

Comparative studies of theoretical and empirical target-strength models of euphausiids (krill) in relation to field-experiment data

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Acoustic backscattering cross-section models can be derived from (1) theoretical models of backscattering from objects of known geometry, (2) empirical models based solely on measurements of specimens, or (3) theoretical models tuned to observations on topical organisms, i.e., euphausiids, copepods, etc.

We considered complete and truncated fluid-sphere models, an approximate fluid-sphere model, complete and truncated fluid finite-length cylinder models, and an empirical model considered as a hybrid fluid bubble/fluid finite-length cylinder model. The main parameters in the computer simulations were the geometrical forms, the specific-density contrast, the sound-speed contrast, the backscattering directivity, and the angular orientation of the specimen. The models were all run with field-experiment data.

In general, the models representing individual zooplankters performed best in resolving mixed-size populations. Compared with biological samples, all the fluid-sphere models and the original fluid finite-length cylinder model produced displaced and truncated length distributions, while the tuned fluid finite-length cylinder model and the tuned hybrid fluid bubble/fluid finite-length cylinder model produced quite accurately located length distributions.

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1. Introduction

When estimating the abundance of zooplankton acoustically, two different approaches have been predominant. The first one is based on an estimated regression equation derived from acoustic measurements at a single frequency and data on biological samples (Pieper, 1979; Sameoto, 1980; Klindt and Zwack, 1984). The second approach relies on mathematical multifrequency scattering models representing the target strengths of the zooplankton species investigated (Anderson, 1950; Johnson, 1977; Pieper and Holliday, 1984; Kristensen and Dalen, 1986). If the target-strength model considered is a function of acoustic frequency, size of the organisms, and physical parameters of the species, and also contains a distinctive transition region versus frequency, then both size distribution and abundance of the zooplankters may be estimated from multifrequency measurements.

The scope of this paper is multifarious. We want (1) to compare estimates of target strengths from com-

monly utilized or potentially applicable models with measured target-strength data, (2) to estimate size distributions of krill using the models of (1), and (3) to compare estimates of size distributions from models with those from biological sampling.

2. The acoustic method of estimating size distribution

Estimating plankton size distribution by multifrequency acoustic backscattering measurements – its requirements, assumptions, and restrictions – has been described by Holliday (1977), Greenlaw (1979), Greenlaw and Johnson (1983), and Kristensen and Dalen (1986), among others.

The backscattering intensity of a plankton community is composed of the superimposed backscattering contributions from many individual organisms. Assuming the objects are randomly distributed in the ensonified vol-

ume, the total intensity will be a sum of the intensity scattered from each individual, as long as extreme volume densities do not require the consideration of extinction or multiple scattering. In acoustic quantities this means that the volume backscattering coefficient $s_v(f)$ at each frequency is the sum of the backscattering cross-sections $\sigma_{bs}(f)$ of each organism per cubic metre.

$$s_v(f) = \sum_{j=1}^M \sigma_{bs,j}(f) n_j \quad (1)$$

where

$\sigma_{bs,j}(f)$ = backscattering cross-section of the (j)th size group at frequency f of the acoustic system,
 n_j = number of scatterers of the (j)th size group,
 M = total number of size groups.

In general, the backscattering cross-section of an object is a function of its size, physical parameters, angular orientation, and acoustic frequency. The target strength is properly defined (Clay and Medwin, 1977; Shotton, 1982) as

$$TS(f) = 10 \log \sigma_{bs,j}(f)/A_{ref} \quad (2)$$

where

A_{ref} = the reference backscattering cross-section equal to 1 m^2 .

By measuring the volume backscattering coefficient at a set of I frequencies, Equation (1) established a set of I equations with M unknowns, which is the number of organisms in each size group. In matrix form this can be written:

$$S = RN \quad (3)$$

where

S = the measuring vector with I elements $s_v(f_i)$,
 R = $I \times M$ scattering matrix with elements $\sigma_{bs,j}(f_i)$,
 N = the number vector with M elements n_j .

The solution of Equation (3) depends on the backscattering cross-sections only, while the quality of a possible solution depends on the accuracy of the measurements, the signal-to-noise ratio, the choice of frequencies, the solution algorithm (here the non-negative least-squares algorithm (Lawson and Hansen, 1974)), and how exactly we can represent the backscattering cross-section at each frequency. The robustness of the inversion procedure and the stability of the solutions of Equation (3) are discussed by Ishimaru (1978), Kristensen (1983), and Greenlaw and Johnson (1983).

3. Target-strength models

We will briefly present the different models considered (Anderson, 1950; Johnson, 1977; Pieper and Holliday, 1984; Kristensen and Dalen, 1986; Stanton, 1988).

3.1. Model (a): Fluid-sphere model

A relevant candidate model for calculating the target strength of zooplankton is that of a fluid sphere. Fluid media cannot support shear movements and therefore only compressional waves can exist inside the sphere.

Anderson (1950) derived an exact analytic expression for the scattering of sound from a fluid sphere (the "ANDERSON model"). The backscattering cross-section in the far field of the sphere can be written as

$$\sigma_{bs}(f,a) = \frac{1}{k^2} \left[\sum_{m=0}^{\infty} (-1)^m \frac{2m+1}{1+iC_m} \right]^2 \quad (4)$$

where

k = wavenumber in water = $2\pi f/c_0$ with f as the frequency and c_0 as the sound speed in water,
 C_m = a function containing 1) spherical Bessel and Neumann functions of arguments, the wavenumbers inside and outside the sphere, and the sphere radius, and 2) the specific-density and sound-speed contrasts.

Figures 1a, 2a, and 3a demonstrate the target strength vs. frequency of a fluid sphere.

3.2. Model (b): Truncated fluid-sphere model

A euphausiid has a nonsymmetrical geometry quite unlike that of a sphere, and its geometry may change while swimming. Probable higher order internal modes will then not be generated inside a euphausiid when acoustic waves penetrate it. Therefore, Pieper and Holliday (1984) have proposed a truncated version including the first two terms of Equation (4), the monopole and dipole terms (the "HOLLIDAY and PIEPER model").

Figures 1b, 2b, and 3b show the target strength of model (b) versus frequency. It is seen that the rapidly varying function in the geometric scattering region is reduced.

3.3. Model (c): Fluid-sphere high-pass model

Johnson (1977) derived a model that overlaps the fluid-sphere model in the low-frequency (Rayleigh scattering) region. In the geometric scattering region the "JOHNSON model" is constant and equals the maxima

of model (a). The expression for the backscattering cross-section is given by

$$\sigma_{bs}(f,a) = 2\alpha \frac{(ka)^4}{2 + 3(ka)^4} \pi a^2 \quad (5)$$

where

$$\alpha = \frac{4}{9} \left(\frac{1 - gh}{3gh^2} + \frac{1 - g}{1 + 2g} \right)^2 \quad (6)$$

Figures 1c, 2c, and 3c show the target strength of this model vs. frequency.

3.4. Model (d): Finite-length fluid-cylinder model

Since euphausiids are elongated organisms, a finite-length fluid-cylinder model may be superior to a fluid-sphere model. A model for a non-resonant penetrable fluid-length cylinder has been proposed by Stanton (1988):

$$\sigma_{bs}(f,a,L,\theta) = \frac{L^2}{\pi^2} \left[\frac{\sin\left(\frac{2\pi L}{\lambda} \sin\theta\right)}{\frac{2\pi L}{\lambda} \sin\theta} \right]^2 \left| \left[\sum_{m=0}^{\infty} B_m (-1)^m \cos(m\pi) \right] \right|^2 \quad (7)$$

where

L = acoustic wavelength,
 L = length of cylinder,
 θ = angle between incidence and normal to length axis,

$$B_m = \frac{-\epsilon_m i^m}{1 + i C_m} \quad (8)$$

C_m = a function containing 1) cylindrical Bessel and Neumann functions of arguments, the wavenumbers inside and outside the cylinder, and the cylinder radius, and 2) the specific-density and sound-speed contrasts.

$$\begin{aligned} \epsilon &= 1 \quad \text{for } m = 0, \\ &= 2 \quad \text{for } m = 1, 2, \dots \end{aligned}$$

The model is only valid for near-normal incidence and for lengths greater than the radius of the cylinder.

Initial analysis of the cylinder models revealed considerable differences in their frequency transition-region locations with the applied equivalent cylinder radius compared with other models. Since success in estimating size distribution is strongly dependent on the proper location of the transition region, we tuned the cylinder model to measured data (Kristensen and Dalen's (1986) were chosen). This was done by increasing the equivalent cylinder radius and decreasing its length while keeping the cylinder volume equal to that of the actual krill. Figures 1d, 2d, and 3d demonstrate the target strength vs. frequency for model (d), the tuned "STANTON model".

3.5. Model (e): Truncated finite-length fluid-cylinder model

In analogy with the truncated fluid sphere we may truncate the fluid-cylinder model. Our analysis shows that four terms are adequate to overlap the first two maxima of the model presented by Equation (7). Figures 1e, 2e, and 3e show the target strength vs. frequency described by model (e), the tuned "truncated STANTON model".

3.6. Model (f): An empirical model based on measurements

Kristensen and Dalen (1986) showed that the target-strength data from single krill specimens of a given length group exhibited a resonance-like behaviour in the frequency domain. Similar resonance structures have been noted by Greenlaw (1977) and Holliday and Pieper (1980). Kristensen and Dalen (1986) proposed an empirical model, the "KRIDA model", essentially a hybrid fluid bubble/fluid finite-length cylinder model described by

$$\sigma_{bs}(f,a,\theta) = \frac{Ka^2 d(\theta)}{\left[\left(\frac{f_0}{f} \right)^2 - 1 \right]^2 + \sigma^2} \quad (9)$$

where

$$K = 4 \left(\frac{1 - gh^2}{3gh^2} + \frac{1 - g}{1 + 2g} \right)^2 \quad (10)$$

giving the backscattering equal dependence on density and sound speed as that of Johnson (1977).

f_0 = resonance frequency,

σ = damping constant,

a = equivalent radius,

$d(\theta)$ = scattering directivity factor of the organism.

We have refined the model based on the data from Greenlaw (1977) and Kristensen and Dalen (1986), replacing Equation (9) by

$$\sigma_{bs}(f, a, \theta) = \frac{Ka^2 d(\theta)t(f)}{\left[\left(\frac{f_0}{f}\right)^2 - 1\right]^2 + \sigma^2} \quad (11)$$

where $t(f)$ is a high-frequency tuning factor chosen to be effective above an acoustic radius of $k = 8-12$. To reflect the data we have chosen $ka = 10$, which yields

$$t(f) = (1 + 0.1 ka)^2 \quad (12)$$

where the relationship between the equivalent radius, a , and the length of the krill is given by

$$a = 0.136 TL^{1.05}. \quad (\text{Kiils, 1979}) \quad (13)$$

The damping constant, $\delta \approx 0.5$, was found to be appropriate for the euphausiids *M. norvegica* and *Thysanoessa* spp.

The observed resonant peak occurs at $ka \approx 0.6$. This gives a transition from Rayleigh to geometric scattering considerably lower in frequency than for the previously published models ($ka = 1$), but consistent with scattering from gas bubbles and fish with swimbladders (Clay and Medwin, 1977). The directivity function, $d(\theta)$, is derived from a finite-length object:

$$d(\theta) = \left[\frac{\sin\left(\frac{2\pi f TL}{c} \sin \theta\right)}{\frac{2\pi f TL}{c} \sin \theta} \right]^4 \quad (14)$$

The target strength vs. frequency of the empirical model is shown in Figures 1f, 2f, and 3f.

4. Experimental work by computer simulations

Our experimental work compares the backscattering models to determine how they represent the backscattering process for euphausiids to yield reliable size distributions by the inversion. We divide the experimental work into two parts:

- (i) Comparison of the different target-strength models with measured target-strength data.
- (ii) Comparison of the relative size distributions from biological sampling with the size distributions estimated from the various models using measured multifrequency volume backscattering coefficients.

Target-strength simulations have been run for three different krill-lengths: $TL = 23, 27,$ and 40 mm, corresponding to measurements by Greenlaw (1977) on *Euphausia pacifica* and by Kristensen and Dalen (1986) on *Thysanoessa* spp. and *Meganyctiphanes norvegica*. The applied average measured values of the sound speed and specific density of sea water were 1480 m/s and 1026 kg/m³, respectively. By linear regression Kristensen (1983) found the following relations of the specific-density contrast, g , versus length, TL , and the sound-speed contrast, h , for (1) *Thysanoessa* spp. and (2) *M. norvegica*.

- (1) $g_1 = 1.058 - 1.039 TL$ for $TL < 0.030$ m,
 $h_1 = 1.025$.
- (2) $g_2 = 1.063 - 0.729 TL$ for $TL \geq 0.025$ m,
 $h_1 = 1.035$.

The equivalent parameters of the *E. pacifica* (Greenlaw, 1977) are:

$$g_3 = 1.043,
h_3 = 1.052.$$

To incorporate the function to account for the angular orientation distribution of free-swimming krill (Dalen and Kristensen, 1981), we vary the angle θ of the directional terms of the models in a stochastic manner which follows a Gaussian tilt-angle distribution as proposed by Kristensen and Dalen (1986).

5. Results and discussion

5.1. Comparison of the target-strength models with measured target-strength data

Greenlaw's (1977) measurements of the target strength of *Euphausia pacifica* were carried out on preserved animals. As pointed out by Greenlaw (1977) and as confirmed by other investigators (e.g., Holliday and Pieper, 1980; Dalen and Kristensen, 1981; and Richter, 1985), the target-strength values presented are considerably lower than the corresponding values from live specimens. The differences are observed to be in the range 6 to 10 dB. In order to make the data on the 23-mm *Euphausia pacifica* consistent with those on *M. norvegica* and *Thysanoessa* spp., the *E. pacifica* data were increased by an average value of 8 dB.

Figures 1a-c show the graphs of the Anderson model, the Holliday and Pieper model, the Johnson model, and the adjusted measured target-strength values of the 23-mm *Euphausia pacifica*. We conclude that these predictions of target strength vs. frequency are too low except for the Holliday and Pieper model above 220 kHz.

Figures 1d-f display the graphs of the two tuned Stanton models, the KRIDA model, and the measured

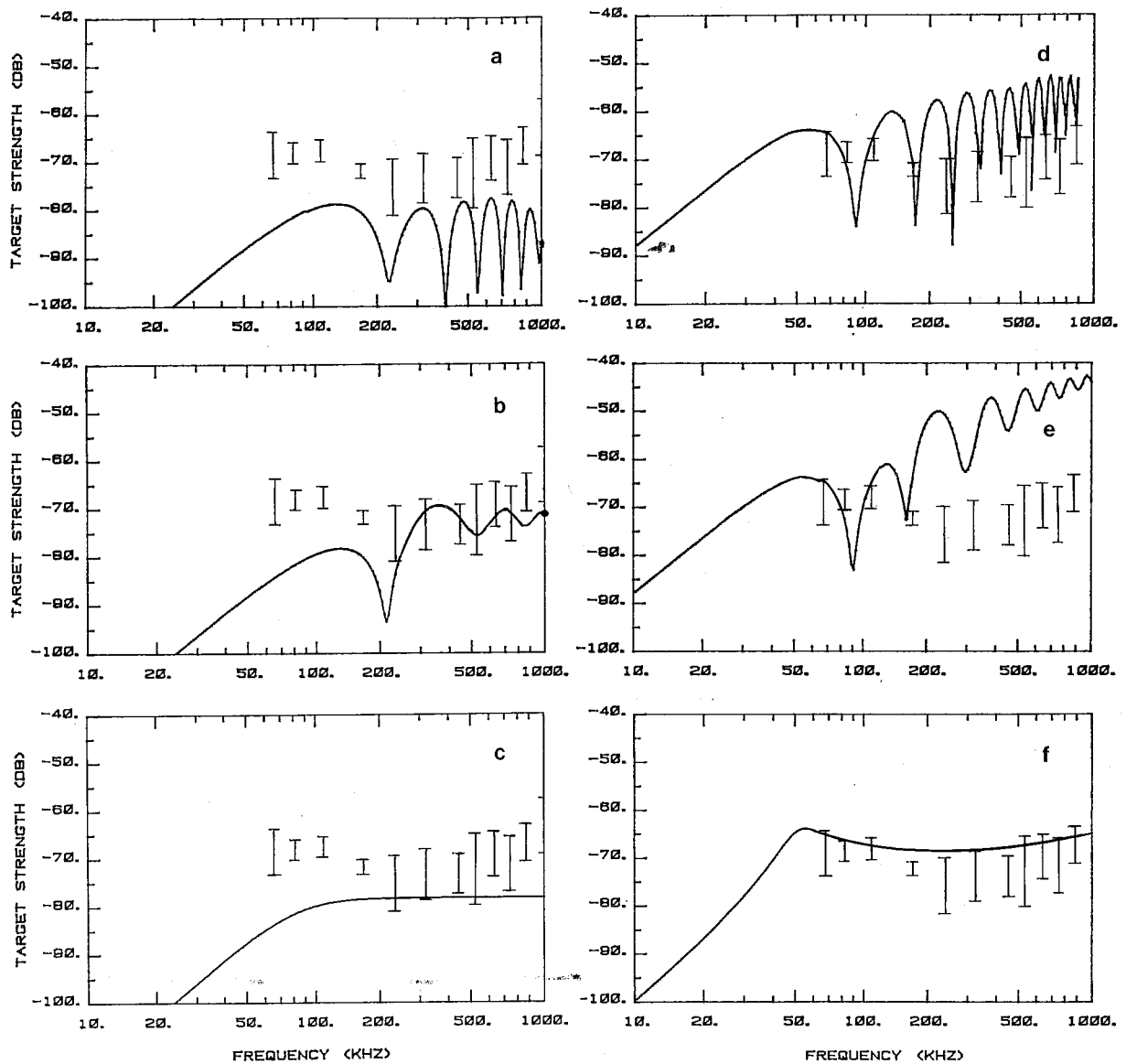


Figure 1. Predicted target strength, solid line, and measured target strength, bars - range of measured values, vs. frequency in dorsal aspect of a 23-mm *Euphausia pacifica*. a) The Anderson model, b) the Holliday and Pieper model, c) the Johnson model, d) the tuned complete Stanton model, e) the tuned truncated Stanton model, and f) the KRIDA model.

target-strength values of the 23-mm specimen. The complete tuned cylinder model yields a good prediction of the target strength, while the truncated tuned cylinder model gives a medium-to-poor prediction. The KRIDA model coincides excellently with the measured target strengths.

Figures 2a-f present the graphs of the target-strength models and the measured target strengths of a group of *Thysanoessa* spp. krill of mean length 27 mm. The three fluid-sphere models predict the observed target-strength progression moderately well at frequencies

above 100 kHz, but they all fail at lower frequencies (Figs. 2a-c).

The complete Stanton model predicts the observed target strength reasonably well, being slightly too high above 200 kHz (Fig. 2d), while the truncated model predicts the observed data points well at frequencies below 120 kHz, whereas the model progression is far too high above this frequency (Fig. 2e). The KRIDA model (Fig. 2f) predicts the target strength rather well at all frequencies, being slightly too high above 80 kHz.

The graphs of the target-strength models and the

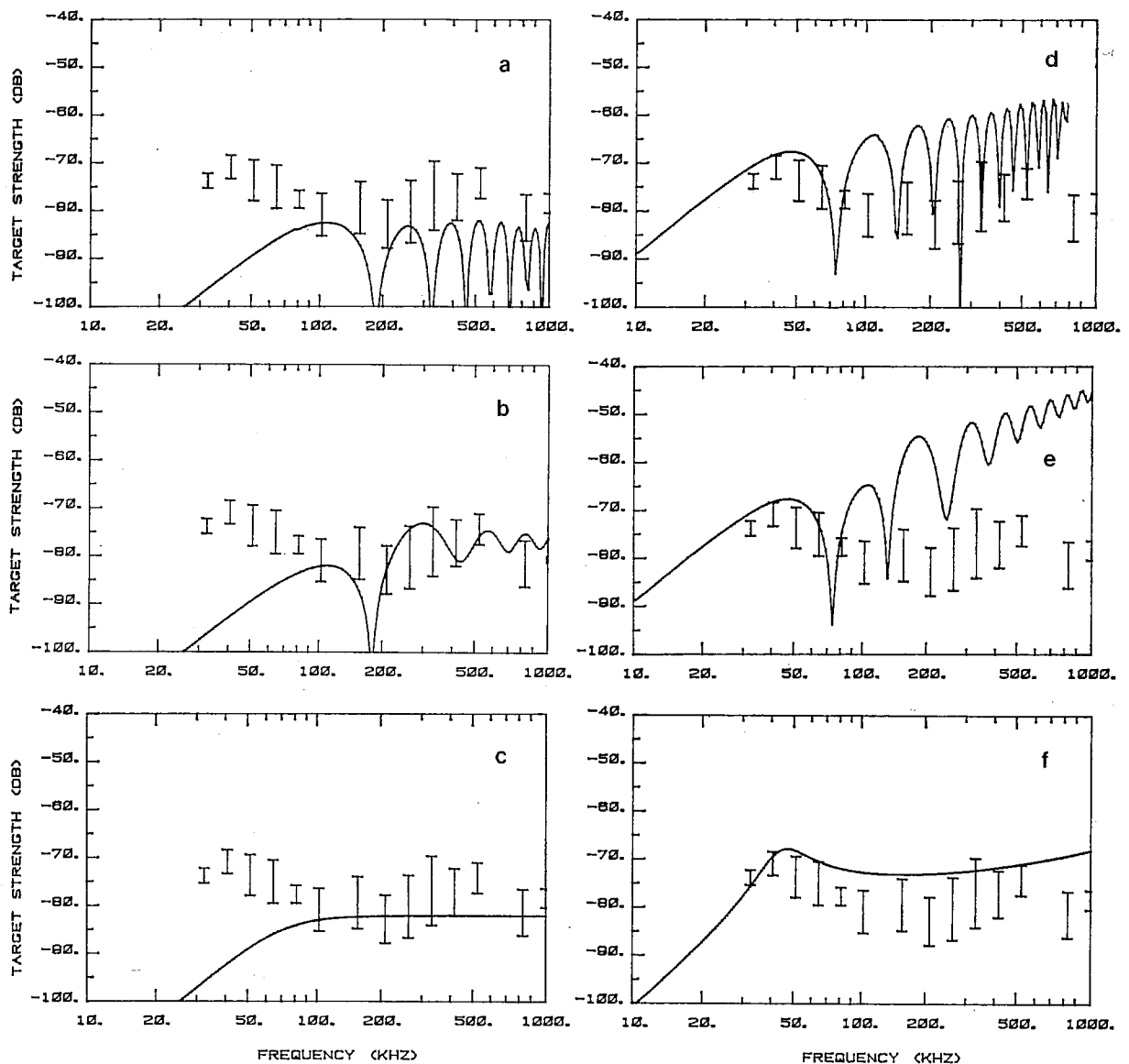


Figure 2. Predicted target strength, solid line, and measured target strength, bars – range of measured values, vs. frequency in dorsal aspect of a group of *Thysanoessa* spp. krill of mean length 27 mm: a) The Anderson model, b) the Holliday and Pieper model, c) the Johnson model, d) the tuned complete Stanton model, e) the tuned truncated Stanton model, and f) the KRIDA model.

measured target-strength values of a group of *Meganyciphanes norvegica* krill of mean length 40 mm are displayed in Figures 3a–f. The Anderson model and the Johnson model predict the observed target strength poorly (Figs. 3a and c) while the Holliday and Pieper model provides good agreement above 170 kHz and fails at lower frequencies (Fig. 3b). The complete Stanton model covers the observed data well below 315 kHz, while it produces too high levels above this frequency (Fig. 3d). The truncated Stanton model shows the same features below 100 kHz and similarly above this fre-

quency as does the complete model (Fig. 3e). The KRIDA model coincides rather well with the observed target strength below 250 kHz but is slightly too high above this frequency (Fig. 3f).

In general, for all specimens, the fluid-sphere models predict the measured target strength vs. frequency rather poorly. The tuned fluid-cylinder models predict the measured data in a varying but better way, while the KRIDA model predicts the measured target-strength progressions relatively well.

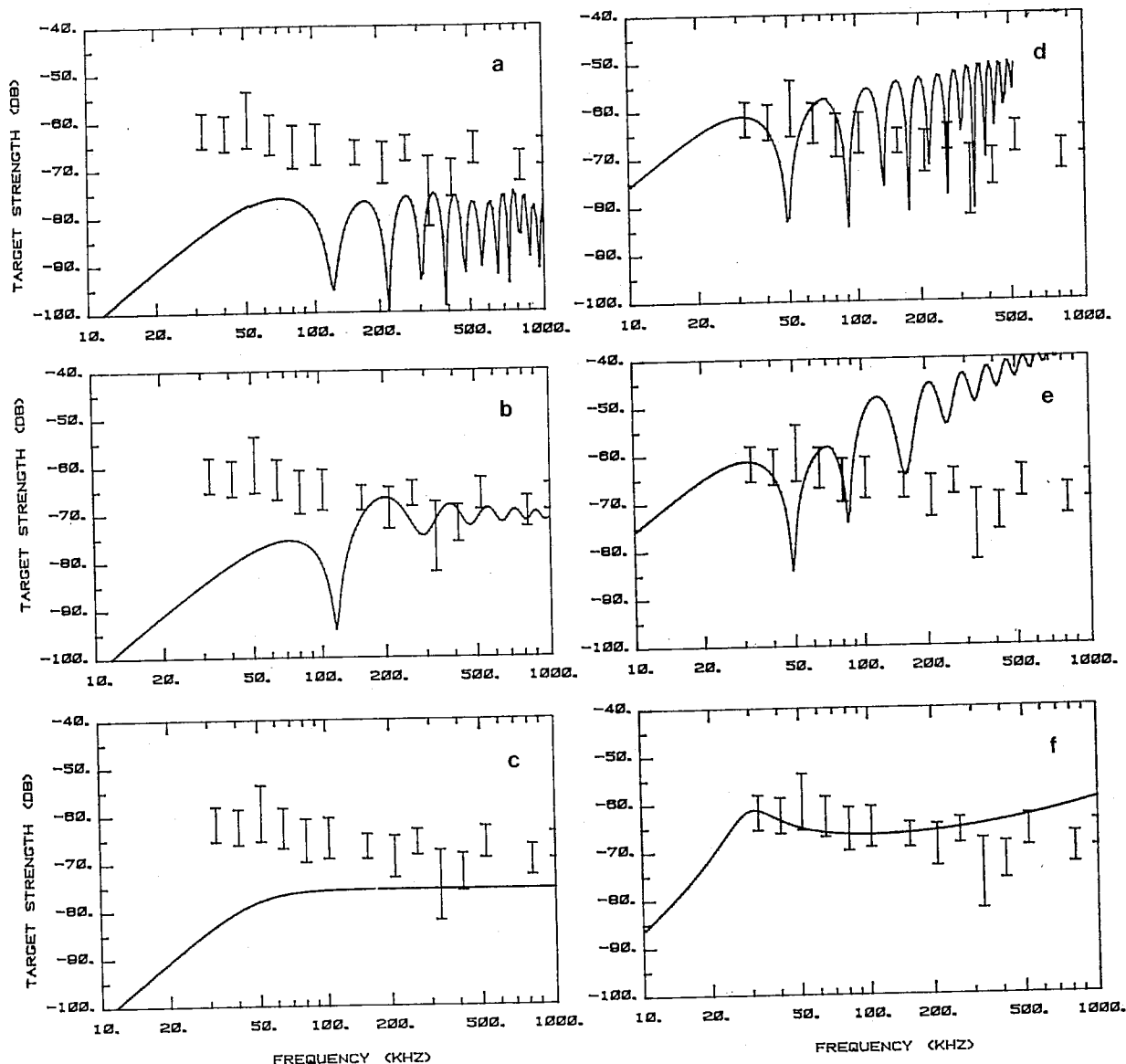


Figure 3. Predicted target strength, solid line, and measured target strength, bars - range of measured values, vs. frequency in dorsal aspect of a group of *Meganyctiphanes norvegica* krill of mean length 40 mm. a) The Anderson model, b) the Holliday and Pieper model, c) the Johnson model, d) the tuned complete Stanton model, e) the tuned truncated Stanton model, and f) the KRIDA model.

5.2. Estimation of size distributions of krill from multifrequency acoustic data

The acoustic and biological data were acquired in Ullsfjorden, northern Norway. Acoustic measurements were made at 10 frequencies in a continuous serial operation from 31.5 kHz to 250 kHz with one-third octave frequency spacing. All transducers had circular beam patterns with beamwidths $10 \pm 1^\circ$. A pulse length of 1 ms was used at all frequencies. The measured volume backscattering coefficients are stochastic quantities (Kristen-

sen, 1983; Greenlaw and Johnson, 1983), so the data at each frequency were averaged over 25 transmissions for the sake of acceptable variance. The transducer frame facing downwards was lowered to 45-m depth just above the plankton layer. Our sonar system had a measuring range approximately 25 m from the transducers. The signal-to-noise ratio of the applied collected data was between 5 and 20 dB over this range.

The biological sampling was done by a 1-m² opening Tucker trawl (Sameoto and Jarosynski, 1976) with a net of 1-mm mesh size and a pelagic trawl with an opening

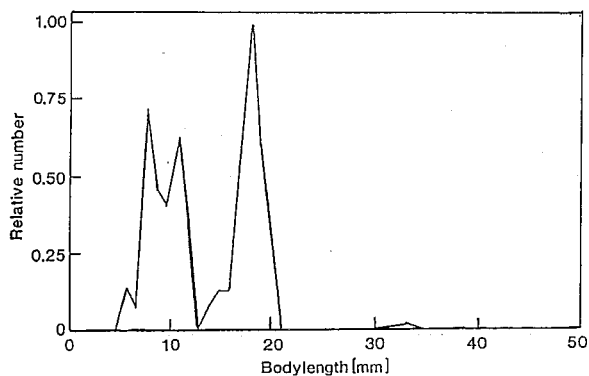


Figure 4. Relative length-frequency distribution vs. bodylength of euphausiids from the biological sampling.

of 18×18 m and fine-meshed net in the codend. The biological sampling took place prior to and just after the period of acoustic sampling as described by Kristensen (1983). The relative size distribution from the biological sampling is shown in Figure 4.

Compared with the distribution seen in Figure 4, we find that the complete fluid-sphere model (Fig. 5a) produces size groups that are almost correct around 33 mm, but this grouping is too wide and has relative numbers that are too high. The estimated size groupings below 29 mm and above 39 mm do not match anything in Figure 4. The truncated fluid-sphere model (Fig. 5b) produced a size grouping around 19 mm as do the biological samples. Any other features presented in Figure 4 are not reproduced. The fluid-sphere high-pass model (Fig. 5c) does not reproduce anything like the size distributions of Figure 4. The positioning of the size

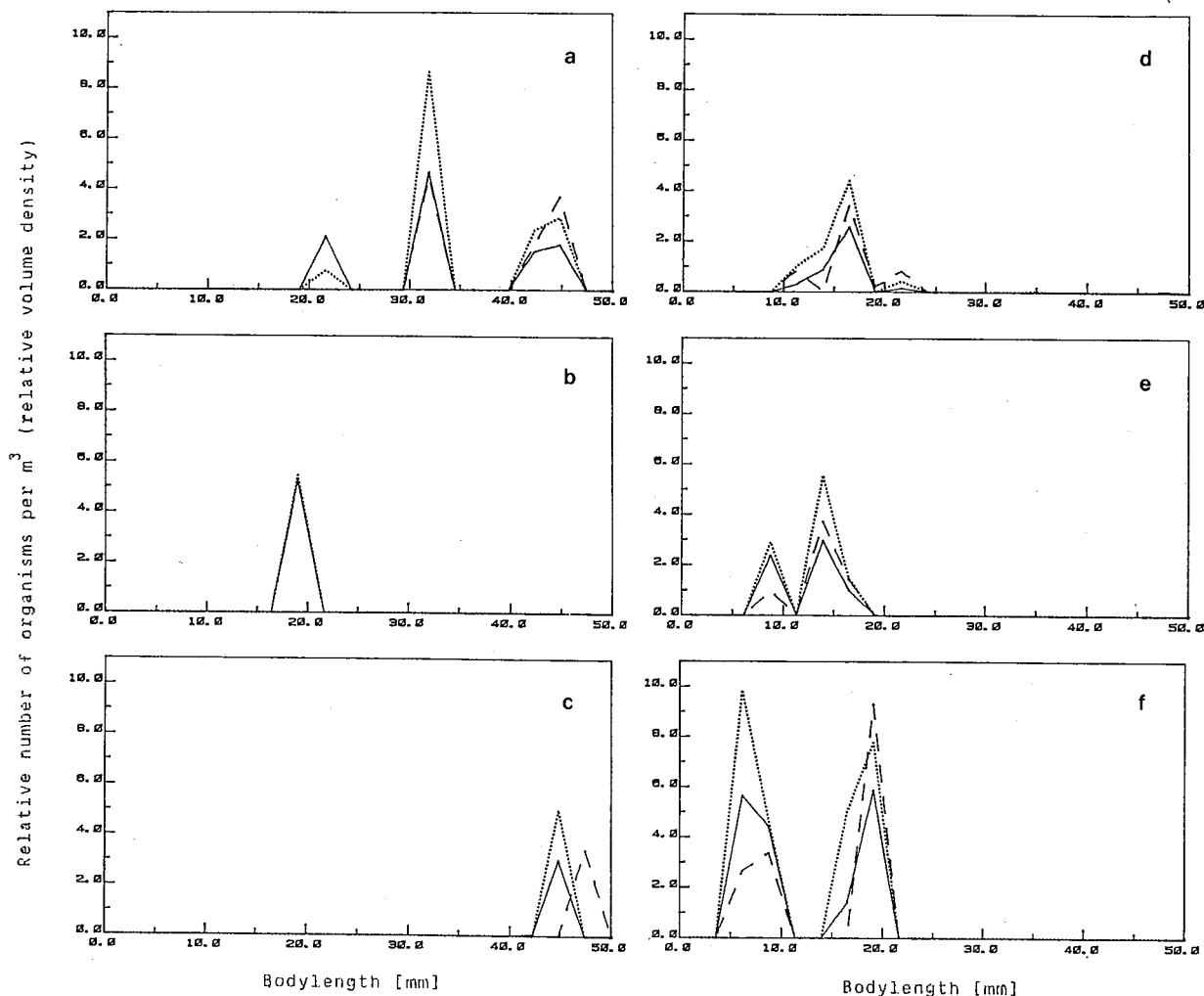


Figure 5. Acoustically estimated relative length-frequency distribution of euphausiids vs. bodylength from three depth intervals. — 50–57.5 m, 57.5–65.0 m, and ---- 65.0–72.5 m. a) The Anderson model, b) the Holliday and Pieper model, c) the Johnson model, d) the tuned complete Stanton model, e) the tuned truncated Stanton model, and f) the KRIDA model.

groupings is determined by the location of the transition region of this model and its constant and low level in the geometric scattering region.

Figures 5d-f present the estimated size distributions from the tuned fluid-cylinder models and the KRIDA model. The tuned complete Stanton model (Fig. 5d) produces size groupings from 9 to 24 mm, covering some of the same length groupings as the distribution displayed in Figure 4, but the relative length-group amplitudes are totally different. The estimates from the tuned truncated model (Fig. 5e) show two size groupings, one from 6 to 11 mm and the other from 11 to 19 mm, coinciding rather well with those of Figure 4, both in length-group positioning and relative length-group amplitudes. None of the tuned Stanton models reproduce the length groups around 33 mm.

The KRIDA model (Fig. 5f) reproduces the two major size groupings from 5 to 12 mm and from 13 to 21 mm, seen in Figure 4, rather well, although the length groups of the smaller organisms are shifted down by approximately 1 mm. The size groups around 33 mm are not reproduced by the KRIDA model.

Concerning the relative numbers of organisms per m^3 (i.e., the relative volume density) within each length grouping from the three depth intervals measured, we find that the relative volume densities differ between the depth intervals from the estimated distributions of all models except the Holliday and Pieper model. The depth-related particulars should represent different relative volume densities of krill within the three depth intervals; this was also confirmed qualitatively from the echograms of a 120 kHz echo sounder.

6. Conclusions

By means of six different acoustic scattering models representing individual zooplankters and *in situ* multi-frequency acoustic backscattering data from plankton aggregations, length distributions of krill were estimated by an inversion procedure. The models produced excellent-to-poor length distributions compared with the net- and trawl-sampled data.

The fluid bubble/fluid finite-length cylinder model (the KRIDA model) and the two fluid finite-length cylinder models (the complete and truncated STANTON models) were seen to be the superior ones.

Although the fluid-sphere models do not seem to be representative for the euphausiid species considered, they may well be suited to other zooplankton species more spherical in body shape, e.g., *Copepoda* spp., *Amphipoda* spp., *Ostracoda* spp., *Cladocera* spp., and *Gastropoda* spp. To improve our scattering models of euphausiids we need further development of finite-length cylinder models of arbitrary shapes. Likewise, we need more experimental field data to investigate the target strength vs. frequency, especially in the transition

region and in the high-frequency region to improve the empirical model, and for size estimation from corresponding acoustic and biological data on plankton communities.

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