# Acoustic contributions to marine ecosystem studies

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Since the early 1970s, acoustic data collected in a form of calibrated measurements of integrated echo energy have been applied by the Sea Fishery Institute in Gdynia to observe the relationships among fish distribution and marine environment. Acoustic, biological, and hydrological data were transferred to the complex data base, enabling spatial correlation and four-dimensional analyses of relationships characterising a wide range of the marine organism behaviour. Selected methods and standards of comparison are described to explain how to improve the recognition of relationships between three-dimensional spatial environmental gradients and fish distribution. Results of several case studies, including the influence of hydrologic and seabed characteristics, illustrate the practical application and validity of the methods. Particular attention is given to indicators of the dependence of local fish biomass density on temperature structure in the sea and diel cycles of fish behaviour. Animations of time-dependent processes, modelled on the collected data, will be included as a new tool for marine ecosystem analysis.

# 1 Introduction

The functioning of the marine ecosystem is consisted from many processes, which are strongly dependent on environmental factors [2, 4, 5, 26]. Adaptation of the life organisms to the aquatic habitat demands following the evolutionary process, optimizing its functioning in the ecotope [6]. In a consequence the organisms strongly respond to the spatial and temporal variability of the environment.

Owing to their very low attenuation in water, acoustic wave present a most promising approach for complex observations of the marine ecosystem at a scale appropriate to its dimensions [3, 8, 14, 18, 22, 25]]. In response to the gradients of physical properties acoustic waves are reflected and refracted. The spatial and temporal distributions of the echoes can be applied, after necessary calibration, to describe 3D components of abiotic and biotic components of the ecosystem. Echoes corresponding to all types of acoustic instability in media are associated with seabed, fish and plankton organisms, hydrologic gradients, gas bubbles, and many other sources reflecting or producing acoustic energy. Measurements of the echoes at different frequency spectra, related to spatial and time factors give a good base to complete the wide range information on the marine ecosystem. The scheme of circulation of the data is given in the Figure 1.

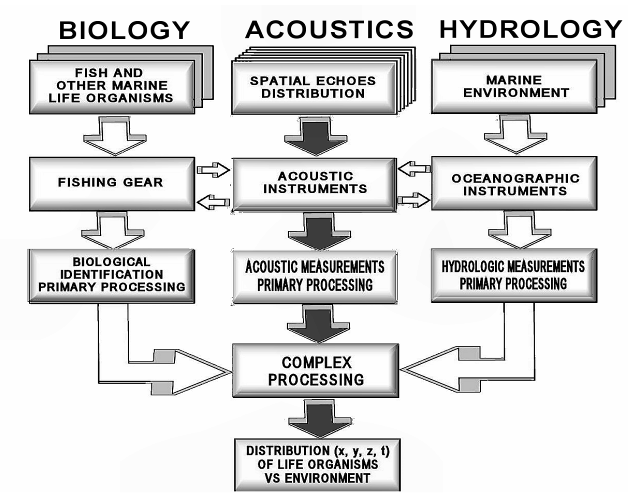


Fig.1. Application of acoustics for correlating cruise data.

This paper describes selected case studies illustrating the practical application of the idea. Details are published in [14, 15, 16, 18, 19, 21, 22, 23]].

# 2 Material and methods

Between 1981 and 2007, research vessels of the Sea Fisheries Institute in Gdynia (r.v. 'Profesor Siedlecki' and r.v 'Baltica') were used for a series of cruises to gather acoustic, biological and environmental data in the southern Baltic. Measurements were collected primarily with EK38 and EY500 scientific echo sounders operating at 38kHz, 24h a day, and stored in the form of standardized intervals of sailed distance and depth for comparison with values of selected environmental parameters, measured concurrently. Both systems used the same hull-mounted 7.2◦×8.0◦ single-beam transducer. The equipment was calibrated with the aid of a standard target in Swedish and Norwegian fjords. To ensure a high degree of measurement comparability, the survey tracks of all cruises were located on the same grid.

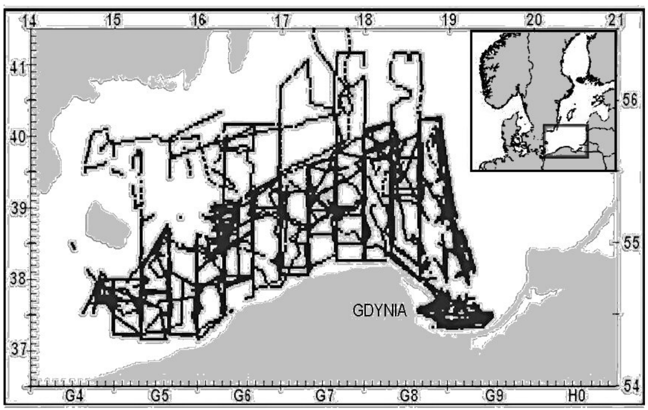


Fig.2. Grid of research transects.

Biological samples were collected with the same pelagic gear, on average every 40 (approximately) n.mi. of the transect. The fish observed during all the surveys were mostly pelagic – herring and sprat (*Clupeidae*).

Hydrographic parameters (temperature (T), salinity (S), and oxygen level ($O_2$) were measured with the Neil-Brown CTD system, mostly at sample haul positions, with a similar biological sampling space density. Each hydrological station was characterized by its geographical position and the values of the measured parameters at 2 m depth intervals (slices).

The sampling density is differentiated according to the methods of the research. The distance of one nautical mile was considered to be the elementary unit (record) of the database. Each unit was characterized acoustically by the mean column backscattering strength ($S_{vc}$), nautical area scattering strength ($S_a$) and volume backscattering strength in normalized depth layers [14, 15, 18, 22]. The acoustic factor characterizing seabed (theta) was also included [21, 23]. For each record, the values of the remaining factors characterizing the biological and hydrological parameters were estimated. By extending the record to include the depth structure of acoustic scattering $S_v(z)$, as well as biological and hydrological components, and by introducing a time factor, a 4D database, called ABO (A-acoustics, B-biology, O-oceanography) can be produced, covering a wide range of parameters. Owing to the limited possibilities of the 2D sampling density of biological and hydrological parameters, their values per EDSU had to be estimated within certain standardised statistical areas (ICES rectangles in the Baltic). Detailed descriptions of the method of applying acoustic soundings for producing a 4D interdisciplinary database in the Baltic are given in Orlowski [22].

The 3D area of research was divided into small cells shown in Fig.3. For each cell the corresponding values of the ABO parameters, correlated with time, were calculated.

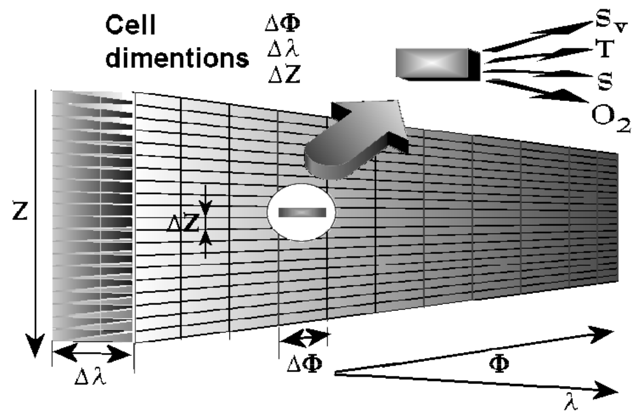


Fig. 3. Elementary units of the surveyed marine ecosystem.

Processing the ABO data base allows to find out important elements of the functioning of the marine ecosystem. The data collected periodically each year reflect natural processes, strongly influenced by environmental variability. By this way we can produce empirical models and new quality of the observations, perfectly matched to the 4D scale of the phenomena. The paper will present few selected applications of acoustics, effectively enhancing the knowledge on marine ecosystem functioning, as macrosounding, year and diel cycle characterization, modeling the fish behaviour, and dependence of bottom fish concentration on seabed characteristics.

# 3 Results

## 3.1 Macrosounding

The macrosounding method was introduced in primary version by the author in 1989 [12,13]. The method is destined to illustrate by graphic patterns data on marine system, collected by acoustic means [9, 10, 24]. Its present version is based on computer transformation of acoustic data, collected over selected distance units, into a graphical picture, showing by color scale the vertical distribution of fish volume backscattering strength together with bottom profile and isolines of selected hydrological factors. The main aim of the method was to give a synthetic presentation of fish distribution in the optional scale, matched to analyzed phenomena. The method gives unlimited range of creating cross-sections, by linking in optional sequence geographic positions of survey distance units. The localization is taken from the cruise chart, generated by PC software, associated with the method.

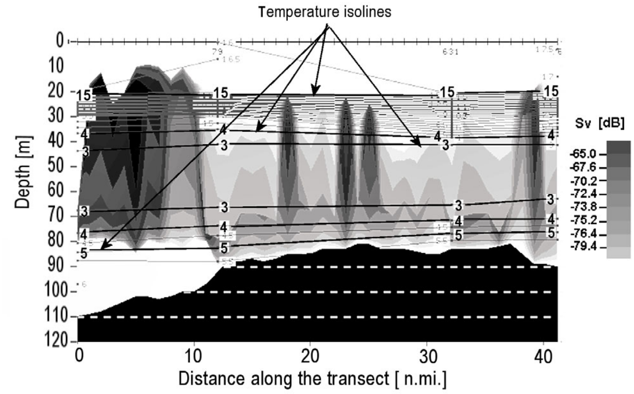


Fig. 4. Macrosounding visualization of clupoeid concentrations in Gotland Deep in the Baltic.

Fig. 3 gives practical example of multi-disciplinary visualization of the distribution of fish in relation to temperature gradients at 20-30m depth. The real visualization is applying full color scale.

## 3.2 Year and diel cycle characterization

The year and diel cycle of fish is one of the most basic processes regulating fish biology [6]. As a consequence, research on characterizing the diel cycle of fish can considerably enhance our knowledge of interactions between fish and the surrounding marine ecosystem. Acoustic methods are one of the most effective means of observing fish and large schools of fish, as shown in [1, 4, 11, 14, 18, 22, 25, 26]. On the other hand, a detailed knowledge of the life cycle of fish can reduce to an absolute minimum any errors in estimating their acoustic scattering properties, influencing strongly results of stock assessment. Application of the ABO database enables many single or cross-correlated characteristics of the marine ecosystem to be estimated. One of the first steps has to be a comprehensive visualisation of the cycle against the environmental background (see Fig. 5). The measurements were carried out during a two day experiment in the south Gotland Deep, during which echo integration was provided along the 4 n.mi. sides of the square track. The visualisation is made by the macrosounding method, but instead of the distance the abscissa is related to the time. Fig. 5 shows that a number of different phases of fish (clupeoid) behaviour can be distinguished. These phases are closely related to characteristic time and spatial limits, and each one yields a different echo pattern. Day and night differences and sunrise and sunset migrations are strongly marked.

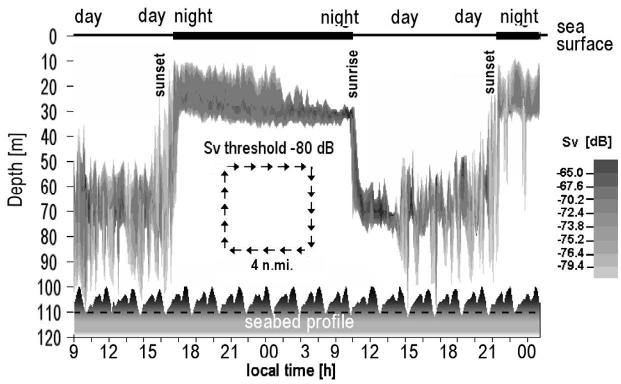


Fig. 5. Diel cycle of fish distribution in Gotland Deep experiment, expressed by acoustic macrosounding.

As it is easily seen from Fig. 5, the diel cycle of fish is related to astronomic night and day. During the day time fish is occupying wider range of depth in deeper water, while during the night fish is associated with warmer waters close to the sea surface. An adequate processing the ABO data shows that the main mechanism influencing the fish night distribution pattern is connected with gradients of hydrologic factors (mainly temperature). The example of the vertical distribution of fish, expressed by Sa (layer scattering strength) and normalized gradients of the temperature, salinity, oxygen level and water density is given in the Fig. 6. The patterns corresponds to the Slupsk Furrow area (southern Baltic) in October 2003.

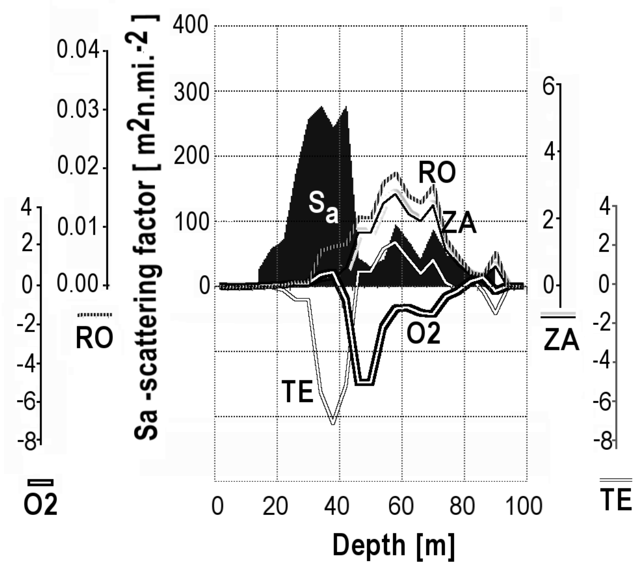


Fig. 6. Layer scattering strength $S_a$ and oxygen ($O_2$), water density (RO), temperature (TE), and salinity (ZA) gradients in a function of depth.

It is clearly seen, that the maximum of the fish density is associated with the biggest value of the temperature gradient. While the minimum is close to the maximum of the oxygen gradient.

Research on year cycle of the marine living organisms demands a systematic collection of the ABO data during different seasons. Interesting comparison of the diel cycle, expressed by temperature at fish main depth during the spring (May) and the autumn (October) , calculated as the average of few cruises is shown in Fig. 7.

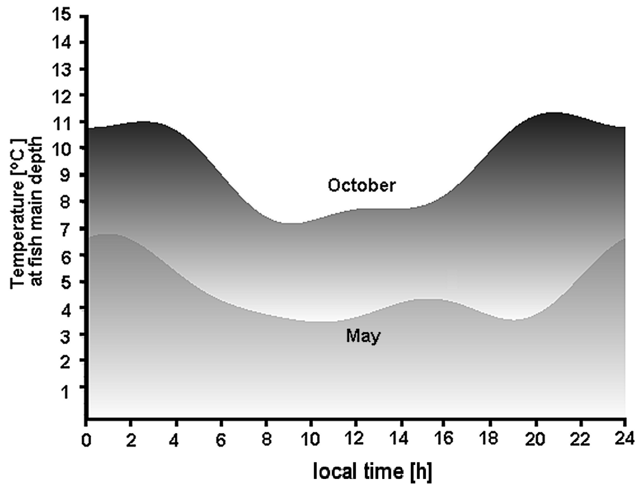


Fig. 7. Spring and autumn diel cycles of clupeoids in southern Baltic, expressed by value of temperature at fish main depth.

## 3.3 Modeling the fish behaviour

Basic fish environmental preferences can be estimated using ABO data set. On this basis environmental factors associated with fish x, y, z, t coordinates, as average depth, temperature, salinity and oxygen level can be calculated. Mentioned magnitudes are estimated for determined space and time resolution (Fig. 3) for each cruise and for groups of cruises, representing the same seasons.

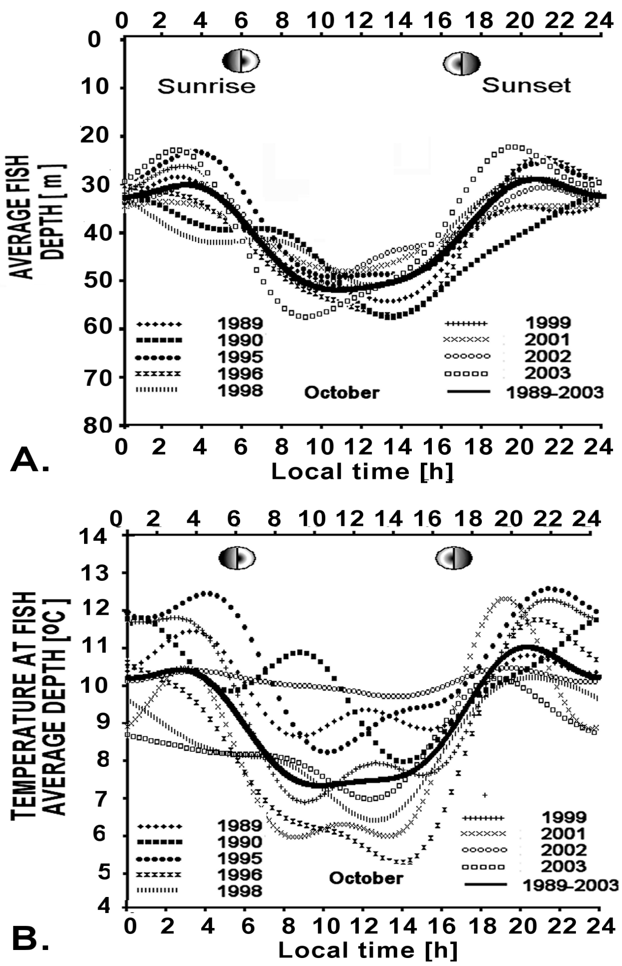


Fig. 8. Models of diel fish behaviour: depth of fish (A) and corresponding temperature (B) as a function of time.

Taking into consideration periodical form of a year or diel period, destined to describe fish behaviour characteristics, trigonometric polynomial approximation for the model were applied [3, 14]. Examples of fish behaviour models, determined for the autumn are shown in Fig. 8.

Diel variability of fish main depth (left panel) and temperature (right panel) are shown by series of approximation curves. A black curve shows the model over the whole period 1989–2003. Remain curves, distinguished by graphical patterns as indicated in the figure legend, correspond to single cruises between 1989 and 2003. Strong variability of the factors (especially temperature) among the years is observed. The modulation is closely dependent on hydrologic structure of the area surveyed. It is important to observe regular quasi-sinus shape of the average pattern. Analysis of this result helps in interpretation of the biology of the living organisms.

Further mathematical operations on the models allow to estimate next factors of fish behaviour, as the process of vertical migration during the sunrise and sunset period (Fig. 9).

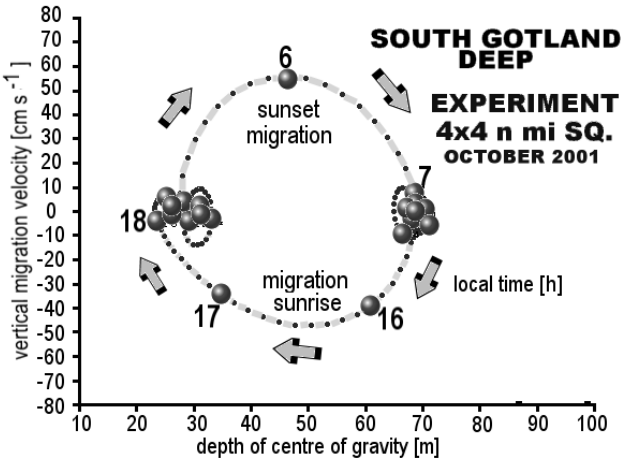


Fig.9. Fish vertical migrations observed in Gotland Deep in function of depth.

Basic diel migrations are associated with the sunrise approximately at 5:30 h. and the sunset 16:00 h. The range of migration closely depends on the fish depth and the biggest inertia was observed for the maximum fish depths. Those relations can be studied in particular for each environmental factor and detailed comparisons among different cruises or seasons can be made.

## 3.4 Seabed and fish

Acoustic measurements of the seabed characteristics enable to provide wide range classification of its properties. As an example the application of the simple parameter *theta* is given. The method of estimating *theta* was devised by Orlowski in [21, 23]. Previously, the author had introduced multiple echo measurements for seabed evaluation (RoxAnn). The main aim of the current method was to simplify the classification procedure. A signal reflected from the seabed is characterised by its amplitude and duration. The duration of a bottom echo $\tau_s$ is dependent on the temporal components of the seabed echo: pulse length, beam angle, scattering from the bottom and from reflections below the water-bottom interface. The value of $\tau_s$ depends on all these components and increases with depth owing to the spherical spreading of acoustic waves. Any application of $\tau_s$ for describing the seabed requires its value to be normalised with respect to depth. The value of the angle Θ'/2 was determined as a one-dimensional parameter describing the complex properties of the seabed and fulfilling the condition that $\tau_s$ be normalised with respect to depth. The angle Θ'/2 is defined by the formula (1):

$$\Theta'/2 = \arccos\left( 1 + (\tau_s - \tau_1)/ t_d\right)^{-1} \qquad (1)$$

Where; Θ'/2 – the *theta* parameter, characterising the acoustic properties of the seabed,

$\tau_s$ – superposition of all seabed echo time components,

$\tau_1$ – component dependent on pulse length,

$t_d$ – pulse travelling time (between transducer and seabed surface).

The value of the *theta* can be associated with the bottom surface morphology (scattering properties) or layered structures beneath the bottom, reflecting the cumulative character of the seabed sediment (values over 30°). The relationships between the *theta* and the bottom fish concentrations were estimated for the southern Baltic area for two different species: cod and flounder. The results are given in Fig. 10.

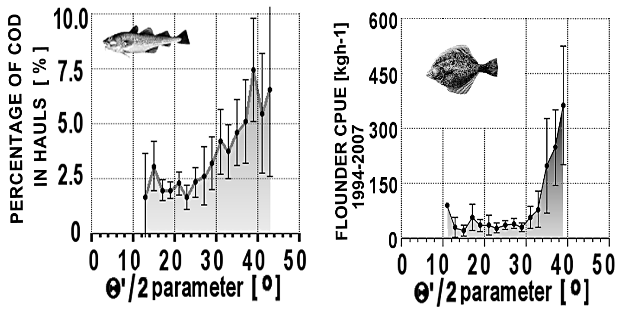


Fig.10. Correlation between the seabed type classified by *theta* parameter and densities of cod and flounder.

The comparison was made by two different factors expressing the fish surface density: the percentage in the sampling hauls in comparison to clupeoids (cod) and by CPUE (catch per unit efford) in the bottom trawling for flounder. In the first case the data corresponds to the period 1995-2003, in the second 1994-2007.

# 4 Conclusion

Selected examples of methods and results show how the application of acoustic data, even in the simplest combination, can effectively enreach the ways to improve our understanding of the functioning of the marine ecosystem. The most important part of this process is associated with producing acoustically coordinated transfer and compiling a common interdisciplinary data base on marine ecosystem (ABO). The value of this data base is higher when data are collected with similar time and spatial strategies and technical means. Each new parameter included in the data collection strongly enhances the range of possible analyses. Relations and trends between the environment and the distribution of life organisms in the 4D structure can be estimated and formulated by mathematical models for further comparisons and multi-dimensional modelling.

The following elements of marine ecosystem dynamics were characterized with a help of acoustic information:

- depth related geographical structure of marine organisms,
- year, season, and diel dynamics of biological cycles in relation to environmental factors,
- environmental pressure on horizontal distribution of fish,
- comparisons of defined standards of fish behaviour for determined periods and areas,
- association of fish species with seabed characteristics.

The application of acoustic information to describe 4D functioning of the marine ecosystem can be significantly improved when normalization of standards, functions and magnitudes characterizing its elements can be precisely determined and contributed to other researchers. It can significantly improve comparability of results and allow for a significant enhancement to the possibilities of supplementing inter-disciplinary data bases, produced in the ABO style. The significance of this fact does not need any discussion.

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