Underwater noise properties in waterway areas of the South Baltic Sea

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Results of underwater noise records completed with single and multi-hydrophone systems performed in the shallow water in the close vicinity of shipping lanes to the Gdansk/Gdynia and Świnoujście/Szczecin harbours are presented. Due to the fact that the bottom properties, bathymetry, and temporally varying sea surface alter the original sound spectra and reduce the acoustic energy, the sound transmission losses have been modelled, and an attempt to predict source levels of ships was performed. The KRAKEN sound propagation model illustrates the problems of the recognition of sources noise spectra on the basis of observations in a far zone from the sources. On the basis of the observed noise data, jointly with the AIS system the potential ecological effects of anthropogenic underwater noise on marine organisms are given for the Pomeranian Bight. In the paper, some examples of algorithms of ship noise recognition are given.

Keywords: shipping noise, shallow sea

1. Introduction

The principal contributors to underwater acoustic noise have been widely recognized for many decades [20]. They are a wind dependent component, biological sounds and technical sources. To the ever-present wind driven component of ambient noise, from the beginning of the XX century a substantial and continuously growing input is from ships. Distant traffic contributes to the acoustic background beginning from infrasound and low audible frequency range; and it is presumed that large geographic areas in the deep Ocean are affected by its influence [15].

Continuous increase of the size, engine power and speed of ships, results in the permanent increase of the noise radiated by a single ship [17]. Rising anthropogenic noise can lead to a disadvantageous influence on organisms living in the seas [7].

Manifold observations of ship noise, were carried out in different areas of the World Ocean, and a variety of empirical formulas regarding their spectra were proposed [16, 18, 19, 9, 13]. The main characteristics of those formulas are: slope of spectrum in the given frequency range; and source level dependency from ship speed, class, and other individualities. Main characteristics of ship noise can be summarized as follow: the noise is broadband, with pseudo harmonic components (mainly at low frequencies), emitted by various sources located inside of a ship. According to many investigators, averaged spectral density level of ship noise has a constant slope.

The Baltic Sea is one of the most heavily trafficked areas by ships in the world. According to Helcom at any given time there are around 2000 ships at sea in the Baltic (http://www.brisk.helcom.fi/risk_analysis/traffic/). The ship traffic density increases on the waterways in the vicinities of the main ports in Poland.

Numerous works investigated properties of noise emitted by different classes of ships, and noise classification was accomplished in the Baltic Sea by the Polish Navy ([12, 6, 8] as examples).

Ongoing BIAS program has more ambitious goals, to deliver maps of shipping noise in the entire Baltic Sea area (https://biasproject.wordpress.com/)

The main aims of this paper were to obtain temporal, spectral, and level characteristics of shipping noise; on the basis of data collected in the shallow waters, in the vicinity of the waterways to harbours.

2. Data acquisition and study area

The recordings of the acoustic noise were performed with autonomous underwater buoys equipped with calibrated hydrophones.

Three different passive acoustic systems were employed in the ambient noise observations:

a) four hydrophone system manufactured by IO PAS (Sopot, Poland) make available simultaneous acquisition and recordings of acoustical signals in frequency band from 7 or 60 Hz up to 15 000 Hz, depending on hydrophones and sampling frequency. Different types of hydrophones were used during various deployments.

b) a newly designed and constructed autonomous system (in the future envisaged as gathering data from a free-drifting platform) for underwater noise recording, manufactured by CEFAS (UK) equipped with a single hydrophone (Neptune, UK, sensitivity -170 dB re 1V/1 μPa and 24 bits dynamics of A/D converter;

c) WildAcoustic SM3M passive buoy commonly used for biological sound recordings (marine mammals such as whales or seals). The buoy was located at the sea bottom at the distance 500 m from the water lane, where the water depth was 13 meters. The hydrophone HTI 96-MIN, which is at the top of the buoy, was located 10 meters above the sea bottom.

More information, regarding the measurements, are in Table 1.

Tab.1. Basic information about conducted measurements.

Area and Time	System	Sea Depth/ Deployment depth [m]	Goal	Freq. band /dynamics/ sampling
Gdynia Harbour ship lane Apr. 2014/ Oct. 2015 400 m from the shipping lane	IO PAS buoy 4 hydrophones placed horizontally	20m / 12 m sandy bottom	Ship noise data collection for training purposes	63-12 500 Hz / 16 bits 30 000 samples/sec
Gulf of Gdansk Sept. 2014	vertical array of 4 hydrophones. from rubber boat	22m/ [2,8,14,20] sandy bottom	How are noise parameters changing with distance to a ship? Impact of movement of floating platform on noise	12-20 000 Hz / 16 bits 48 000 samples/sec
Pomeranian Bight 500 m from the shipping lane (Sept. 2015)	WildAcoustic SM3M buoy 1 hydrophone	13-15m/ 12m sandy bottom	Long term measurements	12-20000 Hz / 16 bits 48 000 samples/sec
Gdynia Harbour Nov. 2015 ~600 m from the ship lane	CEFAS – system deployed on the sea bottom 1 hydrophone	20m/~20m sandy bottom	Characteristics of the system, self-noise measurements, ship data collection	24 bits 30 000 samples/sec;
Gdansk/Gdynia between ship lanes to both harbours Jan. 2016	IO PAS buoy 4 hydrophones placed horizontally	28m/12m sandy bottom	Ship data collection for training purposes. Ship classification. Jointly with AIS	60-10 000 Hz / 16 bits 25 000 samples/sec

All the systems listed above provide the acquisition and collection of the complete raw acoustical data set, enabling further research and analysis of acoustic signatures. The software for analysis was developed in the MATLAB environment. The noise analysis includes, among others: statistical and spectral analysis, cross-correlation of signals between hydrophones, and tests of shipping noise-detection algorithms. In the case of multi hydrophones system, determination of bearing for different sources was also tested.

In our experiments, the sampling rate was changed during different deployments – from maximum 48 000 Hz down to 25 000 Hz.

The IOPAS noise buoy was equipped with three types of interchangeable sensors – hydrophones RESON TC4032, RESON TC4056 and HTI-96 MIN (High Tech Inc., USA). All sets of hydrophones have adequate recent calibration curves issued by the manufacturer (except of the HTI-96 where only one number for the whole frequency range is given). The hydrophones were arranged at the vertices of a horizontally located square, with the distance equal to 4.40 m between the opposite hydrophones.

The IO PAS buoy is fitted with a hydrostatic pressure sensor, compass and inclinometer which enabled identification of the 3D hydrophone positions, and allows us to identify not only the sound pressure and its derivatives, regulated in the recommendations of the EU, but also conducting a bearing of moving noise sources and therefore determining their speed.

3. Data analysis

The raw signals recorded on SD cards were later analyzed in the MATLAB environment, using software developed by the authors.

The basic characteristics of the sound pressure are exploited with the goal to detect and recognise the presence of the anthropogenic component in the underwater noise, and obtain noise statistics in both investigated areas.

Among them are:

a) the averaged noise level (NL) in decibels relative to a reference pressure (averaged over time, the mean square pressure – in dB re 1 μPa);
b) the power spectral density (PSD) and noise spectrum levels – in narrow and one-third octave frequency bands;
c) spectrum slopes in selected frequency bands;
d) cross-covariance functions and bearing to noise source;
e) histograms of averaged noise spectrum levels;
f) signal series statistics.

4. Results

4.1. Pomeranian Bight

The southern part of the Pomeranian Bight is a very shallow, plain area covered with fine sands, with characteristic depths less than 20 m. It is one of the most productive fish areas in the Baltic Sea, where prevailing species are herring and flounder. On the other side, it is an area with heavy maritime traffic entering and leaving the Baltic Sea. In the northern part, passing from the West-North to harbours Świnoujście/Szczecin and regular ferries passed to and from Scandinavia countries.

The measurements of underwater noise were made during the lowest fishery activity in the area. We should add that the hen itsmaximum activity is observed during the spring period, when spawning concentrations of fish are common.

Noise measurements were carried out at a distance about 500 m to the east from the shipping lane to Świnoujście (λ = 015° 07.58'E, φ = 54° 44.61'N) performed with a commercial off-the-shelf WildAcoustic SM3M buoy, equipped with one HTI-96 MIN hydrophone. Sensitivity of the hydrophone is given by the manufacturer.

Signals were sampled using the 16-bit analog to digital converter, with sampling frequency 48 kHz. The 3 minutes noise records were repeated with 10 minute periods.

Recording session started 09 Sept. 2015 00:00 UTC and was finished on 16 Sept. 2015 at 01:33 UTC. However, after 112 hours a nearby sound source started to emit almost constant noise. Thus, here our analysis is limited to the first 112 hours.

4.1.1. Noise characteristics in Pomeranian Bight

According to expectations, the highest contribution to the underwater noise in the area comes from nearby passing vessels.

The time series of the noise level in the frequency range 12.5 Hz – 10 kHz is given in Fig. 1. Presented data are averaged over a 3 minutes period (each record is followed by a 7 minute pause). The peak-finding algorithm ignores peaks that are very close to each other (less than 20 minutes) and less than 3 dB above the 7 data points central running average.

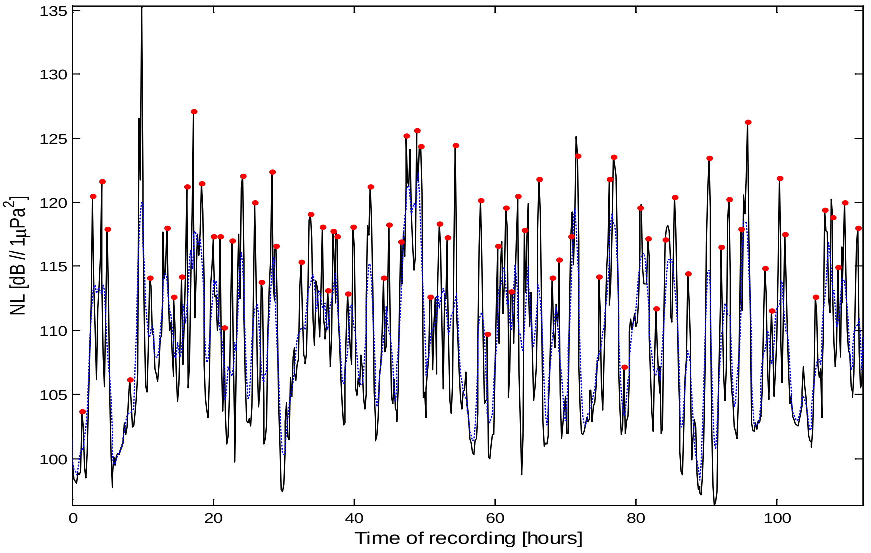

Fig. 1. The time series of the noise level in the frequency range 12.5 Hz – 10 kHz (solid line). Blue dot line represents the 7 data points central running average. Red points symbolize local maxima with distance +3 dB above the running average.

Even though the separation of the wind and ship input might not be possible, it is indisputable that local shipping noise is the dominant contributor in the whole frequency band. In the nearby presence of passing vessels, we always observed a rapid rise of the noise level, by 15-25 dB above the background noise (above local minima of the noise level) in the analysed frequency bands. However, smaller peaks probably from small or distant vessels are also noticed.

Numbers of acoustically identified passing ships for the period of 112 hours in different frequency bands, are presented in Table 2.

Tab.2. Number of identified ships in different frequency bands.

Frequency [Hz]	20	40	80	160	315	630	1250
Peak Number	78	81	88	88	83	77	62

On the basis of the time series of the noise level NL in the whole frequency range we counted 83 ships, which is generally close to the number of local maxima in the time series in frequency bands between 40 and 315 Hz. In autocovariance function of time series of noise power spectral density (in dB) in all 1/3 octave frequency bands, we notice local maximum with 24 hours lag (Fig.2). It is very probably connected with approximately the 24 hours periodicity of the ferry traffic. What is interesting, most of the time anthropogenic noise in our noise records, came only from one ship for a given period of time.

In Fig. 3 the relationship between the noise level in the broadband range and the spectrum level slope (estimated using linear approximation with the least-squares method in dB/octave) for frequencies from 500 Hz to 6300 Hz is shown. It is visible that there is negative correlation between spectrum slope and the noise level. The estimated spectrum slope in the presence of ship noise is steeper in comparison to the cases when wind driven ambient noise prevails, quite frequently exceeding -10 dB/octave.

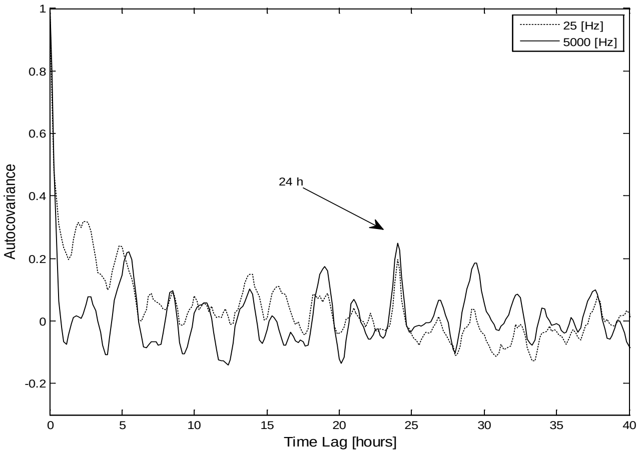

Fig. 2. Auto covariance function of time series in selected 1/3 octave frequency bands.
At all except of the lowest frequencies, i.e. 12.5-20 Hz, changes with 24 hour periodicity are clearly visible.

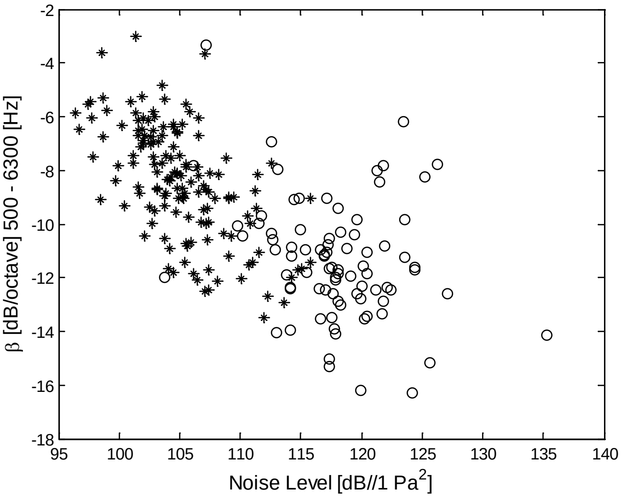

Fig. 3. Relationship between the observed noise level and the spectra slope (for frequency range 500-6300 Hz). Circles are for local maxima of the averaged noise level.

According to Ross [17] or Scrimger and Heitmeyer [18] the slope of the spectrum for all ship classes is linear and equal *-20 log(f,)* i.e. -6 dB/octave , where *f* is frequency in Hz. However, according to other investigators [19] the slope has a more complex form, changing with frequency, as – $NSL(f) \sim -(35.94 \log(f)+9.17 \log(1+f^2/340))$ which is closer to observed here data.

To describe the local shipping noise properties, we calculated time series of the Spectrum Density Level in 1/3-rd octave bands which are represented by histograms in Fig. 4.

The cumulative measure of the impact of the time-varying acoustic energy of sound on marine animals is a Sound Exposure Level (SEL) ([14] for example).

The mean SEL for day was calculated using an integration time of 180 s over the lower part of recorded bandwidth (12 Hz–10 kHz). The Sound Exposure Level at the point of the observation has been found equal to 158.5 dB re 1 μPa^2 s.

The frequencies of occurrence of PSD level values in one-third octave bands and SEL (per day) are similar to levels reported from other studied regions, reaching values that could interfere locally with behaviour of some marine species.

Representative for the period of measurements variations of the noise throughout the observations in select frequency bands are shown in the histograms in Fig. 4. In this figure, the frequency of occurrences of averaged over 3 min period noise spectrum level in 1/3 octave bands is displayed. Vertical lines in Fig.4 mark the herring hearing threshold for a given frequency. Hence, we can infer that at the hundreds of meters distances from the ship lane, anthropogenic noise in different frequency bands could disturb herring behaviour or increase stress level.

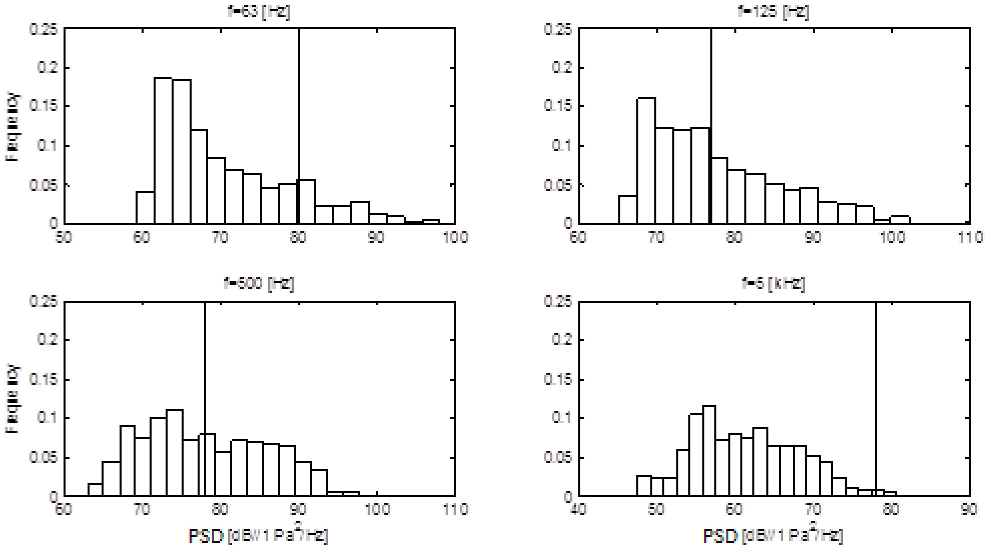

Fig. 4. Histograms of the noise spectrum level in selected 1/3 octave bands. Vertical lines are herring hearing thresholds [4].

Observed ship noise spectra are strongly influenced by sound propagation conditions, due to waveguide geometry and the bottom properties. For modelling of the sound exposure levels, or noise level statistics over the broader area, the KRAKEN normal mode program was exploited.

Based on known sediment properties in the area, the 2D transmission loss fields TL(z,r) for one-third octave bands and source depths 3-4 m have been computed.

In the model the effects of seawater absorption can be disregarded at short ranges and relatively low frequency regime. Due to water mass mixing the sound speed in the shallow water column is almost constant. Only, in quiet sunny days during afternoon hours a thin warm surface layer from solar heating is present.

The sediment characteristics used in the propagation models were based on literature descriptions of the sediment in the area [5], and the mean compressional sound speed was set according to Buckingham [3], as 1730 m/s. Sound attenuation values were taken from contemporary measurements of the frequency dependence of the seabed attenuation in the 50-

3000 Hz band given by Knobles et al. [11] – as an example for 1 kHz the attenuation coefficient is 1 dB km^{-1} Hz^{-1}.

Integrated over water column transmission losses in 1/3rd octave bands, at the distances up to 5000 m from and a source at depth 3 m are presented in Fig. 5.

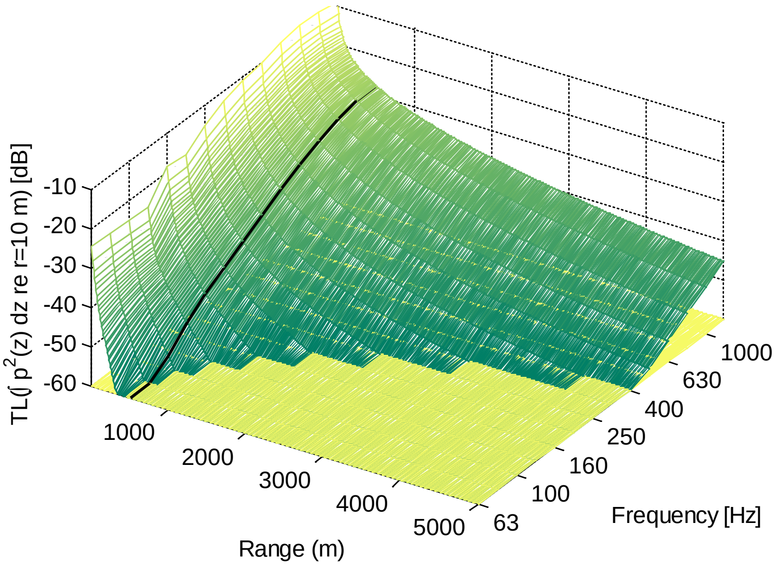

Fig. 5. Transmission losses of sound at different frequencies up to the range 5000 m from a source in the area surrounding the ship lane (mean sea depth 15 m); black line represent data for the distance 500 m from the source.

Even, at so short distance away from the source as 500m, however compared with many water depths, observed spectra of noise are distinctive in comparison to the spectra near a ship. Given exact spectra of source noise (ship) is hard to assess in intense ship traffic region; due to cut-off frequency below 100 Hz in shallow waters of the Pomeranian Bight, in very low frequency range ships contribute to ambient noise at ranges not exceeding a few kilometers.

4.2. Gulf of Gdansk

The measurement point was located near the fairway approach to the Gdynia port at a distance of 2 cables northerly to the navigational buoy GD, (λ = 018˚39.84, φ = 54˚32.07N) Depth at the harbor fairway and nearby area, is approximately 25.0 m. The recording point was selected as the compromise between the high intensity intermittent noise from local fairway traffic, and the ambient noise from more distant shipping, mostly ships heading for and coming out of the Gdansk Harbour.

Noise measurements were carried out with the IO PAS system with four HTI-96 MIN hydrophones at the distance about 3000m south from shipping lane to Gdynia harbour. Sensitivity of each of four hydrophone was around -170dB re V/µPa. Signals were sampled using the 16-bit analog system with sampling frequency 25 kHz. The 20 second noise records were repeated with 41 second period.

Recording session started 31 Jan. 2015 10:25 UTC and ended on 01 Feb. 2015 at 09:26 UTC, due to memory card failure. Analysis includes 23 hours of measurements. Results of observations of noise, at another point in the close vicinity to the water lane to the Gdynia harbor were presented in more details by Klusek et.al. [10].

4.2.2. Noise characteristics in Gulf of Gdansk

Results show that highest contribution to the underwater noise in the area comes from ship traffic on the waterways to Gdansk or Gdynia harbour. Due to the intense shipping, and short period of measurements, separation of the wind and ship component, that contribute to the noise field, was impossible. However in the presence of nearly passing ships, noise levels rose by 15-20 dB above the background noise.

For the purpose of ship traffic analysis in the region of acoustic measurements, information from Automatic Identification System (AIS) was collected, decoded and analyzed. Decoding and data analysis were conducted in the MATLAB environment by using specialized, to this purpose, programs. In order to eliminate an extended amount of data, we exclude from the analysis ships that have speed less than 0.5 knot and were further than 3704m (2Nm) from the place of acoustic buoy deployment.

During measurements heavy ship traffic was observed, 32 ships had transit through the analyzed area, where 3 of them had double transit and 1 triple. During whole measurements, a Trailing Suction Hopper Dredger ship was present in the region, and may have conducted active work, just about 14 km from the deployment of the acoustic buoy. Moreover, the research vessel “Oceania” was anchored at a distance about 2.5 km from the buoy during measurements. This distance to “Oceania” was tested before as safe, and not creating disturbances.

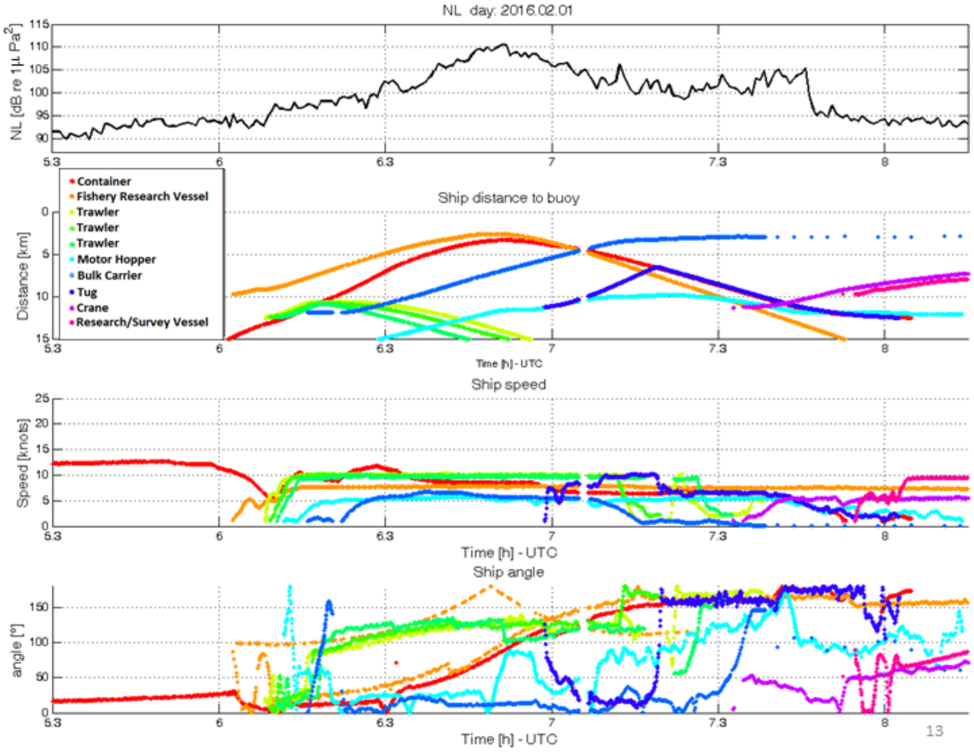

Fig. 6. From the top: 1) noise level changes [dB re 1μPa^2] during 3 hour of measurements 2) distance to ship [km] and class of ship 3) ship speed [knots] 4) ship relative orientation to IO PAS system, 0° - ship is oriented by bow in straight line to hydrophones, 180° - ship oriented by stern.

In the upper section of Fig.6 are presented changes of noise level during a 3 hour period. Below upper section, there is ship traffic information such as (in order from the top): distance to ship, speed of ship and also its orientation relative to the point of measurements. Ship angle 0° represents the situation when the ship is oriented, with the bow straight towards the buoy and 180° represent the ship observed from its stern side.

Intensifications of the Noise Levels are strictly connected with the distance to moving ships and their speed. Due to the intense traffic it is hard to estimate the contribution to noise level by single ship and therefore assess its source level.

What is interesting, that during the measurements we observe 3 times when a ship started to quickly reduce speed the strong harmonics components start to occur near 1 kHz, raising the Noise Level (example: 7:45 UTC, Fig.6).

Due to the shallow depth in the region of measurement, and uniform vertical temperature profile it is expected that spectra will be affected by transmission losses in similar manner as in the Pomeranian Bight, since the seabed is mostly covered by sands. The cut-off frequency is expected to be lower, than in the Pomeranian Bight due to the greater depth.

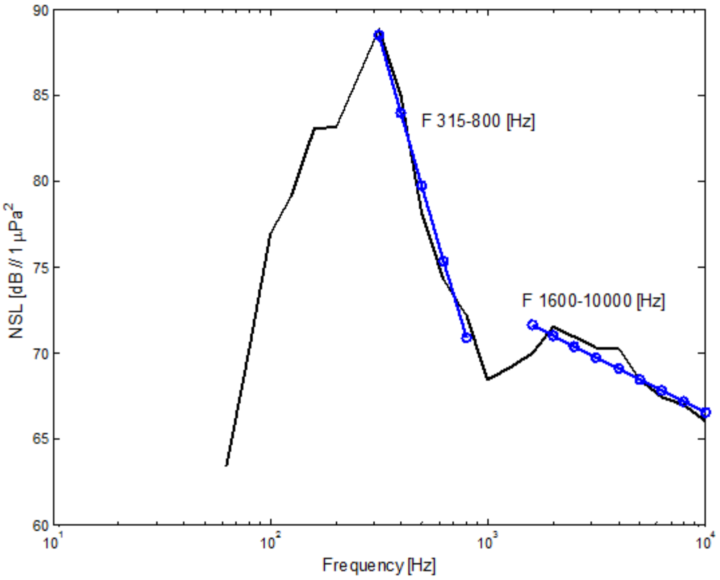

Fig. 7. Spectrum slope in two frequency ranges: 315-800 Hz and 1600 – 10000 Hz given for 1/3 octave spectrum.

It is commonly recognised that the typical spectrum of the Source Level of commercial ships have a maximum in the frequency range 20-200 Hz. However, their one-third octave spectra could have an additional local maximum at higher frequencies [12].

Fig. 7 shows average spectrum in 1/3 octave bands for 20s (one record). In the figure, lines with circle points represent the best fitted line to segments of given frequency ranges, for which spectral slope was calculated. Presented spectrum is a good representation of the situation when a ship is passing at a short distance (2.9 km - “general cargo” ship) in intense ship traffic region (3 other ships at distances up to 12 km) of Gdansk Bay.

There is a good relationship between changes of noise level due to the ship traffic, and the given spectrum slope changes (Fig.8). The relation is negative, when the noise level, due to ship traffic, is rising, the spectrum slope decreaes. The estimated spectrum slope in the presence of a ship is steeper if comparing to cases where wind driven noise is predominant. For frequency range from 315 - 815 Hz, spectrum slope reaches from -15 to -30 dB/octave, where in range 1.6 – 10 kHz it is exceeding -10 dB/octave, in the presence of ships. During the presented period there was one ship that had different spectrum, at 2:30 UTC, and therefore producing a different spectrum slope in 1.6 – 10 kHz range.

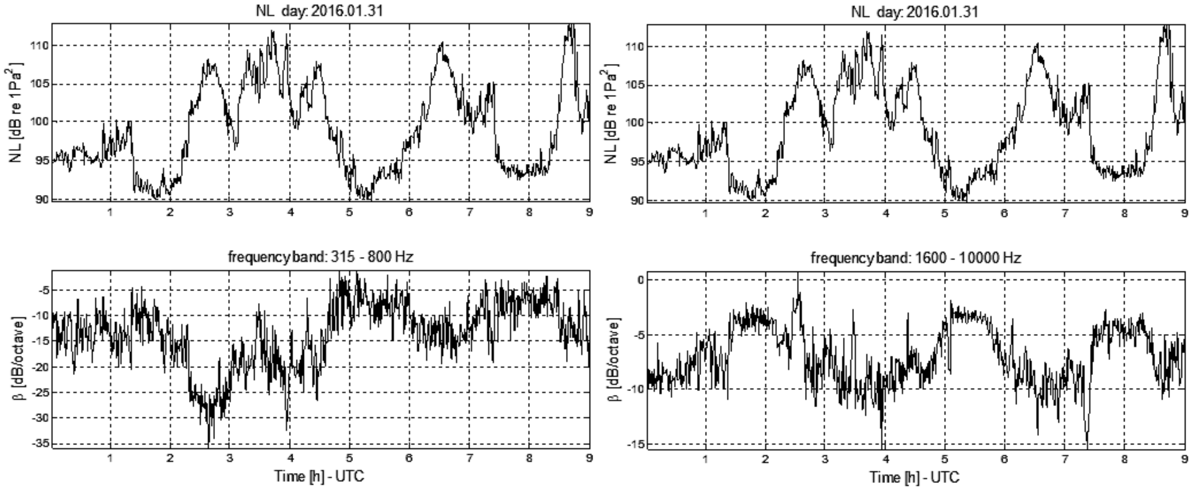

Fig. 8. Spectra slope for two frequency ranges 315-800 Hz and 1600-10000 Hz in 9h time period at 01.02.2015 in vicinity of waterways to Gdansk and Gdynia harbor.

5. Summary

Regions near waterways in vicinity to Gdynia/Gdansk and Świnoujście/Szczecin harbours characterise intense ship traffic which causes relative fast noise level changes, compared with wind driven noise. Due to the intensity of traffic it is hard to separate wind driven contribution from anthropogenic contribution. Nevertheless single passages of ships can be distinguished due to different spectra characteristics and high noise level, compared with periods with the lowest noise level during measurement.

In the Pomeranian Bight herring hearing thresholds, especially at 63Hz and 125 Hz are exceeded at distances 500 m from waterways, even by 30 dB, which may have a significant influence on herring behaviour.

Due to the shallow depth of the sea, frequencies below 100 Hz are highly attenuated, which leads to contribution from the frequencies only in distances up to few kilometres.

A reasonable interpretation of the results from a single ship, especially in the inner Gulf of Gdansk should be taken cautiously due to the fact of interference between multiple ship sources scattered in the area.

During the processing different algorithms aimed for the shipping noise recognition were tested for their usefulness. Examples of inputs for these algorithms are: spectrum slope in various frequency ranges, rate of exceeding some thresholds (noise of natural sources), spectra statistical properties etc. It looks, like we should apply various strategies to detect noise in different areas.

Because of the limitations in the amount of data we were able to collect, regarding weekly and seasonal changes of ship traffic, it would be useful to conduct some further tests in order to confirm the validity of statistics of sound characteristics. Due to temporal and space fluctuations the mobile vs. static observations are highly needed.

Acknowledgments

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