Acoustic Observation of Zooplankton Using High Frequency Sonar

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Abstrak

Observasi Akustik Zooplankton Menggunakan Sonar Frekuensi Tinggi

Teknik sampling zooplankton menggunakan metode akustik bawah air memiliki keuntungan dibandingkan menggunakan jaring tradisional. Penelitian ini menghasilkan kerangka kerja dan metodologi untuk ekstraksi informasi biologi dan fisika menggunakan sonar frekuensi tinggi. Teknologi akustik dengan mudah menghasilkan informasi distribusi spasial dan temporal zooplankton. Untuk membandingkan data zooplankton yang diperoleh menggunakan instrumen sonar, pemodelan hamburan propagasi gelombang akustik berbasis fisika dilakukan dengan komputasi numerik. Pemodelan akustik dilakukan menggunakan Distorted-Wave Born Approximation (DWBA) yang digunakan untuk biota penghambur yang kecil. Hasil pengukuran dan pemodelan DWBA menunjukkan bahwa level hamburan dipengaruhi oleh orientasi dari zooplankton. Selain itu, hamburan balik akustik dari zooplankton ditentukan oleh sifat-sifat material target seperti kecepatan suara dan densitas, bentuk, ukuran, dan orientasi gelombang akustik yang mengenai zooplankton. Model DWBA dapat meningkatkan ketelitian dan ketepatan pengukuran biomassa zooplankton menggunakan metode akustik. Analisis data pengukuran dan model DWBA menyediakan basis data untuk studi akustik lanjutan.

Kata kunci: *zooplankon, akustik, kekuatan hamburan balik volume, model DWBA*

Abstract

Underwater acoustic sampling techniques provide an advantage over traditional net-sampling for zooplankton research. The research presents a methodology for extracting both biological and physical information from high frequency sonar. These methods can easily provide the information that will improve our understanding of the spatial and temporal distribution of zooplankton. Measured acoustic data converted into biological organisms and numerical physics-based scattering models were used in this research. The numerical backscattering process was modeled using the Distorted-Wave Born Approximation (DWBA) to predict the amount of sound scattered by a weakly scattering animal. Both acoustic measurement and DWBA modeled scattering patterns showed that acoustic scattering levels are highly dependent on zooplankton orientation. The acoustic backscattering from zooplankton depends on the material properties (i.e. the sound speed and density of the zooplankton), the shape and size, and the orientation relative to the incident acoustic wave. DWBA model significantly improve the accuracy and precision of zooplankton acoustic surveys. Zooplankton data measurement and DWBA model analysis provide a basis for future acoustical studies.

Keywords*: zooplankon, acoustics, volume backscattering strength, DWBA Model*

Introduction

Zooplankton are the key components of pelagic food webs. Biological sampling methods usually had been used to measure concentration of zooplankton. These methods are based on sampling of zooplankton in nets. Sophisticated zooplankton samplers with towing mechanisms, optical sensors, and gauze have been developed and are commercially available. Underwater acoustic technologies are one other most effective tools available to detect and map the water column organism such as zooplankton (Medwin and Clay, 1998). Quantitative measurement of marine zooplankton with sonars requires detailed knowledge of their scattering properties. This is because sonar systems are capable of collecting data from a wide swath of the water column (Simmonds and MacLennan, 1996). The sonar systems like single beam or multibeam echo

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sounder backscatter signals are used to derive high-resolution ocean observation. However, the backscatter intensity is also provided by some systems such as quantitative side scan sonar. Backscattering strength is influenced by zooplankton properties, such as acoustic impedance relative to the water surround it (Urick, 1983). Underwater acoustic backscatter strength measurements have been used to infer marine zooplankton properties. Understanding the backscattering processes not only allows backscattering predictions to be made from knowledge of the animal size, shape, orientation, and material properties, but also allows sonar instrument to be used as remote sensing tools to infer some of the above properties (Chu *et al.*, 2000). Acoustic backscattering techniques provide a high-resolution compare to traditional net sampling strategies (Medwin and Clay, 1998). The wide variety of backscattering sources of zooplankton was an important factor contributing to the ambiguities in accurately interpreting acoustic backscattering data (Conti and Demer, 2006).

The development of high-frequency sonar instrument lead to decreases in the ambiguities for interpretation of scattering measurements of zooplankton (Stanton and Chu, 2008). Acoustical backscattering strength of zooplankton are measured in order to estimate zooplankton biomass. Physical model employ the Distorted-Wave Born Approximation (DWBA) to estimate the scattering using a description of the shape of the animal (Lavery *et al*., 2010; Smith *et al*., 2010). The DWBA model accounts the complicated function of sonar frequency, the animal's length, shape, zooplankton orientation, and material properties (Chu and Wiebe, 2005, Amakasu and Furusawa, 2006).

Although physical models are mostly consistent with laboratory measurement where the exact size, and orientation of the zooplankton are known, problems have arisen in parameterizing the models in ocean condition (Warren and Wiebe, 2008). The greatest uncertainties are acoustic material properties (contrast or difference between the sound speed and density within the zooplankton body and the medium) and zooplankton orientation. Motivated by these problems, data obtained by measurement and DWBA model were used. This study presents experimental results from zooplankton around the Pari Island, Indonesia.

Materials and Methods

The survey was conducted using the research vessel in the area of Pari Island waters of Seribu Islands Indonesia with a depth of 10-30 m (Figure 1.). Measurements of acoustic target strength were made at frequencies of 120, 200, and 400 kHz. The acoustic transducers were circular with 3^{o} half-power beamwidths. Each transducer was acoustically calibrated for source level, receiver sensitivity, electro-mechanical, and transmit and receive beam patterns. An in situ calibration with a 38 mm tungsten carbide standard target was performed during the ocean experiment (Demer and Conti, 2005; Conti and Demer, 2006; Stanton and Chu, 2008). Effective pulse duration of 0.20 ms and a ping rate of 0.4 ping/s was used. The system's dynamic range allowed target strength data to be collected between -100 and -50 dB. Target strength

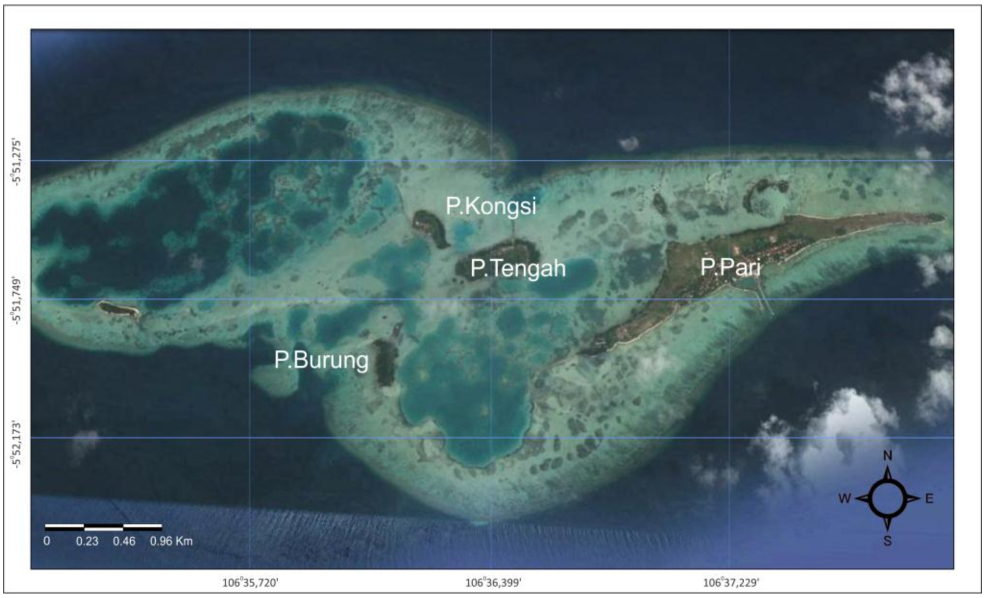

Figure 1. Ocean experiment around Pari Island

measurements were smaller than noise level. Measurements of target strength were made continuosly over the track of survey. Acoustical observation and biological sampling of zooplankton were carried out simultanously during the survey. For data acquisition, acoustic transducer was installed at the side mounted of the vessel. Sonar data were collected using an over the side mount for the echosounder off vessels of opportunity. A Garmin DGPS was connected to PC and simultaneously used for positioning.

The energy backscattered from a sampling of zooplankton is equal to the sum of the energy echoed by each zooplankton. Volume backscattering strength (SV) is defined as the ratio of sound intensity backscattered to the incident sound intensity by a unit volume. This is determined using sonar equation and the volume backscattering strength (*SV*) and acoustic backscattering coefficient (σ_{bs}) using this formula (Medwin and Clay, 1998):

$$SV = 10 \log (N.\ \sigma_{bs}) \quad (1)$$

$$SV = 10 \log N + TS \quad (2)$$

Assuming the numerical density is proportional to weight intensity, equation (2) can be written as follows :

$$SV = 10 \log (\rho) + \langle TS \rangle \quad (3)$$

where $\langle TS \rangle$ is the mean target strength of unit weight of zooplankton.

Data processing was conducted using sonar equation (Urick, 1983):

$$EL = (SL+RS+G) - 40 \log (r) - 2\, \alpha\, r + TS + 10\ \log (\Phi), \quad (4)$$

where

$$\Phi = \int b^2 (\theta,\phi)\, dA \quad (5)$$

and *EL* is measured echo level measured in dB, *SL* is source level, *RS* is receiving sensitivity, *G* is gain in dB, *r* is range from transducer to zooplankton, *α* is absorption coefficient and *b* is beam pattern.

Underwater acoustic data were processed using sonar processing method, which was developed in Borland and Pascal languages programming (Balk and Lindem, 2009) and Matlab programming. Sonar processing method compute the target strength from the energy of backscatter returns by integrating the squared amplitude of the beam time series data. The sonar system used a Time Varied Gain (*TVG*) correction to the backscatter data. TVG correction was quantified and the backscatter data corrected for the geometrical spreading and absorption loss (Simmonds and MacLennan, 1996).

For biological sampling, plankton net was used with a diameter of Ø20 cm and a length of 25 cm. The conical net bag is made of nylon with 30 cm deep. The bag is available in all mesh sizes. The plankton sample can be gathered by dismounting a chromium plated, brass sample cylinder from the PVC ring located at the bottom of the net. The sample can be removed through a valve at the bottom of the sample cylinder. Plankton net was lowered vertically from the bottom to the surface to observe the species composition (FAO, 2009).

In the case of zooplankton, the shape had been modeled as deformed cylinder. Deformed fluid cylinder or deformed fluid cylinder is ray representation of sound scattering by weakly scatterer body like zooplankton. The expression of deformed cylinder is shown in Eq. 6. Backscattering is computed along the lengthwise axis of the cylinder. Target strength calculated by the scattering model used Distorted Wave Born Approximation (DWBA). The general formulation of the DWBA gives a far field scattering amplitude in the backscatter direction (f_{bs}) as an integral over the body's volume (Morse and Ingard, 1968; Forman and Warren, 2010). DWBA assumes that contrast between the sound speed and density within the body and the surrounding seawater are small (weakly scattering bodies) and the body has negligible elastic properties.

Mathematical expression for the scattering amplitude as follow (Forman and Warren, 2010):

$$f_{bs} = \frac{k_1^2}{4\pi} \iiint_V (\gamma_\kappa - \gamma_\rho) e^{1 i k_2 . r_0} dV \quad (6)$$

where f_{bs} is the complex backscattering amplitude, related to σ_{bs} by the relationship $\sigma_{bs} = |f_{bs}|^2$; *k* is the acoustic wave number given by $k = 2\pi/\lambda$, where λ is the acoustic wave length; $\gamma_k = (\kappa_2 - \kappa_1)$ where κ is compressibility, given by $\kappa = (\rho c_2)^{-1}$; ρ is mass density; *c* is sound speed; r_0 is the position vector.

For the deformed cylinder the integral becomes (Smith *et al.*, 2010):

$$f_{bs} = \int_{r_{pos}} \frac{k_1^2 a}{4k_2} \left(\gamma_k - \gamma_\rho\right) e^{2ik_2 r_{pos}} \frac{J_1(2k_2 a \cos\beta_{tilt})}{\cos\beta_{tilt}} \left|dr_{pos}\right| \quad (7)$$

where r_{pos} is the position along the line, *a* is the cross-section radius of cylinder, β_{tilt} id the local angle between the cylinder and the incident wave. J_1 is a

Bessel function of the first kind of order 1. This formulation was implemented numerically using an algorithm where the cylinder's centerline was discretized and the radius, sound speed, and density were evaluated at each discrete point (Stanton and Chu, 2000).

The far-field backscattered is expressed in terms of the target strength (TS) with units of decibel (dB) relative to 1 m², and is given by (Stanton and Chu, 2000):

$$TS = 10\log\sigma_{bs} = 10\log\left|f_{bs}\right|^2 \qquad (8)$$

The acoustic frequency and target properties such shape, length, orientation relative to incident acoustic wave, and material properties were required for input parameters of DWBA model. The material properties used in acoustic modeling are density contrast (*g*) and sound speed contrast (*h*). The sound-speed contrast (*h*) is defined as the ratio of the sound speed in animals to that in the surrounding water. The density contrast (*g*), another important parameter used in describing ratio of the density of animals to the density of surrounding sea water.

Sound speed was computed from CTD instrument at the ship. Bottom water temperature and salinity measured by the periodic CTD casts from the ship to compute absorption coefficient (α) of sound wave with *f* is frequency (Urick, 1983). Spreading and absorption corrections were applied to the data in post processing.

$$\alpha = 3.0\times10^{-3} + \frac{0.1 f^2}{1+f^2} + \frac{44 f^2}{4100+f^2} + 2.75\times10^{-4} f^2 \qquad (9)$$

Result and Discussion

Figure 2 show marine zooplankton echogram. The red color is seabed profile and the marine zooplankton is lied in the water column with blue color.

The species of zooplankton detected are consisted of *Tintinnopsis* sp., *Amphorelopsis* sp., *Favella* sp., *Undella* sp., *Calanus* sp., *Acartia* sp., and *Codenelopsis* sp.. Figure 3 shows zooplankton abundance in each sampling station with the target strength distribution of zooplankton (Figure 4.).

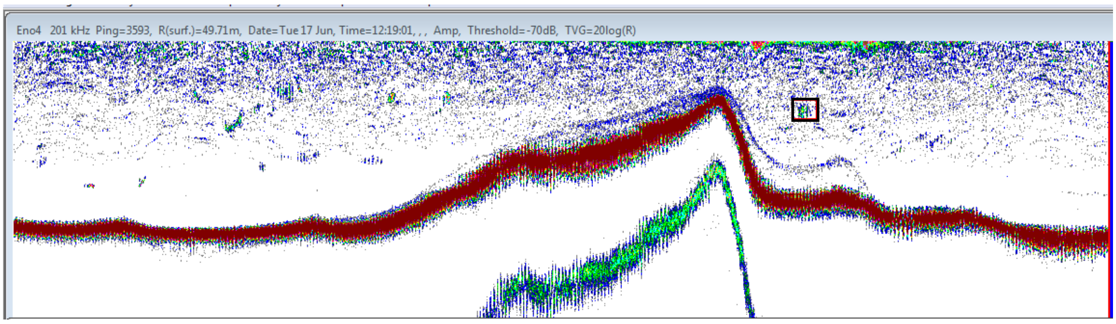

Figure 2. Echogram of sound scattering layer of zooplankton observed at Pari Island, Indonesia.

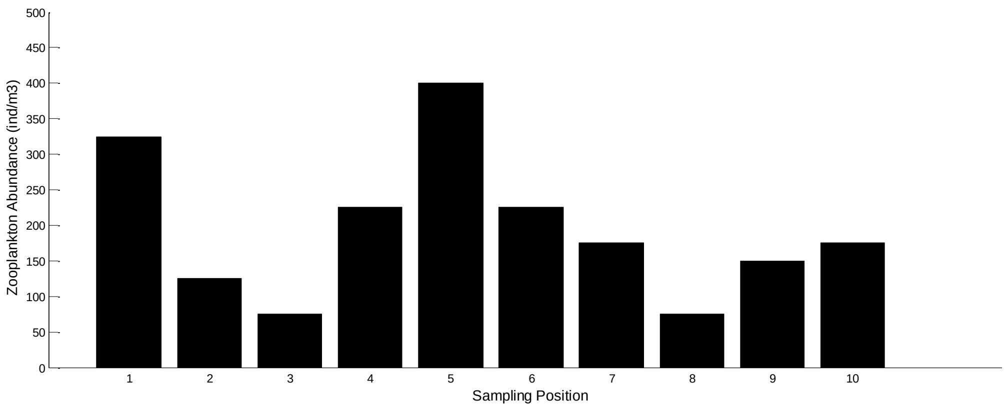

Figure 3. Zooplankton biomass for each sampling position

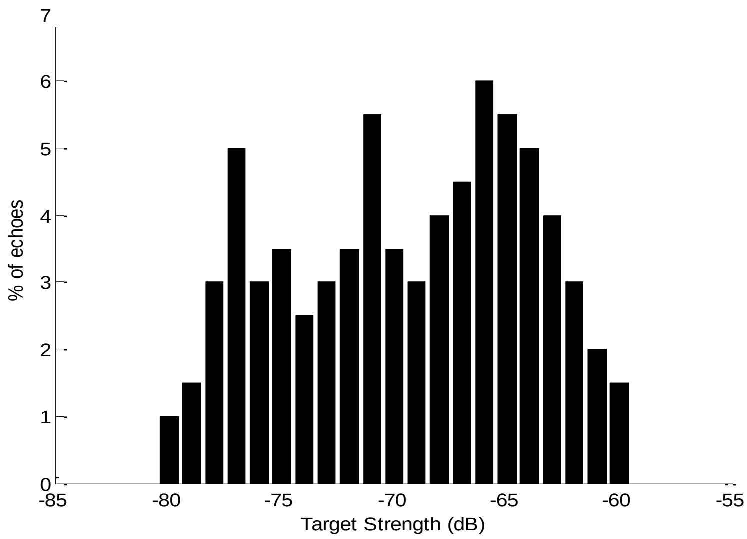

Figure 4. Target Strength histogram

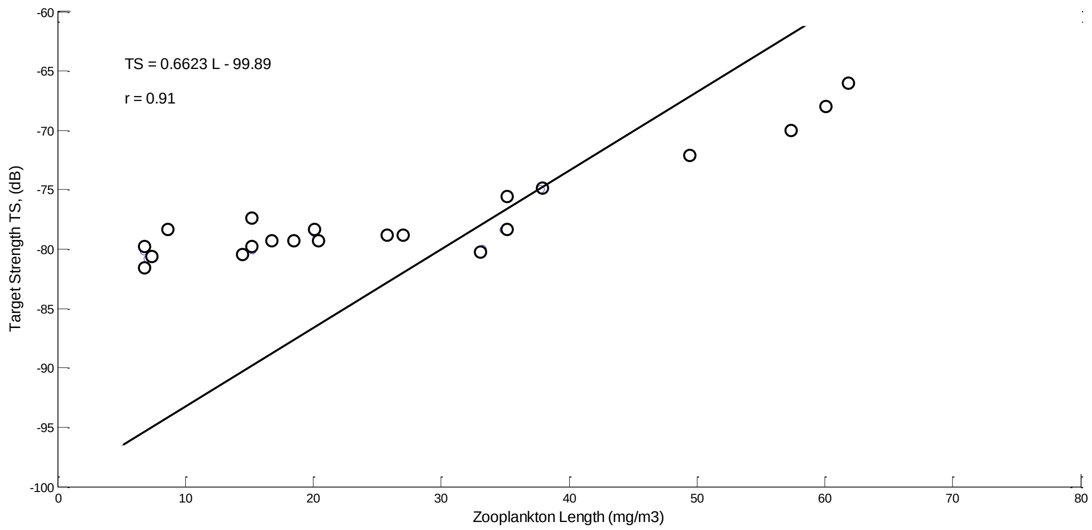

Figure 5. Target Strength (TS) and zooplankton length relationship

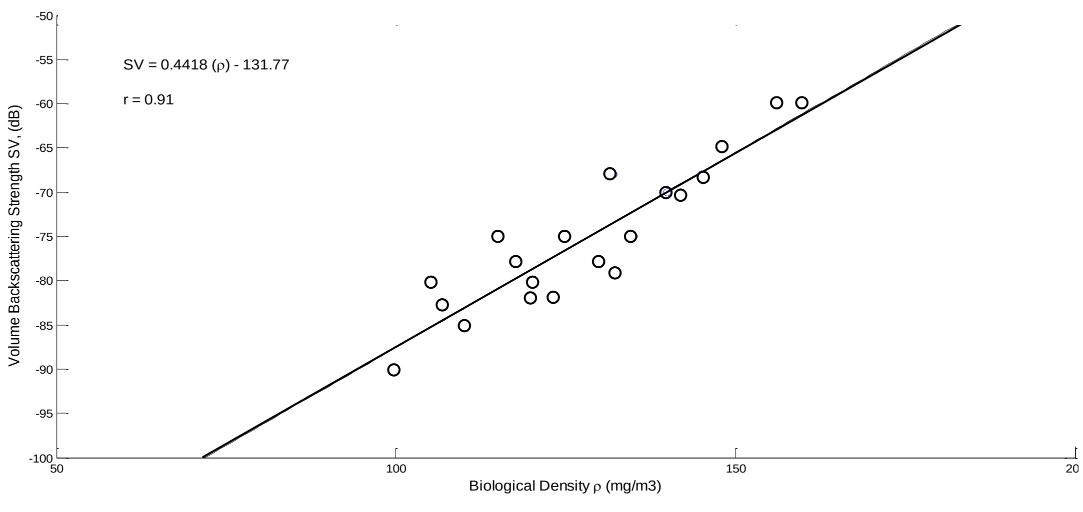

Figure 6. Volume backscattering strength (SV) and biological density relationship

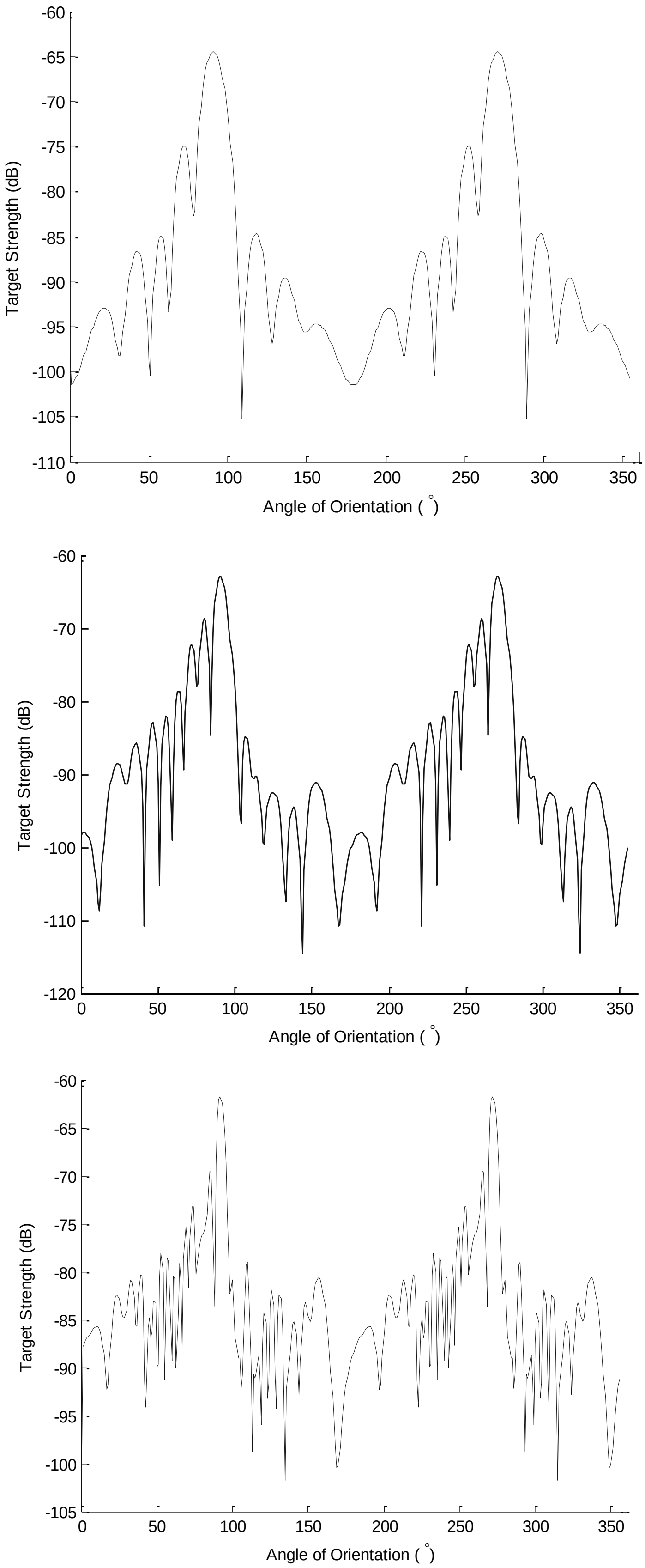

Figure 7. Target strength vs. angle of orientation for individual 20 mm *Copepod* using 120 kHz, 200 kHz, and 400 kHz obtained using DWBA model, consecutively

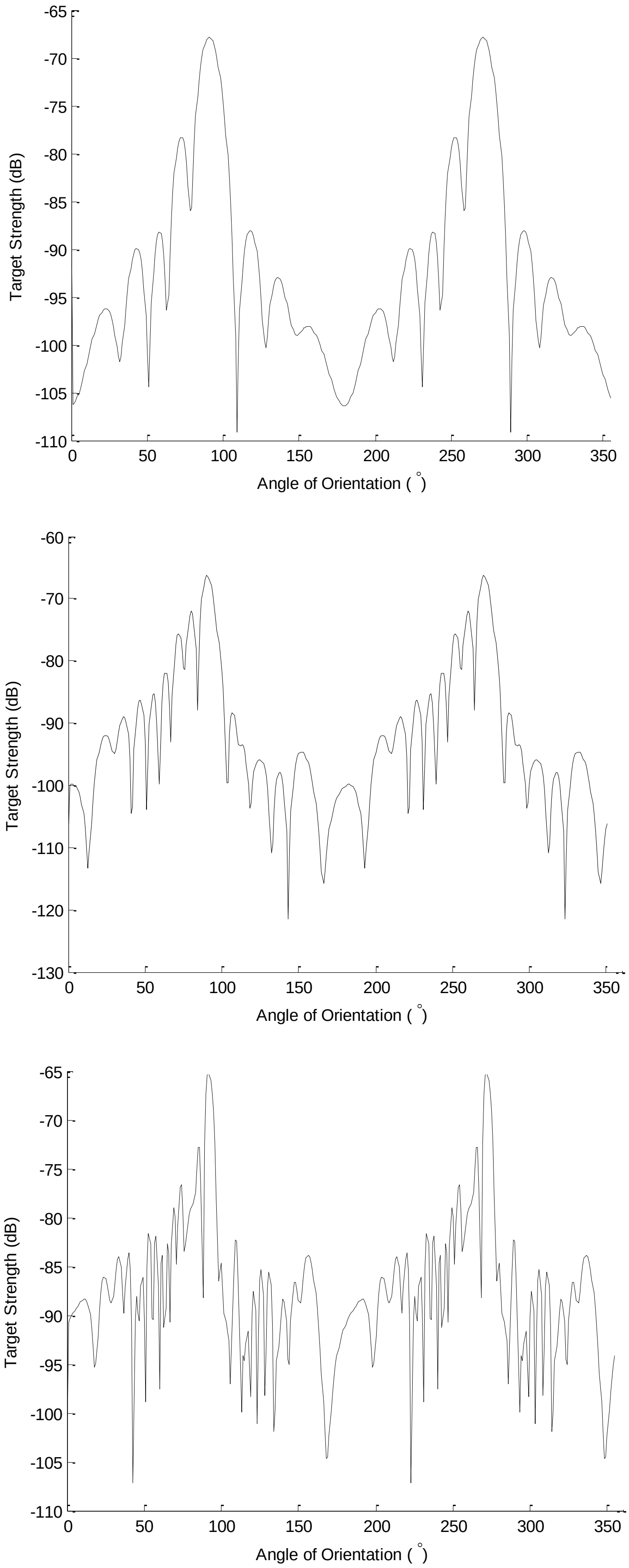

Figure 8. Target strength vs. angle of orientation for individual 20 mm *Acartia* sp. using 120 kHz, 200 kHz, and 400 kHz obtained using DWBA model, consecutively

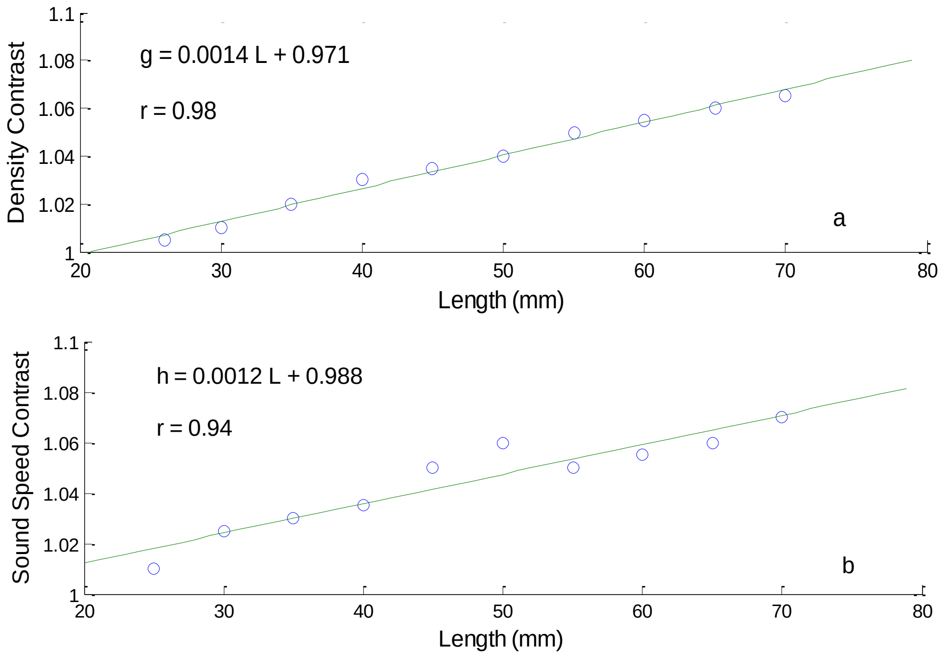

Figure 9. Density and sound-speed contrasts of krill as a function of length. (a) Density contrast as a function of length. (b) Sound-speed contrast as a function of length

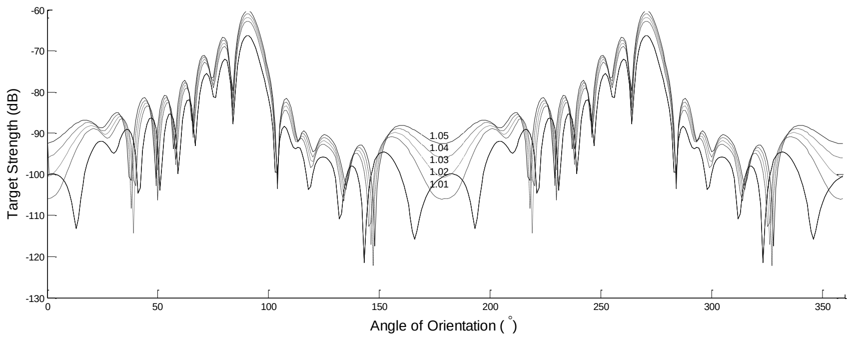

Figure 10. Effects of variations of homogenous material properties of zooplankton on its target strength

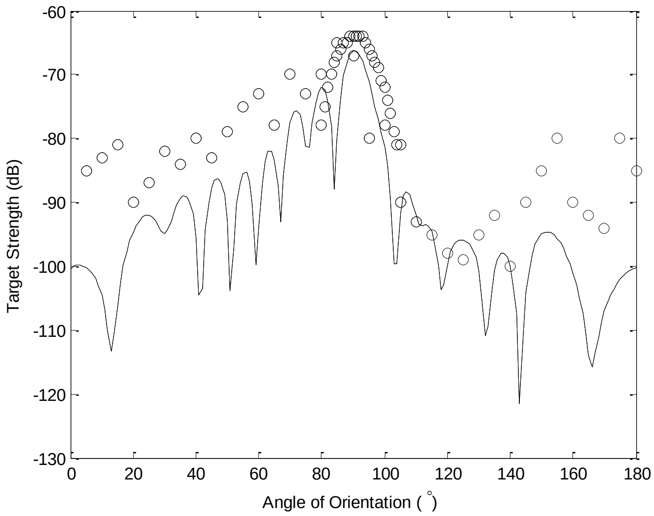

Figure 11. Measured (o) and DWBA model (–) of zooplankton backscatter

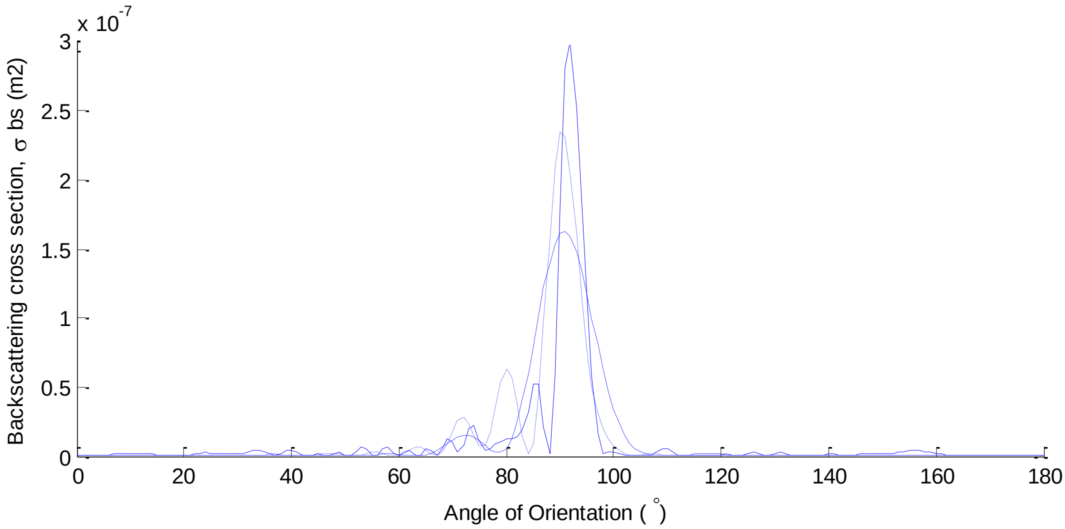

Figure 12. Backscattering cross section of zooplankton for 120 kHz (---), 200 kHz (– –), 400 kHz (–)

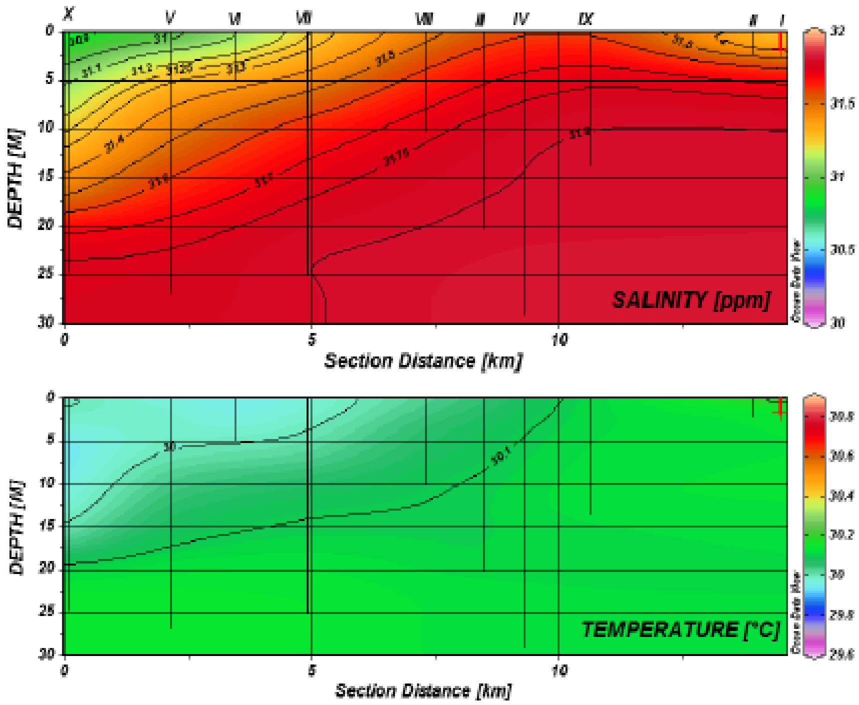

Figure 13. Distribution of salinity and ocean temperature

The highest zooplankton abundance is at station 5 and the lowest is at station 3. Target strength of zooplankton was ranged from -80.0 dB to -60 dB. The increasing of zooplankton length is followed by target strength value (Figure 5.). Length of zooplankton measurements were measured with a standard net sampling technique. This information is needed for accurate backscattering model. Figure 6 shows the relationship between the biological density calculated from plankton sampling and the measured volume backscattering strength (SV). It indicates a linear correlation between biological density and SV value. Volume backscattering strength (SV) is proportional to numerical density of zooplankton.

The present study was to apply multi-frequencies acoustics to distinguish between Calanus and Acartia zooplankton. Holliday and Pieper (1995) measured the target strength at 400 kHz was -1.5 dB less than Target Strength (TS) at 200 and 120 kHz. The difference target strength for

Calanus and Acartia using this frequencies was observed ranging from -2.0 to -0.5 dB, which is of live zooplankton using multi frequencies. The result showed strong frequency dependence. Information on frequency dependent on backscattering will be incorporated into acoustic post processing as a tool for zooplankton species identification. Multifrequency acoustic back-scattering methods expand the range of conditions under which it is possible to interpret the acoustic data in biological parameters such as zooplankton size and abundance (Medwin and Clay, 1998).

The measured sound-speed contrast varied between 1.010 and 1.070, with mean value 1.0258 and standard deviation 0.0064, while the measured density contrast varied between 1.005 and 1.065, with mean value 1.0232 and standard deviation 0.0052. Linear regressions showed that the density and sound-speed contrasts had gradients of $1.4x10^{-4}$ (mm^{-1}) and 1.2×10^{-4} (mm^{-1}), respectively (Fig. 9). The correlation coefficients are 0.98 and 0.94, respectively.

Computations were performed for the rough tapered bent cylinder as a function of angle of orientation for one frequency over a range of material properties (Fig. 10). This figure shows that Target Strength was plotted as a function of angle of orientation for a 20 mm long Calanus at 200 kHz. Four different set of density and sound speed constraints are used $g = h = 1 + \varepsilon$, where $\varepsilon = 0.01$, 0.02, 0.03, 0.04, 0.05 for different sets. The results show the large change of order 15 dB in overall levels of backscattering.

The variation of the material properties is related to size, species, and depth. Improvements in making biological inferences from acoustic data depend on information about the material properties of zooplankton. As a result, for zooplankton species and micronekton as a weakly scattering, the sound-speed contrast (*h*) and density contrast (*g*) are the dominant acoustic parameters. This indicates that the influence of material properties on the TS is comparable to that of the animal orientation and suitable with former researcher especially when an average over orientation and size distribution is quantified (Lawson *et al*., 2006; 2008; Lee *et al.,* 2008; Warren and Wiebe, 2008). Variety of animal size, water temperature, density, and sound speed are difficult to measure for material properties quantification.

Model and measurements were shifted into the same reference frame and plotted together for comparison (Figure 11.). The measurement appears generally to support the model with main lobes in the scattering pattern at similar angles. In the side consistent with Holliday and Pieper (1995). Chu (1992) measured target strength (TS) lobes, away from the main scattering lobes, the measurements were generally both higher than the model predictions. There was discrepancy between measurements and model. The DWBA model depends upon a summation of scattering from a volume of measured object. Our direct measurement of target strength in the main lobe at all frequencies were generally consistent with the previous physical model prediction (Chu and Wiebe, 2005).

Target Strength (TS) prediction from the DWBA model have been experimentally validated for zooplankton near broadside incidence with angles less than 15-30°. Model backscattering cross section for three frequencies were shown in Figure 12. Prediction of TS at larger angles in the same experiment were approximately 8 dB than direct measurements. These results is agreed or suitable with the theoretical value by Wiebe *et al.* (2010) that obtained 5-10 dB between measurement and model. This figure shows that TS was more influenced by the density contrast (*g*) than a sound speed contrast (*h*).

Figure 13 show the distribution of salinity and ocean temperature in the survey area. Increasing of seawater depth is followed by higher salinity and lower temperature. Ocean temperature mediated physiological stresses and phenology changes impact the recruitment success and abundances of many marine zooplankton populations (Medwin and Clay, 1998). The observed distribution of orientations produced target strength predictions from a theoretical DWBA based scattering model that are consistent with in situ observation.

Changes in zooplankton distribution and abundance alter the composition of ocean communities, with possible consequences to the structure and productivity of marine ecosystems. An increase in sea surface temperatures (SST) was caused the risen of air temperature (IPCC, 2007). A decrease in salinity is caused by ice melting. Another influence on the decrease in salinity in Pari Island is increased precipitation. Availablity of nutrients correlate with phytoplankton productivity as the base of the ocean food web.

Conclusion

Volume backscattering strength of zooplankton was proportional to its numerical density. Sound speed contrast and density contrast to zooplankton length had yielded prediction from a DWBA-based scattering model that compared to ocean measurement of target strength of zooplankton. To characterize the material properties of zooplankton, there was no single value of density contrast and sound-speed contrast measurements is sufficient. This was due zooplankton vary between species as well as taxonomi. A more comprehensive study is needed to evaluate the seasonal, spatial, and temporal variation in the material properties of zooplankton. Application of DWBA model allow more accurate estimate of biologically quantities of zooplankton abundance and biomass.

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