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Underwater noise generated by the detonation of historical ordnance in the Baltic Sea, Lithuania: potential ecological impacts on marine life

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Abstract The removal of ordnance and ammunition followed by high levels of impulsive noise is implemented yearly in the Lithuanian area of the Baltic Sea. During the international naval exercise Open Spirit (Summer 2013), an acoustical survey (using submersible cable hydrophone) was conducted in order to measure the underwater impulsive noise levels produced by controlled detonation and to assess their potential ecological impacts. The findings indicate a high noise energy level of explosions having a particularly small weight of charges, reaching up to 190 dB (in low-frequency bands) and theoretical estimations of the initial shock wave of 276 dB.

Keywords *•Acoustics • Underwater explosion • Aquatic life*

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INTRODUCTION

In the marine environment, explosives are used for several purposes including construction, mining, removal of unwanted structures, ship shock trials, military operations or exercises, as well as small charges to deter marine mammals i.e. seal bombs or catch fish i.e. blast fishing (Hildebrand 2009). Underwater explosions are one of the strongest point sources of anthropogenic sound in the marine environment (UNEP 2012). Moreover, underwater explosions are the contributor to the overall background underwater noise level (Frisk *et al.* 2003; UNEP 2012). Approximately 175,000 mines were laid in the Baltic Sea during the World Wars of the 20th century. Thus, in a former mined areas, ~10–30% (in some areas, up to 80%) of the mines remain on the seabed. Subsequent studies of historical minefields have identified 1,985 minefields on the seabed (Fig. 1) (Möller 2011). Consequently, mine clearance operations are implemented yearly in the Lithuanian area of the Baltic Sea. Within the period of 1997–2013, 159 different mines were exploded (Lithuanian NAVY 2013, pers. comm.). Underwater explosions by themselves generate low-frequency shock waves and subsequent pulsations of the bubble sphere at high pressure (Tan 2008), which propagates for long distances, due to decreased attenuation of a low-frequency sound in Seawater (Withlow, Hastings 2008). A high level of impulsive noise has an ecological impact and leads to death risks of animals at the very close proximity to the explosion i.e. < 100 m (Ketten 1995). At the longer range, acoustic traumas (permanent threshold shift) or temporary hearing impairment (temporary threshold shift) can occur. At relatively remote distances, a perturbation of animal's life cycle has been reported (Ketten 1995; Southall *et al.* 2007).

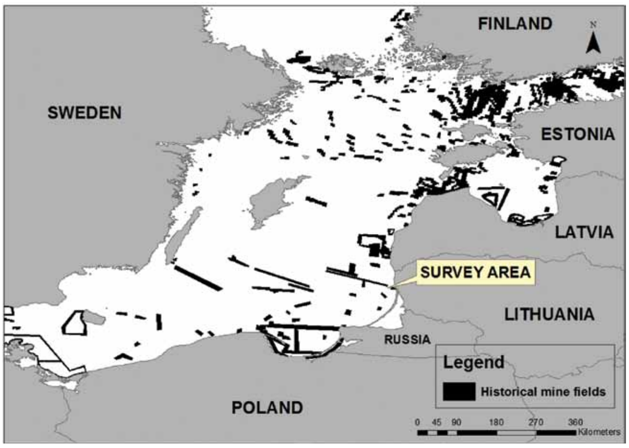

Fig. 1 The survey area and historical mine fields laid on the Baltic Sea bed (after Möller 2011).

In the Baltic Sea area, few studies have addressed the impact of explosions on marine animals. In a survey conducted by Schmidtke *et al.* (2009), the TNT charges of 1 kg and 300 kg were exploded in German waters at a 20 m depth to assess the noise mitigation measures. Sundermeyer *et al.* (2012) used a series of a small test charges in shallow coastal German waters to examine noise impacts on harbour porpoises (*Phocaena phocaena*). Here, the author presents the results of recent acoustic surveys of five noise events produced by detonating charges of a small weight in the shallow (<50 m) of the Lithuanian sector of Baltic Sea. The noise propagating in shallow water attenuates faster than in deeper regions due to extensive reflections of sound waves from the sea surface and bottom (Withlow, Hastings 2008). Although measurements of the explosions have been completed in very shallow water (<50 m), the transmission loss computations show that a low frequency noise propagated for up to 10 km.

The Lithuanian waters are brackish and well mixed (Leparanta, Myrberg 2009) and bottom has no abrupt ridges or seamounts. The sandy bottom sediments dominate in a survey area making its contribution to sound propagation attenuation (Withlow, Hastings 2008; Gelumbauskaitė *et al.* 1999). All these environmental factors produce unique noise propagation conditions. Due to favourable propagation of the noise for distances of kilometres, aquatic mammals, such as grey seals (*Halichoerus grypus fabricius*), and a variety of near shore fish species are potentially threatened during ordnance detonation. The aim of this paper is to present the results of controlled detonation and to assess the potential risks of these noise levels to marine animals.

METHODS

During the period of 2012–2013, as part of the international naval exercise Open Spirit, the acoustic survey was conducted aboard of the vessel M54 "Kuršis" and P11 „Žemaitis" using the hydrophone system H2A with a recording devise ZOOM H1. The effective frequency range of the hydrophone is 0.01–100.00 KHz, with effective recording range of 0.02–48.00 KHz where the hydrophone set has a sensitivity error +/- 4 dB re 1 V/µPa. The data were analysed using 96.00 KHz sampling frequency and 16-bit accuracy. The exploded charges had weights of 0.54, 2, 12, and 24 kg of TNT equivalent. The charges were detonated at different distances from the shore, at depths varying between 28–47 m. The hydrophone was submerged to 15–28 m depth, at a safe distance from the explosion sites (370–725 m).

Acoustic data files were analysed using professional audio software RAVEN PRO v.1.4 and post–processed using MATLAB v7.1 software. Spectral analysis of the audio data was completed using both spectrogram and selection spectrum modes in the RAVEN PRO 1.4 software suite. The software divides a sound (or a selected portion of a sound) into a series of successive short time segments, or records, and calculates a single spectrum for each record using the discrete Fourier transform (DFT) algorithm for the entire sound sequence (Charif *et al.* 2010). The data have been analysed using a selected spectrum computed using 65,536 samples (for visualisation – 3,000 samples) and 512 samples for spectrogram in the hanning window. An initial shock wave is calculated by the relation:

$$SPL_{rms} = 269\ dB + 7.53*log_{10}(w) \quad (1),$$

where SPL_{rms} is a root mean squared sound pressure level at 1 m from an explosion, and *w* – charge weight in pounds (dos Santos *et al.* 2010). For charges with the TNT and C4 mix, the TNT equivalent is calculated using the relation of TNT_{mass} equal to $C4_{mass}*1.19$ (Ackland *et al.* 2012). Sound speed profiling was completed by the Lithuanian Navy varied slightly, depending on a measurement day ("afternoon effect", Whitlow, Hastings 2008). Sound speed profiles measured on August 2013 are given (Fig. 2).

Sound transmission losses were modelled using ACTUP v2.2L underwater acoustic propagation modelling software with RAMgeo parabolic equation algorithm (Maggi, Duncan 2005). Environmental parameters for the computations were chosen as follows: seasonal SSP for a small charge (LMSA 2011), an actual SSP for bigger charges (Fig. 2), the bathymetry data which was of 5 years old (IOW 2008), the substrate type and substrate acoustical parameters (primarily sandy–silty bottom, Gelumbauskaite *et al.* 1999; Jensen *et al.* 2011; Chakraborty, Raju 1994). A noise of explosion with a charge of 24 kg TNT with a 187 Hz centre frequency was chosen for the transmission loss computations. Transmission losses computed starting from a blast position N55°40.45' E20°47.17' (~ 20 km from the coast) along 32 bearings, at every 11.25° azimuth angle since spatial analysis is possible running the 2D models (2D x N method, which ignores horizontal refraction) repeatedly along a number of different bearings (Jensen *et al.* 2011).

The potential risks to marine animals are described using criteria presented in the scientific literature.

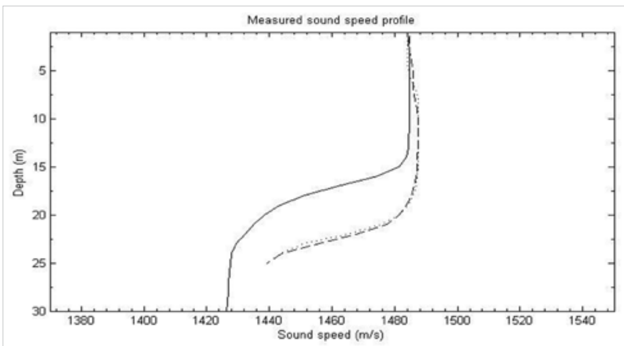

Fig. 2 SSP measured in the Lithuanian Baltic Sea area: even line measured on 22 August, dashed line on 25 August and dotted line on 26 August (NAVY 2013).

Direct auditory tissue effects (injury) and behavioural disturbance were considered using marine mammal exposure indicators (Southall *et al.* 2007). The risks of lethal injuries in close proximity of animals to the explosions are described by Ketten *et al.* (1995) and can be as severe as a partial loss of hearing (damage of inner ear organs) or a complete inner ear damage (or brain trauma). Ketten *et al.* (1995) also describe lethal zones for fish in a close proximity to blasts. Hastings *et al.* (1996) sets a threshold for a fish inner ear injury similar to Nedwell *et al.* (2007), who propose generalised criteria for different effects on animals. However, behavioural criteria for fishes are not described as authors usually refer to the lack of data (Webb *et al.* 2008).

RESULTS

The measurements were completed by sequence: the test case (0.54 kg TNT explosion) was measured in October, 2012 and the series of small charges explosions were recorded in August, 2013. Based on field measurements, the noise energy and shock wave pressure exhibit relatively high levels (Table 1). All measured noise events have a sound exposure levels higher than 175 dB, with low centre frequencies between 187–375 Hz (except a small charge of 0.54 kg).

The estimated shock wave noise levels are found to reach the values higher than 264 dB (rms), which is weighty in a close proximity to the explosion. The pulse durations vary from 1.0 to 1.2 s, which is substantially longer compared with the small charge of 0.54 Kg lasting for 0.1 s. The presence of the bubble pulse in the received signal often acts to increase the calculated signal time without contributing significantly to the total energy content of the signal (McCauley *et al.* 2007). The Figure 3A shows a spectral view of the explosion (24 kg TNT), where the pulse has an initial sudden rise of the amplitude and a subsequent bubble sphere pulsation lasting almost 1.5 s. The Figure 3B shows a power spectral density levels and their dependency on frequency at 1 m from the noise source. The power spectral density reaches a peak level at the low frequency band of 97 Hz, which is significant because a low-frequency sound has lower attenuation in water, thereby transmitting energy for longer distances compared to a higher-frequency component (Withlow, Hastings 2008). The Figure 4A shows a range dependent; Figure 4B the range – depth dependent transmission loss computation results for a 24 kg charge. The 0 m range shows the initial position of a sound event, the range of 10,000 m indicates the position of a hypothetical receiver in the northern direction from the noise source (at 15 m depth). The transmission losses computed along 32 bearings (360º coverage) reveal variations of transmission loss at the different directions average of 10–15 dB due to depth change and convergence–divergence of sound waves (see Lurton 2010).

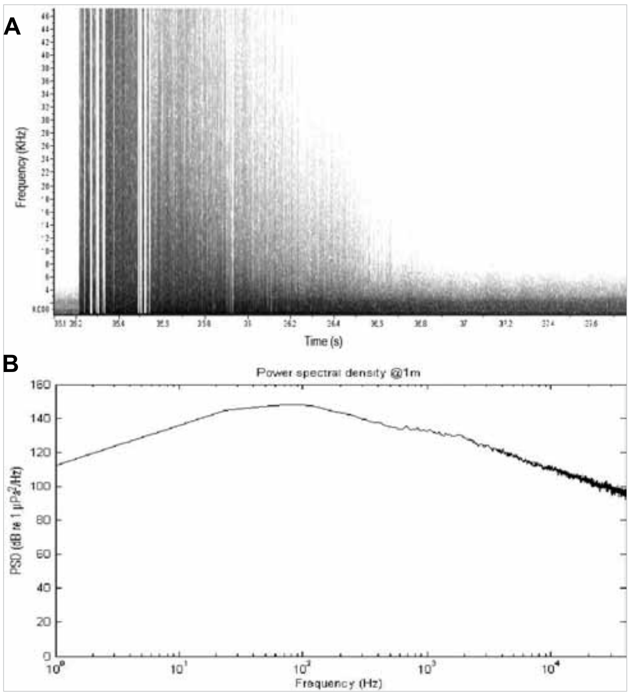

Fig. 3 A. Underwater noise spectra. **B.** Power spectral density on a logarithmic scale (24 kg TNT explosion).

Table 1 Underwater noise measurement results.

Parameter	0.54 Kg TNT	5.2 Kg TNT	12 Kg TNT	24 Kg TNT
Depth of explosion	28 m	44 m	44 m	44 m
Depth of hydrophone	26 m	15 m	15 m	15 m
Pulse duration	0.1 s	1 s	1 s	1.2 s
Centre frequency	1687 Hz	202 Hz	375 Hz	187 Hz
SEL[1] (re1µPa.s)	128 dB@400m	140 dB@400m	137 dB@375m	139 dB@725m
SEL[2] (re1µPa.s)	175 dB@1m	187 dB@1m	184 dB@1m	190 dB@1m
Peak power frequency	157 Hz	68 Hz	39 Hz	97 Hz
PSD peak[–2] (re1µPa^2/Hz)	147 dB@1m	158 dB@1m	154 dB@1m	160 dB@1m
Shock wave sound pressure level	264 dB re 1µPa	271 dB re 1µPa	274 dB re 1µPa	276 dB re 1µPa

Note: [1]Measured in the field. [2]Back calculated to 1 m using PE algorithm.

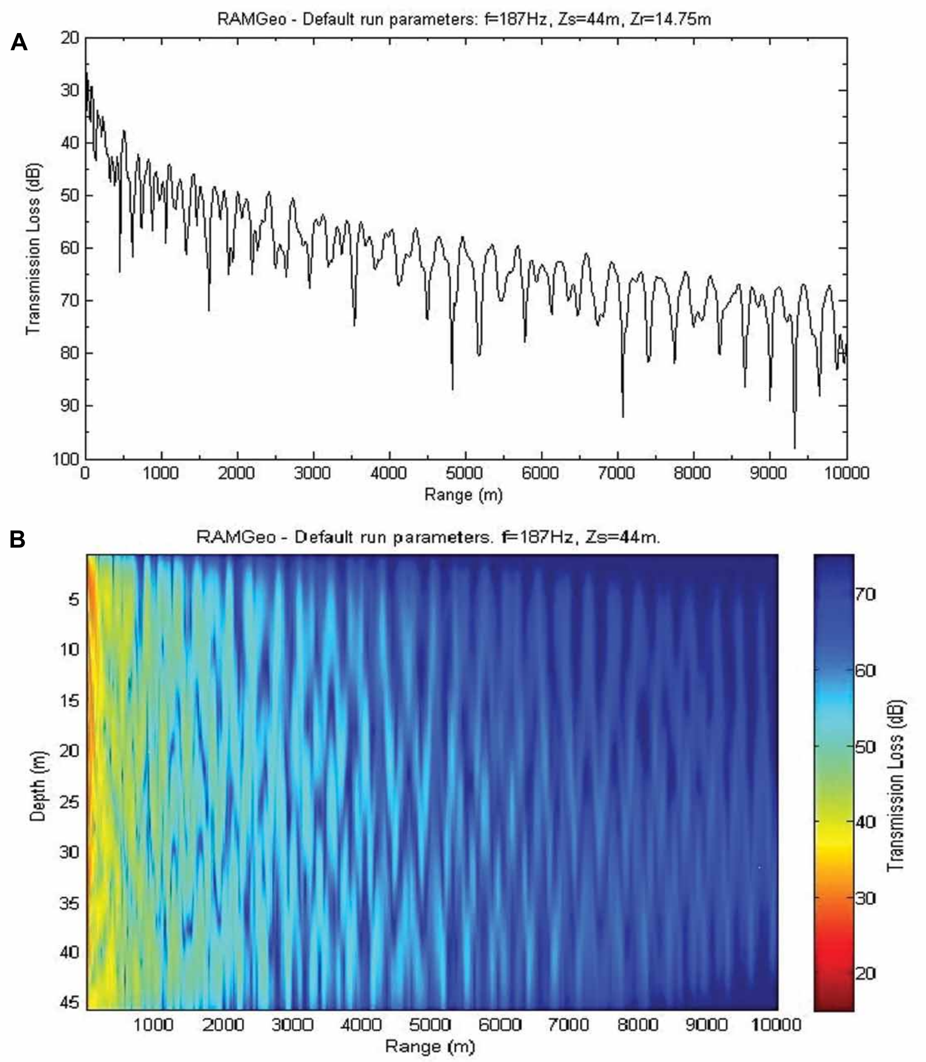

Fig. 4 A. Range dependant noise transmission loss. **B.** Range and depth dependant noise transmission loss (azimuthal direction from South to North).

distance for the seals reaches up to ~ 1000 m for the 24 kg TNT blast. Figure 4B shows the noise propagation throughout the water column, where the noise propagates favourably in all directions. Experiments with seals demonstrate that their hearing organs are complex and that these animals are similarly sensitive to sound both at the surface and at depths up to 100 m (Withlow, Hastings 2008). Animals exposed to either natural or anthropogenic sound may experience physical and psychological effects, ranging in magnitude from negligent to severe. The same acoustic source may have radically different effects depending on operational and environmental variables, and on the physiological, sensory, and psychological characteristics of affected animals. It is important to note that these variables may differ (greatly in some cases) within a species and even among individuals, depending on various factors (e.g., sex, age, previous history of exposure, season, and animal activity; Southall *et al.* 2007). In the case of fish, a distance of less than 100 m from the noise source is often fatal (Ketten 1995), with the noise distances resulting in inner ear injury varying due to hearing thresholds of different fish species (Nedwell *et al.* 2007). The behavioural responses are hardly estimated as authors refer to a lack of data (Webb *et al.* 2008).

DISCUSSION

At least 63 fish species (Repečka 2003) and several mammal species, mostly grey seals (Bacevičius 2002) inhabit the Baltic Sea coastal region. The noise level and transmission loss results can be compared with injury criteria proposed by Southall *et al.* (2007). According to injury criteria used for low-frequency pinniped hearing ability (0.075–75.000 KHz), a sound exposure level of a single 186 dB pulse is capable of inducing injury. During the detonation of a 24 kg charge, the exposure level has reached 190 dB, which means that the criteria would be valid only at very close proximity <10 m to the noise event. The behavioural criteria for exposure level of 171 dB would be valid only at a distance to the explosion less than 40 m due to comparatively small charges. Several authors indicate that deleterious effects on mammals are those exceeding the noise levels of 150 dB (NRC 1994). Comparing the transmission loss results with the proposed values (NRC 1994) (Fig. 4A), the dangerous

CONCLUSIONS

Mine clearance operations are implemented yearly in the Lithuanian area of the Baltic Sea. During the acoustical survey of detonated small charges (up to 24 kg TNT), high sound exposure levels within a low-frequency range (up to 190 dB re 1µPa.s) have been recorded. The environmental conditions affecting the noise propagation in this shallow (<50 m) part of the Baltic Sea are specific to well-mixed waters and sandy–silty bottom. The comparison of noise measurements with the criteria of animal exposure to noise reveals that during an explosion of small charges in a presence of seals, a 100 m distance in all directions can be lethal, whereas a dangerous distance constitutes ~1,000 metres from the blast. For the fish, the lethal distance is also ~100 m from the blast. The distances at which fish can be injured or can experience behavioural reactions should be estimated for individual species as inter-specific hearing abilities vary.

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