl 25660 is shown.
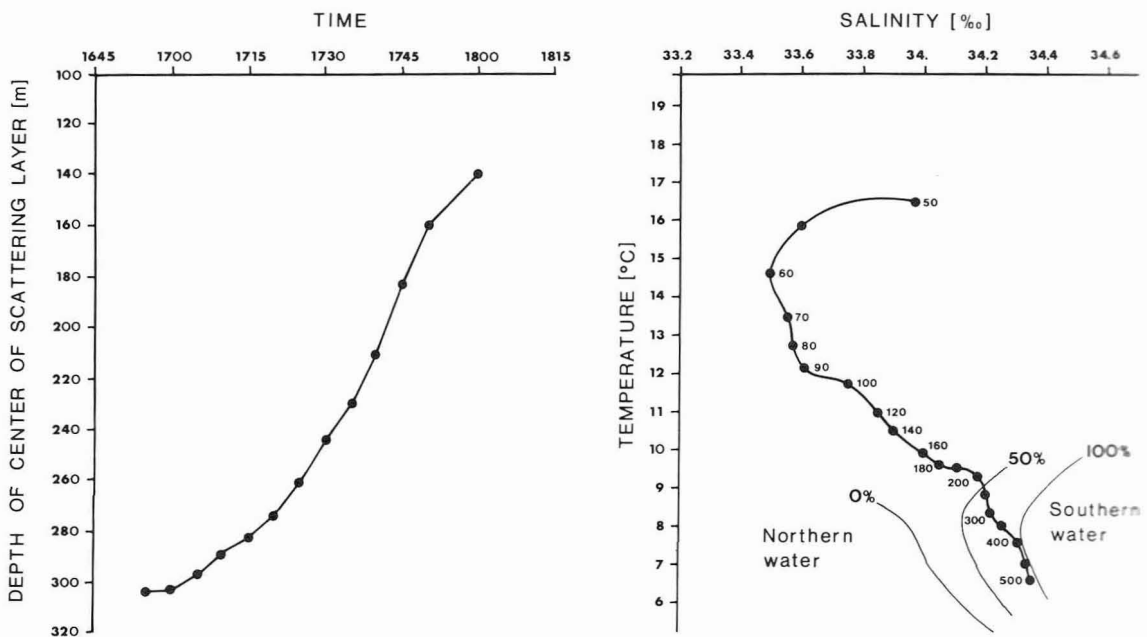

FIGURE 3.—Left: Depth of the center of the 102 kHz scattering layer plotted against time. Right: The temperature-salinity diagram for the water column immediately after trawl 25660.

ure 4). Measurements were not taken <206 m due to increased interference from surface scattering.

The organisms which were responsible for producing the two, shallower, 12 kHz scattering layers are not known since no trawls were taken from the depths of these two layers. Before the migratory period, however, two trawls were completed from depths which might correspond to the distributions of the scattering organisms. Trawls 25657 (1350-1432 h; 292-302 m) and 25658 (1514-1547 h; 267-268 m) were completed before the scattering layers became evident on either echo sounder. They were also from shallower depths than the first appearance of the 102 kHz scattering layer (1638; 315-325 m). Data from these trawls consisted of small numbers of *Argyropelecus sladeni*, *Cyclothone signata*, *Protomyctophum crockeri*, and *Vinciguerria lucetia* (Table 3). Of these four species, only *C. signata* is known not to be a vertical migrator (Rainwater 1975; Pearcy et al. 1977). Swim bladder resonance calculations for the other three species are shown in Table 4.

DISCUSSION

Lanternfishes (Family Myctophidae) have been implicated as the most important scatterers of scattering layers recorded at frequencies around 12 kHz, especially since many of these fishes have air-filled swim bladders of such a size as to be resonant from 1 to 30 kHz (Hersey and Backus 1962). *Triphoturus mexicanus* is a known vertical migrator off southern California (Paxton 1967) and its distribution has been previously correlated with scattering layers which showed diel migrations. Barham (1966) noted that adult *T. mexicanus* were associated with a 12 kHz scattering layer in the California Current, and Holton (1969) correlated collections of 8-10 cm long *T. mexicanus* with a strong scattering layer in the Gulf of California.

This paper reports on a scattering layer recorded at both 12 kHz (Figure 1) and 102 kHz (Figure 2). *Triphoturus mexicanus* dominated the net collection from this scattering layer (Table 1).
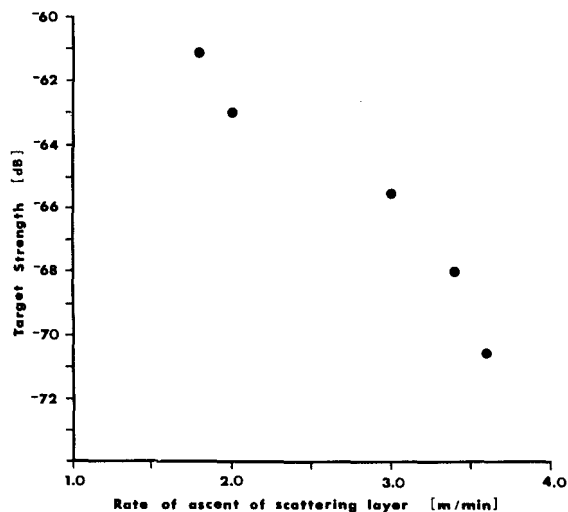

FIGURE 4.—Variations in the calculated target strengths for *Triphoturus mexicanus* at 102 kHz as a function of the rate of ascent of the 102 kHz scattering layer.

Kleckner and Gibbs[6] suggested that lanternfishes probably regulate the gas in their swim bladders during migration to maintain constant gas volume. Assuming that calculations of swim bladder resonance can be approximated by using equations based on a free bubble in water (Hawkins 1977; Love 1978), these fish would show 12 kHz resonance only between 28 and 43 m (Table 4). In addition, a frequency of 102 kHz is too high for possible resonance effects. We suggest that the deepest 12 kHz layer and the 102 kHz layer were due to a large number of *T. mexicanus* rather than a few fishes scattering the sound at resonant frequencies.

Volume scattering strengths (Figure 2, Table 2) and target strengths (Table 2) were calculated at 102 kHz for *T. mexicanus*. Target strength values decreased as the layer migrated upwards from a

[6]Kleckner, R. C., and R. H. Gibbs, Jr. 1972. Swimbladder structure of Mediterranean midwater fishes and a method of comparing swimbladder data with acoustic profiles. Mediterranean Biological Studies Final Report to the U.S. Office of Naval Research 1(4):230-281.

TABLE 3.—Fishes collected from trawls 25657 and 25658, San Clemente basin, southern California, 26 January 1977.

Species	Trawl 25657, 1350-1432 h, 292-302 m			Trawl 25658, 1514-1547 h, 267-268 m		
	Total number caught	Number per 1,000 m³	Mean standard length (mm)	Total number caught	Number per 1,000 m³	Mean standard length (mm)
Argyropelecus sladeni	4	0.4	11.2	12	16.0	12.6
Cyclothone signata	10	0.9	16.6	5	6.5	16.5
Protomyctophum crockeri	5	0.5	22.9	1	1.3	12.5
Vinciguerria lucetia	3	0.3	24.0	4	5.2	23.2

TABLE 4.—Swim bladder size and calculated depths for 12 kHz resonance, assuming regulation of swim bladder volume for the specimens of *Triphoturus mexicanus, Protomyctophum crockeri, Argyropelecus sladeni*, and *Vinciguerria lucetia* in our collections.

Species	Standard length (mm)	Swim bladder				Depth[1] (m)
		Major axis (mm)	Minor axis (mm)	Volume (mm³)	Equivalent spherical radius (μm)	
T. mexicanus	19	1.92	1.00	1.01	622	43
trawl 25660	21	1.83	.92	.81	578	36
	22	2.08	1.00	.96	612	41
	23	2.09	.95	.99	618	42
	24	1.77	.95	.84	585	37
	25	1.96	.89	.81	578	36
	25	2.03	.82	.71	553	32
	27	1.65	.89	.68	546	31
	27	1.58	.83	.57	514	26
	29	2.08	.75	.61	526	28
	33	2.08	.67	.49	⅔ fat invested	—
	39	1.50	.67	.35	Completely fat invested	—
P. crockeri	14	1.60	1.12	1.01	622	43
trawl 25657	22	1.92	1.28	1.68	738	64
	26	2.24	1.28	1.95	775	72
	29	2.24	1.44	2.25	813	80
A. sladeni	11	1.12	.64	.24	385	10
trawl 25658	14	1.28	.80	.43	468	20
	15	1.28	.80	.43	468	20
	24	2.40	1.44	2.60	853	89
	29	3.36	1.92	5.83	1,117	160
V. lucetia	21	3.16	.85	1.20	659	49
trawl 25657	22	3.54	.92	1.56	719	60
and 25658	24	3.80	.89	1.58	723	61
	26	3.86	1.14	2.63	856	90
	27	5.38	1.58	7.03	1,188	182

[1]Where swim bladder would resonate at 12 kHz, assuming constant volume at all depths.

high value of −60.6 dB at 284 m to a low value of −71.3 dB at 206 m.

The change in calculated target strength with depth could be due to two factors: either the density of fishes per cubic meter decreased with time or the target strength decreased due to the changing orientation of the migrating fishes. The second explanation is more likely for two reasons. First, the thickness of the scattering layer appears to be constant over the period where target strengths were calculated (1716-1741 h, Figure 2). Second, the increase in the migratory rate of the layer over time (Figures 2, 3) implies a more rapid, upward swimming of the fishes. This would result in a more vertical orientation of the fish in the water column.

The calculated target strengths for the juvenile *T. mexicanus* at 102 kHz (Table 2, Figure 4) can only be compared with theoretical values since no measured values could be found in the literature. Love (1977) presented formulas for predicting the target strength of an individual fish at any aspect as a function of fish size and insonifying frequency. His equations are valid for the range $1 \leqslant L/\lambda \leqslant 100$ where L is the fish length and λ is the acoustic wavelength. Our data on *T. mexicanus* for a mean standard length of 24.5 mm (Table 1) and at a frequency of 102 kHz would show a L/λ ratio of 1.7.

Using his formulas on our data, calculated target strengths for dorsal aspect vary from −55.6 dB to −56.6 dB and for anterior aspect from −67.1 dB to −67.7 dB. Thus, the target strength would be decreased by 10 to 12 dB as the orientation of the fish changed from dorsal aspect to anterior aspect. The change in target strength values from our data (10.7 dB) indicates that such a change in the orientation of the fish might have occurred.

The absolute values of our calculated target strengths are about 4.5 dB less than the predicted values. Since the data used by Love (1977) to determine his equations did not include myctophids, it is possible that juvenile *T. mexicanus* (and lanternfishes in general) may be poorer scatterers than the larger, nearshore, and surface fishes used for his study.

The migratory pattern shown for this layer is not unique to this study. The increased migratory rate of scattering layers during the middle of the sunset migration has been shown by a number of authors (e.g., Kampa and Boden 1954). Kampa and Boden (1954) also correlated this type of migratory pattern to a similar pattern in the isolume at the scattering layer depths. The interrelationship between isolumes, scattering layer migrations, and vertical water mass structure is not well understood. Thus, the observed change in mi-

gratory rate with change in water type around 180 m (Figure 3) may or may not reflect the reason for the observed migratory pattern.

The scatterers responsible for the two, shallower, 12 kHz scattering layers cannot be specifically determined in the present study. Of the fishes collected from two previous tows (Table 3) only *Cyclothone signata* is known not to migrate into surface waters (Pearcy et al. 1977). Since *Vinciguerria lucetia* has been collected at the surface at night, it is probably a vertical migrator (Grey 1964). The information on the vertical distribution and migration for *Argyropelecus sladeni* and *Protomyctophum crockeri* indicates that vertical migration is unlikely, but the data on these two species are sparse and incomplete. *Argyropelecus sladeni* has been collected both day and night at depths from 0 to 2,000 m (Baird 1971; Rainwater 1975; Pearcy et al. 1977), although the center of their distribution appears to be from 100 to 500 m. The information on *P. crockeri* shows similar broad distributions (Paxton 1967; Rainwater 1975; Pearcy et al. 1977), although Paxton stated that they only reach depths of 150 m at night and Wisner[7] stated that they are not caught above 100 m at night.

Since the two, shallower, 12 kHz scattering layers were not recorded on the 102 kHz echo sounder, it is likely that swim bladder resonance at 12 kHz from a small number of organisms was responsible for the scattering. Based on swim bladder measurements made at the surface and assuming regulation of swim bladder volume to maintain constant volume during migration, the depths where 12 kHz resonance would occur were calculated (Table 4) for the range of sizes of the fishes collected. These calculations indicate that *A. sladeni* and *V. lucetia* would show 12 kHz resonance at depths from 10 to 160 m and 49 to 182 m, respectively. Thus, we suggest that one or both fishes could be responsible for the shallower, 12 kHz scattering layers. The depth range for 12 kHz resonance for *P. crockeri* (43-80 m) indicates that it was probably not the source of either of the scattering layers. In addition, both shallow layers reached a depth of 40-50 m during the migration and *P. crockeri* has not been collected at depths <100 m at night (Paxton 1967; Wisner see footnote 7). It is also possible, however, that the shal-

lower layers resulted from an organism or organisms not collected by the two net tows discussed.

The potential use of high-frequency acoustics for studying the distribution, behavior, and abundance of scattering organisms is strongly indicated. Echo sounders operated at frequencies above 30 kHz are working at frequencies above swim bladder resonance and therefore, reflect the biomass of scatterers more accurately. In addition, they generally have narrow beam angles and utilize short pulse lengths (3.5° beam angle and 1.0 ms pulse length in this study) which produce finer resolution in the scattering patterns. Calibrated, multifrequency acoustic systems used in conjunction with sophisticated net systems are needed to better define distributional patterns and interactions of these midwater organisms.

SUMMARY AND CONCLUSIONS

Triphoturus mexicanus is known to migrate vertically in the water column (Paxton 1967). We have shown that juvenile *T. mexicanus* were the major sound scatterers in a migrating scattering layer recorded at both 102 kHz and 12 kHz. Calculated target strengths for *T. mexicanus* at 102 kHz varied from −60.6 dB at 284 m to −71.3 dB at 206 m. This decrease in target strength with depth was probably due to a change in the orientation of the fish in the water column. The lowest target strength (−71.3 dB) occurred when the scattering layer was migrating towards the surface at its highest rate and, therefore, the fishes should be oriented more vertically in the water column.

Two, shallower, scattering layers were recorded at 12 kHz but not 102 kHz. We suggest that these two layers probably resulted from scattering which occurred from fishes with swim bladders which 1) resonated at 12 kHz and 2) were regulated to maintain constant swim bladder volume during migration. *Vinciguerria lucetia* and *A. sladeni* are both possible scatterers of these layers although *A. sladeni* is not known to be a vertical migrator.

The importance of using acoustics to study mesopelagic organisms is indicated. Echo sounders can be used to both qualitatively direct biological sampling and quantitatively determine distributions and biomass. High-frequency echo sounders (e.g., 102 kHz in this study) have an advantage over low-frequency echo sounders. Target strength measurements on the midwater fishes, however, are needed to better predict the

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[7]Wisner, R. L. 1976. The taxonomy and distribution of lanternfishes (Family Myctophidae) of the eastern Pacific Ocean. Navy Ocean Research and Development Activity, Bay St. Louis, Miss., Rep. 3, 229 p.

concentration of such fishes by the acoustic technique.

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