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In situ measurements of acoustic target strengths of gas-bearing siphonophores

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Acoustic target strengths of free-swimming siphonophores were measured *in situ* at 24 and 120 kHz from a remotely operated vehicle equipped with both acoustic transducers and a video camera. The transducers and camera were co-registered by aiming both instruments at the same volume of water and time-stamping the recorded data. The video system allowed us to search for and identify siphonophores, and verified whether individual animals were centered in, or near, the axis of the acoustic beams. A towed, down-looking acoustic survey system (operating at 120 kHz) measured the target and volume scattering strengths of scattering layers, presumed to be dominated by siphonophores. Spatial density of the sound scatterers was estimated from survey data. Our results confirm that free-swimming physonect siphonophores have relatively high acoustical target strengths caused by a gas inclusion in the pneumatophore of each animal. A relatively small number of these animals can dominate the backscattering detected by acoustic surveys even though other taxa may dominate the plankton on a numerical or biomass basis. Siphonophore colonies are fragile and cannot be reliably censused with nets. Our estimates of siphonophore target strengths can improve the ability to use acoustics to quantitatively census siphonophores and other taxa possessing comparably-sized gas inclusions.

Keywords: siphonophore, acoustic scattering, target strength, gas-bearing zooplankton.

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Introduction

Acoustic surveys can rapidly survey many types of zooplankton within a large volume of water (Wiebe *et al.*, 1997; Medwin and Clay, 1998). Unfortunately, acoustic backscatter patterns from these surveys usually cannot be converted to quantitative estimates of the densities and identities of sound scatterers by a simple method. This is a consequence of the diverse morphologies and material properties of the organisms that make up most zooplankton assemblages (Stanton *et al.*, 1994).

Measurement of acoustic target strengths from different taxa is essential for the development of scattering models and, ultimately, the extraction of meaningful biological parameters (for example, identity, abundance, and size) from acoustic backscatter data. Well-controlled measurements of target strength are both difficult to obtain and logistically complex. For these reasons, most target-strength measurements of zooplankton have been made in the laboratory (Stanton *et al.*, 1994, 1996, 1998a).

Although laboratory measurements can be highly controlled, they suffer from serious artifacts because the animals must be constrained in an artificial setting. The resulting measurements may be biased by low hydrostatic pressure (i.e. pressures corresponding to only very shallow depths) and restricted animal orientation.

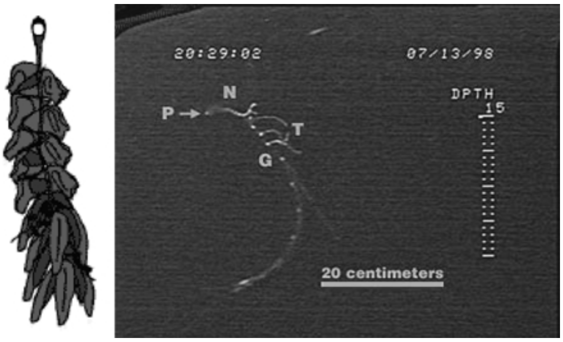

Figure 1. Drawing of a siphonophore (left) with a video capture of a live *Nanomia cara* (right). The animal consists mostly of gelatinous tissue (T) with the exception of a gas inclusion (pneumatophore) (P) at the top. This gas inclusion can be a significant source of acoustic scattering. The animal moves by using nectophores (N) to propel itself, and has numerous gastrozooids (G) with which it feeds.

Further, the mechanical and physiological stresses associated with the capture of the animal may influence target-strength estimates (Stanton *et al.*, 1998a). There is a need for well-controlled estimates of acoustic target strengths of live animals under natural conditions where animals are free to select preferred depths, water temperatures, water densities, and orientations.

Physonect siphonophores (Figure 1) are important constituents of the zooplankton because of their large size and their predation upon copepods, decapod shrimp, fishes, and other taxa (Biggs, 1977; Mackie *et al.*, 1987). Several studies report that they are widely distributed (Totton, 1965), abundant (Pugh, 1975), and potentially important sources of acoustical backscattering (Barham, 1963, 1966). These animals are colonial organisms (Gould, 1984) and, for simplicity, in this paper the term "colony" will be synonymous with "animal". A single animal is made up of a pneumatophore (a gas inclusion), nectophores (tissues used for propulsion), tentacles, and gastrozooids.

Because of the extreme fragility of these organisms most studies of siphonophores have been restricted to direct observations (Madin, 1988; Robison *et al.*, 1998). Typical sampling equipment, such as nets and pumps, often destroy animals so *in situ* observations are generally required. Large siphonophores are also competent swimmers [speeds of 20–30 cm s^{-1} have been estimated (Mackie *et al.*, 1987)] that may be capable of evading slow-moving nets. Because of the challenges in using direct sampling methods on these animals, remote sensing methods such as acoustics provide a potential alternative. Optical methods are attractive, but the sampling volumes are usually not large enough to effectively census siphonophores (Davis *et al.*, 1992).

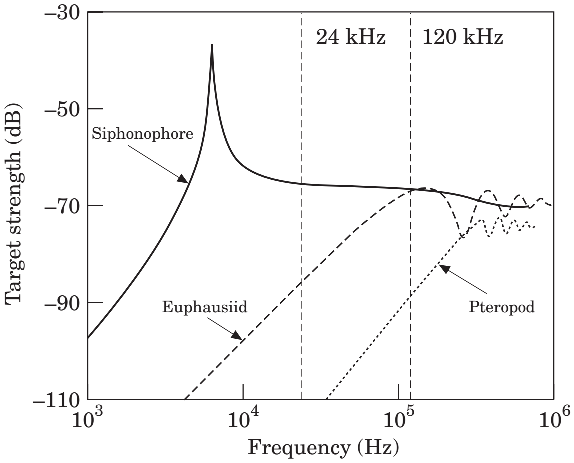

Figure 2. Theoretical calculations of target strength for three different types of zooplankton (gas bearing: 1-mm siphonophore pneumatophore; fluid-like: 3-cm long euphausiid; elastic-shelled: 1-mm diameter pteropod.) using models from Stanton *et al.* (1994, 1998b). Gas bearing animals have a much higher target strength at low frequencies than the other two classes (fluid-like and elastic-shelled), however at higher frequencies, the scattering levels are similar for all animal types. Dashed vertical lines indicate frequencies of 24 and 120 kHz.

A key element in the use of acoustics for assessing distribution, abundance, and identity of zooplankton assemblages is to understand the acoustic scattering properties of the scatterers. Each physonect siphonophore possesses a gas inclusion called a pneumatophore that is filled with carbon monoxide (Pickwell *et al.*, 1964). The pneumatophore, rather than the other gelatinous colony parts, is responsible for the strong acoustic return from these animals (Stanton *et al.*, 1998a,b). The size and physical properties of this gas inclusion may change with increasing hydrostatic pressure which consequently changes the acoustic scattering properties of the animal. At frequencies near resonance for the gas inclusion, target strengths may increase by more than 10 dB compared with those at higher frequencies (Figure 2).

Most recent siphonophore target-strength estimates have been derived from backscattering data collected in tanks where the animals were tethered at a shallow depth (~ 1 m) (Stanton *et al.*, 1994, 1996, 1998a), but there have been some recent estimates derived from acoustic survey data in the ocean where the presumed scatterers were siphonophores (Greene *et al.*, 1998). Whilst the laboratory work provided physical insights into the scattering properties of siphonophores, estimates of the acoustic target strengths of these organisms derived from such studies may not necessarily correspond directly with measurements obtained from free-ranging animals because of the constraints upon the animal in a laboratory environment (Stanton *et al.*, 1998b).

To provide more realistic estimates of acoustic target strength of siphonophores, we collected *in situ* target-strength measurements of the animals in the ocean. The present study utilized a remotely operated vehicle (ROV) and a towed, down-looking system to collect *in situ* measurements of acoustic target strengths of free-ranging physonect siphonophores at two frequencies. The results are compared with the previous laboratory measurements and predictions of target strength from zooplankton from other taxonomic groups and at other frequencies.

Materials and methods

This study was conducted from the RV “Sea Diver” in the waters in and around Massachusetts Bay near Cape Cod, Massachusetts, USA, during July 1998. Two acoustic backscatter systems were used simultaneously: an ROV-mounted, multi-frequency acoustic array; and a towed, down-looking echosounder. The towed system mapped spatial patterns of acoustic backscatter from aggregations of animals, whilst the ROV was used to measure acoustical scattering from individual animals at short ranges. A camera system was mounted on the ROV for the identification of species and tracking of targets. Conductivity, temperature and depth (CTD) casts and Reeve net collections (Reeve, 1981) were taken at various stations during the cruise.

ROV system

We used a MaxROVER ROV (Deep-Sea Systems) operated by the National Undersea Research Program of the National Oceanic and Atmospheric Administration. The vehicle was tethered from the ship via an umbilical cable (for power supply and data telemetry) and was guided by an operator on the ship. Multiple horizontal and vertical thrusters provide the vehicle with maneuverability in three dimensions.

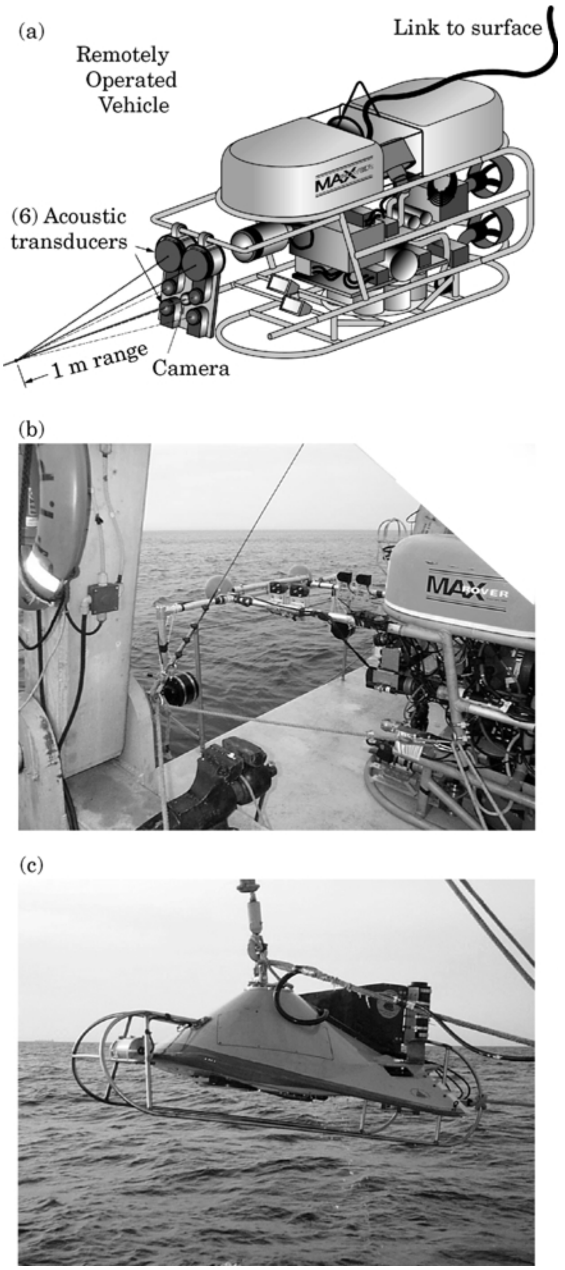

Figure 3. To collect *in situ* target-strength data, the acoustic transducers were configured on the front of the ROV Kraken with a video camera all focused on the same volume for co-located acoustic and video data (a). During calibration a direct path configuration for each pair of transducers was used (each pair separated by either 0.68 or 1.73 m and facing each other) (b). The Greene Bomber down-looking system (c) collected echo integration data for aggregations of animals in the water column as well as target strengths of individual scatterers.

A three frequency (24, 120 and 200 kHz) acoustic array consisting of transmit and receive pairs of transducers (Airmar Corp.) was mounted on the front of the ROV [Figure 3(a)]. The 120 and 200 kHz transducers were aimed at the same focal point located 1 m in front of the array. This focal point was located near the center of the viewable area and within the depth of field of one of the video cameras. By marking the acoustic focal point on the video monitor we were able to determine when an animal was located on the center axis of the beams of the higher-frequency transducer pair. Because of the broad beamwidth of the 24 kHz transducers, the transducers were mounted side-by-side aimed in directions parallel to each other while maintaining a composite beam pattern similar to that which would be achieved if they were aligned at a single point. All echo data that were recorded were in the far-field (distances greater than 52, 38 and 18 cm) of the 24, 120 and 200 kHz transducers, respectively. Unfortunately, electrical noise produced by the ROV thrusters and other systems severely degraded the quality of the 200 kHz data and we were only able to utilize data from the 24 and 120 kHz transducers.

ROV data collection

Collection of ROV-based echo data began when the ROV was deployed over regions of water where the echosounder had located layers of elevated backscatter. The ROV pilot then used one of two strategies to position the ROV so that the siphonophores were aligned on the acoustic axis. The ROV and associated acoustic system were always aimed into the current so that there would not be artifacts in the signal due to the wake of the ROV. One strategy was to bring the ROV close to the ship and then allow it to drift down-current with the water mass. During this period, the ROV was guided toward nearby siphonophores until they were aligned on, or near, the acoustic axis. A second strategy was to allow animals to drift toward the ROV and then apply adjustments to the thrusters to extend the period of time that animals were along the acoustic axis. Using these techniques we were able to track a specific animal for periods of up to one minute. However the maximum number of consecutive detectable echoes of an individual animal was generally five to ten with a maximum of 30. The ping rate varied between 0.5 and 1 Hz and 10 to 15 runs of 200 or 300 pings each were collected at a given frequency and at a given location. Echo data were collected at depths 10–30 m below the sea surface. This limited depth range was a consequence of the short cable length (50 m) which prevented signal degradation and noise problems.

Wire telemetry from the ROV enabled data to be transferred to the ship where video images and acoustic data were registered with a time-stamp and recorded onto Hi-8 video tape and a computer hard-drive, respectively. The hardware and methodologies used to record echoes matched those used for tank-based measurements of zooplankton backscatter conducted at sea and on land (Stanton *et al.*, 1994, 1998a), except for the addition of two hardware signal filters (Krohn-Hite Model 3200) that were needed to reduce electrical noise from the ROV system. We collected acoustic backscatter measurements from several hundred free-ranging siphonophores over a three day period. Within the limits of resolution of the video system, the animals were identified as *Nanomia cara* (A. Agassiz).

ROV calibration and data processing

After collecting echo data we arranged the transducers in a direct path configuration [Figure 3(b)] so that the transmit and receive transducers faced each other separated by a distance of 0.68 m (120 kHz) and 1.73 m (24 kHz). Calibration data were collected in this configuration over the same depth range (10–30 m) that the scattering measurements were made. A calibration procedure identical to that of Stanton *et al.* (1998a) was used.

Examination of the video and acoustic data revealed that some measurements were collected from a solitary animal whilst others were from two or more animals. Accordingly, only pings from single animals were used to estimate target strengths. It was not possible to hold each animal precisely along the acoustic axis because both the siphonophore and the ROV were moving. Such changes in the position of the target expectedly introduced significant variability in echo level because of the acoustic beam pattern.

Raw echo voltage data were collected and examined briefly between data collection runs to verify that the acoustic measurement system was working correctly. The raw echo data were then converted to echo strength (ES) measurements where ES is a logarithmic measure of echo level convolved with the acoustic transducer beam pattern. On-axis values of ES are equal to target strength (TS). Values of ES corresponding to off-axis will be less than that of TS. In order to remove the effects of the beam pattern, histograms of echo amplitudes (once calibrated and adjusted for range from transducer) were deconvolved using the beam pattern of the transducer to produce estimates of the scatterer target strength (Clay, 1983; Stanton and Clay, 1986). The deconvolution method relies on the target having a constant probability of occurrence in the beam pattern. It was apparent that our tracking of siphonophores had changed their distribution in the beam pattern from being a random one to being one skewed towards the center of the beam. Theoretical echo amplitude distribution curves that were consistent with that of a random target location were then fitted to the measured echo amplitude histograms while ignoring the "tracking" artifact. The curves were fit according to the least squares error between the experimental echo amplitude histogram and the theoretical curves. Errors were calculated for the portion of the distribution that excluded the region of the tracking artifact. The deconvolution method was then applied to the theoretical probability distribution function with the least error to produce target strength estimates. An analysis of these data using a different inverse method (Stepnowski and Moszyński, 2000) produced similar target strength estimates.

Towed echosounder surveys

Two down-looking echosounders (Hydroacoustic Technologies Inc. (HTI)) operating at frequencies of 120 and 420 kHz were mounted in a fiberglass V-fin tow-body nicknamed the "Greene Bomber" [Figure 3(c)] (Wiebe *et al.*, 1996, 1997). Due to a hardware malfunction, only data from the 120 kHz transducer could be processed and recorded. The vehicle was equipped with temperature, salinity, and fluorescence sensors. Acoustic and environmental data were transferred to the vessel, processed in real time, and recorded on digital audio tape and computer hard drives.

The vehicle was towed from the starboard side of the ship at a depth of 3 m and at a speed of approximately 5 knots. The transducer sampled at a ping rate of 2 Hz. Acoustic returns were echo-integrated and averaged over 30 s intervals. Data were displayed in real time as volume scattering strength in 0.5 m depth bins.

The split-beam transducer and associated HTI hardware are capable of estimating the target strengths of individual scatterers. This capability was used to independently measure target strengths within the water column, although this system had no video information to verify target identity.

Net tows

On three occasions, net tows were conducted to sample siphonophore layers which had been observed from the ROV video system. The nets were towed horizontally for up to thirty minutes down to a depth of 20 m. In addition, vertical casts were made. A 0.785 m^2 Reeve net (Reeve, 1981) with a 333-µm mesh was used. Very few (fewer than five pneumatophores) siphonophores were captured in the 1.5 hours of tows. None of these specimens were intact. Additional animals collected in the net casts included pteropods, polychaetes, ctenophores, and medusae. These animals were occasionally seen in the video images from the ROV system, but were not as visually prevalent as siphonophores. The video data clearly show that siphonophores were abundant in these waters, however our net tow data indicate shortcomings of traditional net sampling methods.

Acoustic model

The scattering model for the pneumatophore of the siphonophore comes directly from Stanton *et al.* (1998b) and Anderson (1950). It is presented here for a single animal with scattering contributions from the gas-inclusion only.

Target strength (TS) is a logarithmic function of the scattering amplitude

$$TS = 10 \log |f_{bs}|^2 \tag{1}$$

where f_{bs} is the scattering amplitude in the backscatter direction. For a siphonophore, f_{bs} is generally the sum of scattering contributions from the gas inclusion (f_{bubble}) and from the gelatinous tissue (f_{tissue}). Scattering from the tissue is quite weak (at least 10 dB less than scattering from the gas inclusion at 24 and 120 kHz) and is not included in our calculations (Stanton *et al.*, 1998a,b).

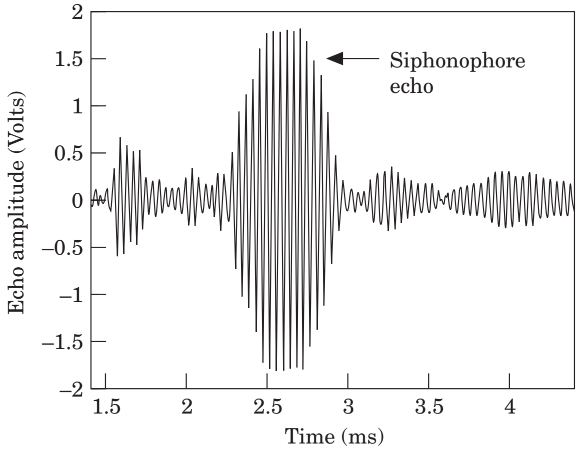

Figure 4. An example of the high quality echo that could be detected with the acoustic system mounted on the ROV. This 24 kHz echo from a single siphonophore is quite similar in shape to the transmitted signal.

The equation used for f_{bubble} is the exact solution for scattering from a fluid sphere (Anderson, 1950).

$$f_{bubble} = -\frac{i}{k_1} \sum_{m=0}^{\infty} (2m+1)(-1)^m b_m^{(f)} \tag{2}$$

The modal series coefficient ($b_m^{(f)}$) is defined as

$$b_m^{(f)} = \frac{-1}{1 + ic_m} \tag{3}$$

and

$$c_m = \frac{\dfrac{j'_m(k_2a)\cdot n_m(k_1a)}{j_m(k_2a)\cdot j'_m(k_1a)} - \dfrac{ghn'_m(k_1a)}{j'_m(k_1a)}}{\dfrac{j'_m(k_2a)\cdot j_m(k_1a)}{j_m(k_2a)\cdot j'_m(k_1a)} - gh} \tag{4}$$

where j_m and n_m are spherical Bessel and Neumann functions of the m^{th} order; j'_m, n'_m are the derivatives with respect to their argument; k_1, k_2 are the acoustic wave numbers in media outside (k_1) and inside (k_2) the gas inclusion; *a* is the equivalent spherical radius of the gas bubble; $g = \rho_2/\rho_1$ and $h = c_2/c_1$ are the density (ρ) and sound speed (c) ratios of the gas inclusion (ρ_2, c_2) and its surrounding media (ρ_1, c_1). When numerically evaluating the summation, the upper limit is replaced by $k_1a + 10$ which is generally the point at which the sum converges.

Results

Echoes from individual siphonophores were generally strong and of high quality (Figure 4), but varied (Figure

Table 1. Mean echo strength ($\overline{ES}$) and target strength ($\overline{TS}$) data from ROV based measurements of siphonophore echoes for various frequencies and subsets of data. The echo strength is a logarithmic measure of echo level convolved with the beam pattern. On-axis ES values correspond to TS; off-axis values of ES are smaller than TS due to beam pattern effects (less acoustic energy insonifies the target when it is located off-axis). Target strength measurements assume that the animal is located directly in the center of the acoustic beam. Large returns are those echoes > − 76 dB. Means are calculated on logarithmic (echo strength values), not linear (echo voltage), data. Measurements of the three echoes when the pneumatophore was visually confirmed to be exactly centered in the acoustic beam pattern have no beam pattern effects and are target strength measurements. The similarity in the 24 kHz data support the assumption that the gas inclusion in these animals is the dominant scattering mechanism.

f (kHz)	Number of echoes	Data set	$\overline{ES}$ (dB)	$\overline{TS}$ (dB)
24	561	All	− 64.5	
24	431	Large returns	− 62.5	
24	3	Pneumatophore		− 62.5
120	236	All	− 73.9	
120	130	Large returns	− 70.1	

5). Variations in echo strength were associated with changes in the position of the animal in relation to the focal point of the beam. Since multiple animals were studied, the size of the pneumatophore is expected to vary, which would also cause variability in echo levels. Mean target strengths calculated by the deconvolution method applied to echoes collected by the ROV system were − 59.9 dB at 24 kHz and − 69.1 dB at 120 kHz. The mean echo strength, which is a logarithmic measure of the echo amplitude convolved with the beam pattern (resulting in an underestimate of target strength) of individual siphonophore animals was found to be − 62.5 dB at 24 kHz and − 70.1 dB at 120 kHz (Table 1). Echo strength is equal to target strength when the animal is aligned with the acoustic axis, but when the animal is located off-axis, then the echo strength is smaller due to beam pattern effects (less acoustic energy insonifies the target when it is off-axis). Target-strength measurements assume that the animal is located exactly in the center of the acoustic beam so the maximum amount of acoustic energy is incident on the target. The echo-strength measurements were based on data when siphonophores were located near, but not exactly at, the center of the video image.

Scattering levels of individual siphonophores measured at depth were consistent with scattering from a gas inclusion with a diameter of about 1 mm, a dimension similar to pneumatophore diameter measurements made at the surface from several animals captured by net tows. The *in situ* target strength estimates are generally consistent with previous studies (Figure 6). Greene *et al.*, (1998) estimated the target strength of siphonophores to be − 75 dB at 420 kHz from measurements made *in situ* with an echosounder attached to a net sampling system. This target-strength estimate was determined by examining the scattering from a region where the net sample was dominated by siphonophores but also contained other animals which would scatter acoustic energy. Measurements from individual siphonophores made at 120 kHz by Stanton *et al.* (1994) were slightly higher than what is presented here. Whilst there is much variability in these estimates the results from this study are *in situ* measurements from siphonophores and are generally more representative of *in situ* target strengths of siphonophores than the estimates from previous field or laboratory data.

Both the ROV-mounted array and the down-looking echosounder produced comparable estimates of the target strengths. While we could not identify the targets measured by the down-looking system, histograms of echosounder target strengths from the 10–20 m layer (Figure 7) are similar to the histogram derived from the 120 kHz *in situ* ROV array, which collected data predominantly from 20–30 m depth. The cause of the increase in target strength with depth shown in the down-looking system data is not known.

Our down-looking acoustic surveys revealed the presence of strong scattering layers between 0–30 m (Figure 8). These layers varied in depth and time and there was a regular diel migration coinciding with sunrise and sunset. Examination of the video images from the ROV collected whilst the down-looking system was in operation suggests that siphonophores were the most significant sound scatterers in the water column. Smaller animals, not seen in the video images, also may have been numerous, but would not be detected at the frequencies used in the acoustic systems due to their small size resulting in very weak scattering at 24 and 120 kHz. Solitary euphausiids were observed with the video system, although they appeared to avoid the ROV. Other zooplankton present in either the video or Reeve net samples included copepods, pteropods, polychaetes, ctenophores and occasional medusae. The scattering that was detected by the ROV-mounted array when

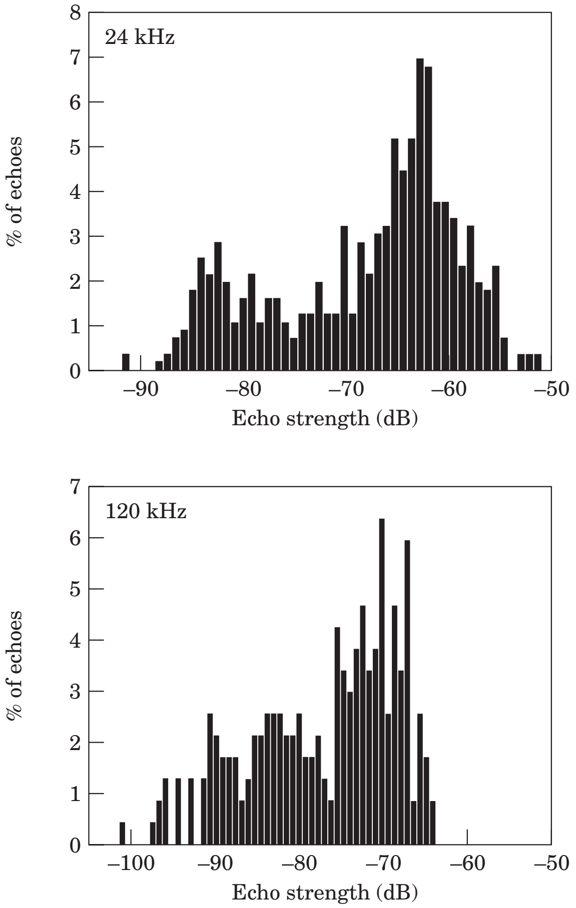

Figure 5. Echo strength histograms for 24 and 120 kHz from the ROV-based system. Echo strength is a logarithmic measure of echo level convolved with the beam pattern. It is possible that the peak in the left tail of this histogram is the result of scattering from the tissue of the animal when the bubble moved out of the beam of the acoustic transducer. A simple calculation based upon a fluid-like cylinder model developed by Stanton *et al.* (1993, 1994) estimates that the scattering from siphonophore tissue is − 80.3 dB at 24 kHz which agrees with the peak in the left tail of the 24 kHz histogram.

targets other than siphonophores were in the field of view was extremely weak (generally less than − 80 dB).

Volume-scattering strength of the water column varied by several orders of magnitude (Figure 8) with a peak value of − 57 dB in one scattering patch although scattering from surface patches at night was also strong. Mean siphonophore target strength at 120 kHz was estimated to be − 69.1 dB from 236 echoes from the ROV-based measurements. Animal abundance density (n_b with units of number of animals m^{-3}) could then be estimated by

$$n_b = \frac{s_v}{\langle \sigma_{bs} \rangle} \tag{5}$$

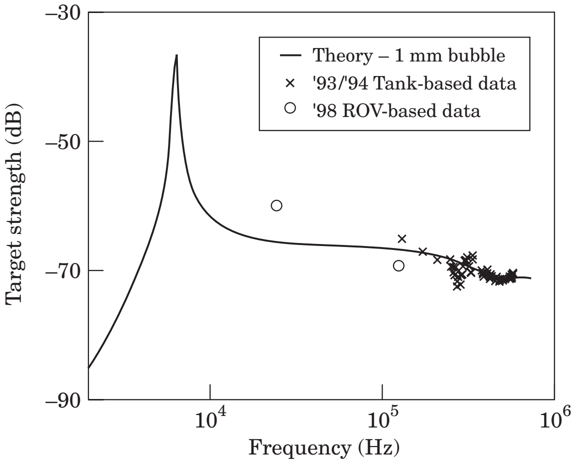

Figure 6. Measurements of average siphonophore target strength [○ from this study, × from Stanton *et al.* (1998b)] plotted alongside theoretical prediction for backscattering from a 1-mm diameter gas inclusion using Equation (1) with the following values: g=0.0012 and h=0.22 which correspond to air at 1 atm pressure.

from Medwin and Clay (1998) where s_v is the volume backscattering coefficient derived from the down-looking system echo integration data and $\langle \sigma_{bs} \rangle$ is the average differential backscattering cross section from the ROV measurements ($\sigma_{bs} = |f_{bs}|^2$). Density estimates based on Equation (5), ROV-based target strength measurements (Table 1), and down-looking system volume scattering strength data (Figure 8) range from 1–3 siphonophores m^{-3} for regions where the ROV measurements occurred and a peak density of 15–20 siphonophores m^{-3} in the scattering patch and the near surface layers. Visual observations from the ROV video system qualitatively agree with the lower density estimate. These observations are consistent with density estimates (1–7 animals m^{-3}) made in the Gulf of Maine from a submersible (Rogers *et al.*, 1978). If target-strength estimates from the down-looking system are used, density estimates rise by an order of magnitude. Since the ROV-based measurements include visual identification of the scatterer, those target strength and numerical density predictions are believed to be more accurate.

Discussion

The use of backscattered acoustical energy as a method to estimate biomass and animal distribution is quite common. The interpretation of acoustic data is still a challenging endeavor. Acoustic waves are reflected from variations in the density and sound speed of the medium that the wave travels through (either the water or the animal's body). Theoretical models used to describe the scattering characteristics of zooplankton

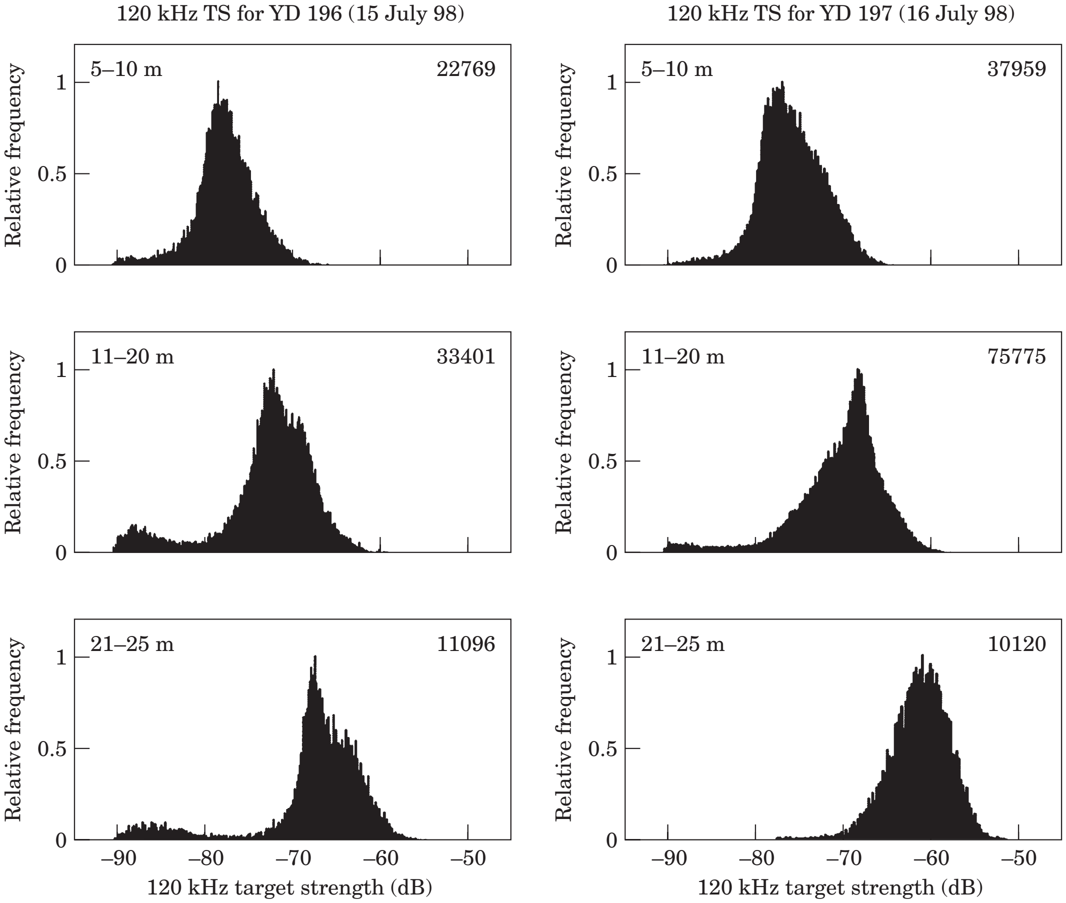

Figure 7. Target strength histograms from the "Greene Bomber" down-looking 120 kHz system for three different depth ranges of targets. The "Greene Bomber" was towed at a depth of 3 m. The number of individual target strengths making up a histogram is given in the upper right corner of each figure.

have undergone a tremendous evolution in the last twenty years [see review in Foote and Stanton (2000)] and these model predictions often agree well with laboratory data. It is well documented that scattering levels from gas bubbles increase as the acoustic frequency approaches the resonance frequency (Medwin and Clay, 1998). Since 24 kHz was near the resonance frequency of the gas inclusion, the system operating at that frequency yielded the highest target strength. This frequency, or ones near it, may be useful for quantifying the distributions and abundances of organisms containing gas inclusions such as siphonophores and small fishes, since target strengths of other zooplankton, such as fluid and shelled animals, are negligible near these frequencies, while at higher frequencies the target strengths become more similar (Figure 2 and Table 2).

A distinct advantage of laboratory studies has been that an animal can be positioned in the center of the beam pattern of the acoustic transducers. Under natural conditions the animal's location within the acoustic beam is variable. Deconvolution methods (Clay, 1983; Stanton and Clay, 1986) have been applied to acoustic studies of various fish schools. These methods use echo statistics and the characteristics of the acoustic transducer to remove beam pattern effects from echo data involving resolved targets. Our data are generally suited for this type of analysis, although not optimally, due to the "tracking" of animals by the ROV pilot. Instead of collecting data from a uniform distribution of targets in the beam pattern, our data are skewed towards the center of the beam pattern creating an upward bias in the results which we attempted to remove by visually fitting the data to theoretical echo amplitude histograms for a randomly located target. Although the "tracking" of the animals introduced this artifact it was necessary in order to collect enough echoes to fully resolve the distribution of target strengths.

The data from the down-looking system show an increase in target strength with increasing depth (Figure 7). One possible explanation is the greater likelihood of

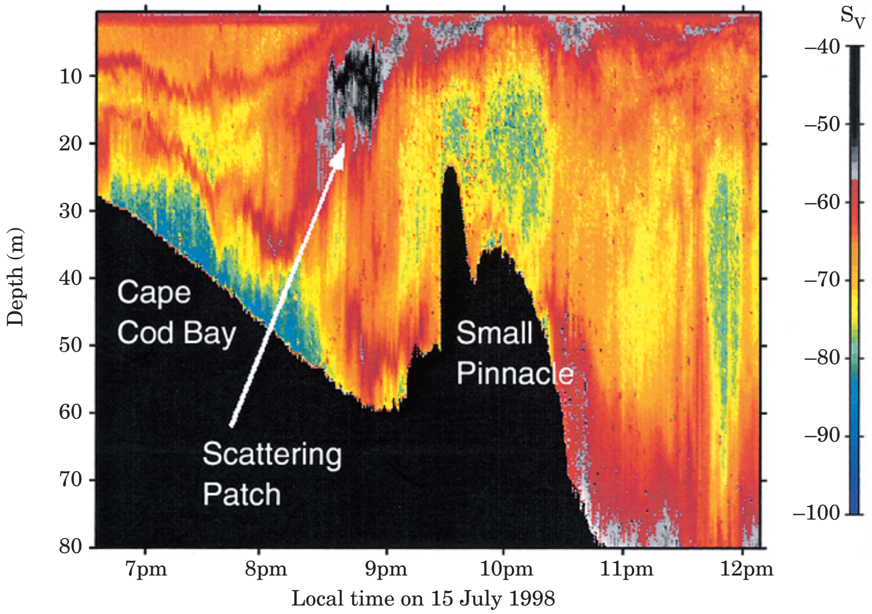

Figure 8. Pattern of volume-backscattering strength (S_v) in the water column during an acoustic survey transect with the down-looking system. Strong scattering regions include a patch occurring at local sunset and patches located at the water surface. The transect was in a straight line from Cape Cod Bay to Stellwagen Bank at a constant speed so the time axis is directly proportional to distance.

Table 2. Target strength predictions at 24 kHz and 120 kHz for siphonophores compared to other animals using models from Stanton *et al.* (1994, 1998b). The 1 mm size of the siphonophore is for the gas bubble only. Differences are much smaller at the higher (and more commonly used in acoustic survey applications) frequency, while quite substantial at the lower frequency. These predictions (supported by measurements in this paper) suggest that lower frequencies may be useful for surveying siphonophores since the target strengths of other zooplankton are negligible when compared with those of siphonophores.

Animal	Size (mm)	TS (dB) at 24 kHz	TS (dB) at 120 kHz
Siphonophore	1 (diam.)	− 66	− 66
Shrimp	30 (length)	− 86	− 67
Pteropod	1 (diam.)	− 116	− 89

multiple targets being recognized incorrectly as single targets by the split-beam system. Another possible explanation is that increasing pressure may cause pneumatophore size to decrease which would cause an increase in target strength at frequencies near resonance of the bubble (Figure 2). It must be emphasized that this latter explanation is possible but perhaps not likely, since siphonophores are able to regulate the volume of gas in the pneumatophore (Mackie *et al.*, 1987).

Our results are important for two reasons. First, our *in situ* measurements are consistent with both laboratory measurements and theoretical predictions of the relatively high target strengths of siphonophores. Second, the data suggest an acoustic methodology for quantifying abundances of siphonophores. Lower frequencies, at or near 24 kHz, are desirable for censusing siphonophores and other gas-bearing animals since scattering by other types of zooplankton at this frequency are often negligible. At higher frequencies siphonophore target strengths are comparable to those from fluid-like and elastic-shelled animals (Stanton *et al.*, 1998b). Given the fragile nature of these organisms, acoustics may represent one of the only viable non-optic methods for quantifying siphonophore abundance.

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