DOI: https://doi.org/10.52320/dav.v21i1.299

Assessment of Seismic Exploration Noise at Lithuanian Area of the Baltic Sea

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(Received in February, 2024; Accepted in February, 2024; Available Online from 10th of May, 2024)

Abstract
An article presents an evaluation of the underwater noise of the performed bottom seismic surveys in the waters of the Lithuanian Baltic Sea, analyzes the underwater noise levels that were determined by mathematical modelling. It presents an assessment of the risks posed to marine mammals by extremely high intensity underwater noise levels in the research area. Possibilities of underwater noise reduction for these noisy activities discussed.
***Key words**: Airgun, Baltic Sea, harbor porpoises, seismic surveys, underwater noise*

Anotacija
Šiame straipsnyje pateikiamas atliktų dugno seisminių tyrimų Lietuvos Baltijos jūros vandenyse sukeliamo povandeninio triukšmo vertinimas, analizuojami povandeninio triukšmo lygiai, kurie buvo nustatyti matematinio modeliavimo būdu. Atliekamas rizikų, kurios kyla jūrų žinduoliams dėl labai aukšto intensyvumo povandeninio triukšmo lygių, vertinimas. Aptariamos dugno seisminių tyrimų povandeninio triukšmo mažinimo galimybės.
***Reikšminiai žodžiai**: Baltijos jūra, dugno seisminiai tyrimai, jūrų kiaulė, povandeninis triukšmas.*

Introduction

The harbor porpoise (*Phocoena phocoena*) is the most common cetacean in northern Europe. The Baltic Proper sub-population listed as critically endangered by International Union for Conservation of Nature (IUCN). The Lithuanian area of the Baltic Sea (Eastern coast of the Baltic Sea) founds to be the foraging area for the Baltic Sea harbor porpoise sub-population (Kyhn et al., 2018). The harbor porpoises are known to be the high frequency cetaceans having the broad hearing range within the frequency bands of 0.125 – 150 kHz (Kastelein et al., 2017) covering the mid to ultrasonic sounds.

Towed airgun arrays used for marine geophysical exploration, producing the sound pulses by releasing compressed air, generating spherical broadband sound waves of short duration usually having high sound intensity. When fired simultaneously, the pulses of the individual airguns reinforce coherently in the direction perpendicular to the plane of the array, emitting the high-amplitude sound waves. These pulses inevitably can lead to the negative effects on the marine animals (Ainslie et al., 2019). The sound energy emitted by the moderate size airgun array corresponds to 243-249 decibel noise level reference to 1µPa^2 in the vertical direction, measured at 1-meter distance from the noise source (Landrø & Amundsen, 2010). While assessing the sound pressure levels in decibel scale, marine sound pressure levels (reference to 1 micro Pascal) can be compared with caution to decibel scale used in atmospheric acoustics, that has the values lower by 61.5 dB (Finfer at al., 2008).

An airgun pulses have its most of energy in the lower frequency bands, typically up to 1 kHz with the highest energy bellow 50 Hz. The seismic surveys often are made in the shallow waters, where sound wave favorable multipath propagation occurs forming the waveguide resulting with smaller attenuation of the sound waves. An airgun pulses in such environments will propagate considerable distances in the horizontal directions and will be detected by the aquatic animals many kilometers away from the noise source (Trimoreau, 2011). Although, the pulses of airgun array directed horizontally will emit the sound pressure levels lower by 15-24 decibel if compared to horizontal sea bottom direction (Landrø & Amundsen, 2010).

The frequency range of the highest acoustic energy radiated by the airgun array into the marine environment bellow 1 kHz overlap with the frequency range of the harbor porpoises. The

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DOI: https://doi.org/10.52320/dav.v21i1.299

hearing threshold of porpoises in the frequency range of 0.125 – 1 kHz lies within 126-81 dB re 1µPa^2 (Kastelein et al., 2017). This hearing threshold can be exceeded at considerable distances from the operating airgun array. In 2022 the seismic exploration activities were caried out with the purpose of the future development of the wind farms at Lithuanian area of the Baltic Sea (Offshorewind, 2023), lasting for 7 days in the shallow marine area having the size of ~883 km^2 (EPA, 2023). These noisy seismic exploration activities inevitably raised risks of hearing impairment of the harbor porpoises.

Methods

An airgun array, having the duty cycle of 10 pulses per minute, with the moving platform at 4 knots was used at Lithuanian area of the Baltic Sea, during the seismic exploration. The exploration area depicted in the Figure 1, located at eastern Baltic Sea coastal shallow area. The seismic surveys were implemented during the period of 22 – 29th July in 2022. The seismic air gun broadband source sound pressure level of 251 dB re 1µPa^2 reported initially at 2.5 m Sea depth (EPA, 2023).

The Svein Vaage airgun test (recorded on 2008-05-22, trace No.19) source sound pulse signature was used to model an airgun signal used in the Lithuanian area of the Baltic Sea. The Svein Vaage airgun test pulse originally was recorded using the shot pulse of 0.98 liter (60 in^3) airgun operating with 13.79 MPa pressure at 6 m Sea depth, with resulting measured SPL of 219.6 dB re 1µPa^2 at 1 meter distance. The scaling laws (*S3*) were applied to obtain the reference 0.65 liter, 4 chamber airgun array source pulse signal (Sman, 2020).

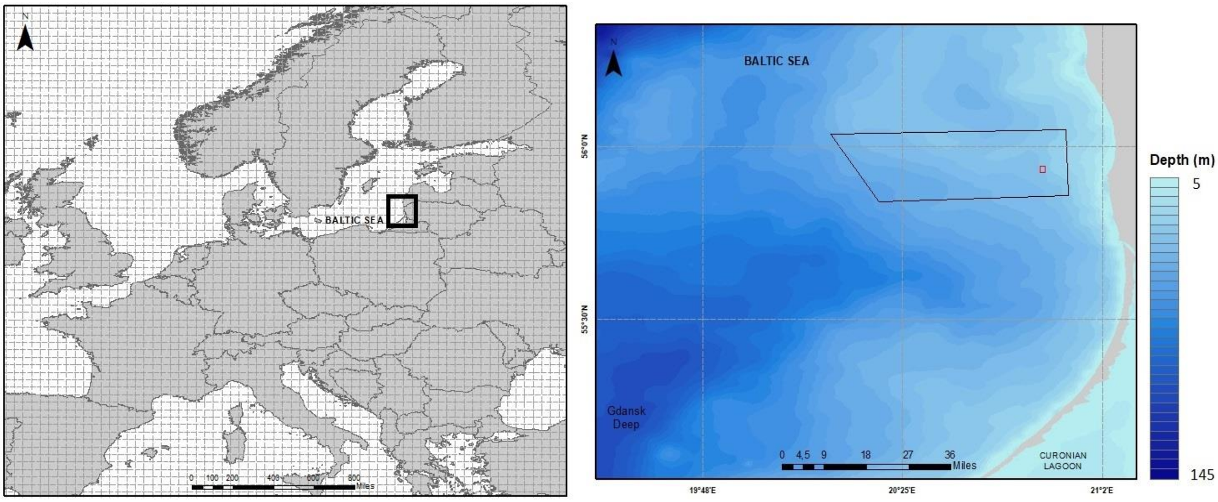

Fig. 1. Left panel – Lithuanian area of the Baltic Sea. Right panel – shallow research location. Red square marks modelled reference airgun array source and the SSP data acquisition area.

1 Pav. *Tyrimų vietovė. Dešiniame paveikslе raudona spalva pažymėta triukšmo šaltinio bei garso greičio duomenų modeliavimo vietovė.*

The scaled airgun array near field source pulse waveform data were processed to acquire the power spectral density levels using the MATLAB® software, applying the *Fast Furrier Transform* (FFT) with the size of 8192 bins, *Hanning* window with 50% overlap, in 0.02 – 10 kHz frequency range (1 Hz frequency bins).

The sound exposure levels of airgun pulses were equated using the equation (Erbe, 2011):

$$L_{S,E} = 10log_{10}\left(\int_T P(t)^2 dt\right) \qquad 1)$$

where $L_{S,E,}$ is the sound exposure level (dB re 1µPa^2.s), P is the airgun sound pressure (Pa), t is the integration time (1 s).

Sound propagation losses were modelled using the Normal Mode model (OALIB, 2023), using the sound speed profiling data and assuming the environment with the constant water depth

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(resulting depth of 40 meters) and the sediment thickness. The sound propagation modelling was completed using the 500 m range steps for the 50 km distance, from the area with the reference pulse emitted by the airgun array, directed to the West (270˚ azimuthal direction).

The sound speed data (SSP) purposed for sound propagation loss modelling were derived from the oceanographic database (GOPAF, 2023). The SSP data were acquired at research location on the 23th and 28th of July 2022, using the Temperature-Salinity-Depth model (Leroy et al., 2008), resulting with the negative gradient, having the magnitude of 1.03 s^{-1}, reflecting the environmental conditions, during the seismic exploration. The following Temperature-Salinity-Depth model is given by:

$$c = 1402.5 + 5T - 5.44 \times 10^{-2}T^2 + 2.1 \times 10^{-4}T^3 + 1.33S - 1.23 \times 10^{-2}ST + 8.7 \times 10^{-5}ST^2 + 1.56 \times 10^{-2}Z + 2.55 \times 10^{-7}Z^2 - 7.3 \times 10^{-12}Z^3 + 1.2 \times 10^{-6}Z(\phi - 45) - 9.5 \times 10^{-13}TZ^3 + 3 \times 10^{-7}T^2Z + 1.43 \times 10^{-5}SZ \qquad 2)$$

where c is the sound speed (m/s), T is the temperature (°C), S – salinity (‰), ϕ is the latitude in degrees.

The bathymetry data needed for sound propagation modelling were acquired from the Baltic Sea Hydrographic Commission database (BSHC, 2013).

The high frequency mammal auditory weighting function was used to assess the HF mammal hearing threshold levels for harbor porpoises (NMFS, 2018). The typical harbor porpoise behavioral hearing audiogram (3 year old male porpoise) is depicted in the Figure 2

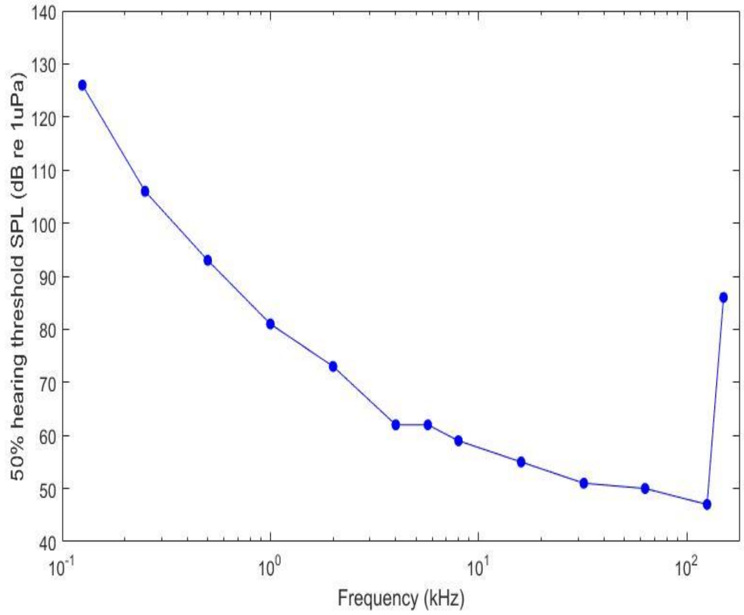

Fig. 2. 50th percentile harbor porpoise behavioral hearing audiogram (Kastelein et al., 2017)
2 Pav. *Jūros kiaulių povandeninė audiograma (klausos slenkstis, mediana) (Kastelein ir kt., 2017)*

The HF cetacean auditory weighting function, applied to assess the sound exposure of harbor porpoises, is given by (NMFS, 2018; Ainslie et al., 2022):

$$W_f = C + 10log_{10}\left\{\frac{({}^{f}/_{f_1})^{2a}}{[1 + ({}^{f}/_{f_1})^2]^a[1 + ({}^{f}/_{f_2})^2]^b}\right\} \qquad 3)$$

where W_f is the sound amplitude weighting function (dB), f is the sound frequency (Hz), a equal to 1.8 (high frequency exponent), b equal to 2 (HF exponent), f_1 is the low-frequency cutoff equal to 12 kHz, f_2 is the high-frequency cutoff, equal to 140 kHz, C is the weighting function gain,

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equal to 1.36 decibel. The hearing permanent threshold shift (PTS) threshold of the high frequency cetaceans (HF) was used, as a reference to assess the risks of negative impulsive noise effects, equal to $L_{S,E}$ = 155 dB re 1μPa^2.s. For the evaluation of the animal sound exposure the low frequency cut-off filter of 275 Hz was used to apply the harbor porpoise hearing auditory weighting in the frequency range under analysis. The 24 hours animal exposure to noise time interval considered to define the cumulative sound exposure levels (recommended duty cycle).

The kurtosis parameter of the airgun array source pulse noise was defined according to the ISO 18405:2017:

$$\beta = \frac{\frac{1}{t_2 - t_1}\int_{t_1}^{t_2}[p(t) - \bar{p}]^4 dt}{(\frac{1}{t_2 - t_1}\int_{t_1}^{t_2}[p(t) - \bar{p}]^2\, dt)^2} \quad (4)$$

where β is the kurtosis parameter, given by μ_4/μ_2^2, μ_n is the nth moment of the sound pressure, μ_2 is the sound pressure variance and $\bar{p}$ is mean sound pressure at the same time period.

Results

The initial source sound pressure level of 251 dB re 1μPa^2, of an airgun array shot was reduced by 20 decibel, to account the realistic sound pressure levels of the group of airguns instead of the nominal theoretical point source levels (after Landrø & Amundsen, 2010). The resulting source sound pressure of the airgun array pulse equal to 231 dB re 1μPa^2 was used to compare the further modelled reference SPL of the airgun array pulse. The reference pulse waveform was scaled to reflect the airgun pulse, having the 4 chambers of 0.65 liter volume (scaling factor of 1.5$^{1/3}$ for 4 chambers). The scaled pulse source near field waveform depicted in the Figure 3.A.

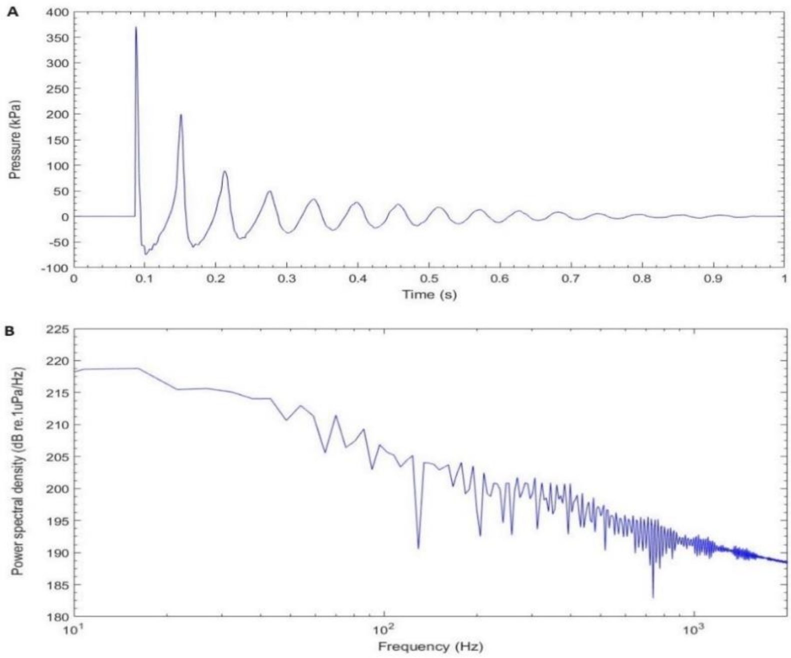

Fig. 3. Upper panel – scaled airgun array source near field pulse waveform (amplitude kPa); Lower panel – FFT transformed spectra of the airgun array source near field pulse signal

3 Pav. *A – apskaičiuota garso patrankos artimojo lauko šaltinio garso amplitude; B - garso patrankos artimojo lauko šaltinio garso amplitudes spektras (Greitoji Furjė transformacija)*

The defined scaled pulse bubble period τ is equal to 64 ms. Nearfield Peak wave to first bubble ratio PBR=P/B is equal to 1.86. The summary of the scaled airgun array near field source pulse characteristics given in the Table 1.

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Table 1. Airgun array near field source pulse characteristics

PARAMETER	RESULT
Source depth	6.0 m
Duty cycle	10 pulse/min
Sound pressure	369.6 kPa
SPL (rms)	231.4 dB re 1μPa^2
SPL (Z to P)	237.4 dB re 1μPa^2
$S_{L,E}$ HF (24 h)*	242.9 dB re 1μPa^2.s
$S_{L,E}$ HF PTS_{imp} threshold	155.0 dB re 1μPa^2.s
Bubble period	64.0 ms
Peak to bubble ratio (PBR)	1.86
Kurtosis parameter (1 sec signal)	42.3
Center frequency	316 Hz
Dominant frequency (1/T)	15.6 Hz
**Assumed noise accumulation period within 24 h period, with the duty cycle of 10 pulses/minute*	

Scaled pulse power spectra depicted in the Figure 3.B. The highest sound power of the obtained pulse prevailed in the frequncy bands bellow 500 Hz. Defined dominant frequency is euqal to 15.6 Hz. The spectral components in the higher end of the spectra have shaped with the magnitude of –10 decibel/decade.

In the Figure 4.A it can be found the decay graph of the power spectral density levels due to sound wave propagation in the marine environment. Modeling results revealed the considerably higher decay of the airgun array pulse source levels at higher frequency tail of the spectra in comparison to the low frequency end. The source levels above 2 kHz although, notably propagated with the distances of tenths kilometers conveying relatively high noise energy audible for harbour porpoises.

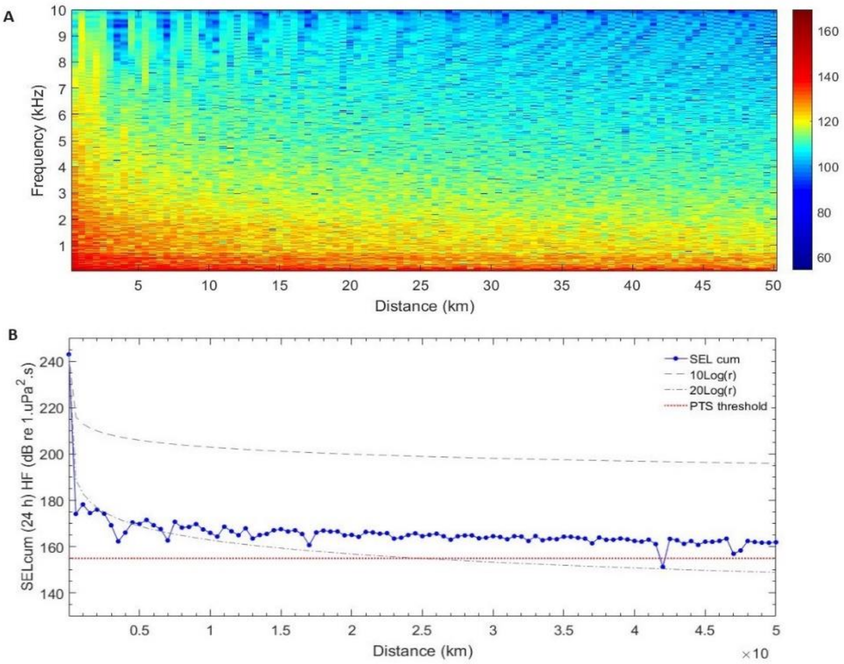

Fig. 4. Upper panel – decay of the spectral power density levels with distance (color bar – units dB re 1μPa^2/Hz); lower panel – decay of the SEL cumulative (24 h) with distance (red line – harbor porpoise PTS hearing threshold)

4 Pav. *A – Garso patrankos garso spektro reikšmių pokytis kintant atstumui (vienetai dB@1μPa^2/Hz); B - Garso patrankos išspinduliuoto garso ekspozicijos lygio silpimas kintant atstumui (raudona punktyrinė linija žymi jūros kiaulių klausos slenkstį)*

The broadband sound propagation losses of the weighted HF cumulative sound exposure levels revealed the exceedance of the mammal PTS (24-hour accumulation) with the distance beyond 50 km from the airgun noise source location. The graph of the decay of the sound exposure

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levels is depicted in the Figure 4.B. In addition, the sound propagation losses in the Figure 4.B compared against the geometric sound propagation loss laws.

Discussion

The seismic exploration research conducted at Lithuanian area of the Baltic Sea within the period of 22 – 28th of July in 2022. The area occupied by the seismic exploration activities extended in 883 km^2, in the shallow territorial waters and Exclusive economic zone of Lithuania. The sound pressure of the airgun pulse reached the 369.6 kPa with the resulting spectra of the source pulse having the greatest sound energy in the low frequency bands. Typical volumes of airguns used for exploration vary from 0.33 liter (20 in^3) to 13.1 liter (800 in^3) at some exclusion can be used volumes up to 26.2 liter (1600 in^3). Airgun arrays usually are constructed from 18-48 individual guns, although at some cases 100 single airguns can form an array. The common individual gun pressure is 13.79 MPa (2,000 psi). Typical airgun arrays usually emit the source sound pressure levels within 243-249 dB re 1 μPa^2. The technique of arranging few (2-4) airguns in a cluster close together to make them to behave as a larger single gun is often used with the aim to improve signal characteristics (Landrø & Amundsen, 2010). During seismic exploration in the shallow Lithuanian area of the Baltic Sea the four single airguns arranged in the array were used, each having the 0.65 liter (40 in^3) volume. The pulse of this array was synthesized using the S^3 scaling laws to obtain the source spectra. An estimate of the source sound pressure levels of the airgun array used in Lithuanian marine waters yielded the 231.4 dB re 1μPa^2 (in comparison the initial theoretical SPL of 231 dB re 1μPa^2) and the kurtosis parameter equals to 42.3 (Gaussian distribution equals to 3). The kurtosis parameter reflects the impulsiveness of the sound signal and can be interpreted as the parameter signifying the additional risk level of physiological impact on marine animals. To roughly compare the kurtosis parameter for 2.46 liter (150 in^3) single chamber airgun pulse lasting for 2 seconds estimates to 122.1 (Müller et al., 2020). From the obtained estimates it can be assumed, that the airgun array used in Lithuanian marine waters was comparatively small. I.e. an array, having the total volume of 55.67 liters (3397 in^3) would emit the sound pressure equal to 260 dB re 1μPa^2 Peak to Peak amplitude (Landrø & Amundsen, 2010).

The sound propagation loss modelling revealed the higher propagation losses in the higher end of the spectra. The combination of these spectral properties – the lower sound power levels in the higher frequencies and the higher sound wave propagation losses in the higher frequencies led to the estimates of the propagated pulse spectra, having the sound power levels above 124 decibels in frequency bands below 5 kHz. The sound power levels in the frequency bands above 5 kHz estimated as considerably lower, even at the shorter distances. The threshold of 124 dB re 1μPa^2 is known to be a roughly defined "effective quiet" - the highest SPL that would not produce a significant hearing temporary threshold shift of mammals or affect the recovery from a TTS produced by a prior, higher-level exposure in their most sensitive frequencies (Finneran, 2015). The most sensitive hearing range of harbor porpoises is experimentally defined as lying within 16-140 kHz. Although the hearing thresholds of harbor porpoises in the frequencies of 0.25-5.7 kHz still lie in the 62-106 dB re1μPa^2 range, where the slope of the audiogram has the magnitude of 30 dB per decade. When the SPL increases beyond effective quiet, the relationship between TTS and SPL becomes exponential, so that TTS increases with SPL in an accelerating fashion. Some of these TTS experiments were conducted with harbor porpoises using the 4 kHz experimental sound signals (Kastelein et al., 2012; Kastelein et al., 2017). As found by Hermannsen et al., (2015) harbor porpoises can be affected by single chamber 0.65 liter airgun arrays at distances extending beyond 1300 m, in the frequency bands up to 10 kHz. Its notable that during this study the estimates of the high frequency mammal auditory weighted sound exposure levels (HF weighted for 24-hour duration) resulted with the values above the threshold of the PTS with the distances beyond the 50 kilometers. Taking the radii of 50 km the area exposed to impulsive noise exceeding the harbor

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porpoise PTS threshold, roughly would cover an area of 7800 km^2. This area exceeds the Lithuanian territorial waters and Exclusive economic zone, that covers 6400 km^2 (BISE, 2023). It implies that the exceedance of the PTS threshold of harbor porpoises was reached in the significant area of the Lithuanian marine waters during the seismic exploration in 2022, that lasted for 7 days and foraging areas of harbor porpoises were potentially exposed to impulsive sound of high intensity.

There were not any mitigation measures reported in the Lithuanian marine waters during seismic exploration. Mitigation measures are known to be effective and are listed as replacement of airguns by vibroseis systems, that can produce lower peak to peak sound pressure levels by 12 dB at distances extending up to 5 km (Duncan et al., 2017); usage of lowest possible source levels of airguns; ceasing of the firing of airguns when the survey vessel transits between survey lines (Merchant, 2019); replacement of the airguns with technologies that utilizes minimized noise in high frequencies; pre-survey marine mammal searches; rump-up (soft start); use of exclusion zones (Bröker, 2019).

Conclusions

1. The seismic exploration activities were implemented in the shallow Lithuanian marine waters using an airgun array emitting the SPL of 231.4 dB re 1μPa^2, that lasted for the 7 days period. This high SPL's of an airgun pulse are comparable to underwater sound energy emitted by detonated explosives in marine environment;
2. Modelling results shows that SPL's of the airgun pulses propagated considerable distances and prevailed in very large part of the area of the Lithuanian marine waters, exceeding the hearing impairment threshold of harbor porpoises, causing the risks to these marine mammals;
3. The underwater noise measurements of the airgun pulses in the Lithuanian area of the Baltic Sea are needed to describe the particular noise levels in more detail during the future seismic explorations;
4. By the date, the demand of the seismic exploration mitigation and environmental impact assessment policy measures exists, as these measures are not mandatory at present in Lithuanian marine waters.

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Seisminių jūros dugno tyrimų povandeninio triukšmo vertinimas Lietuvos Baltijos jūros teritorijoje

(Gauta 2024 m. vasario mėn.; atiduota spaudai 2024 m.vasario mėn.; prieiga internete nuo 2024 m. gegužės 10 d.)

Santrauka

Norint ištirti geologines, požemines jūros dugno struktūras, atliekami akustiniai-seisminiai dugno tyrimai. Dažniausiai šiam tikslui jūrose yra naudojamos akustinės garso patrankos, velkamos tyrimų laivu. Ši akustinė įranga spinduliuoja labai aukšto intensyvumo garso signalus, nukreiptus į jūros dugno sluoksnius. Tačiau seisminių dugno tyrimų metu išspinduliuota povandeninio garso energija sklinda ne tik vertikalia bet ir horizontalia kryptimis

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nukeliaudama šimtus, o kartais ir tūkstančius, kilometrų vandenynuose ir jūrose dėl garso sklidimo ypatybių jūrinėje aplinkoje. Dugno seisminių tyrimų garso bangos, sklisdamos jūrose dideliais atstumais, gali neigiamai paveikti įvarius jūros gyvūnus. Šie neigiamai poveikiai gali pasireikšti įvairiomis formomis – nuo žuvų priegaudos sumažėjimo iki jūros žinduolių pasitraukimo iš jų buveinių. 2022 m. Lietuvos jūriniuose vandenyse buvo atliekami dugno seisminiai tyrimai, kurių metu buvo tiriamos vietovės būsimiems vėjo jėgainių parkams vystyti. Atliktų dugno seisminių tyrimų metu nebuvo naudojamos triukšmo mažinimo priemonės, taip pat nebuvo vertinamas šių veiklų neigiamas poveikis gyvūnijai prieš atliekant šias triukšmingas veiklas. Šiame straipsnyje pateikiamas Lietuvos jūriniuose vandenyse atliktų dugno seisminių tyrimų triukšmingumo bei šių veiklų sukeliamų rizikų jūrų kiaulėms vertinimas.

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