Characterisation of aggregated Baltic herring - technique for assessment of possible vessel avoidance reaction

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Abstract: *The orientation of herring individuals significantly influences their backscattering properties, which are crucial for accurate hydroacoustic biomass assessments. Vessel-induced avoidance reactions may alter fish orientation distributions during biomass measurements, as observed in many species. However, according to our best knowledge, there is a gap in information regarding the orientation of aggregated Baltic herring as well as its reaction on the approaching vessel during the biomass estimation campaigns.*

To address this gap, we developed an inverse method for assessing the orientation of aggregated Baltic herring. The method compares histograms of herring target strength (TS) obtained numerically for the different fish orientation distributions with TS data collected during routine hydroacoustic biomass assessments in the frame of Baltic International Acoustic Survey (BIAS) cruises. This technique incorporates a novel backscattering model, improving the accuracy of backscattering predictions for Baltic herring. The orientation distributions for herring escaping from the vessel during the herring biomass estimation have been defined. The approach provides a more detailed interpretation of acoustic data, facilitates the characterization of Baltic herring, and enables the assessment of herring responses to passing research vessels.

Keywords: *Target Strength, fish orientation, Baltic Herring.*

1. INTRODUCTION

The realibility of hydroacoustic biomass assessments of Baltic herring (*Clupea harengus*) depends on the accuracy of the used fish target strength (TS) [1], which strongly depends on fish orientation [1 - 3]. Avoidance behavior in response to approaching vessels can alter orientation distributions, potentially biasing biomass estimates [4,5]. Despite its importance, orientation of aggregated Baltic herring is not taken into account during standard acoustic surveys, Baltic International Acoustic Survey (BIAS), carried out every year as the initiative of International Council for the Exploration of the Sea (ICES).

To address this gap, we developed an indirect inverse method to estimate Baltic herring orientation distributions using routine hydroacoustic data [6]. Unlike the existing techniques, this method is low-cost and does not require complex equipment or data collection procedures as well as sophisticated data analysis.

Our approach compares TS histograms from BIAS empirical data with simulated TS distributions generated under various orientation scenarios. In [6] the unimodal herring orientation distribution was considered as the scenario. In this paper the two-modal herring orientation distribution were used and the comparison with the previous approach was done.

2. METHOD

In order to estimate the herring orientation distribution, an algorithm developed in Żytko et al. (2025) [6] was used. The algorithm is described in detail in the publication so below we present only its main idea.

The algorithm is based on comparing the measured TS distributions with the synthetic TS distributions generated for herring aggregations characterized by different orientation distributions. For the TS calculations used in this algorithm, a modified backscattering model was developed that does not have the limitations of the previously used models [6]. The model extended the scope of application of the prolate spheroid resonance model [7] for Baltic herring to the transitional region so as to be in agreement with the Kirchoff approximation. The algorithm is applied to the individual hauls made during the BIAS cruises using biological and TS data collected for each haul.

2.1. Synthetic TS histograms

To estimate the orientation of the herring the numerical TS histograms should be generated for the considered haul. For this, firstly a herring aggregations were generated numerically. In aggregation, each individual was characterized by parameters such as fish length, depth of occurrence, and orientation angle θ (defined as the angle between the fish's longitudinal body axis and the horizontal plane). The herring total length distribution was taken for the selected haul. The fish distribution over the depth was obtained from the echogram corresponding to this haul. For each haul, 100 realizations of the aggregation were generated.

In opposite to the approach presented in [6], two types of herring orientation distributions were considered: unimodal (we use the name “unimodal” for this approach) and bimodal (bimodal approach is used below to define this approach). The Gaussian unimodal orientation distribution was assumed:

$$\Phi(\theta) = \frac{1}{s_{\theta\sqrt{2\pi}}} e^{\left(\frac{-(\theta-\bar{\theta})^2}{2s_{\theta}^2}\right)}, \tag{1}$$

where $\bar{\theta}$ – mean orientation angle and s_{θ} – standard deviation. positive angle indicates the position of the fish with its head up, and negative angle for its head down.
Bimodal orientation distributions, composed of two Gaussian components, were described by five parameters: the mean angles and standard deviations of each component, as well as the proportion of the population belonging to the first component. The mean orientation angles varied within the range from –40 ° to 0°, and the standard deviations ranged from 3° to 15°.

2.2. Comparing measure and numerical TS distributions

Modeled TS distributions were computed for various herring orientation distribution parameters and stored as a multidimensional matrix. For the unimodal approach, the matrix was two-dimensional, with dimensions corresponding to the varying mean orientation angle and standard deviation. In the case of the bimodal approach, the matrix was five-dimensional, accounting for two mean angles, two standard deviations, and the proportion between the two modes.

For each haul, the modeled TS distributions were compared to the measured TS distribution using χ^2 test [8]. The modeled TS distribution with the smallest χ^2 distance was considered the most similar to the measured TS distribution, and the corresponding orientation distribution was therefore assumed to be the most likely.

2.3. Data

The acoustic and biological data used in the algorithm were collected during the annual BIAS cruises, conducted by the National Marine Fisheries Research Institute (NMFRI) in Gdynia, aboard the R/V *Baltica* within the Polish Exclusive Economic Zone. Specifically, we utilized data from the autumn BIAS cruises carried out in 2010 [9].

Acoustic data were collected using a Simrad EK60 echosounder equipped with a 38 kHz split-beam transducer, hull-mounted and downward-facing. Single target strength data as well as target depth data were extracted using SonarData Echoview software (version 4.90.81.19054). To filter out information that is not connected with herring, a cutoff at the -55 dB threshold was applied to the measured TS histogram.

Biological data were obtained from hauls and included species composition and fish length distributions. For the purposes of this analysis, we selected four hauls (z7, z25, z26, z27) with a herring content exceeding 90%, ensuring that the acoustic signals could be confidently attributed to herring aggregations.

3. RESULTS AND DISCUSSION

The algorithm was applied to four hauls. In Fig. 1 a comparison of the results for the unimodal and bimodal approach for the example haul z27 is shown. The bimodal approach yields better matches - the χ^2 value for this case ($\chi^2 = 0.119$) is smaller than for the unimodal orientation distribution case ($\chi^2 = 0.164$). This better fit is also confirmed by comparison of the measured and modeled TS-histograms in Fig.1a and 1b. In the bimodal case (Fig. 1b) the fit is better.

In terms of orientation distributions, the unimodal approach yields for this haul: $\bar{\theta}$ = -20° and s_θ = 5° (Fig. 1c). In the case of the bimodal approach (Fig. 1d) one mode is similar to this mode with mean angle and standard deviation $\overline{\theta_1}$ = -20°, $s_{\theta 1}$ = 3° respectively. The second mode is with a steeper mean angle $\overline{\theta_2}$ = -40° ($s_{\theta 2}$ = 3°). The first mode includes 89% of individuals of the modeled herring aggregation. The second mode can be interpreted as corresponding to fish escaping into deeper water in response to the approaching vessel [4,5].

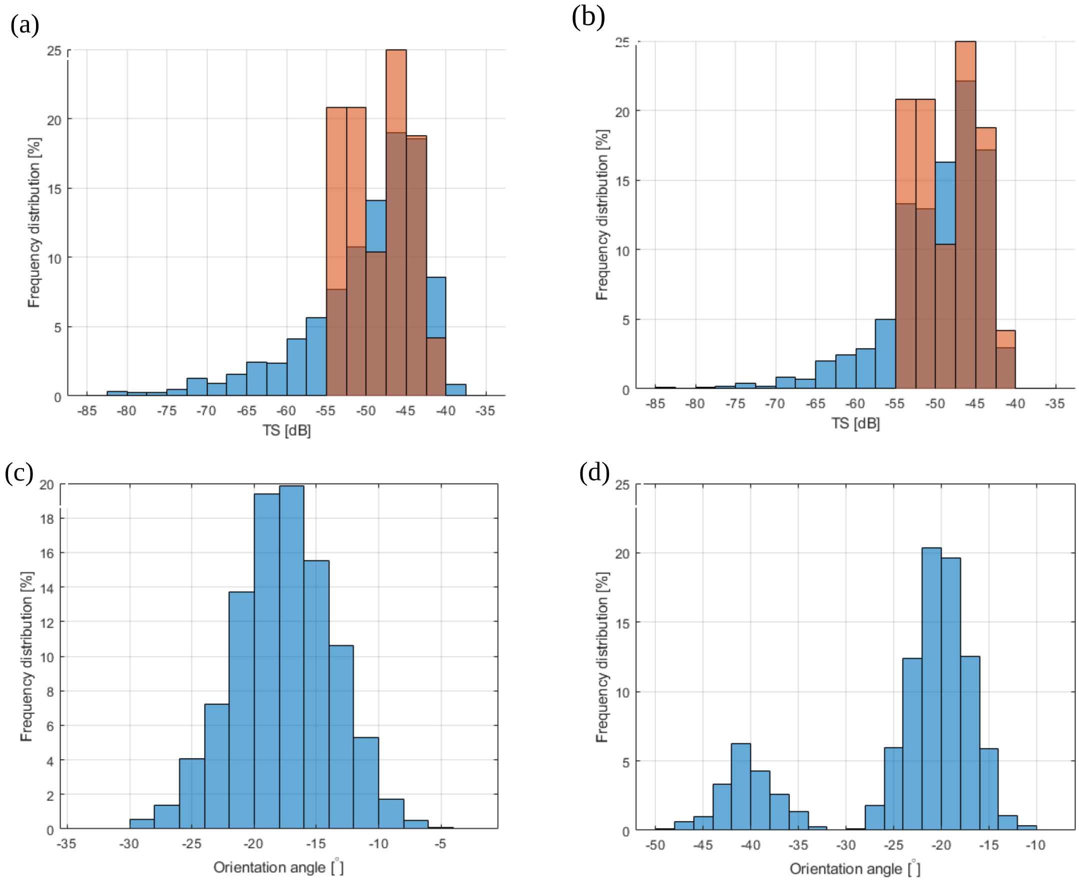

Fig.1: Comparison of distribution of TS measured in the z27 haul (orange) and the closest modelled distribution (blue) for unimodal (a) and bimodal (b) approach. Unimodal (c) and bimodal (d) orientation distributions obtained using the algorithms are presented.

Fig.2 shows the boxplot of the shortest $\chi 2$ distances between the modeled and the measured TS distributions for unimodal (blue lines) and bimodal (red lines) approaches. In case of the bimodal approach, χ^2 distance are smaller than in case of the unimodal approach for all considered hauls.

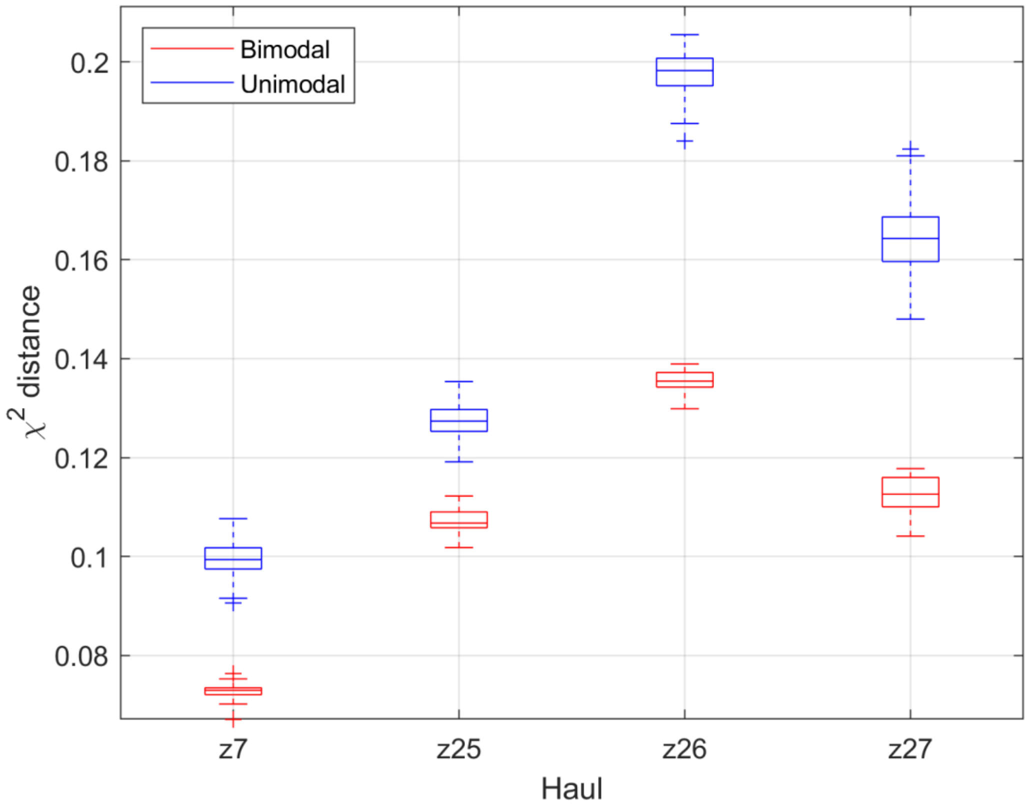

Fig.2: Comparison of the shortest χ^2 distance for unimodal and bimodal approach for four analysed hauls. On each box, the central mark indicates the median and the bottom and top edges indicate the 25th and 75th percentiles, respectively.

The occurrence of complex, multimodal orientation distributions can be explained by the variability of fish avoidance reaction in response to the approaching vessel. It is plausible that aggregation can split into parts, one of which escapes into the depths from the noise of the ship (diving), and the other swims in an unchanged manner or escapes horizontally (lateral escape) [4,5]. Such behavior would naturally result in a broader and more complex distribution of tilt angles.

Alternatively, the data may reflect the presence of multiple aggregations encountered sequentially during the sampling period - a single haul is likely to contain information from more than one aggregation. As a result, the orientation distributions may exhibit multiple modes, each corresponding to different groups of fish or distinct behavioral phases of the same aggregation.

Even if the true orientation distribution is unimodal, it may deviate significantly from a standard Gaussian shape. In such cases, a better fit can be achieved using more flexible unimodal models that account for asymmetry or excess kurtosis. Therefore, the assumption that a single Gaussian distribution can adequately describe the entire dataset may not be valid. In the bimodal approach, the two modes of the orientation distribution can overlap, forming a more complex distribution shape that better captures the observed variability and addresses this limitation.

4. CONCLUSIONS

Applying the bimodal approach to the previously developed algorithm for the determination of Baltic herring orientation distribution provided a more accurate result than in case of the unimodal approach. The bimodal fish orientation distributions, composed of two modes, give more detailed information than a single broad mode in unimodal distribution. The bimodal approach appears to yield more accurate and plausible results and represents a step forward in the development of the method.

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REFERENCES

[1] **Simmonds, J., MacLennan, D.N**., *Fisheries Acoustics: Theory and Practice. 2nd Edn*., Blackwell Publ., London, 2005.
[2] **Fässler, S.M.M., Gorska, N.,** On the target strength of Baltic clupeids, *ICES J. Mar. Sci.* 66, 1184–1190, 2009, https://doi.org/10.1093/icesjms/fsp005.
[3] **Gorska, N., Idczak, J**., On Baltic herring morphometry and its impact on the backscattering properties. *Oceanologia,* 64(1), 198-211, 2021, https://doi.org/10.1016/j.oceano.2021.10.001.
[4] **De Robertis, A., Handegard, N. O.**, Fish avoidance of research vessels and the efficacy of noise-reduced vessels: a review. *ICES J. Mar. Sci.*, 70(1), 34-45, 2013
[5] **Evans, T. M., Rudstam, L. G., Sethi, S. A., Warner, D. M., Hanson, S. D., Turschak, B., Esselman, P. C.** Fish avoidance of ships during acoustic surveys tested with quiet uncrewed surface vessels. *Fisheries Research*, 267, 106817, 2023.
[6] **Żytko, A., Gorska, N., Chu, D., and Schmidt, B.**, Hydroacoustic technique for determination of the orientation of aggregated Baltic herring, *Oceanologia*, 67(2), 2025.
[7] **Scoulding, B., Chu, D., Ona, E., Fernandes, P.G.**, Target strengths of two abundant mesopelagic fish species. *J. Acoust. Soc. Am*. 137(2), 989–1000, 2015. https://doi.org/10.1121/1.4906177
[8] **Pele, O., Werman, M.,** The quadratic-chi histogram distance family. [in:] Computer Vision–ECCV 2010: 11th European Conference on Computer Vision, Heraklion, Crete, Greece, September 5–11, 2010 Proceedings, Part II, Springer, Berlin, Heidelberg, 749–762, 2010.
[9] **Grygiel, W., Łączkowski, T., Podolska, M., Wodzinowski, T.**. Research report from the Baltic International Acoustic Survey (BIAS) on board of the Polish r.v. Baltica (20.09–08.10.2010). Working paper on the WGBIFS meeting in Kaliningrad (Russia), 21–25.03.2011. [in:] ICES CM 2011/SSGESST:05, REF. SCICOM, WGISUR, ACOM; Annex 9; 396–429, 2011.