Covariance Mean Variance Classification (CMVC) techniques: Application to the acoustic classification of zooplankton

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Abstract: The Covariance Mean Variance Classification (CMVC) techniques classify broadband echoes from individual zooplankton based on comparisons of observed echo spectra to model space realisations. These classifiers assign observations to a class based on similarities in covariance, mean, and variance, while accounting for model space ambiguity and validity. The CMVC techniques were applied to echoes from 18 individuals to invert for scatterer class. They were also applied to echoes from 11 euphausiids to invert for angle of orientation using both theoretical and empirical model spaces.

To make accurate estimates of zooplankton biomass from acoustic backscatter measurements of the ocean, the acoustic characteristics of the species of interest must be well-understood. Work on the forward problem in zooplankton bioacoustics has resulted in the identification of three classes of acoustic scatterers (1): ES (elastic-shelled, e.g. pteropods), FL (fluid-like, e.g. euphausiids), and GB (gas-bearing, e.g. siphonophores). The relationship between backscattered energy and animal biomass has been shown to vary by a factor of ~19,000 across these categories (1), and variations in zooplankton characteristics (e.g. orientation, size, etc.) within a category also affect echo energy levels significantly. Feature based (2) and model based (2,3) classification schemes have been developed to invert broadband echoes from individual zooplankton for scatterer type as well as for particular parameters such as animal orientation (4).

THE CMVC APPROACH

The Covariance Mean Variance Classification (CMVC) techniques are a suite of model-based classifiers which invert the frequency spectrum of an acoustic return resulting from the broadband (~350-750 kHz) insonification of an individual zooplankter (echo spectra) for scatterer class and/or animal characteristics (e.g. orientation). An observed echo spectrum may be assigned to a class based on a global maximum "best match", which reveals the theoretical model (and associated parameter values) which best predicts the observation. Alternatively, a certainty score or probability for each class may be computed based on a subset of sub-optimal matches (local maxima); an observed echo spectrum may then be assigned to the class with the highest score/probability. All the CMVC techniques incorporate a model space for each class, a means to account for the redundancy, ambiguity, and validity of these model spaces, and a CMV metric to measure correspondence between the observations and the model spaces.

The model space for each class consists of model realisations representing predictions of a theoretical scattering model for particular parameter values spanning the entire parameter space. A ray-based model, including contributions from a direct return and a circumferential wave, is used to describe the scattering for the ES class (5). Members of the FL class are modeled as weakly scattering deformed cylinders (5) based on the distorted wave Born approximation (DWBA), which includes orientation as a parameter. The GB class is represented by a spherical gas bubble plus fluid-like tissue ray model adapted from (5). A model space may contain redundancy if different combinations of parameter values predict similar or virtually identical model realisations; this redundancy is removed from the model spaces via a redundancy weighting function. Ambiguity between model spaces can arise if the theoretical model for a particular class predicts model realisations which are similar or identical to model realisations predicted by the theoretical model for another class, and is accounted for with the ambiguity weighting function $W_A$. The validity of theoretical models in predicting known data is quantified with the validity weighting function $W_V$; observed echo spectra may resemble some model realisations frequently, whereas other model realisations are scarcely observed in real data.

The CMV metric is defined as $C = CMV(M, D) = K \cdot X - U$, where "\cdot" indicates element-wise multiplication of matrices. This metric quantifies the correspondence between observed echo spectra (D) and model realisations in the model space (M) based on their covariance ($K = D^T M$, which compares their spectral structure), weighted by the similarity of mean echo levels (X) and the variance similarity (U). Three distinct classification techniques have been developed using the CMVC approach; the Integrated Score Classifier (ISC), the Pairwise Score Classifier (PSC) and the Bayesian Probability Classifier (BPC). Although they are based on the same CMV metric, the means by which the ambiguity and validity weighting functions $W_A$ and $W_V$ are calculated differs between classifiers.
CMVC PERFORMANCE

The ability of the CMVC techniques to invert for scatterer class was evaluated with 775 experimentally collected echoes from 18 different individuals (Figure 1). PSC classifications based on the global maximum best match model realisation were best overall. The PSC also performed better than the ISC and BPC when classifying based on the maximum score. PSC performance improved considerably when $W_A$ and $W_V$ were included in the classification.

![Classification results (% correct) for n=200 pteropod (L. retroversa) echoes, n=350 euphausiid (M. norvegica) echoes, and n=225 siphonophore (A. okeni) echoes. Results based on assigning observations to class with maximum score (max $S$) shown at left; those based on assigning echoes to class with the best match model realisation (max $C$) shown at right. ISC and PSC implemented with (+W) and without (-W) $W_A$ and $W_V$. BPC implemented with TYPE I and TYPE II probability mass functions.

The best match (max $C$) PSC was implemented to invert 5200 echoes from 11 fluid-like Antarctic krill for animal orientation. Experiments involved simultaneous acquisition of broadband echoes and video footage from each krill. Orientation corresponding to each insonification was extracted with a novel video analysis technique. These orientations were compared to inversion results obtained using theoretical and empirical model spaces (Figure 2). The empirical model space was better able to invert for angle of orientation than was the theoretical model space.

![Bin-averaged (over 5 echoes) inversion results for krill 03 using the PSC (max $C$) with theoretical (left; based on the DWBA) and empirical (right) model spaces, assuming symmetry about 90°. Observed orientation $\varphi$ (solid line) shown along with inversion results (points); 45° dashed line in scatter plot indicates perfect agreement between inversion results and observations.

Application of CMVC inversion techniques in situ will allow more correct apportionment of backscattered energy to animal biomass, thereby significantly improving estimates of zooplankton biomass based on acoustic surveys.

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