

AMBIENT SEA NOISE IN THE BALTIC SEA – REVIEW OF INVESTIGATIONS

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A short review of results of the ambient sea noise investigations in the Baltic Sea is presented in the paper. Historical collected data on the ambient noise completed by different investigators at stations located in different Baltic Sea basins are provided and their results are discussed. Furthermore, results of latest ambient sea noise measurements performed with autonomous acoustic buoys are presented.

INTRODUCTION

The purpose of the paper is to present and summarize investigations focused on the basic aspects of the Baltic Sea ambient noise and to give the reader an admission into the literature of the topic. The present list of references shows a total of 17 references to works performed in the last forty years.

In Poland, field measurements of the ambient noise started out in the early 70's performed by the laboratory of the Polish Navy in Gdynia. Some years later, both field and theoretical investigations, began in the IO PAS Sopot [1, 2, 3, 6] and continued with different intensity until now. Polish investigations were performed in Polish Economy Zone from a small boat, often not anchored, mainly in summer period. Due to the methodology of measurements, the noise records were frequently contaminated by the pseudo-noise, due to the system drift and by cable strumming.

In these early days, the ambient sea investigations in the Baltic Sea, likewise as in other countries, were driven mainly by Navy interests, aimed at the prediction of probability of a submarine detection or in the case of ship noise collections included in mine warfare plans.

More recent works in the field of the ambient sea noise are focused primarily on the acoustical oceanography problems. It is believed that results of the ambient sea noise investigations in the area would provide useful tool for understanding many dynamic phenomena in the sea.

This paper is organized as follows: A brief introduction to the history of ambient sea measurements in the Baltic Sea and their dependence on wind speed is given in Section 1. Seasonal and diurnal changes of the noise and some statistic are presented in Section 2.

The contemporary attempts aimed at showing the utility of the ambient sea noise in the investigations of bubble injection depths and wave breaking are referred to in Section 3.

1. NOISE-WIND DEPENDENCE

Ambient noise spectra in the literature usually have used wind speed as a basic parameter for prediction of their values. Fitting of the wind-driven component of the ambient sea noise to the wind speed is the common practice also in the Baltic Sea [6, 13, 15, 16]. The preferred expression in all history of the ambient noise investigations is in the form

$$NSL(f, U_{10}) = B(f) + 20n \log_{10}(U_{10}) \quad (1)$$

where: NSL is the noise spectrum level in dB re 1 μ Pa at frequency f , $B(f)$ is the noise level at a wind speed of 1 knot or 1 m/s, n is an empirical coefficient, and U_{10} is the wind speed in knots or m/s. The special case is for $n = 1$, when the noise intensity increases quadratically with the wind speed. From the physical point of view, the value $n = 1$ is the most expected, as the stress of the wind upon the sea surface, and the drag force of different form obstacles in a moving fluid, also vary as the square of the fluid speed.

In contradiction to non-wind dependent noise as ship traffic and biological origin sounds, due to similarity of processes involved in the generation of the sea noise it is expected that the wind noise component with correction of bottom reflection should have the same level at the same wind speed in different areas. However, up to the recently some unexplained differences between the data given in the literature are presented. The differences are probably due to prevailing wave fetch during measurements, different wind profiles or gustiness, salinity, existence of surface active substances or sound propagation conditions in area.

The results of measurements collected in Poland during 70 s – 80 s in the broad frequency band from 2 Hz up to 12 kHz gave rather an incoherent picture relating to the form of noise spectra in different areas, their dependence on wind speed, seasons and depths of observation point [6].

Some years later, Wille and Geyer [4] made measurement in October, in the Central Baltic with soft bottom sediments in 90m depth region. The stationary hydrophone, placed at 50 m, was probably above the lower edge of the seasonal thermocline. (The authors did not present sound speed profiles). Their main results were as follows: the wind dependence of the ambient noise manifested regularly above 63 Hz, the noise level was several dB lower, as taken for comparison Piggott's measurements also performed in the shallow area, the spectrum slope changes with wind speed from -5 dB/octave to -8 dB/octave, and the noise variability was very high.

What is interesting, the wind dependence of ambient noise spectrum level in the area was quadratically with the wind speed i.e. 6 dB/wind speed octave.

Swedish Defense Research Agency (FOI) recommends the functional dependence of the noise spectra level on the wind speed in the Baltic Sea, in the form independent of other factors, as time of year or the depth of observation, except the wind speed (after [9]):

$$NSL(f, U) = \max \begin{cases} 24 \log(1 + U) - 17 \log(f) + 35 \\ 20 \log(f/6) \end{cases} \quad (2)$$

where U – wind speed in knots, f – frequency in kHz, \max – maximum between two options depending on the higher value, NSL – noise spectrum level in dB re $1\mu\text{Pa}^2/\text{Hz}$.

Eqs 2 a) gives stronger than quadratic dependence of the noise intensity on the wind speed.

Dalberg et. al. [10] analyzed noise spectra data vs. wind speed collected during an experiment carried out in August, in a shallow, 40 m water depth strait in the Stockholm archipelago. The sea bottom in the area consists of acoustically hard crystalline granites covered by unconsolidated sediments.

The ambient sea level for frequencies above 500 Hz was found to increase 6 dB/wind speed octave below the threshold value of 6 m/s, and for higher values of wind is growing slower.

In spite of complicated shore line and the wind fetch depending on the wind direction the influence of the wind bearing was not predictable.

In series of measurements conducted by the team of IO PAS, the ambient sea noise records were made using an autonomous hydroacoustical buoy constructed to make mutually records of the ambient sea noise and to observe the subsurface bubble layers. In each case, the noise was received by a pair of omnidirectional hydrophones. The ambient noise data were recorded at the same time at two depths with vertical distance between hydrophones 22 m. The experiments were performed in two areas, with sound profiles manifested characteristic for summer or winter sound propagation conditions. In both places the soft muddy sediments prevailed.

One site, where measurements were performed during winter propagation conditions, situated in the Bornholm Basin, was close to major shipping lanes. The other site, in Gdansk Basin, was located in the area with much lower density of traffic.

Experiments extended for many days gave a unique opportunity to investigate the role of Baltic waveguide properties in shaping the ambient noise field.

During the winter time, due to the existence of the Baltic subsurface winter waveguide, at frequencies of interest, good transmission from distant sources is observed. The wind-dependent noise is frequently contaminated by fishery and traffic noise observed in the whole frequency band under analysis (350–12500 Hz). Due to the upward refraction, all components of the observed noise within the waveguide were higher as at the deeper hydrophone located below the halocline outside of the waveguide. The traffic and fishery noise is uncorrelated with the high-frequency noise component where local noise predominates.

Inside the waveguide, beneath the sea surface the functional wind dependence of the noise was frequently negative, especially at lower frequencies where the noise level decreased with increasing wind. The trend, observed also by other investigators could be explained through bubble's clouds insertion into the water body through wave breaking. In this case, the good propagation conditions are deteriorated and the noise from distant sources, despite of increasing with the wind speed efficiency of sound generation is attenuated and scattered more effectively at the bubble clouds. The other observed changes can be results of diminishing the ship traffic intensity or fishery activity connected with the higher sea state.

In the summer time, the upper hydrophone was located in mixed water layer, another one inside of the deep-water summer waveguide. The noise spectrum level, in spite of relatively small vertical span, was very different at lower frequencies up to about 4 kHz. In higher frequency range the spectra are similar and their level comparable, for the same wind speeds.

At lowest recorded frequencies the noise spectrum level in the waveguide is about 12 dB higher than those registered in the upper layers and not dependent on wind conditions.

Above the thermocline, in the absence of the non-wind-dependent noise sources, the sound intensity level is well correlated with the wind speed.

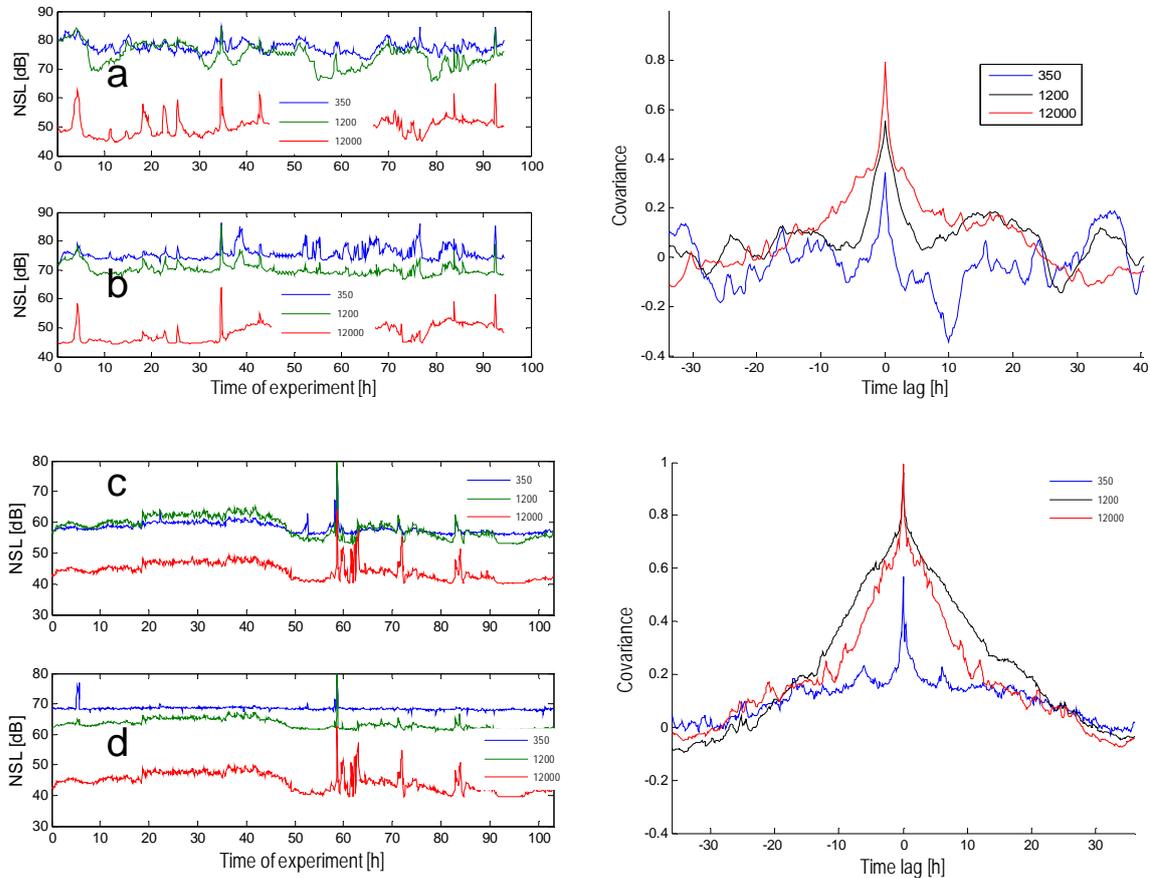


Fig. 1. Time series of the ambient sea noise in the three frequency bands from the buoy in the Baltic Sea (in left panels) and covariance functions between noise data in the same frequency bands, recorded inside and outside of the seasonal waveguides in the area (right panels).

Data marked with *a* and *b*, were collected in the winter propagation conditions; *a* – inside and *b* below the winter subsurface waveguide. Data indicated by *c* and *d* recorded in the upper mixed layer and deeper inside of the deep water summer waveguide respectively

Fitting a functional relationship, given by Eq.1, to the noise intensity and wind speed above threshold value of 4 m/s and estimating the values of $n(f)$ for third-octave bands and for each campaign at different depths, we have found:

- in the summer season, in the subsurface constant-sound-speed layer, starting from about 1 kHz, near square power law exists in the whole upper frequency range. Inside of the deep seasonal waveguide, values of n increase from near zero at 350 Hz, and at frequencies above 4 kHz reach comparable values as in the upper layer i.e. around $n = 2$,
- in winters: within the waveguide the higher negative correlation with wind and negative values of n are observed at 3 kHz. The $n \approx 2$ are only in the deep water layer, i.e. below the subsurface waveguide, at high frequencies above 4-6 kHz depending on the strength of the waveguide.

In the subsurface winter sound channel and in the deep-water summer channel the noise – wind correlation is poor particularly at low frequencies. This effect can be explained by influence of changing propagation conditions on the level of distant sources.

Below the critical depth, defined as the depth at which the velocity is the same as at the surface, the noise level decreases with depth as the trapped modes (or rays) attenuate quickly with increasing distance from the waveguide boundary. With increasing frequency, the listening area is decreasing and 'above head' sources increase the wind-noise correlation.

Measurements in ultrasonic frequency band in the North Baltic Sea have been made recently by Poikonen [16]. His measurements showed an unpredicted by other investigators increasing correlation with wind. A reasonable physical explanation for the observation is that fresh and brackish water have a lower fraction of small bubbles than oceanic water which could attenuate noise generated in the thin layer at the sea surface. On the other hand, the observed threshold wind speed value characteristic for acoustically excited bubbles creation increased.

2. NOISE VARIABILITY

The time variability of the noise depends on the depth of observations. When we observe a noise near the sea surface we detect the transients' sounds of breaking waves with characteristic periods mirrored breaking events on the surface. Longer-term changes include variations with characteristics seasonal and diurnal periods.

Seasonally changing sound propagation conditions in the Baltic Sea affect the ambient noise in a different of ways. First of all the noise level changes could be explained taking into account altering amount of far-off from a hydrophone shipping noise.

In 70-s, a ray-based model has been developed to explore the sensitivities of wind-wave generated surface source directionality, from the mid- to high-frequency band in a relevant seasonal changing of the Baltic Sea environment.

On the basis of the model it was predicted that seasonal variations of sound speed profiles in the Baltic Sea could strongly change the level and spectra of the sea noise. In contradiction to Wille and Geyer [4] position which stated that the influence of propagation conditions in the shelf seas on the wind-dependent fraction of the noise is rather insignificant, according to the model, the seasonal changes might reach 10 dB and are different for different frequency ranges.

This theoretical forecast was confirmed by Wagstaff and Newcomb [5] investigations which carried out all-year-around noise observations in the Central and Western Baltic Basins with acoustic autonomous sonobuoys.

Later the modeling was extended to lower frequencies using the parabolic approximation method and discrete shipping noise was included for different types of ship and different scenarios of ship distribution. However, the model usage was limited only to the Gdansk Basin.

Recently published data of experiments by Poikonen and Madekivi [15] carried out in the Gulf of Finland and by Klusek and Lisimenka [11, 12, 13] in the Southern Baltic Sea maintain the idea of a strong influence of the seasonal changes of sound speed profiles on the spectra of ambient noise in the Baltic Sea. Poikonen and Madekivi reported 10 dB winter – summer – differences of the ambient noise level in shallow water in the Northern Baltic.

It was hypothesized that observed in Gdansk Deep higher noise level inside of the summer waveguide is partly the result of scattering of sound at internal wave movements [3] in the thermocline and/or inhomogeneities in the soft bottom sediments. There can be no doubt that during the summer season the soft bottom in Baltic Basins is the important sound conducting medium, especially at frequencies below the cut-off frequency of water waveguide in the water.

It is also likely, that near the Hel Peninsula ‘down-slope conversion effect’ of the sound originating at the sea surface has place, and the noise is pumped into the summer waveguide.

During the transition period of switching between the winter and summer propagation conditions changes of velocity profile across the West-East transect could also pump the sound from the shallow layer into the deeper water masses, forming deepwater waveguide.

Besides of seasonal changes of the noise attributable to varying propagation conditions, diurnal variations caused by vertical migrations of fishes were observed [12, 13]. The noise level in the shallow waveguide is generally higher by 5 dB than in the deeper water layer. During the winter, 24 hours period variations of ratio of the noise intensity at the two depths were observed. The variations are synchronized with the diel migrations of the acoustical scattering layers and the strongest effect is observed at frequencies which match the resonance frequencies of swimbladder of fish in the area. Quantitatively the phenomenon was explained as the additional attenuation and scattering caused by the fishes migrating into the surface waveguide.

Swimbladder resonance due to its size and morphology can potentially be used to help identify fish species or size using passive methods. The noise attenuation due to resonance scattering by swimbladdered fish in principle could be used also to estimate numbers of fish in the area and support common investigations in practice of fisheries research.

The Monte-Carlo models with different state of complexity were introduced to explain yearly seasonal changes of the ambient noise, observed short term variations of the noise level at the thermocline induced by the vertical migrations [7, 13]. The modeling of last phenomena was rather unsuccessful giving values much lower than observed in the experiments.

The other long-period climate induced changes are not observable at the present time due to lack of long time series of noise measurements. We could only predict some changes induced by lowering of sound attenuations caused by growing acidity of the seas. Another long-term changes could be induced by observed rising temperatures of water masses in the Baltic Sea interior.

Because of the random and singular measurements of the ambient noise in the past, we can not document changes of the anthropogenic noise levels as well as to provide a baseline for future changes prediction. Firstly, lowering due to the crisis in 1990’s and afterward the technical noise level should arise with the growing traffic intensity in the Baltic Sea in the XXI Century.

Due to changes in the ship number and increasing of their power and speed, in areas where shipping noise component is significant increasing of the noise by 5 dB/decade under the same propagation condition is observed. The same should be observed in the Baltic Sea, however we do not have any long-lasting several-decade-time series of measurements.

3. CONTEMPORARY INVESTIGATIONS

Though, it is generally acknowledged that the strongest correlation of the ambient noise is with wind speed, but other related to the wind forcing sea-state parameters should play the important role in the noise generation. As example, comparing data collected in consecutive years in the same area and under similar propagation and wind conditions we found significantly different parameters of the wind-noise relationship (Eq. 1) and distinct values of statistical relationships (correlation). Efforts to explain the observed difference by analyzing the influence of the wind direction and wind fetch during the registration were not satisfactory.

Initializing further investigations of the ambient sea noise in the Baltic Sea we have included observations and measurements of other parameters.

Among them are measurements of the depth extension of air bubble plumes in the Baltic Sea at different wind conditions conducted together with the ambient sea noise registration to find associations between noise and parameters of bubble population. Relationships between different parameters of bubble depth profiles (*entrainment depth*, *bubbles detection depth* as examples), wind and ambient sea noise were derived, and presented in [14].

The correlation coefficient estimations for different combinations of parameters measured in two summer campaigns are summarized in Tab. 1. The ambient noise was recorded in the subsurface mixed layer. Only data for $U_{10} > 4$ m/s were used in the computing.

Table 1. Correlation coefficients between different data sets of wind, ambient noise and bubbles.

| Correlation coefficient | 2005 | 2006 |
|---|------|------|
| R (<i>wind speed, noise level</i>) | 0.90 | 0.81 |
| R (<i>wind speed, bubbles detection depth</i>) | 0.70 | 0.51 |
| R (<i>bubbles detection depth, noise</i>) | 0.71 | 0.64 |
| R (<i>characteristic depth, wind speed</i>) | 0.98 | 0.59 |

Regarding another direction of investigations we have started with examination of the noise sensitivity to wind wave's parameters, wave energy dissipation and frequency of breaking events. In addition, it is expected that the atmosphere stability could be used as a discriminator of the character of the atmospheric forcing, shaping the wind waves and subsequently noise generation. Some preliminary results of these investigations are presented in the paper presented at the Symposium by Dragan and Klusek [14, 17].

4. SUMMARY

Despite the fact that the some properties of the ambient sea noise in the Baltic Sea are not explained till today, its applications to monitor physical processes on the sea surface, biological activity and anthropogenic activities in the area are expected to be fruitfully.

More complete and extended investigations of relationships between the noise, wind, wind waves and gas bubbles, among others, are needed.

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