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# Sound propagation experiments in a Norwegian fjord

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**Abstract**

Results from an experiment on surface duct propagation in Sognefjord, Norway, are presented. The research cruise was conducted with RV ELISABETH MANN BORGESE (IOW, Germany) in November 2016. The surface duct with positive sound speed gradient had a depth of 68 m and showed a two-layer structure with a pronounced step in sound speed at 26.5 m depth. The experiment was performed with a freely drifting projector buoy and a horizontal receiver array. The array was towed at 3 kn speed up to a distance of 10 km from the sound source. Source and receiver were positioned both at 22.5 m depth. The work addresses frequency dependency and spatial variability of transmission loss in the surface duct within the frequency regime from 1.1 kHz to 3.25 kHz.

Keywords: Underwater acoustics, sound propagation, transmission loss, surface duct

## INTRODUCTION

Many applications in underwater acoustics, such as underwater noise measurements [1, 2], underwater communication [3], or SONAR[4], require a profound knowledge of the sound propagation conditions in the sea. The propagation of sound is substantially influenced by spatial (and temporal) variations of the sound speed as well as by sound attenuation, for instance, due to absorption [5].

The speed of sound depends on temperature, salinity, and pressure and due to stratification in the sea substantial variations of sound speed can occur in vertical direction [7]. A gradient in a vertical sound speed profile causes sound refraction and deep sound channels form at (local) minima of a vertical sound speed profile, such as, e.g., the SOFAR channel in the deep ocean [6]. In a sound channel the transmission loss related to geometrical spreading is substantially reduced in comparison to spherical spreading.

The sea surface behaves approximately like a pressure release boundary and acts as a reflector for underwater sound. In case of a positive sound speed gradient in the surface layer, a sound duct forms in which sound is trapped and prevented to travel into deeper water layers. In an ideal surface duct the (geometric) transmission loss is governed by cylindrical spreading, however, losses due to absorption and other mechanisms also occur in a realistic surface duct. Attenuation mechanisms are, e.g., scattering at the sea surface and diffraction (at low frequencies) [8, 9, 10, 11, 12]. Surface duct propagation is of relevance, e.g., in ship acoustics, since surface ships represent near-surface sound sources.

In this work results from an experiment on transmission loss in a surface duct that formed in the Norwegian Sognefjord in November 2016 are presented. A focus of the work is given to the spatial variability of transmission loss as well as the frequency dependence of sound attenuation.

## SOUND SPEED PROFILES IN SOGNEFJORD

The Sognefjord in Norway is a fjord-type estuary with a sill at the fjord entrance that determines the exchange of water between ocean and fjord. The main thermocline in Sognefjord is typically located at about 90 m to 150 m depth with a seasonal variability in the upper layers. The surface layer in Sognefjord is influenced by fresh water inflow from the surrounding mountains as well as by wind, waves, and tidal currents.

In Figure 1 (a) two vertical profiles of sound speed measured in central Sognefjord, south of Høyanger fjord, on November, $23^{rd}$, and, for comparison, on November, $20^{th}$, are presented. The former profile was recorded shortly before the acoustic measurements. The profiles were obtained with the on-board CTD probe of RV ELISABETH MANN BORGESE.

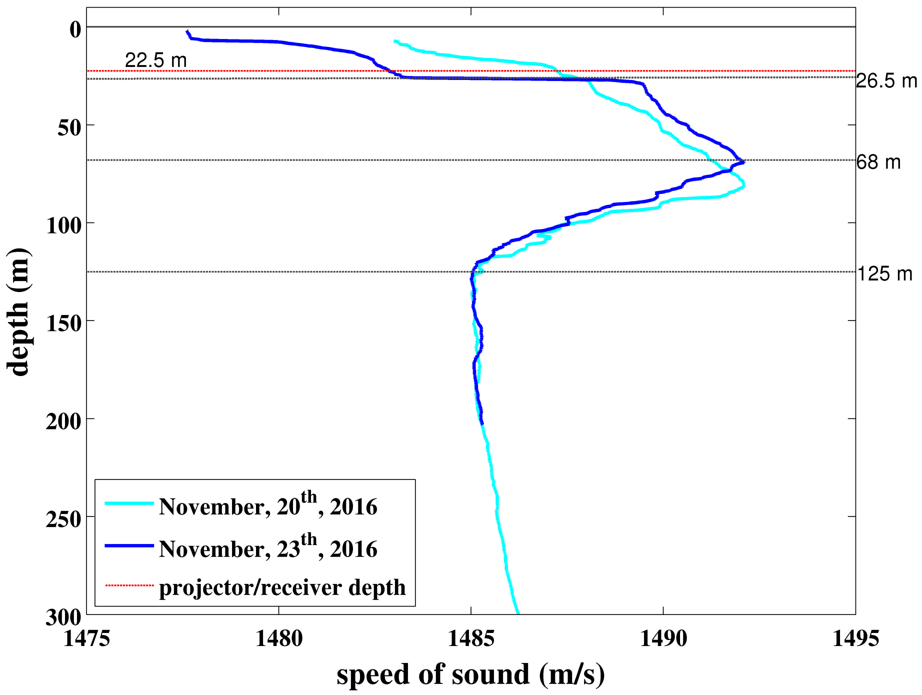


Figure 1: Vertical sound speed profiles measured in Sognefjord (Norway) in November 2016. The surface duct on November, $23^{th}$, had a depth of 68 m and showed a two-layer structure in sound speed. Receiver array and projector were both located at a depth of 22.5 m during the acoustic measurements.

A deep sound channel with an acoustic axis located at about 125 m depth as well as a surface sound channel with a positive sound speed gradient can be found in both profiles. Shortly before the acoustic measurements on November, $23^{rd}$, the surface duct had a depth of 68 m and a two-layer structure with a pronounced step in the sound speed at 26.5 m depth. During the experiments receiver and transmitter were positioned at a depth of 22.5 m, i.e. above the step in sound speed.

## TOWING EXPERIMENT

The acoustic experiment was performed with a freely drifting projector buoy that was deployed at the CTD measurement position. The drift buoy consists of an electronic unit with a cylindrical projector at 22.5 m depth and a communication unit equipped with AIS and GPS. With a period of 40 s HFM down-sweeps (*hyperbolic frequency modulation*) with a center frequency of 2.5 kHz, a bandwidth of 3 kHz, and length of 1 s were repeatedly emitted. Pulse emission was triggered by GPS. During the measurements the projector buoy experienced a (weak) drift in Sognefjord due to wind and currents.

The emitted pulses were recorded with a horizontal array towed from RV ELISABETH MANN BORGESE at a speed on 3 kn and a depth of 22.5 m. The towed array has a total length of 9.2 m and consists of 16 hydrophones having an equidistant spacing of 7.5 cm [13]. The travel time of pulses have been determined by matched filter techniques [14]. Acoustic path lengths can been calculated from the travel times and the (average) sound speed along the paths.

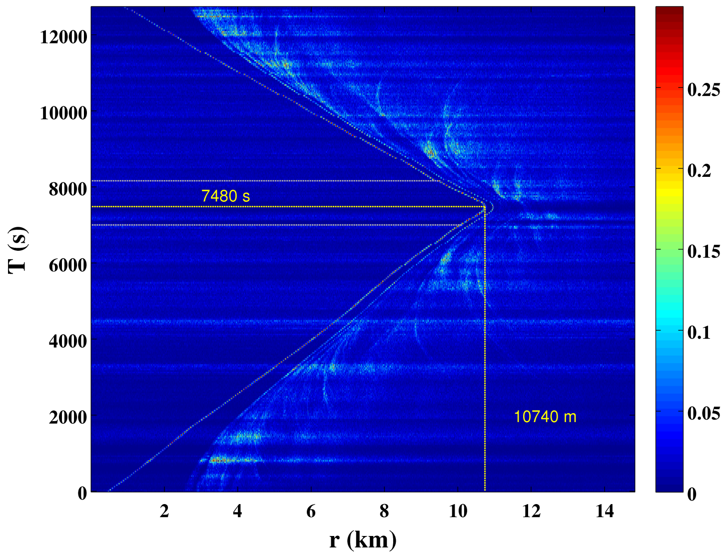


Figure 2: Space-time diagram showing the acoustic path length between sound source and receiver (corresponding to the horizontal distance) as well as the reverberation due to multipath propagation in Sognefjord. The direct pulse is separated from the reverberation. Note, that path length corrections for reverberation due to sound speed variations along the acoustic paths are not applied.

The space-time plot depicted in Figure 2 displays the output of a matched filter and reflects the acoustic path lengths $r$ of the received pulses for each HFM pulse emitted at time $T$. Since path lengths are calculated in this diagram from the sound speed at measurement depth, it is only exact for the direct pulse. For this pulse the path length corresponds to the horizontal distance between transmitter and receiver. In this work transmission loss is only analyzed, however, for the direct pulse, so corrections of path lengths due to sound speed variations were omitted in Figure 2. It can be seen that the direct pulse is clearly separated from the reverberation.

Since the receiver is towed at constant speed, an almost straight line appears for the direct pulse in the space-time plot in Figure 2 up to the turning point at 10740 m. This point was reached after 7480 s of measurement time.

## FREQUENCY-DEPENDENT TRANSMISSION LOSS

Transmission loss (TL) is defined as the ratio of sound intensities at a reference distance $r_0$ = 1 m and the distance $r$ between sound source and receiver, given in decibel. It comprises of geometrical spreading of sound power $\mathrm{TL}_{geo}$ as well as of sound attenuation $\mathrm{TL}_{att}$, i.e. $\mathrm{TL} = \mathrm{TL}_{geo} + \mathrm{TL}_{att}$. While spherical spreading yields $\mathrm{TL}_{sph,geo} = 20 \cdot \log_{10}(r/r_0)$, cylindrical spreading leads to $\mathrm{TL}_{cyl,geo} = 10 \cdot \log_{10}(r/r_0)$. The transmission loss for a point source in an idealized surface duct is given by [5]:

$$\mathrm{TL}_{\mathrm{sd}} = 10 \cdot \log_{10}(r/r_t) + 20 \cdot \log_{10}(r_t/r_0) + \mathrm{a}(\mathrm{dB/km}) \times r \tag{1}$$

The horizontal distance $r_t$ reflects a transition zone beyond that sound rays from the point source are trapped in the surface duct. In general only a fraction of the sound power emitted from a near-surface source is entering into a surface duct. Transmission loss in a surface channel includes not only geometric spreading, but also attenuation $a = (a_{abs} + a_{loss})$ due to absorption $a_{abs}$ and other loss mechanisms $a_{loss}$, such as scattering or diffraction.

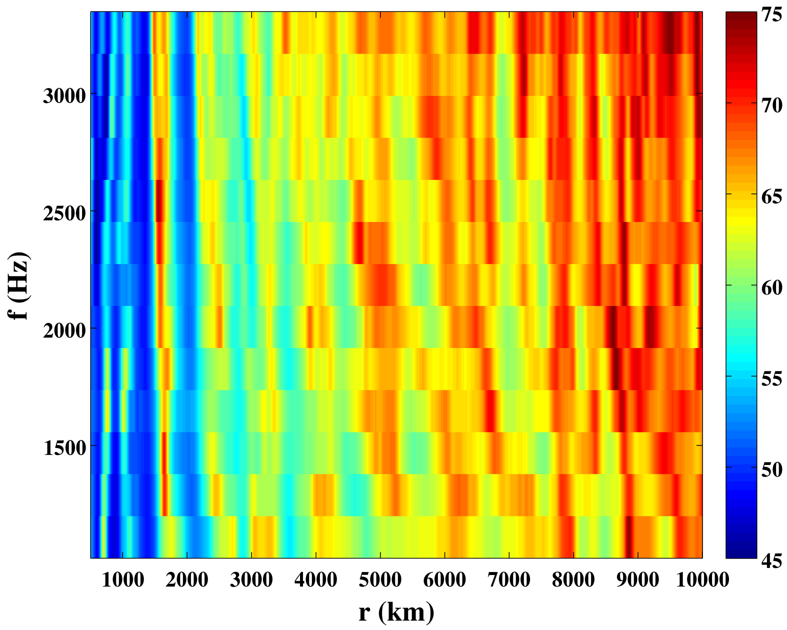


Figure 3: Transmission loss in the surface layer of Sognefjord measured at 22.5 m depth. Note, that only the direct pulse has been considered in the TL calculations.

The transmission loss in the surface duct formed in Sognefjord on November, $23^{rd}$, is depicted in Figure 3. It is determined from spectral analysis of the received pulses in the frequency regime from 1.1 kHz to 3.25 kHz. For distances up to a few kilometers the TL exhibits an undulating pattern showing only weak frequency dependence. Sound attenuation, on the other hand, depends significantly on frequency. This is reflected by increasing TL towards higher frequencies, which becomes apparent for distances larger than a few kilometers.

In Figure 4 the transmission loss due to sound duct propagation at 1.1 kHz (a) and 3.25 kHz (b) is depicted. The results of the surface duct model (equation 1) with an assumed transition range of $r_t$ = 200 m is plotted for comparison. A reasonable agreement can be achieved in case the attenuation coefficient is significantly larger than the corresponding absorption coefficient $\alpha$. Since the frequencies considered in this work are well above the critical channel frequency, it is not unreasonable to conclude that scattering processes play a crucial role as a dominant loss mechanism.

A striking feature that can be recognize in both experimental TL curves is an undulation with a peak-to-peak value up to 15 dB. This behavior is particularly pronounced within a range of a few kilometer distance between source and receiver and is not captured in the surface duct model. It should be stressed, that transmission loss is only determined in this work for the case in which source and receiver move away from each other.

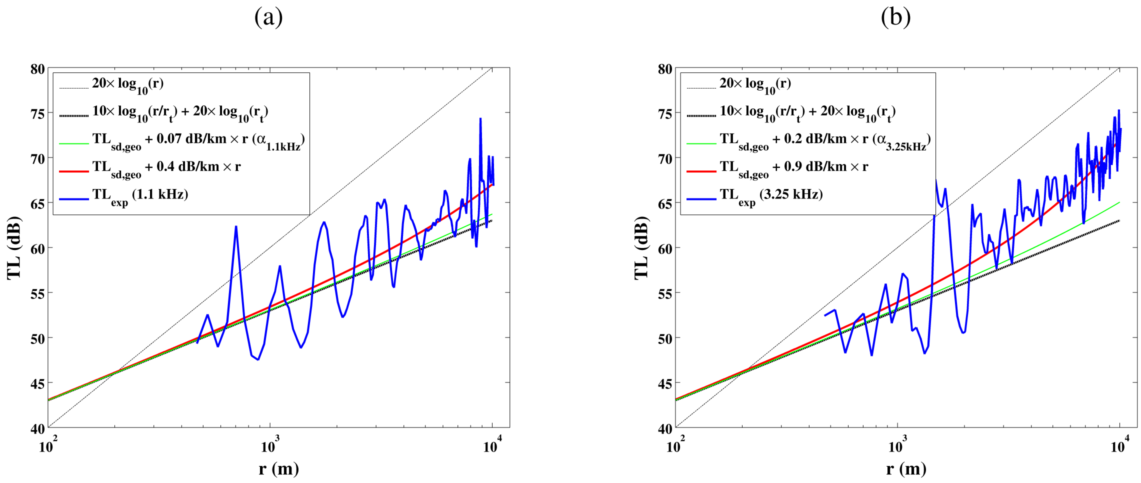


Figure 4: Transmission loss for 1.1 kHz (a) and 3.25 kHz (b). For comparison the transmission loss of the surface duct model (equation 1 with $r_t$ = 200 m) with and without attenuation is plotted. The coefficient $\alpha$ reflects the (frequency-dependent) absorption.

## CONCLUSIONS

A sound propagation experiment has been conducted in a surface duct in Sognefjord, Norway, in November 2016. The surface duct with positive sound speed gradient had a depth of 68 m (measured shortly before the acoustic experiment) and a pronounced two-layer structure with a step in sound speed at 26.5 m depth. A receiver array was towed from RV ELISABETH MANN BORGESE (IOW, Germany) at low speed and a depth of 22.5 m, while a freely drifting projector buoy acted as a sound source. The experimental results reveal a frequency-dependent attenuation, which is dominated by mechanisms other than absorption in the frequency regime between 1.1 kHz and 3.25 kHz. The TL curves show an undulating spatial variation having a peak-to-peak value up to 15 dB within a range of one kilometer or below. Though it is not unreasonable to conjecture the two-layer structure of the surface duct to underly the pronounced spatial variation in the TL curves, a definite answer, however, must await a numerical investigation of this phenomena. This is beyond the scope of this work.

## ACKNOWLEDGEMENTS

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