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Dynamic characteristics of s_V, representing diel variability of fish within full depth range

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Acoustic methods could play an important role in monitoring vertical and horizontal fish distribution, including fish stock assessment, however the fish as acoustic target is not precisely specified still. The paper describes a new type of approach to express diel variability of acoustic parameter s_v, characterizing fish volume density. Multi-depth-channel integration of fish echoes was applied to estimate the average diel models of s_v dependence on time of a day. The final characteristics was calculated by computer as a vectoral field, showing quasi-continuous diel transformation of depth distribution of s_v values. Example based on data collected during October 1996 RV "Baltica" research cruise was given and discussed. Strong variability of s_v values with time and depth was exposed and clearly different diel phases of fish behaviour were separated. Results indicate a necessity of further research on fish target strength within separate periods of a diel cycle, to define more accurately biomass conversion factors. The method shown could enreach significantly systematic physiological studies on fish behaviour also.

1. Introduction

Acoustic methods for fish abundance are based on integration of received echoes energy and it is assumed [1] that integrator output s_A is proportional to the density of targets ρ. Each target is described by its individual averaged acoustic reflecting property, as backscattering cross-section <σ>. Formula (1) expresses simple relations among factors discussed:

$$s_A = \rho \times \langle\sigma\rangle \qquad (1)$$

$$s_A = \varepsilon \int_{z_1}^{z_2} s_v(z)\, dz \qquad (2)$$

where:

s_A - integrator output [m^2nm^{-2}],
$\langle\sigma\rangle$ - backscattering cross-section of fish [m^2],
ρ - surface density of targets [nm^{-2}],
ε - conversion constant [$m^2nm^{-2}sr$],
$s_v(z)$ - volume backscattering strength [$m^{-1}sr^{-1}$],
z, z_1, z_2 - depth and layer limits [m].

In the acoustic literature factor σ is commonly known as the target strength TS and defined as:

$$TS = 10 \log (\sigma / 4\pi) \qquad (3)$$

Effective value of TS for fish is closely dependent on echosounder frequency, fish species, the size and tilt angle [1, 3, 7, 17]. Increasing number of TS research shows that more factors have to be taken into account for to precise estimation of the average <TS> value. Very significant dependence of TS on fish behaviour stages was described in [1, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17]. An analysis of physiology related to a life fish [2, 5, 9, 19] predicts relationships between its physical (environmental background, body contents, and composition) and physiological characteristics. Differences can be identified with short-term (diel cycle) and long-term rhytms (maturation, feeding, spawning, hibernating, etc.).

The main subject of this paper is the analysis of variability of volume density of fish echoes energy (s_v, see formula 1 and 2), proportional to individual fish sound reflecting properties determined by <σ>

or TS. The variability is examined in a function of different depth and time during the diel cycle of fish life. The analysis is based on computer reconstruction of a numerical model of dynamic changes (gradients in time and depth) of volume backscattering strength s_v, measured during fish assessment research cruises of RV "Baltica".

2. Materials

Materials for this investigation were collected during two cruises of RV "Baltica", conducted in October 1995 and 1996 in the southern Baltic in good weather conditions, in comparable areas. Each cruise lasted three weeks and had a potential to collect data from approximately 2 thousand nautical miles of acoustic transect. Samples were collected continuously, every one nautical mile, 24 hour a day. The time distribution of samples was homogeneous to give a good base on which to analyse the diel characteristics of fish echoes. EK-400 (38 kHz) with QD echo-integrator plus a Hewlett-Packard Vectra PC and self-made soft-ware were used for measurements. Calibration of acoustic system was carried out with a standard sphere in the fjord, near Västervik , in Sweden. In both cruises instrument constant was estimated at the same level (SL + VR = 128.5 dB). Hull-mounted transducer 7.2° x 8.0° was used in the studies. Biological identification of fish was provided by sample trawls, on the average every 40 n.mi of the transect. Fish observed during both surveys were mostly pelagic, from the family Clupeidae (94.5% in 1995, 96.9% in 1996).

3. Method

Echo-integration was conducted in 8 independent channels and output values for each mile interval were converted into non-decibel values of s_v. Due to a draught of the vessel, hull reverberations and aeriation zone, integration process have been started at 15 m depth. Eight channels were used to separate basic layers in the following order: 15-25 m, 25-35 m, 35-45 m, 45-55 m, 55-65 m, 65-75 m, 75-85 m, 85-115 m. Each channel comprised 10 m integration layer, only the last one (the deepest) comprised 30 m. Fish below 115 m depth is not usually expected in the area of reported research.

Following the homogeneous time distribution of samples further assumptions were made to build a model of diel dynamic characteristics of fish reflecting properties, expressed by variability in s_v time-depth distribution ($s_v(t, z)$). Average values of s_v, expressed in linear scale, have been calculated for 2-h intervals for each integration channel, assuming that samples in every interval were dispersed randomly from geografical and bathymetrical point of view. Taking into consideration periodical form of a function describing s_v variability for 24-h period, trygonometric polynomial approximations, expressed in general by formula (4), have been applied for modeling for each integration layer [18]:

$$s_{vnm}(t, z = z_n) = \sum_{k=0}^{m} (a_{nk} \cos kt + b_{nk} \sin kt) \tag{4}$$

where:

a_k, b_k - Fourrier 's coefficients [$m^{-1}sr^{-1}$],
m - degree of approximation polynomial,
n - number of integration channel, corresponds to determined average value of z_n,
t - time [h],
z - depth [m].

For all measured layers approximations of the third degree were applied. Full description of s_v time-depth variability required to evaluate the relation between s_v and depth in each interval of time. For this purpose the simplest linear functions to correlate s_v and z for each 2-h interval were applied. Final results have been expressed by visualization of dynamic changes of $s_v(t, z)$, characterized by gradients $\delta s_v/\delta t$ and $\delta s_v/\delta z$. The gradients were considered as vector components and adequate vectoral field was calculated. Its graphical pattern was finally applied to express a dynamic picture of s_v time-depth variability. Such a characteristics was realized by a soft-ware prepared by the author, enabling to introduce numerous ways of vectors filtering due to their characteristic parameters (modulus, sense and direction) and with different field resolution. Conditional observations of the $\delta s_v/\delta t \delta z$ vectoral field have been opened out a wide range of unique analyses of fish behaviour and its ifluence on properties of fish as acoustic targets.

4.Results

Fig. 1 shows models of s_v variability with time for separate layers of integration, estimated, on the basis of data collected during October 1996 research cruise. Aproximation curves calculated for 1995 were very similar. Different colours were used to distinguish variability at different depth layers. The highest s_v values were found for the nighttime

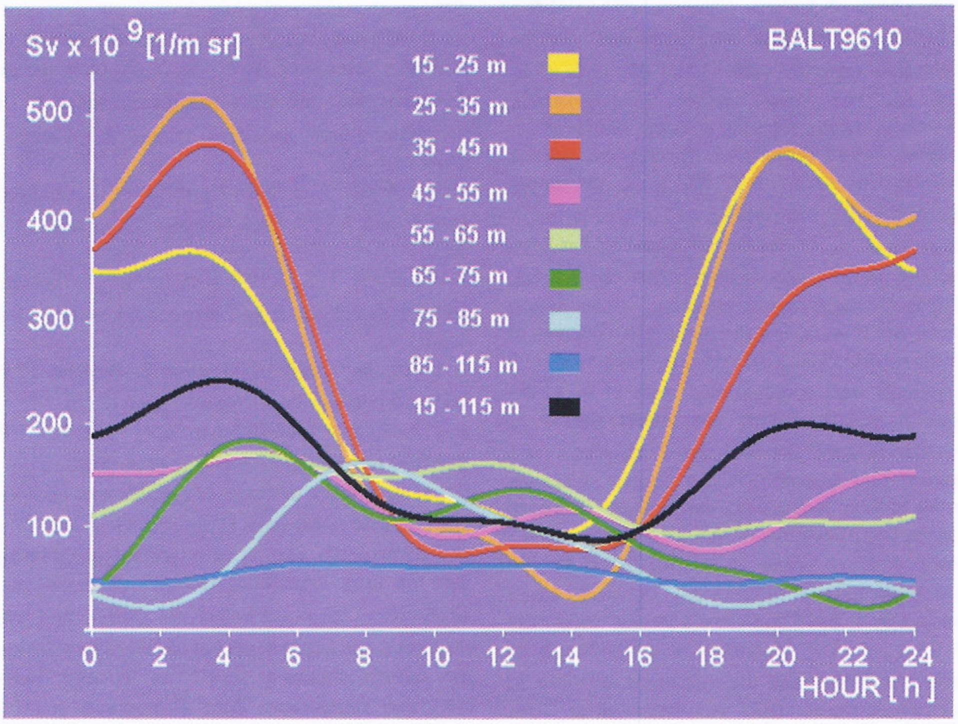

Fig. 1. Diagrams of models of the s_v variability with time, approximated by 3-rd degree of trigonometric polynomials for different layers of integration, marked by different colours.

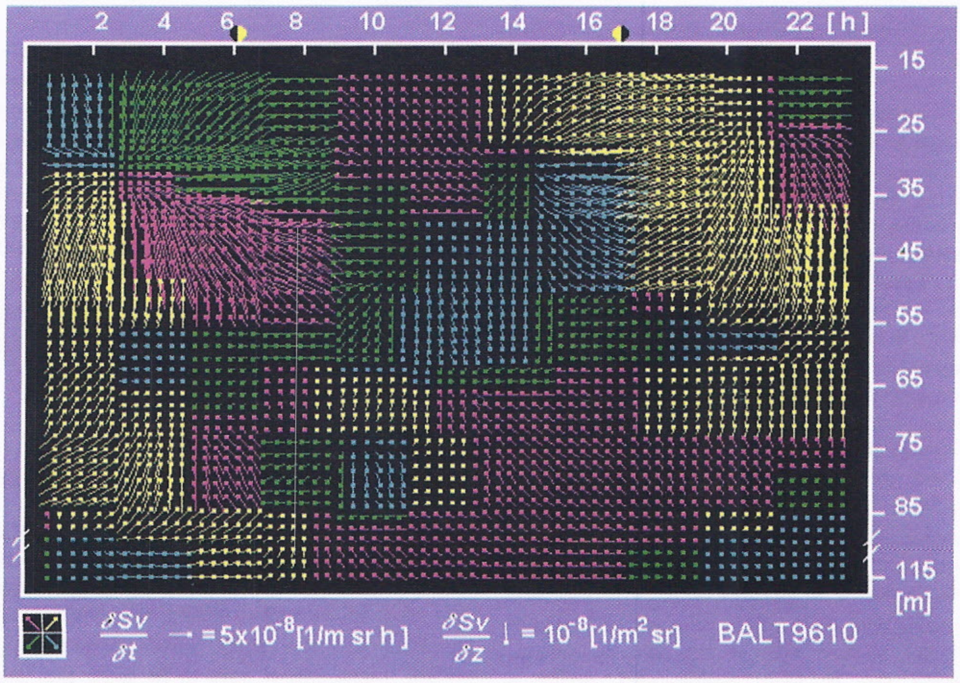

Fig. 2. Vectoral field showing 24-h period dynamic changes of $s_v(t, z)$, expressed by gradients $\delta s_v/\delta t$ and $\delta s_v/\delta z$, as vector components. Colours differentiate vectors directions in four basic quadrants.

for the layers between 15 m and 45 m. In the same time s_v values for deepest channels were minimal. The highest values of s_v were identified for the twilight time (approx. 4:00 h) and the early night (20:00 h). The lowest values were generally observed during the daytime, with the minimum at 1-2 hours before the sunset. During the sunrise period (approximately 6:00 h), s_v in the upper channels decreased sharply up to 20 % of its night average value. S_v in the deepest channels has been increasing significantly earlier before the sunrise, during the twilight period, attaining values over 4 times higher than during the nighttime. Changes of s_v in the central (55-65 m) and the deepest (85-115 m) channels were minimal (less than 15 % of the maximum value). During the sunset period s_v increased sharply in the upper channels and decreased very smoothly in the deepest. Changes near the surface took a place earlier than in deeper channels. Significant delay was observed for 35-45 m layer. Average values of s_v calculated for the whole depth interval (15-115 m), shown by black curve in Fig. 1, have indicated a strong variability over 24-h period. Maximum s_v value has been observed at 4:00 h and the minimum at 15:00 h. Maximum/minimum ratio was estimated at 2.74, expressing a wide range of s_v diel unstability. Changes of s_v during the nighttime were stronger than during the daytime. The most stabilized period was found during the daytime, between 8:00 h and 16:00 h.

Observations of the vectoral field (Fig. 2), expressing diel variability of s_v with depth indicate few various phases of fish behaviour which were reflected by a strong changes in time-depth distribution of targets and their summary acoustic reflecting properties, described by black curve in Fig.1. The Fig. 2 shows the situation for October 1996, but the pattern for October 1995 was very similar. It is easy to realize that s_v changes are appearing in the first order due to the basic factor influencing the diel cycle - the light. The primary classification of the vectoral field was limited to distinguish four basic quadrants, corresponding to the basic vector directions. It is possible to define time-depth zones in which s_v changes are characterized by similar trends, as i. e. green zone between 2:00 h and 8:00 h and 15 m and 35 m depth, in which s_v was decreasing with time and increasing with depth. Each zone can be correlated with the selected area of fish activity pattern. Filtering can be more sophisticated, giving a possibility to select numerous elements to distinguish more such patterns.

If we reduce our observations to the areas of the highest gradients of $\delta s_v/\delta t$ or $\delta s_v/\delta z$ only, we can determine four the most significant zones of s_v variability (upper index of t and z indicates a gradient sign):

1. t^- : $\delta s_v/\delta t$ <- $3.33.10^{-8}$ [$m^{-1}sr^{-1}h^{-1}$] - between 4:00 h and 9:00 h and between 15 m and 55 m depth,
2. t^+: $\delta s_v/\delta t$ > $3.33.10^{-8}$ [$m^{-1}sr^{-1}h^{-1}$] - between 16:00 h and 20:00 h and between 15 m and 55 m depth,
3. z^- : $\delta s_v/\delta z$ <- $6.67.10^{-9}$ [$m^{-2}sr^{-1}$] - between 17:00 and 8:00 and between 30 m and 55 m depth,
4. z^+ : $\delta s_v/\delta z$ > $6.67.10^{-9}$ [$m^{-2}sr^{-1}$] - between 1:00 and 7:00 and between 15 m and 25 m depth.

Some significant increase of $\delta s_v/\delta t$ was observed close to 2:00 h between 35 m and 55 m and 75 m and 85 m depth also. It is important to underline that the most significant changes of $\delta s_v/\delta t$ and $\delta s_v/\delta z$ were localized before the sunrise and after the sunset periods at depths of high temperature and low salinity, shallower than 55 m. Zones t^- and t^+ were very comparable. Zone z^+ was very small in comparison with z^-, what indicates a strong predominance of negative correlation between s_v and depth.

Recapitulating basic results it can be concluded that s_v variability have to be identified with time and depth factors closely dependent on 24-h periodicity, characterized by fish vertical migrations and differentiate behavioural stages. Due to assumptions made (each time interval of observations represents average density of targets and s_v should be a constant) s_v variability have to be interpreted as a variability of $<\sigma>$ or TS. In a consequence $\delta s_v/\delta t\delta z$ have to be treated as $\approx\delta\sigma/\delta t\delta z$, expressing diel fluctuations of the average fish acoustic backscattering cross-section.

5. Discussion

Application of the approach described in the paper afforded possibilities to systemize a description of diel time-depth variability of fish echoes and to compare results with other authors. Changes of the average effective fish cross-section $<\sigma>$, observed through variability of s_v, were mostly correlated with fish depth, variable due to diel vertical migrations. It have to be taken also into consideration that the Baltic Sea is characterized by two-layer structure and its upper layer is homegeneous considering salinity, which never exceeds 8 PSU. In the lower layer salinity is comprised between 8 PSU and 20 PSU, with heterogeneous structure.

Higher values of <σ> were observed during the night, when the most of fish were concentrated in upper layers (less than 55 m depth). In spite of depth, the area was characterized by highest water temperature (average 9.6 °C), highest oxygen level (6.9 ml/l), and lowest salinity (average 7.31 PSU). It means that total water density in that area was the lowest also. During the daytime the fish were dispersed in the whole range of depth (comparable s_v values among layers in Fig. 1) and <σ> was significantly lower.

Variability of <σ> can be finally divided into seven different periods, characterized by its absolute value and values of its gradients:

1. - morning twilight (2:00 to 5:00) - moderate increase of <σ> in upper depth layers, maximum value of <σ> ,
2. - sunrise (5:00 to 8:00 h) - strong decrease of <σ>, vertical migration of fish towards deeper layers, maximum negative gradient of <σ> in time,
3. - proper day (8:00 to 15:00) - stabilized value of <σ> in time, fish at full range of depth, minimum value of <σ>,
4. - downwelling light (15:00 to 16:00) - beginning of increase of <σ> in upper depth layers,
5. - sunset (16:00 to 18:00) - strong increase of <σ>, vertical migration of fish towards upper depth layers, maximum positive gradient of <σ> in time,
6. - evening twilight (18:00 to 20:00) - moderate increase of <σ> in upper depth layers, maximum value of <σ> ,
7. - proper night (20:00 to 2:00) - stabilized value of <σ> in time, close to the maximum, most of fish in upper depth layers.

It must be underlined that characteristics presented above correspond to average pattern of analysed factors. In particular days fish behavioural reactions are quicker and shifted +/- in time, due to cloudiness and the moon phasis [13].

A diel cycle of fish behaviour characteristics obtained by analisis of acoustic data shows very complicated pattern of fish environmental response. In [3] and [19] were given detail biological descriptions of 24-hour periodicity of fish behaviour. Some chacteristics of diel fish cycle, observed by acoustic methods were given in [6, 7, 8, 9, 10, 12, 13, 14, 15, 16]. Aglen [1], and Misund [7] suggested the possible influence of swim-bladder on depth dependence of <σ>. Mukai & Iida [8] showed decreasing of <σ> with depth for live kokanee salmon by cage experiments.They determined an empirical formula describing a reduction of fish <σ>, applying Boyle's law. Migration of fish 40 m deeper causes 1.85 times decrease of <σ> due to Mukai & Iida experiments. Similar trend was observed by Reynisson & Sigurdsson [16] for oceanic redfish. Decrease of <σ> with depth observed in this paper can be correlated with water pressure and also with water temperature and salinity having important influence on fish physiological state [5, 19].

Increase of <σ> during the nighttime, for the evening and morning twilight time (periods 1 and 6) can be caused by additional feeding of fish, as availability of plankton organisms in the upper layers is evidently higher and light conditions are comparable with the daytime at higher depths, as indicated in [19]. Arrhenius in [2] is neglecting feeding of sprat during the nighttime. His studies were based on sampling small aereas in the north of the Baltic (58°N), characterized by significantly different environmental conditions in comparison to RV "Baltica"surveys. The other reason of <σ> changes during the nighttime can be explained by tilt angle differences due to behavioural stages. Also a high level of oxygen in upper depth layers can influence fish metabolism and their physical condition.

Results and analyses described in the paper show the importance and complicated character of the influence of fish behaviour on acoustical measurements of fish density. As it was showed every new approach to processing and to analysing the acoustic data can significantly enrich studies on fish diel behaviour. In the other hand reasons of variability of fish echoes have to be studied by all availaible techniques in the areas identified in this paper.

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