ANNEX 6

REPORT OF THE FIRST MEETING OF THE SUBGROUP ON ACOUSTIC SURVEY AND ANALYSIS METHODS (SG-ASAM)

(La Jolla, USA, 31 May to 2 June 2005)

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BACKGROUND TO THE SUBGROUP

Introduction

The Subgroup on Acoustic Survey and Analysis Methods (SG-ASAM) met at the Southwest Fisheries Science Center in La Jolla, USA, from 31 May to 2 June 2005, following recommendations from WG-EMM (SC-CAMLR-XXIII, Annex 4, paragraphs 4.89 to 4.93), WG-FSA (SC-CAMLR-XXIII, Annex 5, paragraph 10.8) and SC-CAMLR (SC-CAMLR-XXIII, paragraph 13.5).

2. The terms of reference for this meeting were restricted to two issues relating to hydroacoustic surveys of *Euphausia superba* (Antarctic krill, hereafter 'krill'), namely:

(i) models of krill target strength (TS)
(ii) classification of volume backscattering strength (S_v).

3. The meeting was convened by Dr R. Hewitt (USA) and attended by Drs S. Conti (USA), D. Demer (USA), T. Jarvis (Australia), S. Kasatkina (Russia), R. Korneliussen (Norway), Mr Y. Takao (Japan) and Dr J. Watkins (UK).

4. The subgroup acknowledged the peer-reviewed publications and CCAMLR working papers by Drs Demer and Conti that formed the foundation for this meeting; this body of work was summarised by Dr Demer in a presentation at the start of the meeting.

History of the krill TS model currently endorsed by CCAMLR

5. Estimates of the pre-exploitation biomass (B_0) of krill in a given area have been derived from hydroacoustic surveys since FIBEX in 1981 (Trathan et al., 1992).

6. CCAMLR uses the estimate of B_0 to set a precautionary catch limit for the krill fishery by means of a yield model, with the current GYM (Constable and de la Mare, 1996) representing a development of the KYM first described in 1991 (Butterworth et al., 1991, 1994).

7. Target strength (TS, measured in dB re 1 m^2) is the factor used to scale hydroacoustic data (mean volume backscattering strength, S_v, measured in dB re 1 m^2) to biomass (areal biomass density, ρ, measured in g m^{-2}). Of the various contributing factors, estimates of B_0 from hydroacoustic data are thought to be most sensitive to the TS model used (Demer, 2004).

8. The krill TS model currently endorsed by CCAMLR is that of Greene et al. (1991), which is an empirically-derived linear regression model relating TS to log-length ($\log_{10}L$). The regression is based on empirical measurements of TS at 420 kHz made on 43 individuals

of ‘representative zooplanktonic and micronektonic taxa’ (not including *E. superba*) in a 30 m^3 enclosure (Wiebe et al., 1990). The ratio of acoustic wavenumbers ($10\log_{10}k_f / k_{420kHz}$, where $k = 2\pi f/c$) is used to transform the model to a different frequency (f) at a given sound speed (c).

9. Despite being corroborated with empirical data (Foote et al., 1990; Hewitt and Demer, 1991a, 1991b; Pauly and Penrose, 1997, 1998), and endorsed as an improvement over the previous BIOMASS TS model (SC-CAMLR-X, paragraph 3.34, and Annex 5, paragraph 4.30(i)), it has also been recognised from the outset that there are four main problems with the Greene et al. (1991) model when applied to krill:

(i) As Greene et al. (1991) themselves note, it is not applicable to the Rayleigh scattering regime, meaning that it will only be accurate for krill that are larger than the wavelength of the sound pulse (e.g. $\lambda 1_{20kHz}$ = 12.5 mm).

(ii) It does not account for changes in target morphology, physiology and orientation, all of which have been shown to significantly affect TS (Demer and Martin, 1994, 1995).

(iii) It was not actually derived from measurements of *E. superba* at 120 kHz, but rather from ‘representative zooplanktonic and micronektonic taxa’ at 420 kHz (Wiebe et al., 1990); the most similar species measured was *E. pacifica*.

(iv) It predicts that the TS of crustacean zooplankton is dependent on the animal’s volume, when it is actually thought to be dependent on its area (Demer and Martin, 1994, 1995).

10. When SC-CAMLR endorsed the original Greene et al. (1991) model, it also endorsed the recommendations of WG-Krill for future work (SC-CAMLR-X, paragraph 3.35, and Annex 5, paragraph 4.30(ii)), namely:

(i) *in situ* single animal TS measurements with dual- or split-beam echosounders;

(ii) *in situ* and experimental TS measurements of aggregations over a range of frequencies, animal lengths and physiological condition;

(iii) measurements of the morphology, orientation and physical condition of krill whenever possible;

(iv) theoretical modelling to predict the *in situ* distributions of individual TS, parameterised with available empirical data.

Development of a physics-based krill target strength model: the DWBA and the SDWBA

11. With reference to paragraph 10(iv), a physics-based TS model has been developed (DWBA: Morse and Ingard, 1968; Stanton et al., 1993, 1998; Chu et al., 1993a, 1993b;

McGehee et al., 1998, 1999) that represents an improvement to the Greene et al. (1991) model because it considers not just size, but all of the parameters that contribute to TS (Figure 1), namely:

(i) size, measured as the total length (*L* mm = anterior edge of eye to tip of telson, Morris et al., 1988);

(ii) shape, described as a series of *n* linked cylinders of radius *r* mm and length *l* mm;

(iii) material properties, described in terms of the density contrast (g) and sound-speed contrast (h) between the animal tissue and the surrounding seawater;

(iv) incidence angle of the acoustic wave relative to the longitudinal axis of the krill, referred to hereafter as orientation (θ, measured in degrees) and implemented as a Gaussian (normal) distribution of orientations ($\theta = N[\bar{\theta} = x°$, s.d. $= y°]$).

12. McGehee et al. (1998, 1999) empirically validated the DWBA model by making TS measurements of 14 live, loosely constrained individual krill at 120 kHz in a chilled tank. They obtained data over a range of orientations, finding a good fit[1] between empirical measurements and DWBA-model predictions when the sound impinged on the animal from a dorsal, ventral or lateral aspect (referred to by the authors as an incidence angle of 90°), but a poor fit at orientations away from 90° when predicted scattering was much less than that measured.

13. The poor fit between DWBA predictions and empirical measurements at orientations away from 90° were explained theoretically by Demer and Conti (2002a, 2003a, 2004a) using a modified DWBA model (the so-called ‘stochastic DWBA’, or SDWBA), which takes additional account of three stochastic parameters: (i) scattering in a field with noise, (ii) the complexity of krill shape, and (iii) the flexure of the body as it swims.

14. Demer and Conti (2002b, 2003b, 2004b) went on to validate the theoretical SDWBA model with empirical measurements of krill total TS (TTS). These measurements were obtained using a new technique (De Rosny and Roux, 2001) that permits good measurement accuracy and precision (Demer et al., 2003) and which is independent of both orientation and equipment calibration. TTS values were obtained over a broad range of frequencies (36–202 kHz) and a broad range of *L* (17–58 mm), and the SDWBA was solved for a krill ‘shape’ that was representative of the experimental animals. The empirical measurements agreed closely with the SDWBA-model predictions over the frequency range 60–202 kHz (‘to better than about 1 dB’); the empirical measurements at lower frequencies (36–60 kHz) were slightly higher than theory and the discrepancies were attributed to noise.

15. In a final step, Demer and Conti (2004c, 2005) applied the SDWBA to data from the CCAMLR-2000 Survey (Watkins et al., 2004) to explore the consequences of their new TS model to the overall estimate of B_0. Depending on the orientation distribution used, the original B_0 estimate of 44.3 million tonnes (CV 11.4%) was increased to as much as 192.4 million tonnes (CV 11.7%).

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[1] Note: The authors reported that the accuracy of the empirical orientation measurements was ±15°, which may help to explain the spread of the empirical points around the 90° peaks.

History of the S_v classification technique currently endorsed by CCAMLR

16. For hydroacoustic studies in general, early efforts to classify hydroacoustic data by taxon have typically relied on the subjective visual analysis of echograms combined with information from net catches if available (e.g. Yudanov, 1971; Forbes and Nakken, 1972; Jefferts et al., 1987; Rose and Legget, 1988; Richards et al., 1991). In the same way, the first official CCAMLR hydroacoustic survey to estimate krill B_0 (BROKE: Pauly et al., 2000) used 'interpretation aided by the catch data from target trawls' to filter the data used.

17. The subject of S_v classification was considered further for the second CCAMLR krill survey (CCAMLR-2000 Survey: Hewitt et al., 2004). At the post-survey 'B_0 Workshop' to analyse the data 'it was accepted that [the visual analysis technique] was very much dependent on operator skill and experience and was subject to considerable individual variation. The workshop agreed that a processing algorithm would offer a better approach by providing a formalised and objective method' (SC-CAMLR-XIX, Annex 4, Appendix G, paragraph 3.22). The technique agreed on is based on the dual-frequency dB-difference technique ($\Delta S_{v120-38kHz}$) described by Madureira et al. (1993a, 1993b) and further validated and refined by Watkins and Brierley (2002). This is an empirical technique, having been derived from field observations.

18. While additional developments of relevance to CCAMLR surveys have been made, such as the use of three-frequency algorithms to help further reduce the possibility of misclassification (e.g. Azzali et al., 2000; Hewitt et al., 2003), the CCAMLR-2000 Survey ΔS_v classification protocol remains as the currently endorsed technique by CCAMLR.

INFORMATION CONSOLIDATED BY THE SUBGROUP

TS models for krill

19. The subgroup recognised that there are a variety of parameters that influence TS (Figure 1), and that these were not all encompassed in the Greene et al. (1991) model.

20. Based on both paragraph 19 and an agreement that theoretical models have the capacity to encompass all of the relevant parameters implicated in TS, the subgroup endorsed the change in philosophy from the use of an empirical-only TS model (i.e. Greene et al., 1991) towards the use of theoretically-based, empirically-validated models.

21. The subgroup considered which type of theoretical TS model was most appropriate to use for krill:

(i) The Kirchoff-ray mode (KRM) model is used to quantify fish and zooplankton backscatter as a function of frequency, size (length) and orientation (e.g. Clay, 1992; Clay and Horne, 1994; Horne and Clay, 1998). However, this model is considered to be appropriate for targets with a strong density discontinuity; it is therefore appropriate for fish with swimbladders, but not for fluid-filled type organisms such as krill. Furthermore, it is not valid in the Rayleigh regime, nor at high orientation angles.

(ii) The subgroup recognised that the most comprehensive guidance to date on which type of theoretical model to use is contained in a review paper by Stanton and Chu (2000). This review recommended the use of the DWBA for krill, but predates the development of the SDWBA.

(iii) The subgroup agreed, based on the information available to them at the time, that the most appropriate theoretical model for krill TS was currently the SDWBA; however, the subgroup also agreed that the use of the SDWBA is subject to the caveats described below (paragraph 22).

22. Caveats on the use of the SDWBA:

(i) The SDWBA utilises multiple parameters (Figure 1). Since the range of values associated with each parameter is not well characterised, the subgroup recognised that determining the distributions of these parameters should be accorded a high priority.

(ii) The subgroup emphasised the importance of determining krill orientation distributions that are representative of those occurring under the ship during survey conditions.

(iii) The orientation distribution (θ = N[$\bar{\theta}$ = 15°, s.d. = 5°]) used in the published application of the SDWBA (Demer and Conti, 2005) was derived from the CCAMLR-2000 Survey data and has a potential for refinement. Another solution (θ = N[$\bar{\theta}$ = 11°, s.d. = 4°]) provides what may be an improved least squares fit to the CCAMLR-2000 Survey data (Demer and Conti, pers. comm.) but may imply that small krill at low densities have been underestimated (Figure 3). Alternatively, the implication may be an artefact of the analysis. This point needs to be investigated further.

(iv) The phase variability term of the SDWBA (φ) takes account of noise, complexity of shape and flexure of the body (Demer and Conti, 2003a). While these terms should ideally be individually characterised and used in the DWBA, this is not practical at present and the SWDBA offers a pragmatic solution.

S_v classification algorithms for krill

23. When employing the ΔS_v method for classifying krill, the subgroup recognised that there are two major types of misclassification that can occur: (i) non-krill targets classified as krill (hereafter 'acoustic by-catch'), and (ii) krill targets not classified as krill (hereafter 'acoustic bypass'). The effect of 'acoustic by-catch' will be to overestimate the biomass of krill, while the effect of 'acoustic bypass' will be to underestimate the biomass of krill. These two phenomena are not necessarily mutually exclusive.

24. The subgroup recognised that a variety of information and processing protocols can be used when attempting to classify S_v (Figure 2). These can be used either in isolation or, preferably, in conjunction with each other (see Horne, 2000 for a review). The subgroup also

recognised that combined approaches have the potential to reduce both acoustic by-catch and bypass. Further work on developing these techniques to make them suitable for adoption as standard CCAMLR techniques was encouraged.

25. The subgroup recognised that, for CCAMLR applications, classification has typically been implemented using SonarData Echoview software. However, it was also recognised that there are a variety of other software packages in which classification of volume backscatter has been implemented. Two such packages that were described by Dr Korneliussen at the meeting are given below:

(i) Korneliussen and Ona (2002, 2003, 2004a, 2004b) have described S_v classification techniques used in the Bergen Echo Integrator (BEI) software. Acoustic backscatter of marine organisms is divided into one, or a combination of, three fundamental scattering classes: (i) 'fluid-like', (ii) 'resonant', and (iii) 'hard'. Each of these scattering classes is described by the relative frequency response, $r(f) = s_v(f)/s_v(38 \text{ kHz})$. $r(f)$ measured over all available acoustic frequencies is the main acoustic feature used by the BEI when the acoustic component of the separator algorithms is established; other features such as depth, time and position are also used if the acoustic category is identical to a single species. Smoothed, noise-corrected and geometry-adjusted multi-frequency data-points are used as input to the categorisation system to discriminate between the acoustic categories. In Stage-1 of the BEI categorisation system, strong model-based or empirical requirements must be fulfilled by a multi-frequency data-point in order to put the corresponding volume-segment (pixel) into one of the specific acoustic target categories. The acoustic requirements on the data-point become weaker for each of the categorisation stages, but the requirement of belonging to the same category as the nearest neighbours (found in previous stage) are strengthened.

(ii) Lebourges-Dhaussy (1996), Lebourges-Dhaussy and Ballé-Béganton (2004) and Lebourges-Dhaussy et al. (2004) have described a multi-frequency, multiple model method implemented in Matlab and MOVIES software that is capable of classifying S_v by species and size. This method is based on the algorithm described by Holliday and Pieper (1995) for the classification of small zooplankton using high frequencies. The use of lower frequencies allows for classification of larger organisms. The data used are the S_v values at each available frequency. The method is based on the NNLS inversion algorithm, applied to a system of equations with as many equations as there are measured frequencies. A set of backscattering models is used to describe copepods, euphausiids and gas-filled organisms. In order to classify the organisms figuring in a sample, the algorithm looks for the optimal population (type, sizes and abundances) that minimises the residual error between the S_v measured and S_v calculated using the corresponding backscattering model. The algorithm yields a lower level of success when the number of frequencies decreases. The range of the size vector initialising the algorithm with respect to the sizes actually present in the population has been found to be an important parameter.

26. The subgroup recognised that with the adoption of a physics-based model for TS it would also be possible to derive theoretical backscattering spectra that can be used to improve classification of krill currently derived from empirical observations.

RECOMMENDATIONS OF THE SUBGROUP

Implementing the SDWBA for general use

27. The subgroup recommended that the SDWBA be used to estimate krill TS (see paragraphs 20 and 21(iii)).

28. The subgroup recommended the use of a 'simplified SDWBA' with constrained parameters to generate a 'base case' estimate of B_0 for CCAMLR acoustic surveys for krill.

29. The subgroup recommended also making the full SDWBA available, and encouraged researchers to work towards both improving the model and characterisation of the parameters, and assessing the implications for estimates of B_0. Drs Demer and Conti agreed to work with the Secretariat to make the source code available to all Members.

Characterising the parameters and running the simplified SDWBA

30. The subgroup recommended that the model parameters (Figure 1) be considered as probabilistic as opposed to deterministic. That is to say, one should characterise them as a probability density function (PDF) rather than as a single value (e.g. the mean).

31. The subgroup recognised that the use of a probabilistic model implies that there is uncertainty associated with the input parameters, and that this uncertainty must be accounted for in estimates of TS and hence B_0.

32. The subgroup considered how to implement a probabilistic approach into the model:

(i) It was agreed that the most comprehensive method would be to use the full PDF for each parameter to estimate TS and its variability; this could be performed by applying either a bootstrapping analysis or a Monte Carlo simulation.

(ii) However, it was also recognised that not only is this comprehensive approach computationally extensive, but that also there is insufficient empirical information at present with which to characterise the PDF of any of the parameters with any degree of confidence.

(iii) As a compromise, it was therefore agreed to consider each parameter in terms of its mean value ±1 standard deviation.

33. The final values chosen to parameterise the simplified SDWBA are given in Table 1. The details of the implementation of the simplified SDWBA using these parameters are given in the appendix. The reasons for choosing these values are considered in turn as follows:

(i) Orientation (θ): The subgroup deemed this to be the most objective information available at present (see paragraph 22(iii) and Figure 3).

(ii) Density contrast (g) and sound-speed contrast (h): These values were both taken from Foote (1990) because they were already implemented in the SDWBA computer code (Demer and Conti, 2003a, after McGehee et al., 1998), and because time precluded consideration of other measurements (e.g. Chu and Wiebe, 2005; Takao, pers. comm.).

(iii) Shape ('fatness coefficient'): The subgroup agreed that the starved krill described by McGehee et al. (1998) would represent a fair approximation of a minimum 'fatness' value. The maximum value was empirically obtained from a photograph of a gravid female during the meeting (Demer, pers. comm.). As a value that lay between the chosen minimum and maximum, the subgroup agreed that the '40% fatter' shape described by Demer and Conti (2005) would represent a fair approximation of a median value.

(iv) Speed of sound in water (c): The weighted harmonic mean calculated by Demer (2004) for the CCAMLR-2000 Survey covered the full range of environments that krill are likely to encounter in Southern Ocean; the subgroup therefore agreed that this was an appropriate value to use.

34. The outputs of the subgroup's agreed run of the constrained, simplified SDWBA are shown graphically in Figure 4 (krill TS as a function of L at 38, 70, 120 and 200 kHz), Figure 5 (krill TS as a function of θ at 38, 70, 120 and 200 kHz) and Figure 6 (krill ΔS_v as a function of L for three dual-frequency scenarios).

35. Figure 4 implies that there is a large range of uncertainty in TS (and hence B_0), and that this range is both frequency and length dependent. This can be illustrated at f = 120 kHz for two different values of L: (i) where L = 25 mm, SDWBA-predicted krill TS ranges from –88 to –73 dB (range = 15 dB); (ii) where L = 50 mm, SDWBA-predicted TS ranges from –77 to –71 dB (range = 6 dB). The subgroup recommended that this uncertainty should be incorporated into estimates of krill TS and hence B_0.

S_v classification algorithms

36. The subgroup agreed that, for the time being, the ΔS_v technique continues to represent the most objective and pragmatic technique for classifying S_v by taxon.

37. The subgroup agreed that when using the ΔS_v technique, acoustic by-catch and bypass should be minimised by constraining the ΔS_v windows to the size range of krill measured in the survey area. To facilitate this step, the subgroup calculated the minimum and maximum ΔS_v values for different size ranges of krill using the constrained, simplified SDWBA model (Table 3).

Recommendations for further research relating to TS models and S_v classification

38. The subgroup emphasised the importance of understanding the orientation distribution, sound speed contrast, density contrast and animal shape for krill under the surveying vessel. The subgroup encouraged further work on these topics as a high priority.

39. The subgroup recognised that the use of 70 kHz transducers should improve krill detection, classification, and estimation of B_0 (Furusawa et al., 1994; Korneliussen, pers. comm.; Demer, pers. comm.), and recommended their use during krill surveys whenever possible.

SUMMARY

40. With respect to the issues considered during this meeting (paragraph 2), the subgroup recommended for CCAMLR hydroacoustic surveys to estimate krill B_0 that:

(i) the simplified SDWBA model (appendix equation 10; Table 2) with constrained parameters (Table 1) be used to define krill TS as a function of L at a given f (Figure 4);

(ii) the minimum and maximum TS values shown in Figure 4 should be used as a first estimate of the error associated with krill TS;

(iii) the classification of S_v to filter out non-krill targets should be undertaken using the ΔS_v technique, with the ΔS_v windows constrained for the appropriate size range of krill as specified in Table 3.

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Table 1: The range of parameter values used in the constrained, simplified SDWBA model to estimate error in the prediction of krill TS, where frequency (f_0) = 120 kHz, number of cylinders (n_0) = 14, krill length (L_0) = 38.35 mm and phase variability (φ_0) = $^{\sqrt{2}}/_2$.

	–1 s.d. (scenario 1)	Mean (scenario 2)	+1 s.d. (scenario 3)
Radius of cylinders (r_0 multiplier: see text)	1.0	1.4	1.7
Density contrast (g: after Foote, 1990)	1.0290	1.0357	1.0424
Sound speed contrast (h: after Foote, 1990)	1.0255	1.0279	1.0303
Orientation ($\bar{\theta}$, s.d.: Demer and Conti, pers. comm.)	N(7, 4)	N(11, 4)	N(15, 4)
Sound velocity in water (c m s^{-1}: after Demer, 2004)	1451	1456	1461

Table 2: Coefficients and reference length (L_0) for the simplified SDWBA model of krill TS (appendix equation 10), averaged over the krill orientation distribution (θ = N[$\bar{\theta}$ = 11°, s.d. = 4°]). Exponential notation ($\times 10^x$) is denoted by ''e±x''. The simplified model has an rms error of 0.75 dB over this range of kL.

A	6.64558746e+000
B	1.27909076e-001
C	4.46318146e-001
D	-1.19209591e-011
E	7.42324712e-009
F	-1.73916236e-006
G	1.86327198e-004
H	-8.67465215e-003
I	1.32140873e-001
J	-8.09830343e+001
L_0	38.35e-003 m

Table 3: The recommended ranges (min–max) of ΔS_v values (in dB) to use to classify different size distributions of krill on hydroacoustic echograms. The values shown on the upper, middle and lower lines of each cell represent the ΔS_v ranges for 120–38 kHz, 200–120 kHz and 200–38 kHz respectively. These values are based on constrained, simplified SDWBA calculations made for an orientation distribution of (θ = N[$\bar{\theta}$ = 11°, s.d. = 4°]).

Minimum krill length (mm)	Maximum krill length (mm)			
	30	40	50	60
10	11.1–17.7 0.4–6.8 11.5–24.5	7.7–17.7 -0.3–6.8 7.4–24.5	4.6–17.7 -0.5–6.8 4.1–24.5	2.5–17.7 -0.5–6.8 2–24.5
20	11.1–14.7 0.4–2.1 11.5–16.8	7.7–14.7 -0.3–2.1 7.4–16.8	4.6–14.7 -0.5–2.1 4.1–16.8	2.5–14.7 -0.5–2.1 2–16.8
30	- - -	7.7–11.1 -0.3–0.4 7.4–11.5	4.6–11.1 -0.5–0.4 4.1–11.5	2.5–11.1 -0.5–0.4 2–11.5
40	- - -	- - -	4.6–7.7 -0.5– -0.3 4.1–7.4	2.5–7.7 -0.5– -0.3 2–7.4

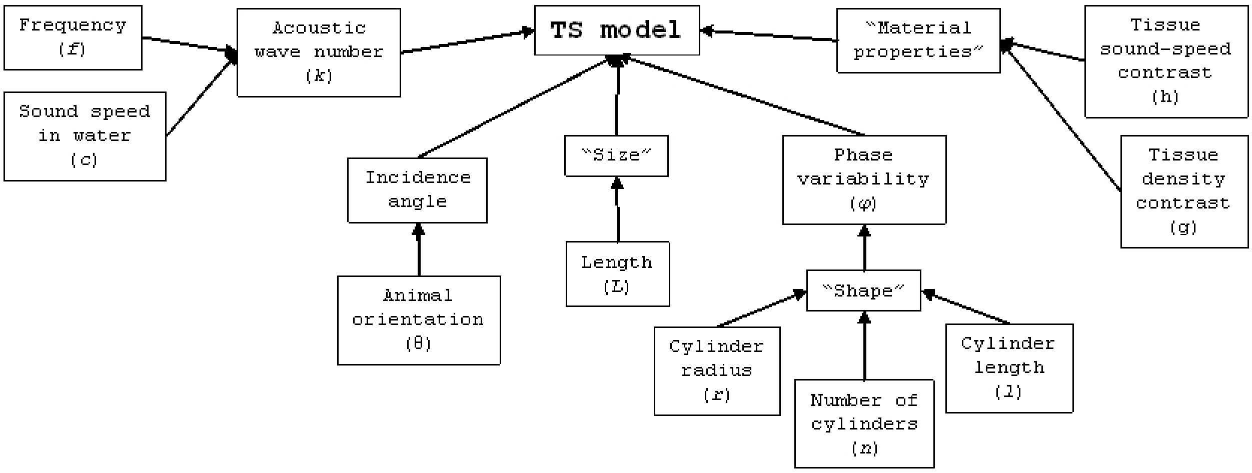

Figure 1: The relationships of the parameters that contribute to the target strength of Antarctic krill. Note, this is a simplified approximation and does not account for co-dependencies.

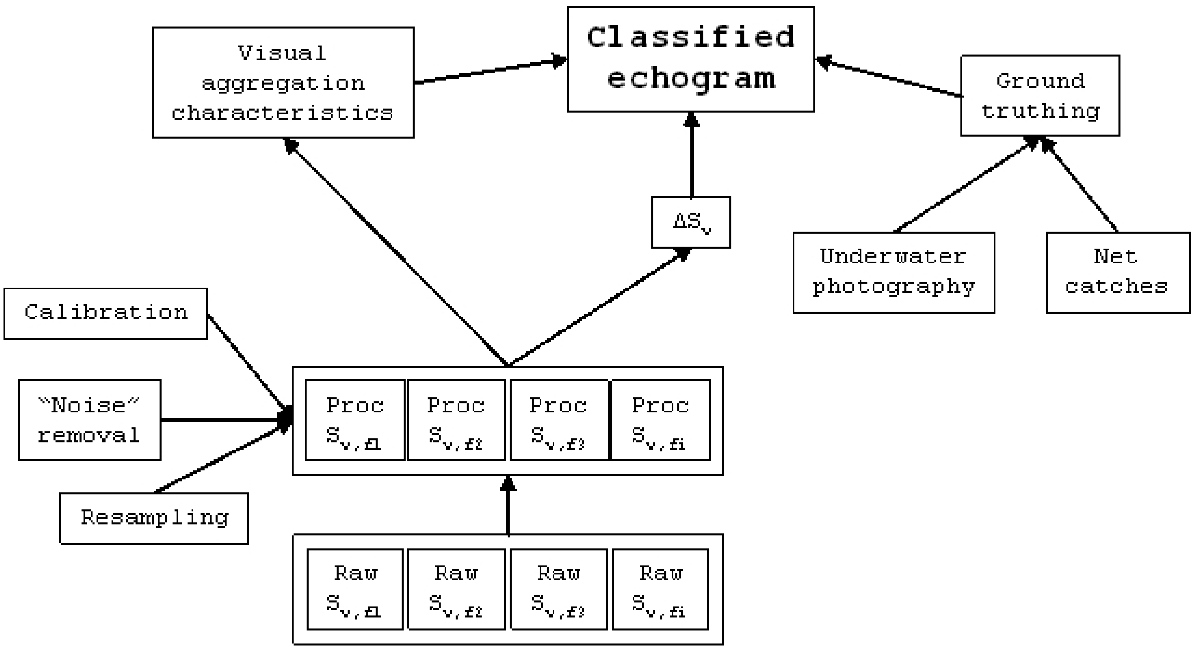

Figure 2: The relationships of the generalised information and procedure categories that are currently available for classifying S_v data by taxon. Proc – processed S_v data.

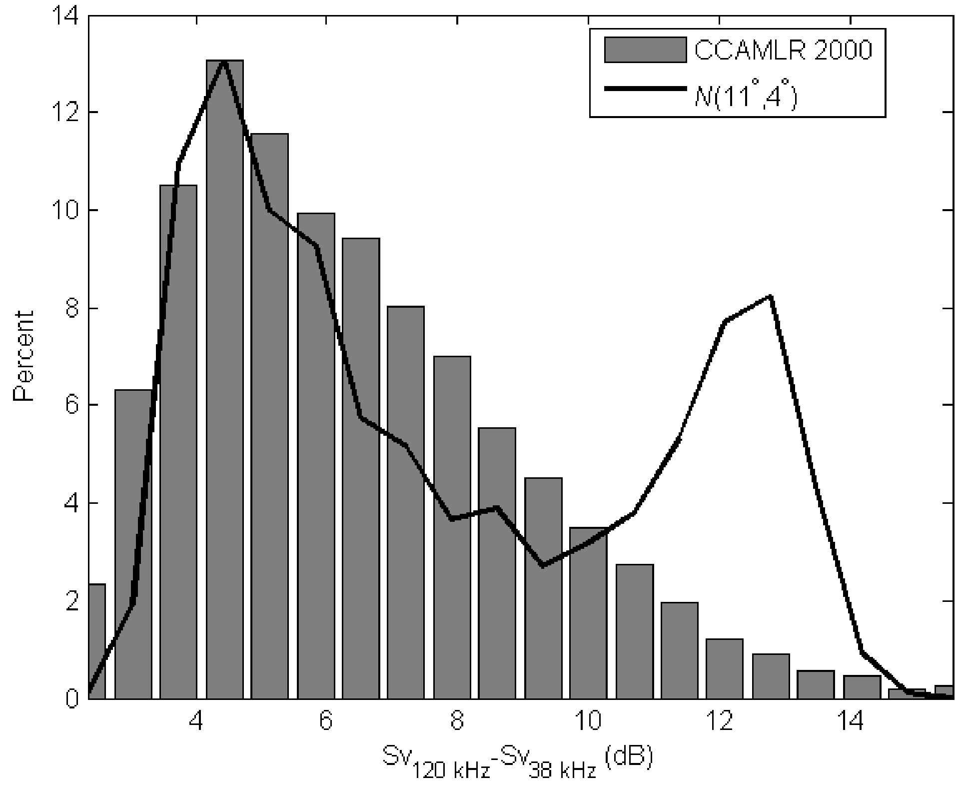

Figure 3: The differences in volume-backscattering strengths (ΔS_v) attributed to krill at 120 and 38 kHz measured from RV *Yuzhmorgeologiya* during the CCAMLR-2000 Survey (grey bars), compared to predictions from the SDWBA model solved with the CCAMLR-2000 krill length-frequency distribution and the (θ = N[$\bar{\theta}$ = 11°, s.d. = 4°]) krill-orientation distribution (black line).

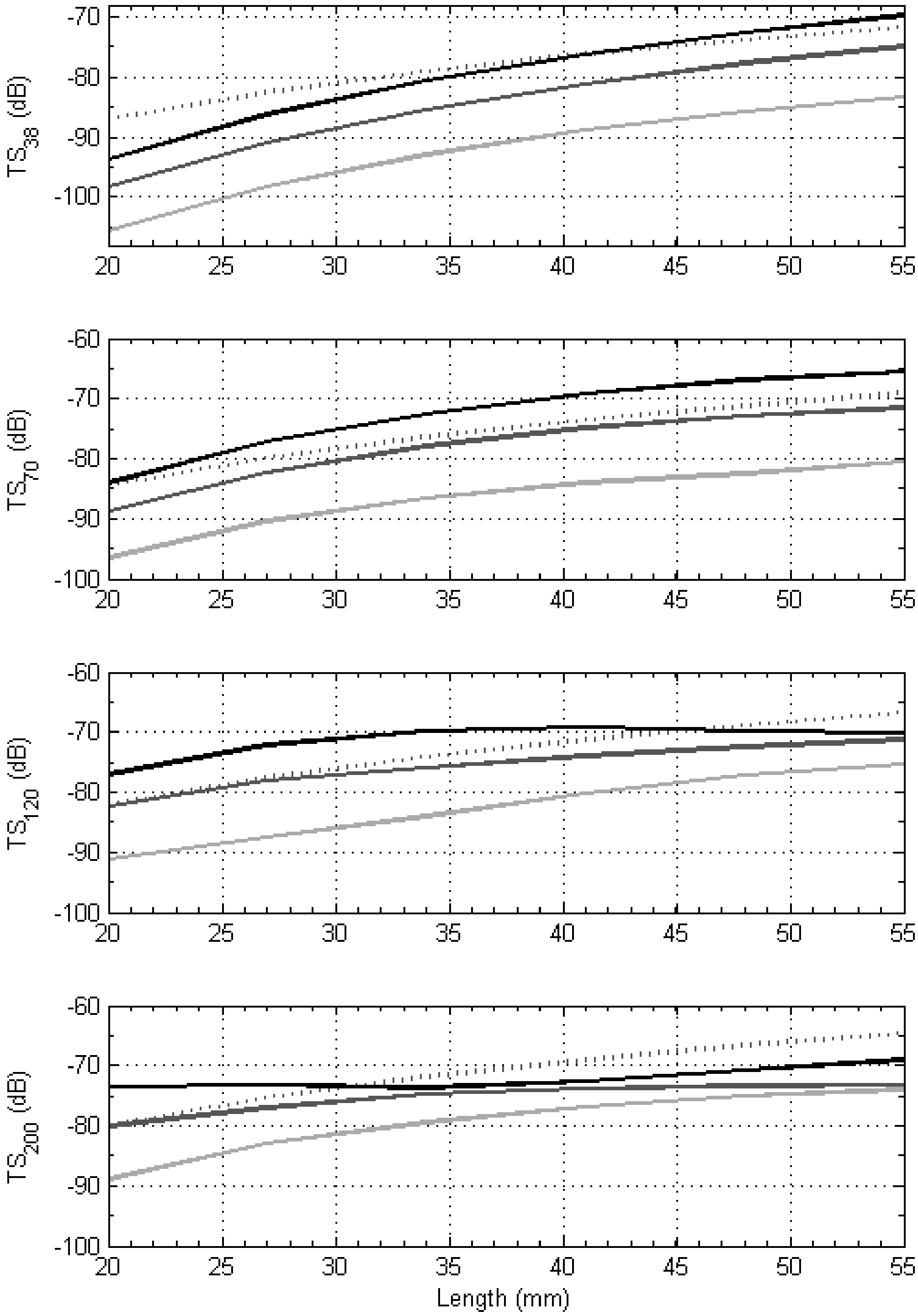

Figure 4: Constrained, simplified SDWBA-predicted TS as a function of *L* at 38, 70, 120, and 200 kHz. Model parameters are from Table 1 for scenarios 1 (solid light), 2 (solid grey) and 3 (solid dark). The dashed line corresponds to the predictions for Greene et al. (1991).

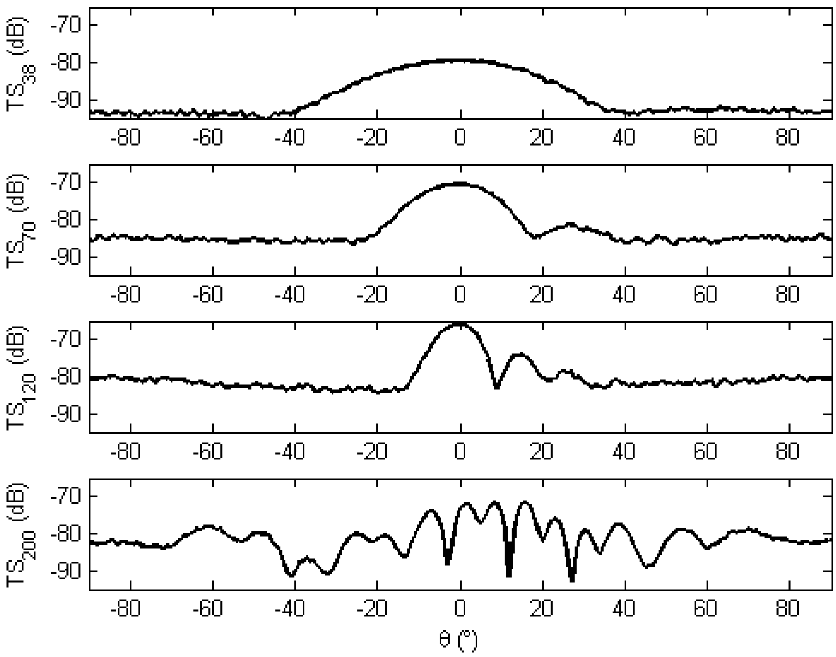

Figure 5: Constrained, simplified SDWBA-predicted TS as a function of orientation angle at 38, 70, 120 and 200 kHz. Model parameters are from Table 1 scenario 2.

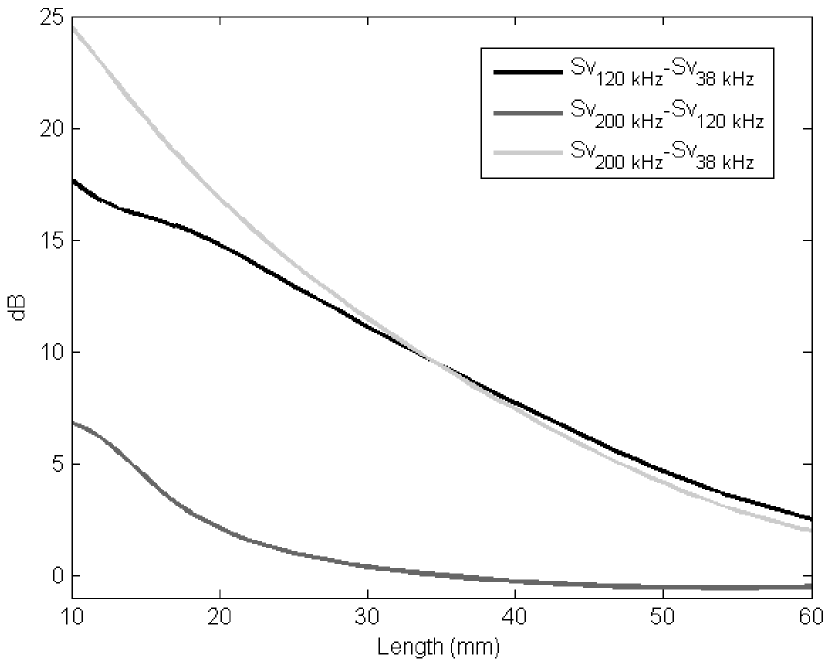

Figure 6: Differences in constrained, simplified SDWBA-predicted S_v at 200, 120, and 38 kHz as a function of *L*. These relationships may be used for minimising acoustic by-catch and bypass (see Table 3).

APPENDIX

THE STOCHASTIC DISTORTED-WAVE BORN APPROXIMATION (SDWBA) MODEL

Krill is approximated by N discretised-bent cylinders of various radii a_j. In that case, the backscattering form function for the cylinder j and incident angle θ is:

$$f_{bs\,j}(\theta)=\frac{k_1}{4}\int\left[\gamma_\kappa-\gamma_\rho\right]\exp\left(-2i\vec{k}_i\vec{r}_0\right)\frac{a_j J_1\left(2k_2 a_j\cos\beta_{tilt}\right)}{\cos\beta_{tilt}}dr_0 \tag{1}$$

where $\gamma_\kappa=\left(\rho_1 c_1^2/\rho_2 c_2^2\right)-1$, $\gamma_\rho=\left(\rho_2-\rho_1\right)/\rho_2$, the subscript 1 denotes the ambient seawater, and 2 the krill. J_1 is the Bessel function of first kind of order 1, $\vec{r}_0$ the position vector, $\vec{k}_i=k_1\begin{bmatrix}\sin\theta\\0\\\cos\theta\end{bmatrix}$ the incidence wave vector, and β_{tilt} the angle between the cylinder and the central axis of the body. The form function for the SDWBA is obtained by summing the components from each cylinders with a different random phase φ_j:

$$f_{bs}(\theta)=\sum_{j=1}^{N}f_{bs\,j}(\theta)\exp\left(i\varphi_j\right) \tag{2}$$

The phase variability φ_j is obtained from a Gaussian distribution centered on 0, with standard deviation sd_φ, for each cylinder j along the body. Finally, the backscattering cross section $\sigma_{bs}(\theta)$ is obtained from the average of multiple realisations of the ensembles of phase φ_j:

$$\sigma_{bs}(\theta)=\left\langle\left|f_{bs}(\theta)\right|^2\right\rangle_\varphi, \tag{3}$$

and

$$TS(\theta)=10\log_{10}\left(\sigma_{bs}(\theta)\right). \tag{4}$$

The generic krill shape was defined by McGehee et al. (1998, standard length L_0 = 38.35 mm). The width of the generic shape was increased by 40% in Demer and Conti (2003a), because freshly caught animals were found to be fatter than the starved animals measured by McGehee et al. (1998). At $f_0=120$ kHz, and using $N_0=14$ cylinders, $sd_{\varphi 0}$ was estimated to be $\sqrt{2}/2$ radians from comparison of the SDWBA predictions to the experimental measurements. Because the factors *N*, sd_φ, *f* and *L* are co-dependent in their effects on the SDWBA results, $sd_\varphi(f)f$ was held constant,

$$sd_\varphi(f)f = sd_{\varphi 0}f_0 . \tag{5}$$

Similarly, as *f* and *L* were modified, *N* was also adjusted so that the spatial resolution of the body of the krill remained constant relative to the wavelength. Therefore, the ratio between the wavelength λ and the length of each individual cylinder was held constant:

$$\frac{L}{N\lambda} = \frac{L_0}{N_0\lambda_0} \tag{6}$$

or

$$\frac{Lf}{N} = \frac{L_0 f_0}{N_0} . \tag{7}$$

From Equations (5) and (7):

$$N(f,L) = N_0 \frac{fL}{f_0 L_0} \tag{8}$$

and

$$sd_\varphi(f,L) = sd_{\varphi 0}\frac{N_0 L}{N(f,L)L_0} . \tag{9}$$

Thus, sd_φ and *N* were adjusted to the desired *L* and *f*. TS was estimated versus *L* at *f* = 38, 70, 120 and 200 kHz (Figure 4) by solving the SDWBA with a generic fat krill shape, and adjusting *N* and sd_φ according to Equations (8) and (9). The parameters are summarised in Table 1.

The SDWBA *TS* predictions are concisely expressed as a function of the product of the acoustic wave number $k=(2\pi/\lambda)$ and *L*. Averaging this function over a normal distribution (θ = N[$\bar{\theta} = x°$, s.d. = $y°$]) of krill orientations, Demer and Conti (2005) presented a simplified or polynomial representation of the *TS*(*kL*) function:

$$\begin{aligned} TS(kL) = {} & A\left[\frac{\log_{10}(BkL)}{BkL}\right]^C + D(kL)^6 + E(kL)^5 + F(kL)^4 \\ & + G(kL)^3 + H(kL)^2 + I(kL) + J + 20\log_{10}\left(\frac{L}{L_0}\right) . \end{aligned} \tag{10}$$

New parameters for this model were generated using the parameters in Table 2, and kL ranging from 0 to 200, for (θ = N[$\bar{\theta}$ = 11°, s.d. = 4°]) (Table 1). The average rms error over this range of kL is 0.75 dB.

The (θ = N[$\bar{\theta}$ = 11°, s.d. = 4°]) distribution of orientation was estimated using the CCAMLR 2000 data. The S_v differences between 120 and 38 kHz measured during the survey was compared to the predicted values using the model and the distribution of length measured during the survey (Figure 3). Using a least mean square optimisation with mean and standard deviation of the orientation between 0° to 25° and 1° to 30° respectively, the best fit was obtained for (θ = N[$\bar{\theta}$ = 11°, s.d. = 4°]).