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Pilot study underwater sound Wadden Sea

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Pilot study underwater sound Wadden Sea

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Summary

The Wadden Sea is a designated UNESCO World Heritage Site since 2009. Achieving (or maintaining) a good environmental status in this area is of great interest, but there is currently very little information on underwater sound. Therefore, Rijkswaterstaat initiated a pilot project to build up knowledge about the collection and analysis of underwater sound in the shallow Wadden Sea, and to make a first inventory of underwater sound levels, with a focus on the sound from vessel traffic and the individual contributions of various vessel types.

The Wadden Sea underwater sound pilot project has produced a valuable set of data from two weeks of recording along the navigation channels between Lauwersoog and Schiermonnikoog and between Harlingen and Terschelling.

The purpose of this study was to get insight in the soundscape of the Wadden Sea and the contributions of different vessel types. No source levels of individual vessels were derived from the measurements and no conclusions can be drawn from the measured sound of individual passing vessels.

The median underwater sound pressure level in the Wadden Sea is much lower than at locations in the North Sea during (at frequencies below about 2 kHz). This is likely explained by the lower shipping density and the shorter sound propagation distance because of the much shallower water and the shielding provided by the islands. In the higher temporal percentiles of the sound pressure level, that are dominated by contributions from individual vessel passages at closer distance from the hydrophones, the difference between the sound in the Wadden Sea and in the North Sea is smaller, but the Wadden Sea is still quieter.

A substantial fraction of the SPL measurements during vessel passages along hydrophones is of sufficient quality to determine characterize the vessel underwater radiated sound, i.e. at appropriate CPA range without interference from other vessels. Automated processing of the SPL per vessel passages results in a useful dataset, that can be used for analysing trends with relevant parameters

The pilot provides an excellent starting point for further studies towards monitoring the underwater sound in the Wadden Sea via sound mapping, as done for the deeper water in the North Sea in the Jomopans project.

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Contents

1 Introduction

The European Union adopted an ambitious Marine Strategy Framework Directive (MSFD) in 2008. The main goal of this MSFD is to achieve Good Environmental Status (GES) of EU marine waters, where GES is defined as "the environmental status of marine waters where these provide ecologically diverse and dynamic oceans and seas which are clean, healthy and productive". The eleventh descriptor of GES requires that "introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment". This characterizes underwater noise as pollution. As part of its marine strategy, The Netherlands has actively participated in the InterReg North Sea region program Jomopans , that developed a framework for joint monitoring of underwater noise in the North Sea. This monitoring is based on modelled maps of underwater sound (initially from ships and wind), validated by underwater sound measurements at selected locations. The Jomopans modelling is applicable for water depths greater than 10 m. Extension to shallower water requires further model development, because sound reflections from and sound propagation in the seabed have a much larger influence in shallow water than in deeper water.

The Wadden Sea is a designated UNESCO World Heritage Site since 2009. Achieving (or maintaining) GES in this area is of great interest, but there is currently very little information on underwater sound. Therefore, Rijkswaterstaat initiated a pilot project to build up knowledge about the collection and analysis of underwater sound in the shallow Wadden Sea, and to make a first inventory of underwater sound levels, with a focus on the sound from vessel traffic and the individual contributions of various vessel types.

WaterProof BV was contracted for the data collection and processing, see (van Tol, Olivierse, & Brinkkemper, 2022). TNO was contracted to assist RWS in the acquisition process for the data collection, to define the measurement protocols and for the analysis of the data.

Objectives of analysis:
1. Inventory of underwater sound at Wadden Sea locations;
2. Inventory of underwater sound from selected vessels;
3. Initial interpretation of measured underwater sound
    a. Effect of water depth at sensor location;
    b. Effect of bathymetry along source-receiver trajectory;
    c. Effect of tide;
    d. Effect of wind and waves;
4. Initial interpretation of vessel sounds
    a. Effect of vessel type;
    b. Effect of speed;
    c. Effect of size / length.

2 Measurements

As described in (van Tol, Olivierse, & Brinkkemper, 2022), acoustic measurements were performed during two separate one-week campaigns at two different locations in the Wadden Sea, near the ports of Lauwersoog (see §2.1) and Harlingen (see §2.2). Underwater sound data were collected along cross-channel transects with measurement rigs placed at different water depths, to collect data on sound radiated from vessels in the channels as well as on the propagation of this sound toward and across intertidal areas. Simultaneous with the acoustic measurements, environmental data were collected, and visual observations were conducted to log the vessels that passed the measurement stations.

2.1 Lauwersoog

The measurement stations near the port of Lauwersoog were placed at the locations shown in table 2.1, figure 2.1 and figure 2.2, during the period shown in table 2.2.

Table 2.1: Coordinates of the deployed measurement stations in the navigation channel Lauwersoog-Schiermonnikoog, from (van Tol, Olivierse, & Brinkkemper, 2022).

Lauwersoog				WGS84 UTM31N (EPSG: 32631)		WGS84 (EPSG: 4326)	
Transect	Measurement station	Station type	Remarks	X	Y	Long (dec)	Lat (dec)
1	Station - Low water line	Pole		711039.0	5926810.9	6.178117	53.447985
1	Station - Middle	Frame		710863.7	5926924.8	6.175559	53.449077
1	Station - Deep	Frame	Continuous CTD	710780.2	5926984.7	6.174343	53.449648
~~2~~	~~Station - Low water line~~	~~Pole~~		~~711095.5~~	~~5924239.6~~	~~6.177244~~	~~53.424885~~
2	Station - Middle	Frame	With hydrophone shield	711071.9	5924176.3	6.176846	53.424326
2	Station - Deep	Frame	With hydrophone shield	710931.3	5923881.2	6.174535	53.421733

Table 2.2: Date and times of deployment/retrieval Lauwersoog, from (van Tol, Olivierse, & Brinkkemper, 2022).

Measurement station	Deployment time (CEST)	Retrieval time (CEST)
Lauwersoog Transect 1 – Pole low water line	12/09/2022 20:00	21/09/2022 12:30:00
Lauwersoog Transect 1 - Frame middle	13/09/2022 12:25	21/09/2022 09:15:00
Lauwersoog Transect 1 - Frame deep	13/09/2022 12:45	21/09/2022 14:45:00
~~Lauwersoog Transect 2 – Pole low water line~~	~~12/09/2022 19:00~~	~~21/09/2022 12:15:00~~
Lauwersoog Transect 2 - Frame middle	13/09/2022 07:45	21/09/2022 11:45:00
Lauwersoog Transect 2 - Frame deep	13/09/2022 12:45	21/09/2022 11:00:00

The recorder on the pole at the low water line on transect 2 at Lauwersoog did not record any data due to a technical issue.

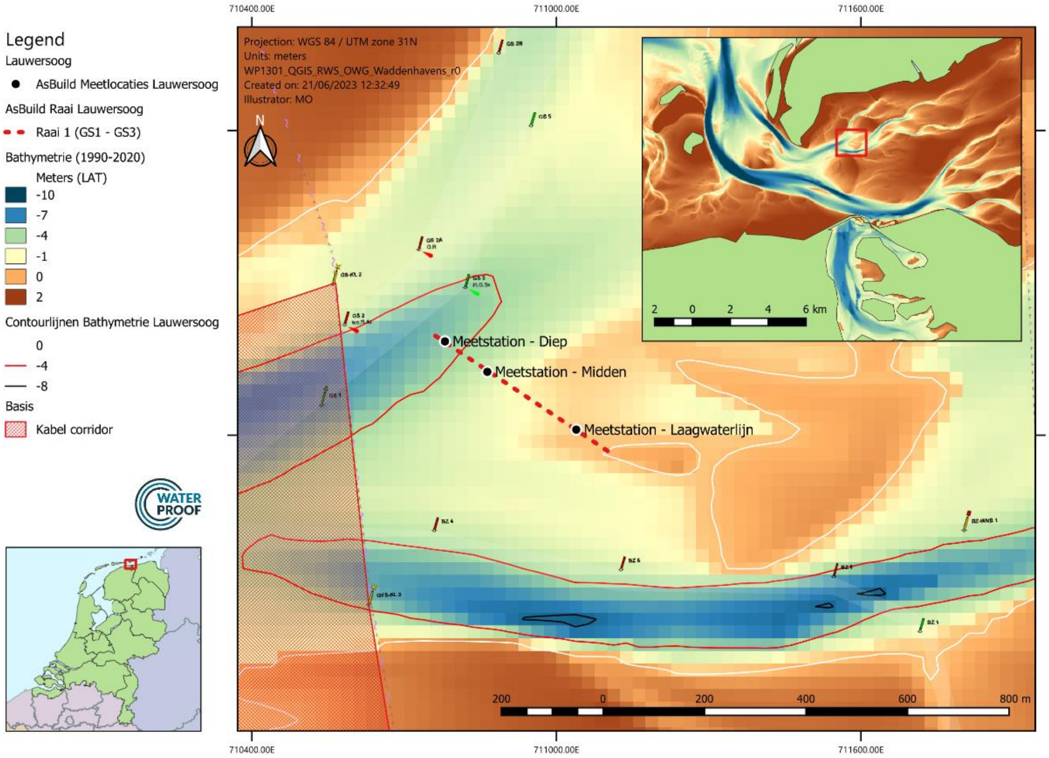

Figure 2.1: Measurement locations transect 1 Lauwersoog-Schiermonnikoog, from (van Tol, Olivierse, & Brinkkemper, 2022)

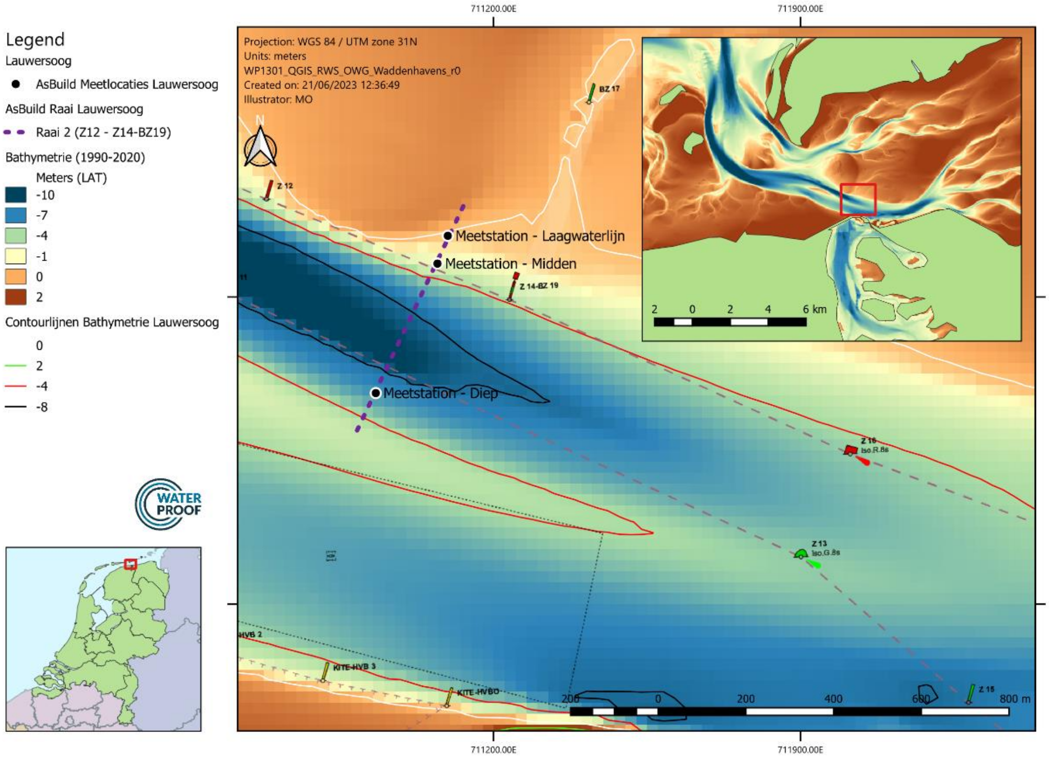

Figure 2.2: Measurement locations transect 2 Lauwersoog-Schiermonnikoog, from (van Tol, Olivierse, & Brinkkemper, 2022).

At Transect 1, the 'middle' and 'low water line' hydrophones are at respectively 102 m and 311 m from the 'deep' hydrophone. At Transect 2, the 'middle' hydrophone is at 326 m from the 'deep' hydrophone.

Visual observations of the vessel traffic were conducted at transect 1 during the first campaign (Lauwersoog-Schiermonnikoog) on Wednesday 14/09/2022. During the period from 05:01 and 17:45 UTC (07:01 to 19:45 CEST) 67 vessel passages were recorded along this transect, from 33 vessels. 18 of these vessels were represented in AIS, 15 not (mainly recreational sailing boats and motorboats).

2.2 Harlingen

The measurement stations near the port of Harlingen were placed at the locations shown in table 2.3 and figure 2.2, during the period shown in table 2.4.

Table 2.3: Coordinates of the deployed measurement stations in the navigation channel Harlingen-Terschelling, from (van Tol, Olivierse, & Brinkkemper, 2022).

Harlingen				**WGS84 UTM31N** (EPSG: 32631)		**WGS84** (EPSG: 4326)	
Transect	Measurement station	Station type	Remarks	X	Y	Long (dec)	Lat (dec)
1 (North)	Station - Low water line	Pole		648045.4	5900739.7	5.218232°	53.2352745°
1 (North)	Station - Middle	Frame	With hydrophone shield	648041.6	5900659.3	5.2181377°	53.2345533°
1 (North)	Station - Deep	Frame	With hydrophone shield	647979.6	5899707.7	5.2167677°	53.226023°
2 (South)	Station - Middle	Frame	Continuous CTD	647958.0	5899604.1	5.2163963°	53.2250985°
2 (South)	Station - Deep	Frame	Station moved unintentionally during campaign	647917.2	5898957.3	5.2154857°	53.2193°
2 (South)	Station - Low water line	Frame		647914.7	5898775.7	5.215364°	53.2176695°

Table 2.4: Date and times of deployment/retrieval Harlingen, from (van Tol, Olivierse, & Brinkkemper, 2022).

Harlingen Transect 1 - Pole low water line (North)	11/10/2022 16:53	19/10/2022 12:10
Harlingen Transect 1 - Frame middle (North)	11/10/2022 12:57	19/10/2022 09:27
Harlingen Transect 1 - Frame deep (North)	11/10/2022 12:16	19/10/2022 11:15
Harlingen Transect 2 - Frame middle (South)	11/10/2022 15:57	19/10/2022 10:45
Harlingen Transect - Frame deep (South)	11/10/2022 11:20	19/10/2022 13:35
Harlingen Transect 2 - Frame low water line (South)	11/10/2022 10:39	19/10/2022 14:15

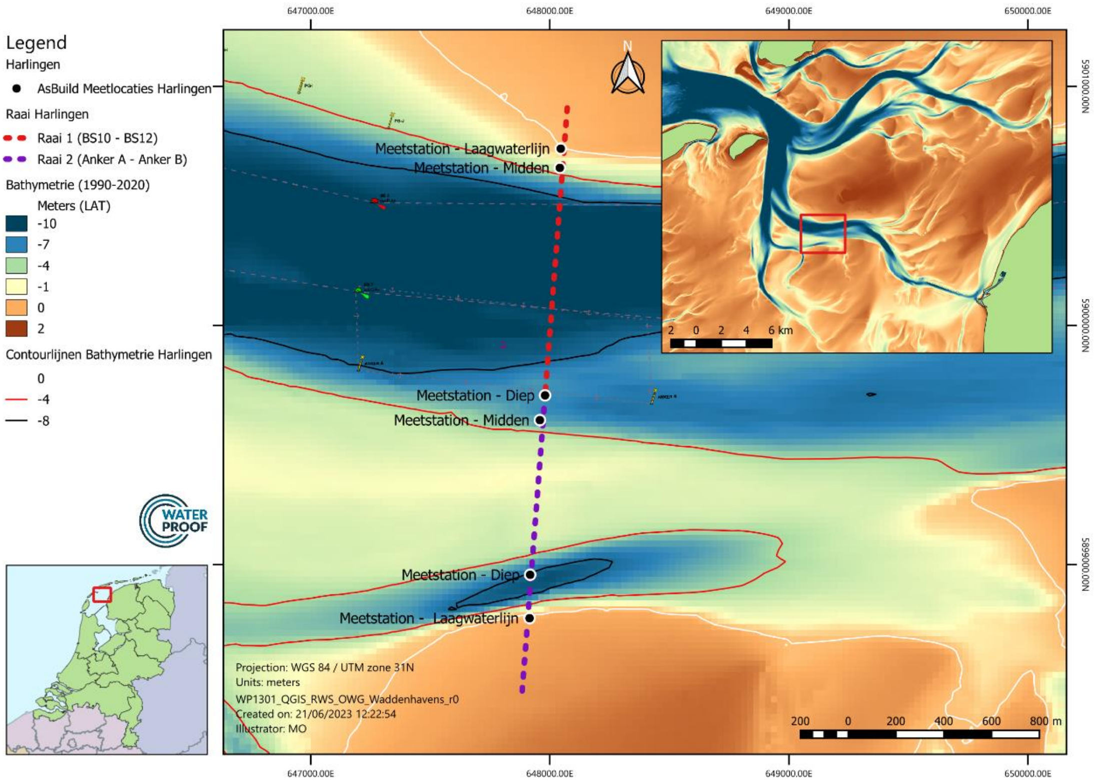

Figure 2.3: Measurement locations transects 1 and 2 Harlingen-Terschelling, from (van Tol, Olivierse, & Brinkkemper, 2022).

At Transect 1, the ‘middle’ and ‘low’ water hydrophones are at respectively 952 and 1033 m from the ‘deep’ hydrophone. At Transect 2, the ‘middle’, ‘deep’ and ‘low’ water hydrophones are at respectively 106, 752 and 933 m from the ‘deep’ hydrophone of Transect 1.

The ‘deep’ measurement station at Harlingen on Transect 2 (South) was relocated unintentionally, as during retrieval it was noted to be out of position by approximate 200 m (van Tol, Olivierse, & Brinkkemper, 2022). The relocation was quantified using the data, see §5.2.2

Visual observations of the vessel traffic were conducted during the second campaign (Harlingen-Terschelling) at transect 1 on Wednesday 12/10/2022. During the period from 06:19 to 16:43 UTC (08:19 to 18:43 CEST) 87 vessel passages were recorded along this transect, from 66 vessels. 50 of these vessels were represented in AIS, 16 not (sailing, motor and fishing boats).

3 Analysis

3.1 Processing

Following the Jomopans processing standard (Ward, Wang, Robinson, & Harris, 2021), WaterProof BV has processed and analysed the recorded underwater sound. The recorded raw voltages were corrected to sound pressure using instrument-specific, frequency-dependent calibration curves. Sound pressure levels were calculated in decidecade frequency bands between 10 Hz and 80 kHz for each second of data, following standards determined as part of the EU Interreg JOMOPANS project (Ward, Wang, Robinson, & Harris, 2021). The sound pressure metrics were delivered in HDF5-datafiles.

3.2 Sound characteristics

Figure 3.1 shows an example of the sound spectra recorded during a single day by one of the stations near Lauwersoog. The colours represent the sound pressure level (SPL), which varies over time (UTC; horizontal axis) and frequency (vertical axis).

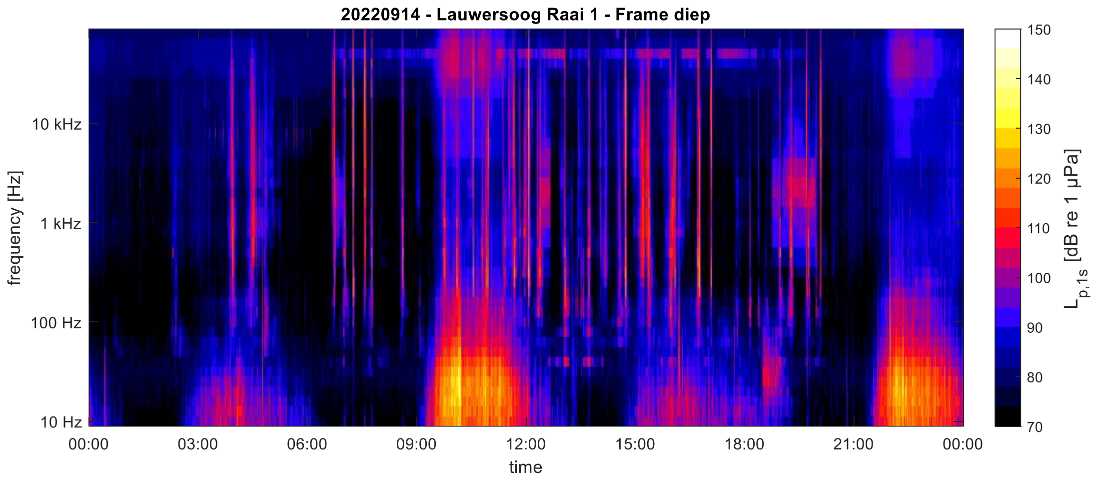

Figure 3.1: Underwater SPL_{1s} in decidecade bands, measured on 14 September 2022 at location 'Transect 1 – deep' between Lauwersoog and Schiermonnikoog.

At lower frequencies (roughly below 100 Hz), the SPL varies strongly, at a period of approximately 6 hours. This is caused by tidal flow. The turbulence in the flow along the hydrophone leads to pressure fluctuations, that disturb the underwater sound measurements. This so-called 'flow-noise' depends strongly on the geometry of the hydrophone and its mounting. It is not representative of the sound observed by aquatic animals.

At higher frequencies (roughly above 100 Hz), vertical lines in the SPL appear that are likely caused by vessel passages along the hydrophone.

3.3 Ambient sound

One objective of this pilot study was to get an impression of the underwater ambient sound levels at various Wadden Sea locations. The processed SPL timeseries have been analysed with the aim to create an inventory of sound levels and an initial interpretation of the influence on the SPL from various factors such as:

a. Effect of water depth at sensor location;
b. Effect of bathymetry along source-receiver trajectory;
c. Effect of tide;
d. Effect of wind and waves.

This analysis is described in Chapter 4.

3.4 Vessel radiated sound

A second objectives of this pilot study was to get an impression of the contribution of various vessel types to the underwater soundscape. With the help of vessel traffic information from AIS ('automatic identification system', a tracking system that uses transceivers on vessels), individual vessel passages along hydrophones have been identified. The processed SPL timeseries corresponding with these passages have been analysed with the aim to create an inventory of vessel radiated sound levels and an initial interpretation of the influence of various factors such as:

a. vessel type;
b. vessel speed;
c. vessel length.

This analysis is described in Chapter 5.

4 Ambient sound

4.1 SPL statistics

The daily variation of the SPL_{1s} spectra have been quantified in statistical percentiles. The daily N^{th} percentile is the SPL below which N% of the SPL_{1s} values during the day fall.

- The 1st percentile represents the lowest SPL_{1s} values measured during the day. This background noise in the recordings is ultimately limited by the self-noise of the equipment.
- The 50th percentile (or median) represents the SPL below which the SPL_{1s} values during half of the time of the day fall.
- The 90th percentile (or median) represents the SPL below which the SPL_{1s} values during 90% of the time of the day fall. This is likely dominated by sound from vessel passages.

Graphs of the daily SPL percentiles are presented in Appendix B. Figure 4.1 shows the SPL percentiles over the full recording periods (8 days) at the stations near the ports of Lauwersoog and Harlingen.

The 1st percentile SPL graph is clearly dominated by the electronic self-noise of the recorders, which appear to be similar. At the stations along Lauwersoog Transect 2 the lowest SPL measured by the sensors appears to be dominated by ambient sound in the frequency range between 500 Hz and 5 kHz. This is likely due to the relatively high wind speed during a part of the recording period, see the environmental condition graphs in Appendix C.

The median (50th percentile) SPL exceeds the recorder self-noise in most frequency bands, except the highest. It shows significant variation between locations. At lower frequencies (below about 400 Hz) the SPL is highest at the 'low water line' sensors, likely due to the surf around the shallow hydrophones. At mid frequencies (between 500 Hz and 5 kHz) the median SPL at the locations near Lauwersoog is generally higher than that at the locations near Harlingen.

The 90th percentile SPL graphs show similar characteristics as the median SPL, though with a significantly larger variation. Details of individual vessel passages along the hydrophones have a strong influence on the variability of this percentile, due to the relatively short observation time and the limited number of vessel passages. Flow noise along the hydrophones appears to dominate the low-frequency (below about 100 Hz) part of this percentile at several locations, particularly where no flow shield has been applied (see §4.3).

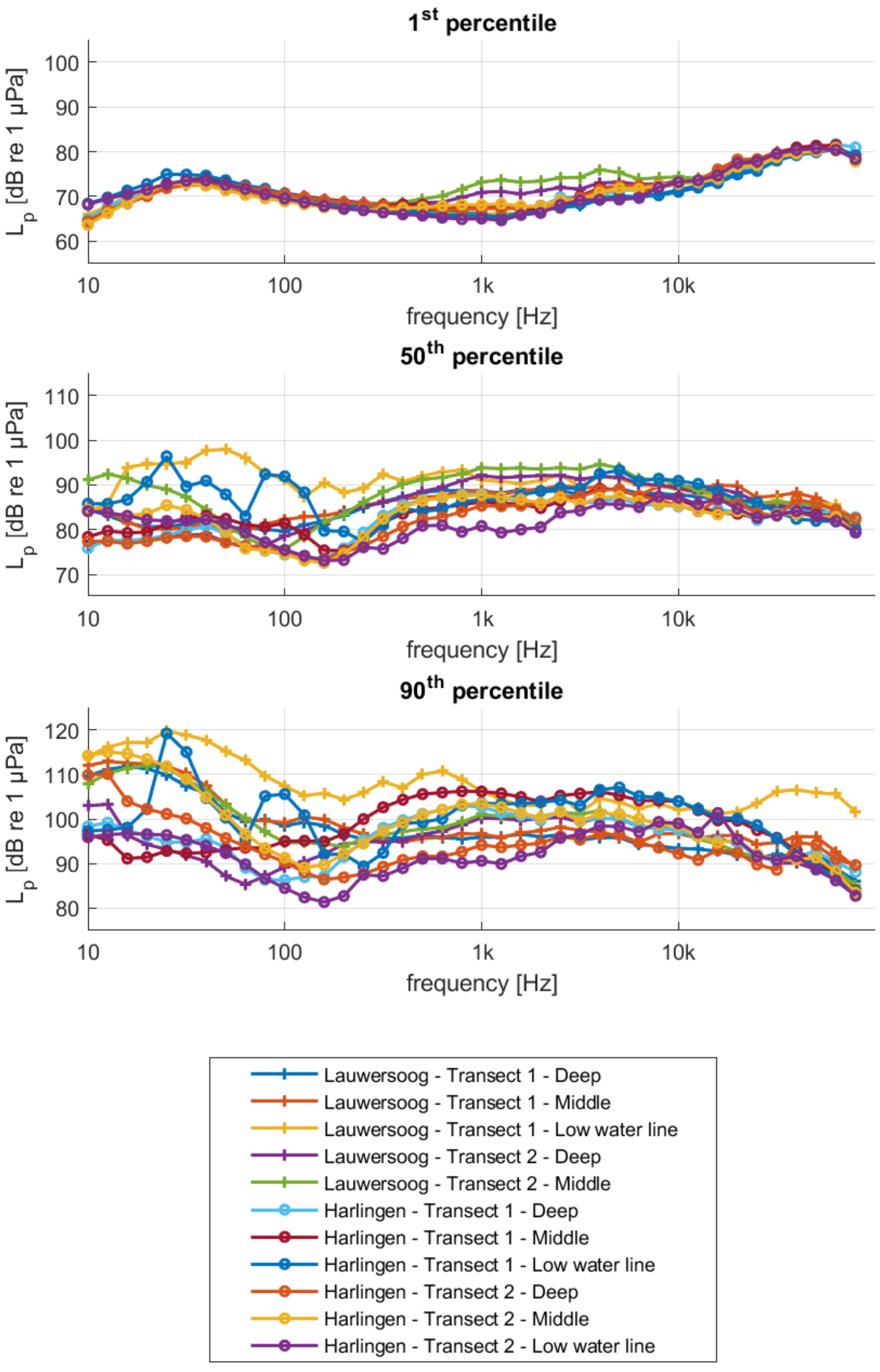

Figure 4.1: 1st, 50th and 90th percentiles of the measured SPL_{1s} in decidecade bands at the measurement stations near the ports of Lauwersoog and Harlingen over the full recording period.

4.2 Initial analysis of influences

A detailed analysis of the various factors that influence the ambient sound measurements is beyond the scope of this pilot study, but some initial observations from the measurements can be made:

The main effect of the **water depth at the sensor location** is observed at the low water line sensors. As expected, the received SPL from passing vessels is lower at these sensors, partly because the vessels pass at larger distance but also because of the higher propagation loss in shallower water. Understanding and being able to model and predict propagation loss in water depths of a few metre requires further study. This also holds for the **effect of bathymetry along source-receiver trajectory**.

The measurements show that **tidal variations** have a strong effect on the low frequency flow noise. Tidal variations also affect sound propagation if these lead to relative changes in water depth of more than a few percent.

Wind and waves can dominate the soundscape, at higher frequencies and in the absence of vessel passages. The measurements at Lauwersoog confirm this in the lower SPL percentiles at mid-frequencies.

The data contain a lot of information about such sound propagation, that is valuable for future studies.

4.3 Effectiveness of hydrophone flow shields

On some measurement stations (see table 2.1 and table 2.3) the hydrophone has been mounted in a nylon enclosure that increases the distance between the hydrophone and the turbulent tidal flow. Figure 4.2 provides a possible illustration of the effectiveness of this flow shield. It compares the SPL measured by the deep hydrophone at Transect 1, with flow shield, and the middle hydrophone at Transect 2, without flow shield. These hydrophones are located at about 100 m from each other (see §2.2 and figure 2.3). At frequencies below 100 Hz, the measured SPL with flow shield is clearly lower than without flow shield. This effect can also be observed in the 50^{th} and 90^{th} percentiles of the measured SPL_{1s} at these stations over the full recording period (figure 4.1). In the 90^{th} percentile, the difference below 50 Hz is more than 10 dB.

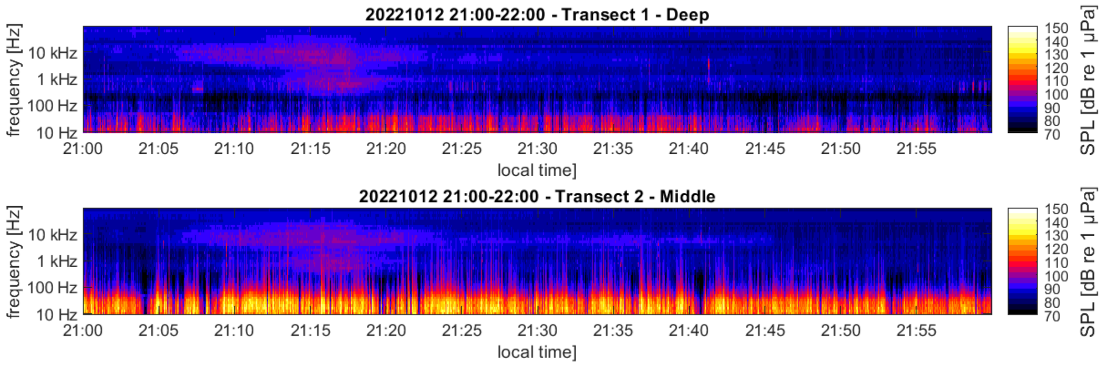

Figure 4.2: Underwater SPL_{1s} in decidecade bands, measured on 12 October 2022 between Harlingen and Terschelling, by hydrophones with (upper graph) and without (lower graph) flow shield.

That the low frequency sound is dominated by tidal flow noise can be demonstrated by comparing the time variation of the low frequency sound with the tidal water depth variation. This comparison is made for the sound pressure level over the frequency bandwidth that includes the 10 Hz to 80 Hz decidecade bands, power averaged over 10-minute intervals. Figure 4.3 shows that the peaks in the low frequency sound at the Harlingen stations occur with the same time pattern (6-hour cycle) as the tidal water height. It also shows that the flow noise peaks at the Transect 1 Deep and Middle sensors (upper two graphs), that included a flow shield, are less prominent than at the Transect 2 Deep and Middle stations, that did not include a flow shield.

Figure 4.4 shows the same comparison for the Lauwersoog stations. Here, the Transect 2 Deep and Middle sensors included a flow shield. This appears to have reduced the flow noise peaks at the Deep station, but to have been less effective for the Middle station.

Hence, placing hydrophones in a nylon enclosure that increases the distance between the hydrophone and the turbulent tidal flow reduces the contribution of flow noise to the acoustic measurements. However, there are no standard guidelines for the design of such an enclosure. The enclosure should be transparent to acoustic waves, while sufficiently robust to survive the harsh conditions at the offshore measurement location.

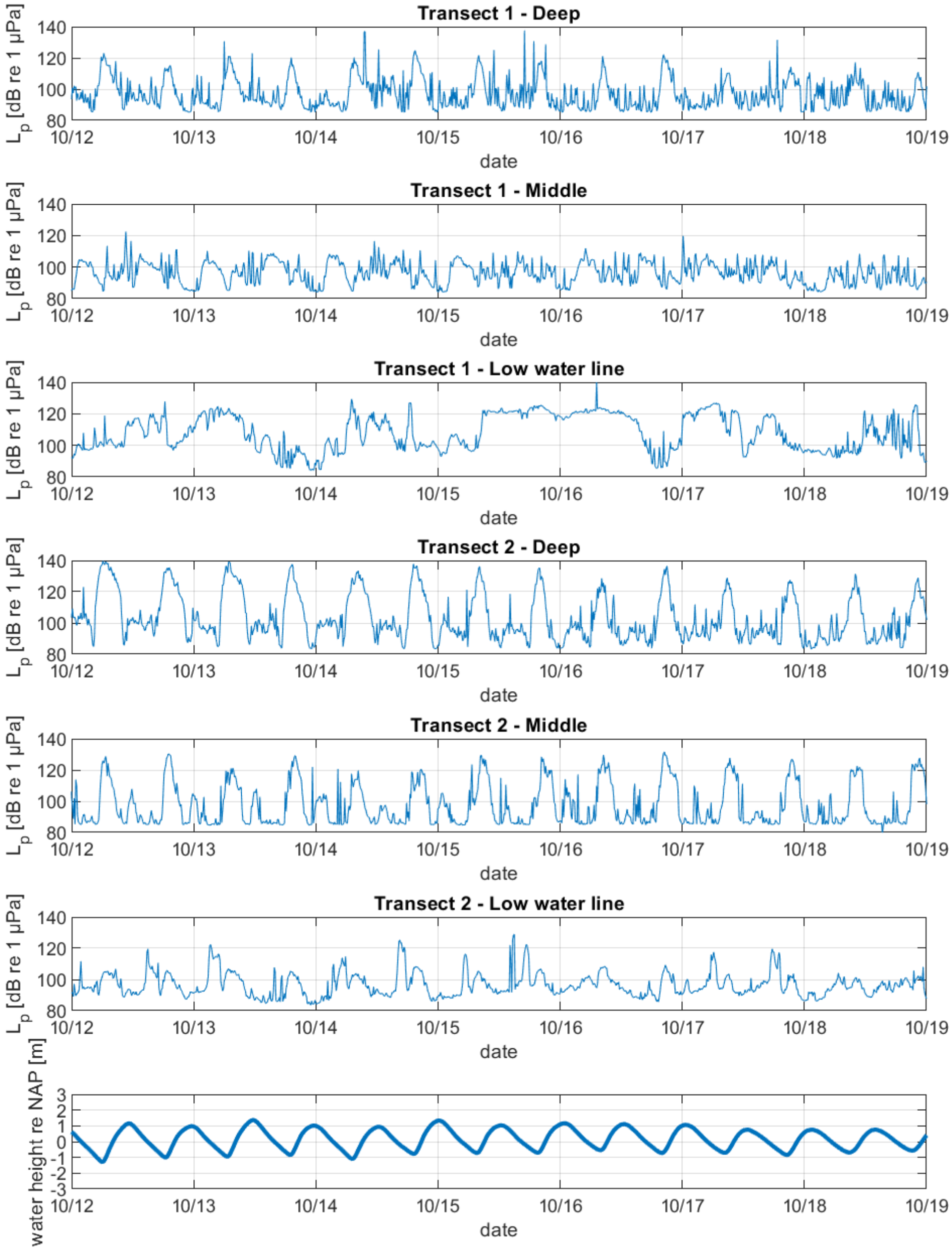

Figure 4.3: SPL of the low frequency sound at the Harlingen measurement stations, in the frequency bandwidth that includes the 10 Hz to 80 Hz decidecade bands, compared with the tidal water height (bottom graph). The Transect 1 Deep and Middle stations included a flow shield, the others not.

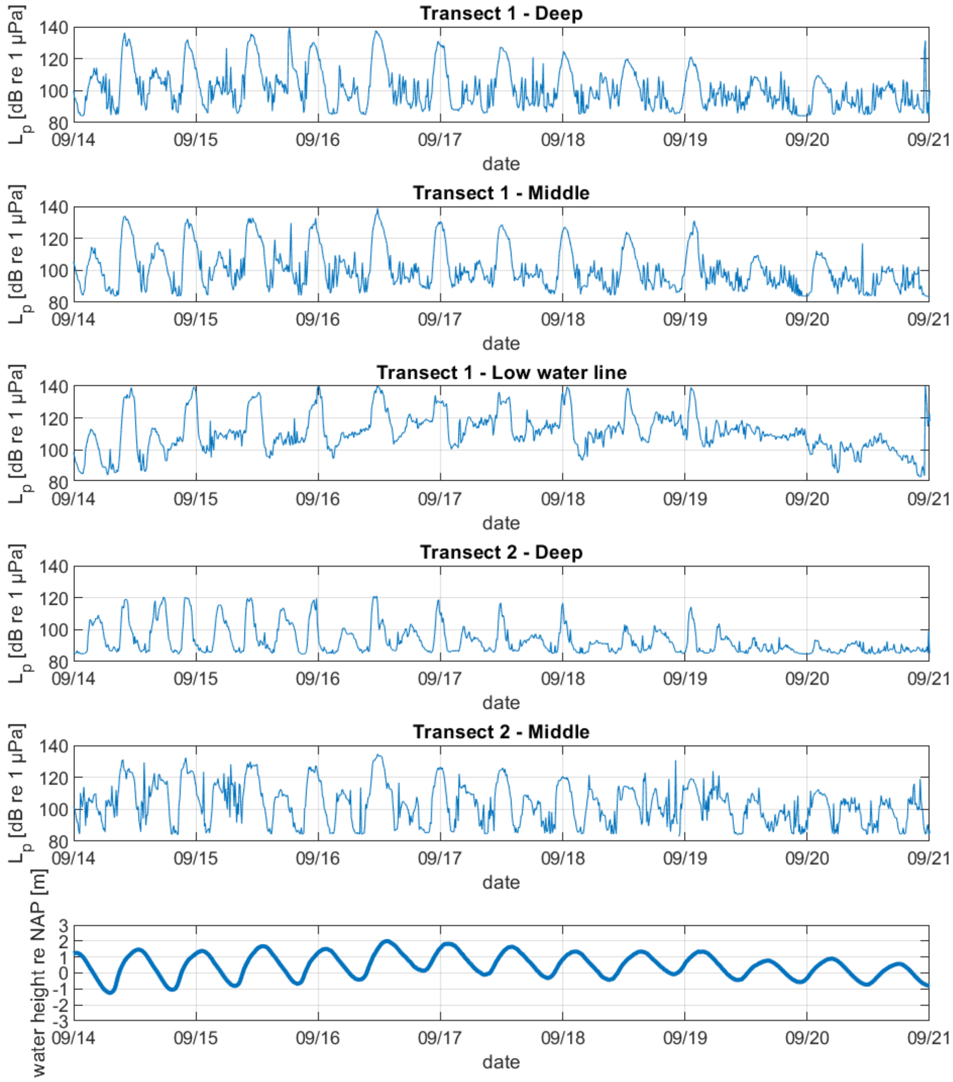

Figure 4.4: SPL of the low frequency sound at the Lauwersoog measurement stations, in the frequency bandwidth that includes the 10 Hz to 80 Hz decidecade bands, compared with the tidal water height (bottom graph). The Transect 2 Deep and Middle stations included a flow shield, the others not.

4.4 Comparison with North Sea locations

To put the results of this pilot study with some context, the underwater sound in the Wadden Sea during the recording periods in September and |October 2022 was compared with the underwater sound recorded in open sea during previous projects.

Figure 4.5 shows a comparison of the sound pressure level statistics from the Wadden Sea measurements (over all locations measured during the two weeks), with the statistics of long-term underwater sound measurements in the North Sea.

One North Sea dataset is from the EU InterReg North Sea Region project Jomopans (Joint Monitoring Programme for Ambient Noise North Sea) (de Jong C. , Binnerts, Robinson, & Wang, 2021; de Jong C. , Binnerts, de Krom, & Gaida, 2022). It concerns data from measurements from the Dutch underwater noise monitoring station at 30 km west of Texel, over the periods between April and October 2019 and between January and June 2020.

The other North Sea dataset is from a study related to the monitoring programme for the Borssele Offshore wind farms (de Jong, et al., 2023). In this study, WaterProof deployed 7 underwater sound recorders over the period between October 2019 and September 2020.

All measurements were performed by WaterProof BV, using the same type of recorder (SoundTrap ST300HF), and applying the same data processing to 1 second decidecade spectra of SPL (Ward, Wang, Robinson, & Harris, 2021).

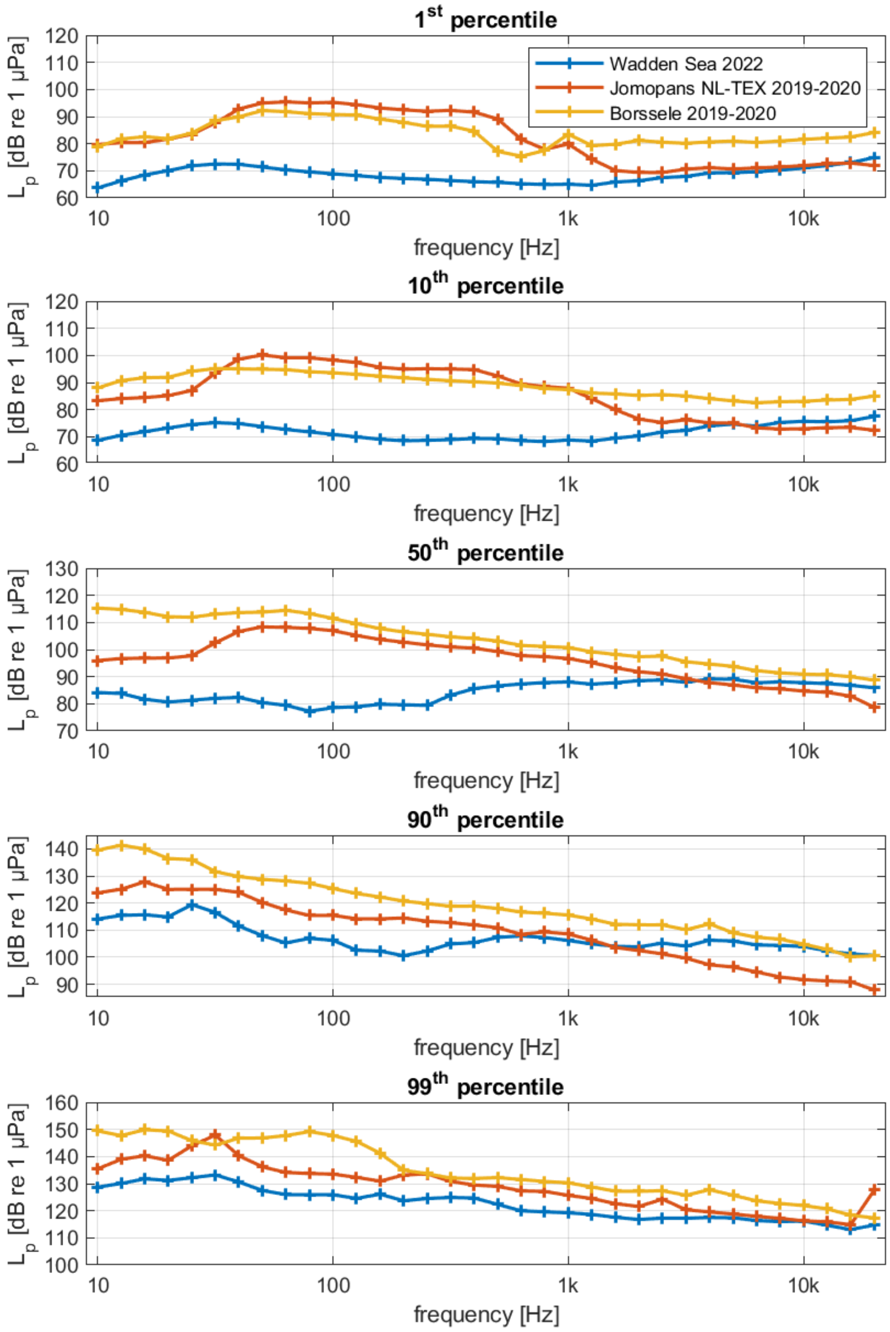

Figure 4.5: 1st, 10th, 50th, 90th and 99th percentiles of the measured SPL_{1s} in decidecade bands at all measurement stations in the Wadden Sea (2 weeks in 2022), at the JOMOPANS Texel location (13 months in 2019 and 2020) and in the Borssele wind farm area (2019-2020).

This comparison illustrates that the median underwater sound in the Wadden Sea is much lower than in the North Sea during (at frequencies below about 2 kHz). This is likely explained by the lower shipping density and the much shorter sound propagation distance because of the much shallower water and the shielding provided by the islands. In the higher temporal percentiles, that are dominated by contributions from individual vessel passages at closer distance from the hydrophones, the difference between the sound in the Wadden Sea and in the North Sea is smaller, but the Wadden Sea is still quieter.

5 Underwater radiated sound

The sound recordings have been analysed to determine the underwater radiated sound from individual vessels passing the hydrophones. In this pilot project, the analysis is limited to quantifying the received sound at the sensors. This is affected by the local sound propagation. As explained in section 5.1, quantifying propagation loss to characterize the radiated sound from the vessel in terms of an acoustic source level (ISO 18405, 2017) is in development, but beyond the scope of this pilot study.

5.1 Measuring underwater sound from ships

Measurement procedures for quantifying underwater sound from ships are complex. The sound has to be measured at sufficient distance from the ship to be able to characterise it as a single source. The sound propagation to the measurement location will be affected by characteristics of the environment such as water depth and seabed properties.
In 2016, the International Organisation for Standardization (ISO) published a standard procedure (ISO 17208-1, 2016) for deep water measurements of underwater sound from ships. The quantifies ships in terms of a deep water radiated noise level (RNL), which depends on the ship as well as on the geometry of the measurements. In 2019, this was supplemented with a standard procedure (ISO 17208-2, 2019) for converting this RNL into the source level (SL) of an equivalent monopole source at a nominal specified source depth. This characterizes the ship as a sound source, independent of the location and geometry of the measurements.
These standards require that the water depth in which the measurements are taken is more than 150 m, or 1,5 times the overall length of the ship under test, whichever is greater. A standard procedure (ISO 17208-3) to determine ship SL from measurements in shallow water is currently being developed, and expected to be published in 2024. This will require calculation of the propagation loss between ship and hydrophone(s). The uncertainty in propagation loss calculations increases with decreasing water depth.

5.2 AIS data

For this project, Rijkswaterstaat has shared vessel traffic information from AIS ('automatic identification system', a tracking system that uses transceivers on vessels). For the sake of privacy, the vessel data has been anonymized. Each vessel in the dataset has been given a unique number, and the following parameters are provided:

Static:
- Vessel type (AIS/IMO);
- Vessel type (ERI);
- Length;
- Width;
- Draught.

Dynamic timeseries:
- Timestamp;
- Speed over ground;

- Course over ground;
- Latitude;
- Longitude.

Figure 5.1 gives an overview of the vessel tracks from AIS that have passed around the measurement locations during the measurement periods.

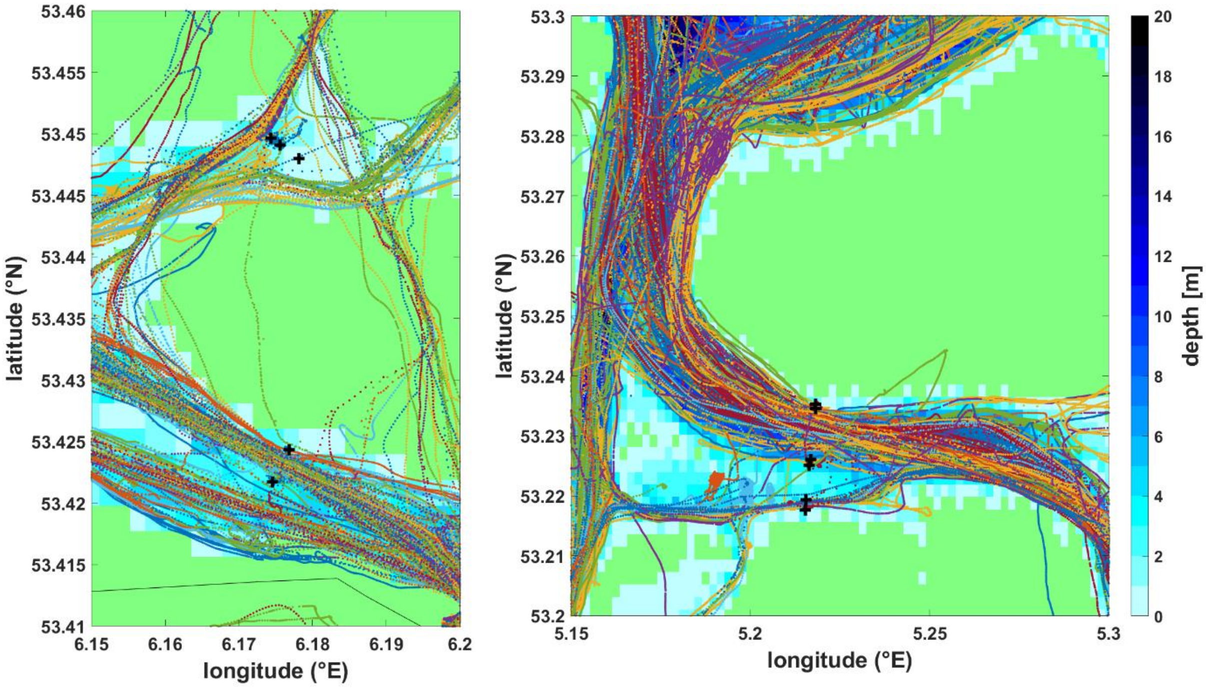

Figure 5.1: Overview of the vessel tracks from AIS for the measurement periods near Lauwersoog (left) and Harlingen (right). The light green area represents the areas where the seabed is above NAP. The black + markers indicate the positions of the hydrophones.

5.2.1 Selection of vessel passages

Individual vessel passages along the hydrophones are selected to determine the underwater radiated sound. The provided location (lat-lon) time series from AIS are used to calculate the time at which the vessel is at its closest point of approach (CPA) to each hydrophone and the corresponding CPA-distance.

The radiated sound from individual vessels is determined for all vessel passages along a hydrophone that fulfil the following criteria:

- The closest distance of approach between the vessel and the hydrophone must be smaller than 500 m;
- The time between the moments that individual vessels are at their closest point of approach to the hydrophone must be larger than 10 minutes. Both vessel passages are discarded if this time interval is shorter than 10 minutes.

5.2.2 Harlingen sensor relocation

The 'deep' measurement station at Harlingen on Transect 2 (South) was relocated unintentionally. During retrieval it was noted to be out of position, see (van Tol, Olivierse, & Brinkkemper, 2022).

Judging from the sound recording (figure 5.2), this relocation occurred around 01:45 on 12 October, in the first night after the deployment. According to the AIS data, the event coincides with the passage of a fishing boat (length 23 m, speed about 3 knots) over the sensor location. The horizontal distance at its closet point of approach to the (original) sensor location was about 15 m.

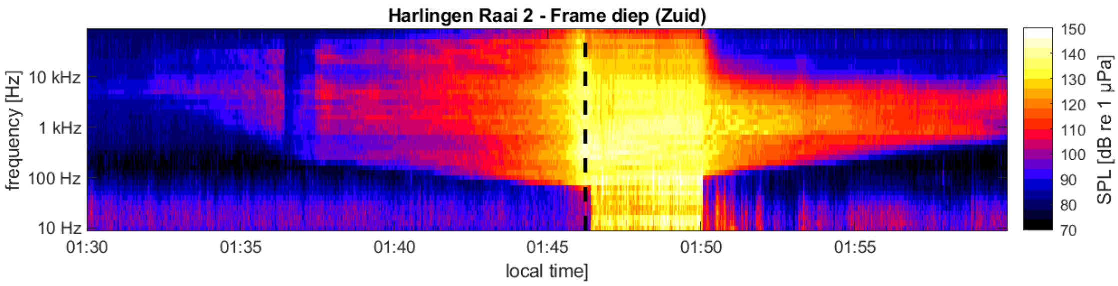

Figure 5.2: Underwater SPL_{1s} in decidecade bands, measured on 12 October 2022 at location 'Transect 2 – deep' between Harlingen and Terschelling. The vertical dashed line indicates the passage of a fishing boat over the sensor location, identified from its AIS tracking.

The same fishing boat sailed nearly the same track, in opposite direction, in the evening of 12 October 2022, passing over the relocated sensor, see figure 5.3. The vertical dash-dotted line indicates the passage of a fishing boat over the original sensor location, identified from its AIS tracking. The vertical dashed line indicates the passage over relocated sensor.

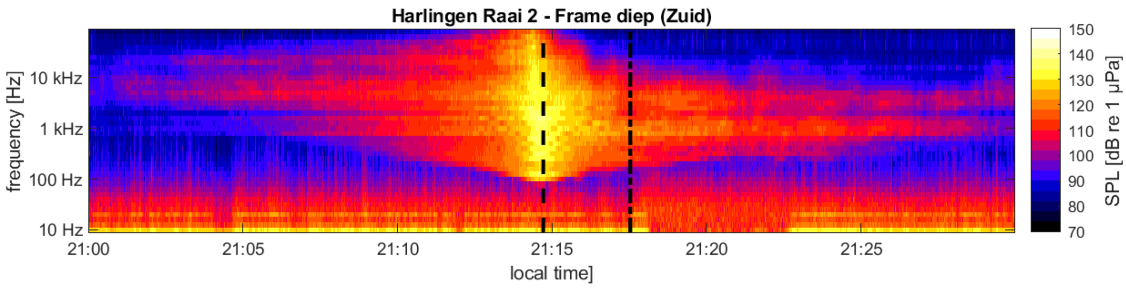

Figure 5.3: Underwater SPL_{1s} in decidecade bands, measured on 12 October 2022 at location 'Transect 2 – deep' between Harlingen and Terschelling. The vertical dash-dotted line indicates the passage of a fishing boat over the original sensor location, identified from its AIS tracking. The vertical dashed line indicates the passage over relocated sensor. The SPL in the frequency bands below 100 Hz is higher than in figure 5.2, due to the stronger tidal current at this time of day (flow noise).

Assuming that the boat passed straight over the new sensor location during this second track, the new sensor location can be estimated from the AIS location of the vessel at the time of the peak in the sound recording. This new location is at 295 m from the original location:

	Estimated location (WGS84)	
Measurement station	LON	LAT
Harlingen Transect 2 (South) - Deep	5.2111669°	53.2186661°

5.3 SPL processing

The underwater radiated sound from individual vessel passages is quantified here in terms of the received sound pressure level (SPL) spectrum at the hydrophones. The averaging time (data window period) for the SPL is determined according to the ISO 17208-1 standard for measuring radiated sound of vessels in deep water.

ISO 17208 defines the data window period as the time it takes the vessel under test to travel the data window length at a certain speed. This data window length is defined by fixed data window angles around the closest point of approach of the vessel to the hydrophone, see figure 5.4.

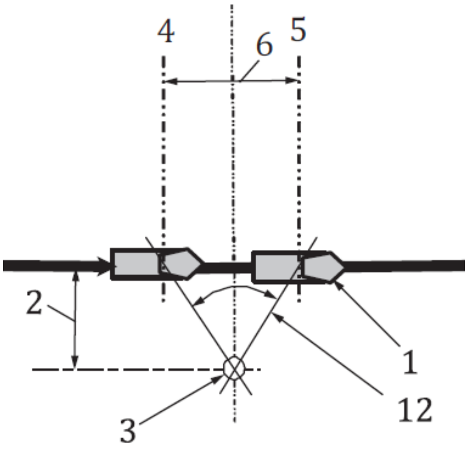

Figure 5.4: Test geometry from ISO 17208-1. 1 is the vessel under test, 3 is the hydrophone, 2 is the distance d_{CPA} at closest point of approach (CPA), 6 is the data window length l_{DW}, between starting point 4 and end point 5, and 12 is the data window angle ($\pm 30°$).

The data window length l_{DW} depends on the horizontal distance d_{CPA} between the vessel and the hydrophone at closest point of approach (CPA):

Eq. 5.3.1 $l_{\mathrm{DW}} = 2 d_{\mathrm{CPA}} \tan(30°)$.

It is assumed that the vessel sails along a straight course with a constant speed V during the data window period t_{DWP}, so that:

Eq. 5.3.2 $t_{\mathrm{DWP}} = l_{\mathrm{DW}} / V$.

5.3.2 Example of processing a single vessel passage

To illustrate the processing, consider the passage of a ferry from Schiermonnikoog to Lauwersoog. Figure 5.5 gives an overview of the received sound pressure at the hydrophones as a function of time and frequency. As explained in §5.3, the time duration over which the sound pressure is averaged (the data window period) is proportional with the distance at which the vessel passes the hydrophone. The ferry crosses Transect 2 about 8 minutes after it crossed Transect 1. The Transect 2 recordings (lower two graphs) also show the sound from two other vessels. The spectrogram of the sound recorder at the Transect 1 low water line hydrophone (middle graph) shows additional noise that is not seen in the other recordings, including two rather constant horizontal noise band below 100 Hz. The origin of this peak in the background noise is unknown.

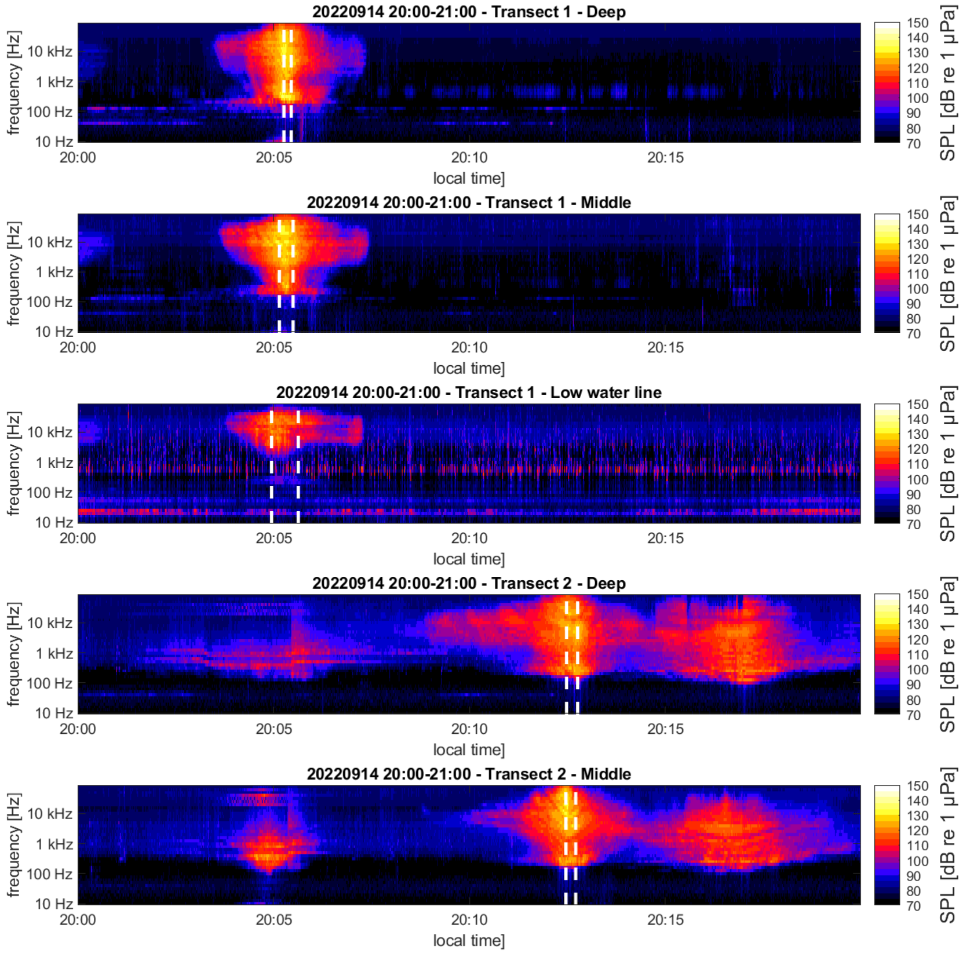

Figure 5.5: Spectrograms of the sound recordings during the passage of the ferry along Transect 1 (upper three graphs) and Transect 2 (lower two graphs). The colour scale represents the measured SPL_{1s} at the hydrophones in the decidecade frequency bands that are represented along the vertical axes. Time is along the horizontal axes. The white dashed lines indicate the data window period over which the SPL of the vessel radiated sound is measured, see §5.3.

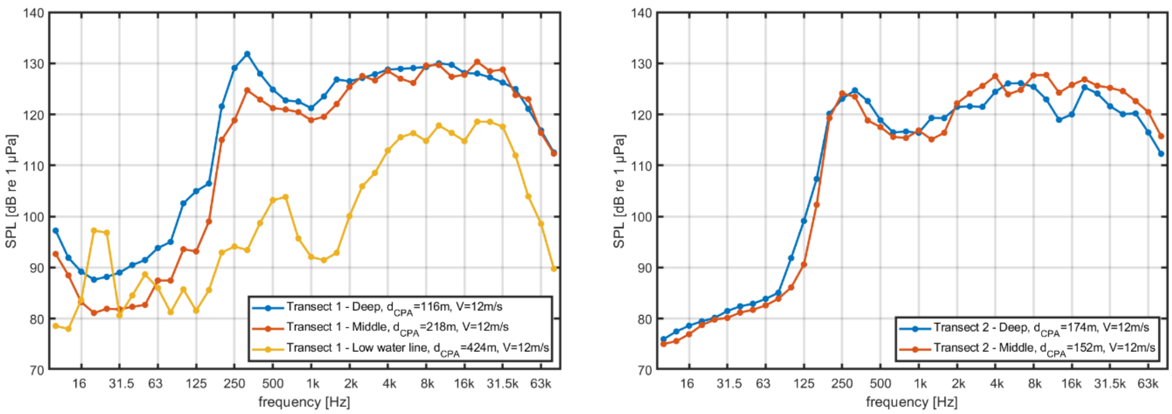

Figure 5.6: decidecade spectrum of the SPL of vessel radiated sound from the passing ferry, as measured by the hydrophones along Transects 1 and 2.

Figure 5.6 shows the sound spectra of the ferry as measured by the five hydrophones. The greater distance to the vessel and the lower water depth at the Transect 1 low water line hydrophone lead to a significant decrease of the received sound, particularly below 5 kHz.

5.3.3 Underwater radiated sound per vessel class

The processing was repeated with an automated script for all identified vessel passages (at distances smaller than 500 m and larger than the length of the vessel, and with at least 10 minutes difference between passages) over the two recording periods in September and October 2022.

Table 5.1 and table 5.2 present an overview of the statistics of the main parameters associated with the measured vessel passages per vessel class. The vessel classes are described in appendix D. Figure 5.7 shows spectra of the underwear radiated sound measured from individual vessels passages, grouped per vessel class.

Table 5.1: Statistics of the vessel underwater radiated noise measurements between Lauwersoog and Schiermonnikoog. The SPL is measured at the hydrophone locations while the vessels passed at a CPA distance greater than the vessel length and not more than 500 m . The reported SPL is summed over the decidecade bands from 100 Hz to 80 kHz.

Vessel class	Nr vessels	Nr pass.	length [m]			speed [m/s]			CPA distance [m]			SPL [dB re 1 µPa]		
			min	mean	max	min	mean	max	min	mean	max	min	mean	max
Fishing	33	117	18	22	40	0.8	3.6	6.2	52	214	477	105	122	137
Sailing vessel	7	13	9	12	14	2.2	2.5	2.9	35	189	330	98	106	118
Pleasure craft	2	3	8	16	23	2.4	3.0	4.3	208	355	449	108	113	119
Passenger	6	338	22	40	58	2.4	8.1	13.1	49	162	263	107	128	141
Other	13	54	10	20	38	2.3	10.7	18.0	56	188	453	104	122	139

Table 5.2: Statistics of the vessel underwater noise measurements between Harlingen and Terschelling. The SPL is measured at the hydrophone locations while the vessels passed at a CPA distance greater than the vessel length and not more than 500 m. The reported SPL is summed over the decidecade bands from 100 Hz to 80 kHz.

Vessel class	Nr vessels	Nr pass.	length [m]			speed [m/s]			CPA distance [m]			SPL [dB re 1 µPa]		
			min	mean	max	min	mean	max	min	mean	max	min	mean	max
Fishing	27	43	16	33	44	1.2	4.0	6.0	27	263	479	103	122	138
Dredger	6	14	10	42	80	1.0	4.1	6.1	80	323	493	106	123	135
Sailing vessel	24	29	9	13	37	1.9	3.3	4.7	91	321	497	91	106	128
Pleasure craft	12	19	7	13	20	2.2	7.0	19.2	14	309	500	92	112	133
Passenger	14	57	12	41	70	0.3	6.7	15.5	65	332	497	100	123	136
Cargo	5	7	52	73	98	4.2	5.5	7.3	175	289	493	114	125	130
Other	13	50	10	26	55	0.3	9.3	19.8	29	287	500	102	119	128

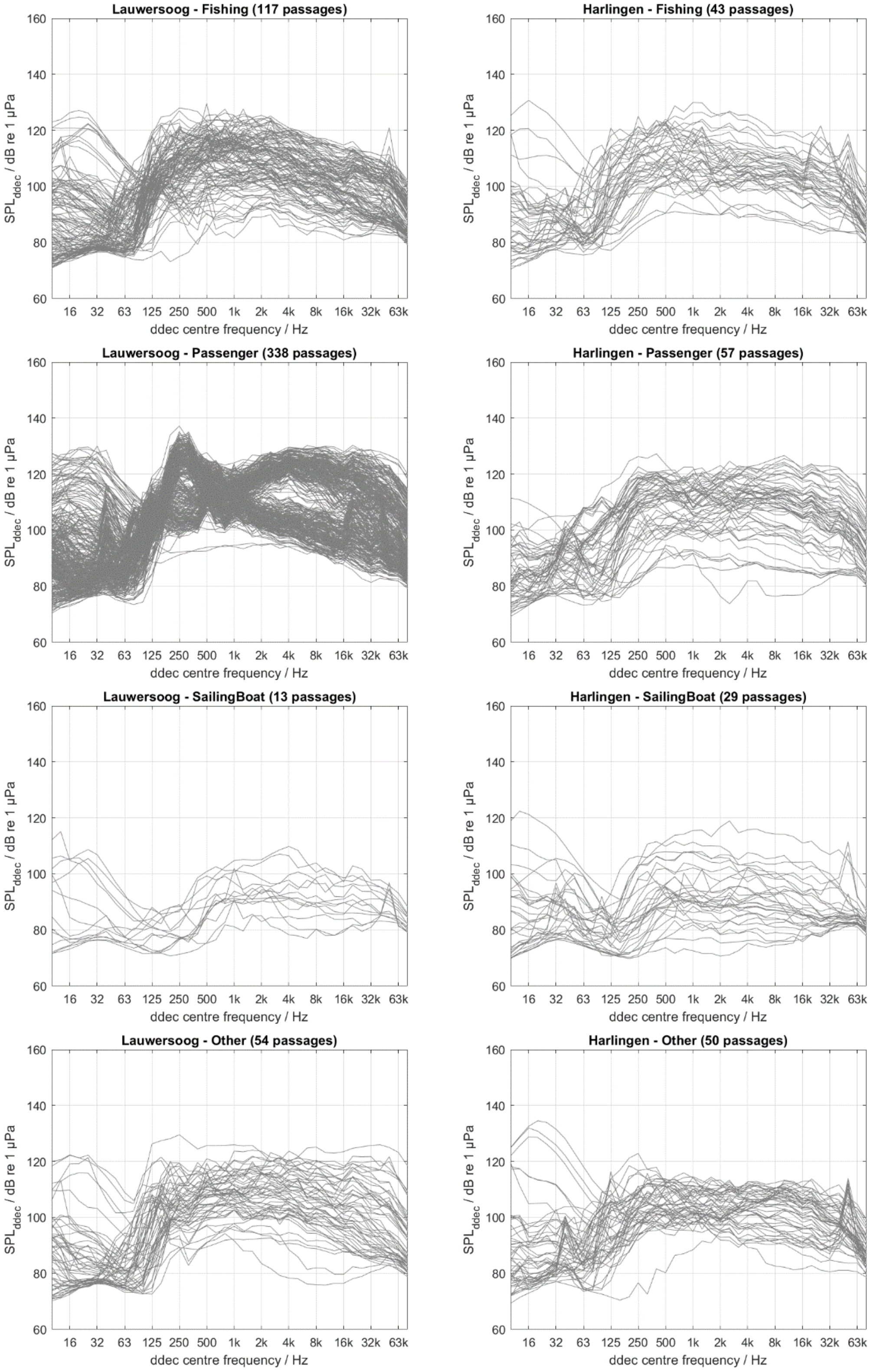

Figure 5.7:Decidecade spectra of the SPL recorded for individual vessel passages at Lauwersoog and Harlingen, grouped per vessel class.

The variation in the vessel SPL spectra at frequencies below 100 Hz is related with disturbance of the measurements by tidal flow noise. Therefore, the further analysis of the vessel underwater sound is based on the broadband SPL over the frequency bandwidth covered by 100 Hz to 80 kHz decidecade bands. Inspection of the spectrograms indicated that vessel sound dominates the measured SPL in this frequency range for most vessel passages. A detailed analysis of the background sound per vessel passage is beyond the scope of this pilot project, so some of the 'quieter' vessel passages measurements may be uncertain. The statistics of this broadband SPL per vessel class is reported in table 5.1 and table 5.2.

The variation in the recorded SPL per vessel class is related with variations between individual vessels, including their length and speed, as well as to variations in the distance at which their sound is measured, and the effects of the local water depth and seabed properties on the sound propagation. Assessment of the vessel underwater radiated sound characteristics independent of the environment and measurement location is beyond the scope of this pilot study.

Trends of the broadband SPL from vessel passages with CPA distance, vessel speed at CPA and vessel length are shown in figure 5.8. The horizontal axes to these graphs are logarithmic, because the vessel source levels are expected to depend logarithmically on these parameters, see for example (MacGillivray & de Jong, 2021).

Although there is a lot of scatter in the data, because each trend graph shows the dependence on a single factor while ignoring the effect of the other parameters, some global trends can be observed:
- The SPL generally decreases with increasing observation distance.
- The SPL generally increases with increasing ship speed.
- The vessel length appears to have less influence on the SPL than the other two parameters.
- The highest observed broadband SPLs are from passages of passenger vessels at Lauwersoog.

The passenger vessel measurements at Lauwersoog are dominated by many passages of the two ferries between Lauwersoog and Schiermonnikoog. Figure 5.8 shows that the smaller and faster ferry produces the highest SPL. The SPL spectra of these two ferries can be clearly identified in figure 5.7 (in the Lauwersoog - Passenger graph). The smaller and faster ferry has a peak in the 200 - 320 Hz decidecade bands.

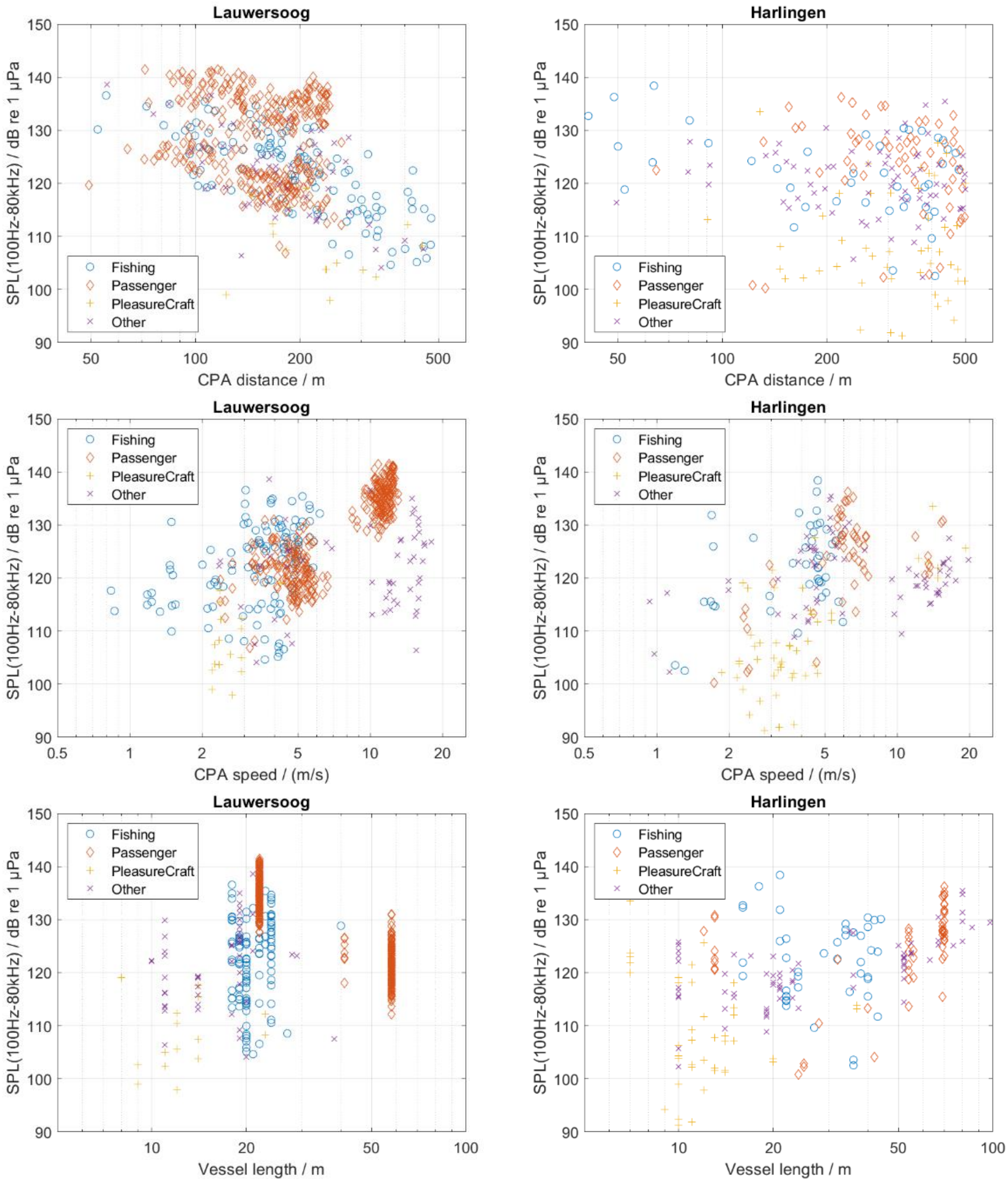

Figure 5.8: Trends of the broadband SPL recorded for individual vessel passages at Lauwersoog and Harlingen with CPA distance (upper graphs), vessel speed at CPA (middle graphs) and vessel length (lower figures), grouped per vessel class.

6 Conclusions and way forward

The Wadden Sea underwater sound pilot project has produced a valuable set of data from two weeks of recording along the navigation channels between Lauwersoog and Schiermonnikoog and between Harlingen and Terschelling.

The purpose of this study was to get insight in the soundscape of the Wadden Sea and the contributions of different vessel types. No source levels of individual vessels were derived from the measurements and no conclusions can be drawn from the measured sound of individual passing vessels.

Lessons learned from the measurements are:
- Underwater sound monitoring is proven to be feasible.
- Redundancy in measurements is essential (one system did not record; another system was displaced).
- Flow-noise limits the measurements of ship radiated sound at low frequency. Placing hydrophones in an enclosure that increases the distance between the hydrophone and the turbulent flow reduces the contribution of flow noise to the acoustic measurements. However, there are no standard guidelines for the design of such an enclosure. The enclosure should be transparent to acoustic waves, while sufficiently robust to survive the harsh conditions at the offshore measurement location.
- Observations confirm that a substantial fraction of the passing vessels is not tracked by AIS, but these seem to be mainly recreational vessels, that do not generally dominate the soundscape.

Lessons learned from the analysis are:
- The median underwater sound pressure level in the Wadden Sea is much lower than at locations in the North Sea (at frequencies below about 2 kHz). This is likely explained by the lower shipping density and the much shorter sound propagation distance because of the much shallower water and the shielding provided by the islands.
- In the higher temporal percentiles of the SPL(1s), that are dominated by contributions from individual vessel passages at closer distance from the hydrophones, the difference between the sound in the Wadden Sea and in the North Sea is smaller, but the Wadden Sea is still quieter.
- A substantial fraction of the SPL measurements during vessel passages along hydrophones is of sufficient quality to determine characterize the vessel underwater radiated sound, i.e. at appropriate CPA range without interference from other vessels.
- Automated processing of the SPL per vessel passages results in a useful dataset, that can be used for analysing trends with relevant parameters.

Way forward
- Assessment of the potential effects of underwater sound on marine life in the Wadden Sea requires a broader temporal and spatial overview than can be obtained from local monitoring.
- Sound mapping, as done for the deeper water in the North Sea in the Jomopans project, seems the preferred way forward to get a broad overview.
- This requires further development of shallow water propagation models.

- Some form of shallow water propagation modelling will also be needed to derive vessel source levels from the Wadden Sea SPL measurements.
- The collected data can be used to test procedures for determining ship source levels, as, for example, being developed by ISO (17208-3).

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Appendix A
Underwater ambient sound metrics

Underwater ambient sound varies over time, space and frequency. These variations must be somehow incorporated when characterizing underwater ambient sound. In Jomopans, the following choices were made for analysing sound pressure measurements:
- temporal analysis window (TAW): 1 month;
- temporal observation window (TOW) for measured sound: 1 s;
- monthly percentiles (P00, P01, P05, P10, P25, P50, P75, P90, P95, P99, P100);
- frequency:
  - 'Broadband', covering the 10 Hz to 20 kHz decidecade bands;
  - 'Decade 1', covering the 20 Hz to 160 Hz decidecade bands;
  - 'Decade 2', covering the 200 Hz to 1.6 kHz decidecade bands;
  - 'Decade 3', covering the 2 kHz to 16 kHz decidecade bands;
  - 63 Hz decidecade band;
  - 125 Hz decidecade band.

Jomopans deviated from the suggestions from the IQOE Workshop Report: "Guidelines for Observation of Ocean Sound" (13 July 2019) on two aspects:
- temporal observation window (TOW) for measured sound: 60 s;
- arithmetic mean and specified percentiles (5, 10, 25, 50, 75, 90, 95th).

The Wadden Sea measurements were limited to a period of approximately 8,5 days per location. The SPL was processed according to the Jomopans standard:
- temporal observation window (TOW) for measured sound: 1 s;
- 10 Hz to 20 kHz decidecade bands.

A.1 Example: a one day recording

Take the underwater sound recorded at Lauwersoog, Transect 1 - deep, on 14 September 2022. The measured spectrogram is shown in Figure A.1.

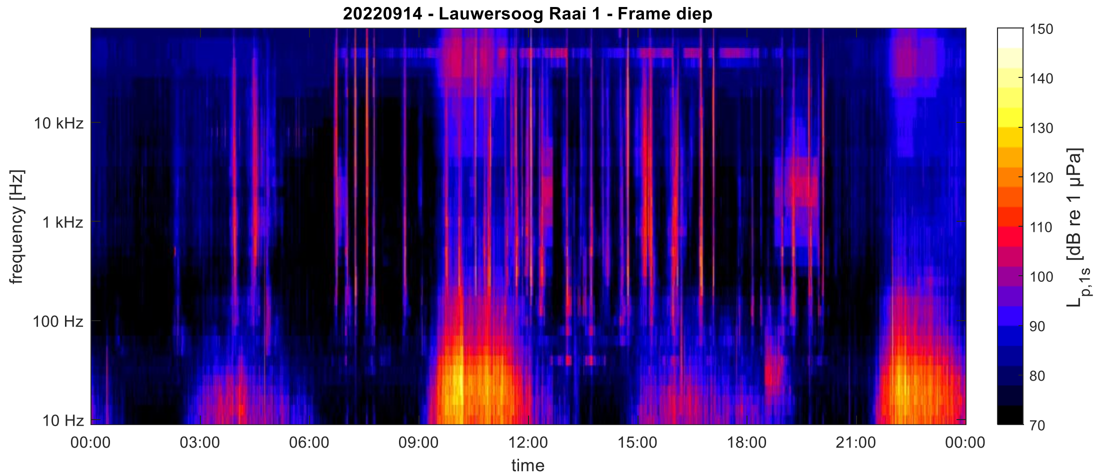

Figure A.1: Underwater SPL_{1s} in decidecade bands, measured on 14 September 2022 at location 'Transect 1 - deep' near the port of Lauwersoog.

A.2 Daily percentiles

The daily statistics associated with the measured SPL_{1s} is shown in figure A.2.

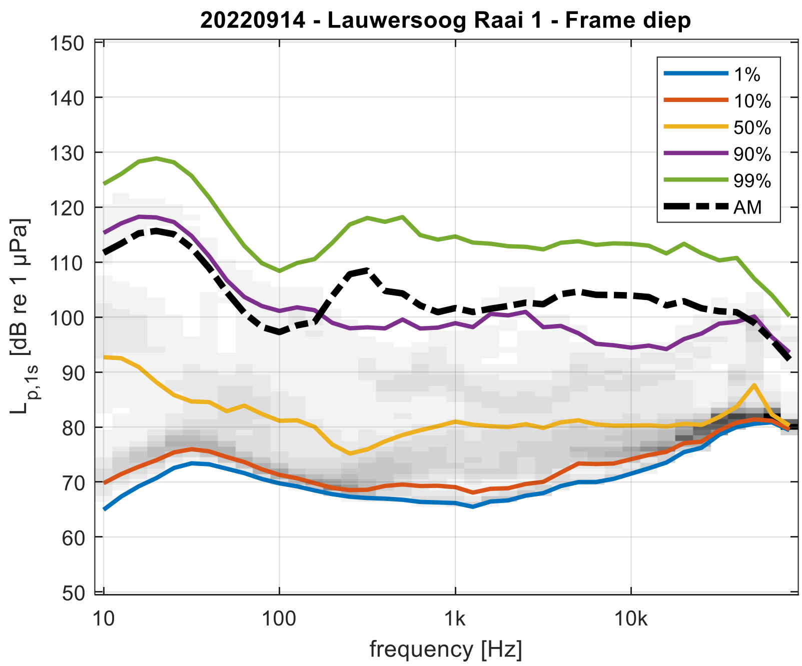

Figure A.2: Daily percentiles of SPL_{1s} in decidecade bands, measured on 14 September 2022 at location 'Transect 1 - deep' near the port of Lauwersoog. The grey shading indicates the spectral probability density and the solid lines show selected temporal percentiles. The black dashed line presents the arithmetic mean (SPL_{24h}).

The black dashed line in this figure presents the arithmetic mean, i.e. the SPL for a TOW equal to one day (24h). This represents the total amount of sound energy that is observed during the day. This appears to correspond with SPL_{1s} values that are observed during only 10% or less of the time during that day.

A.3 Temporal observation window (TOW)

The choice of TOW is important for the temporal percentiles. To demonstrate this, the SPL_{60s} (arithmetic mean) has been recalculated for each TOW of 60 s (as advised by IQOE). This smooths the spectrogram, as shown in figure A.3.

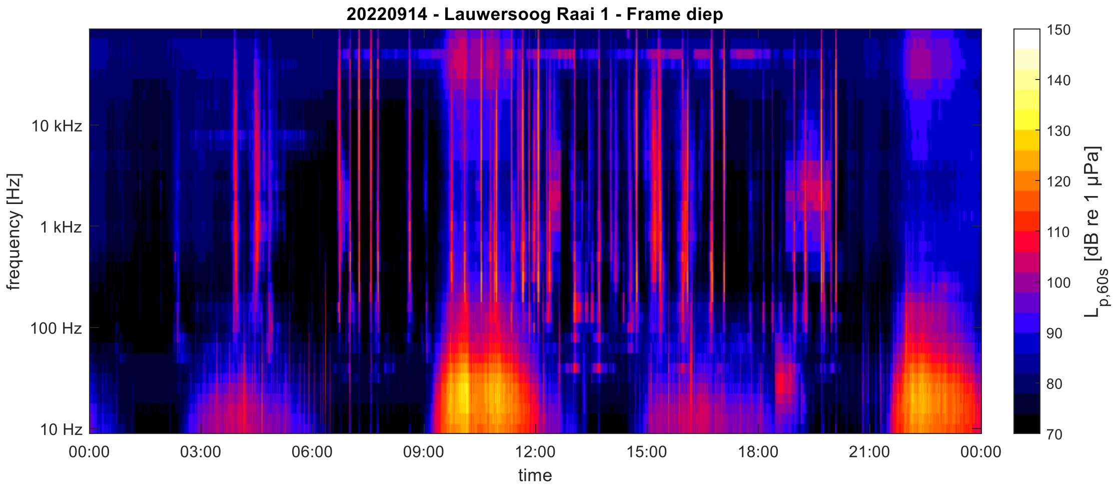

Figure A.3: SPL_{60s} in decidecade bands, measured on 14 September 2022 at location 'Transect 1 – deep' near the port of Lauwersoog.

The duration of the TOW influences the daily statistics, as illustrated in the following figures that compare the daily percentiles for SPL_{1s} (solid lines) and SPL_{60s} (dashed lines).

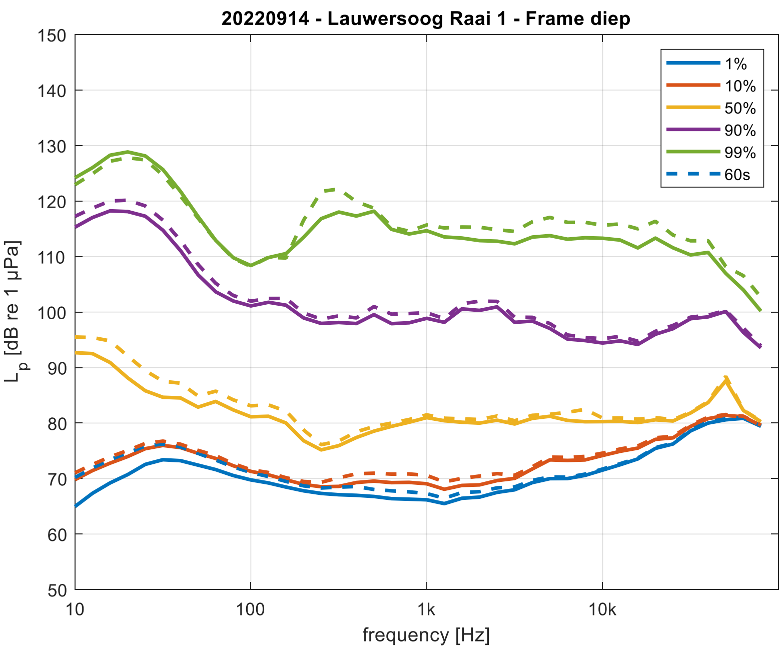

Figure A.4: Selected daily percentiles of SPL_{1s} (solid lines, see figure A.2) and SPL_{60s} (dashed lines) in decidecade bands.

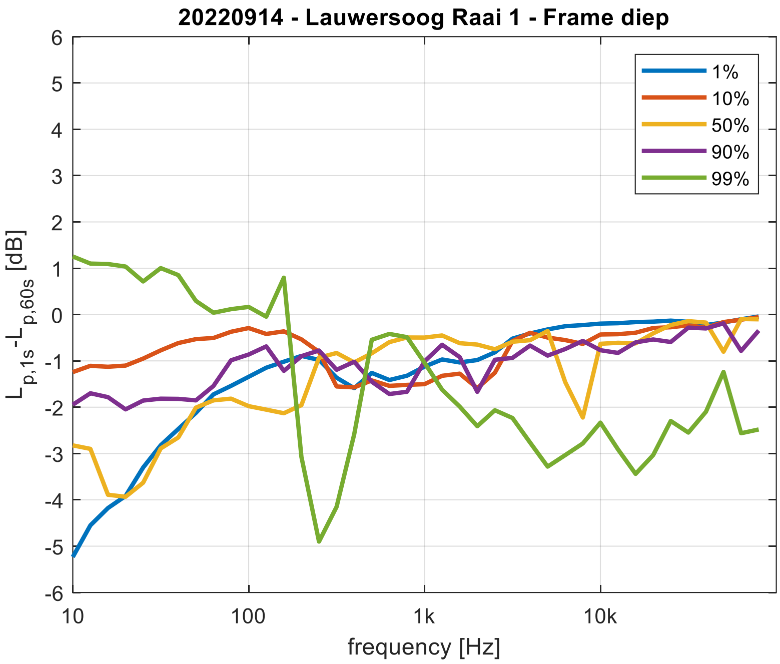

Figure A.5: Difference between selected daily percentiles of SPL_{1s} and SPL_{60s} in decidecade bands.

This means that a comparison of temporal percentiles of SPL between different time periods or locations must ideally be done for the same TOW duration, to avoid uncertainties (here of the order of 1 to 5 dB).

Which TOW duration is preferred depends on the application. Jomopans selected 1 s as a compromise between being representative for the (mammalian) auditory integration time (order of magnitude ~0.1 s) and reducing uncertainty in the calculation of spectral band levels. This choice is followed here, to be consistent with the Jomopans monitoring. It is noted that this deviates from the TOW of 60 s advised by IQOE, which may complicate comparison with other projects.

Appendix B
Daily SPL percentiles

B.1 Lauwersoog-Schiermonnikoog

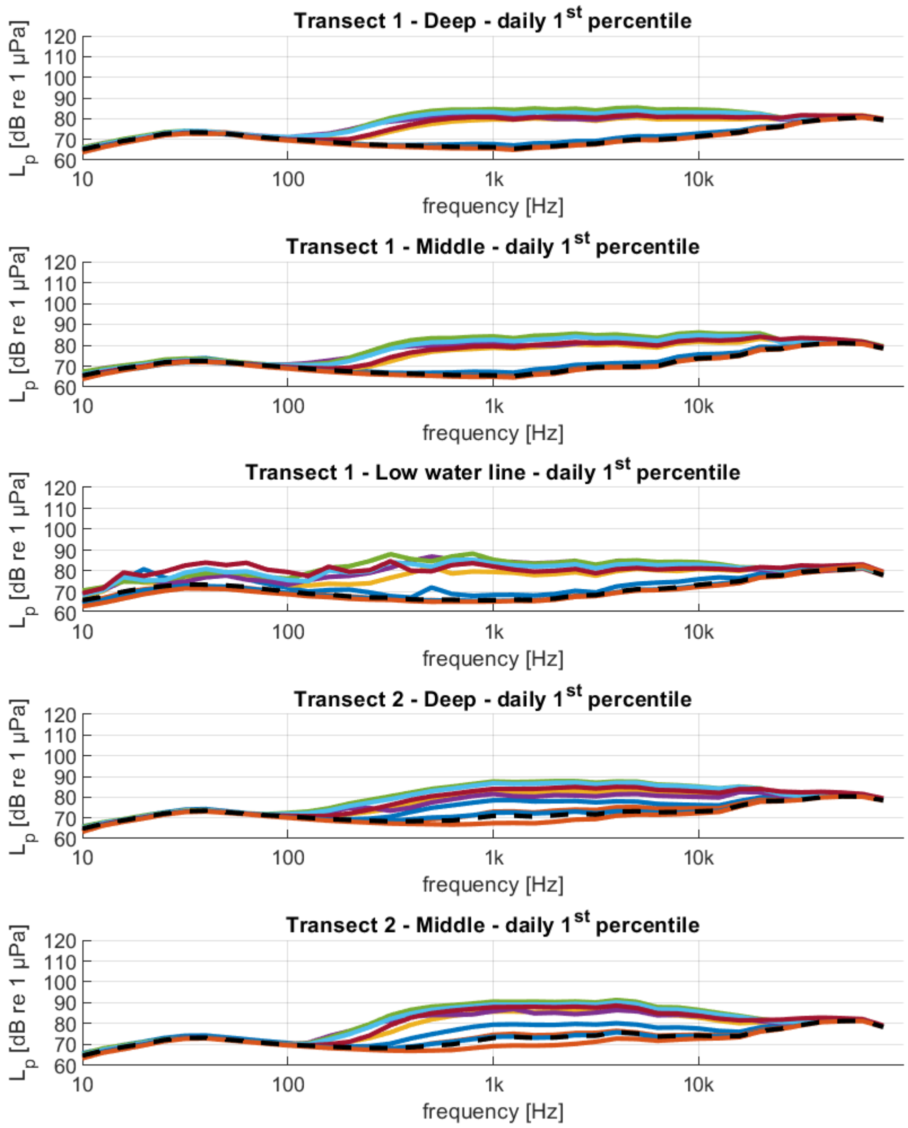

Figure B.1: Daily 1st percentile of the measured SPL_{1s} in decidecade bands at the five measurement stations near the port of Lauwersoog for the 9 measurement days (coloured lines). The black dashed lines give the 1st percentile over the full measurement period.

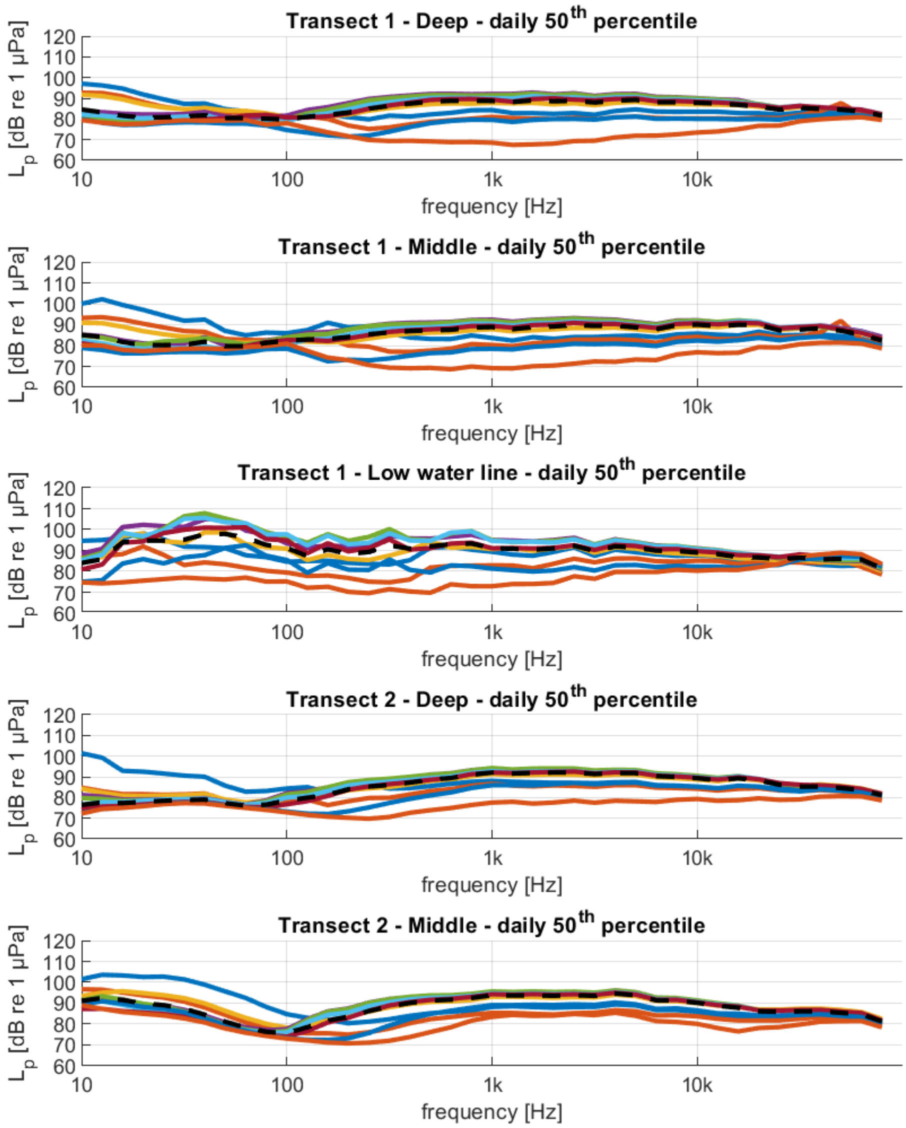

Figure B.2: Daily median (50th percentile) of the measured SPL_{1s} in decidecade bands at the five measurement stations near the port of Lauwersoog for the 9 measurement days (coloured lines). The black dashed lines give the median over the full measurement period.

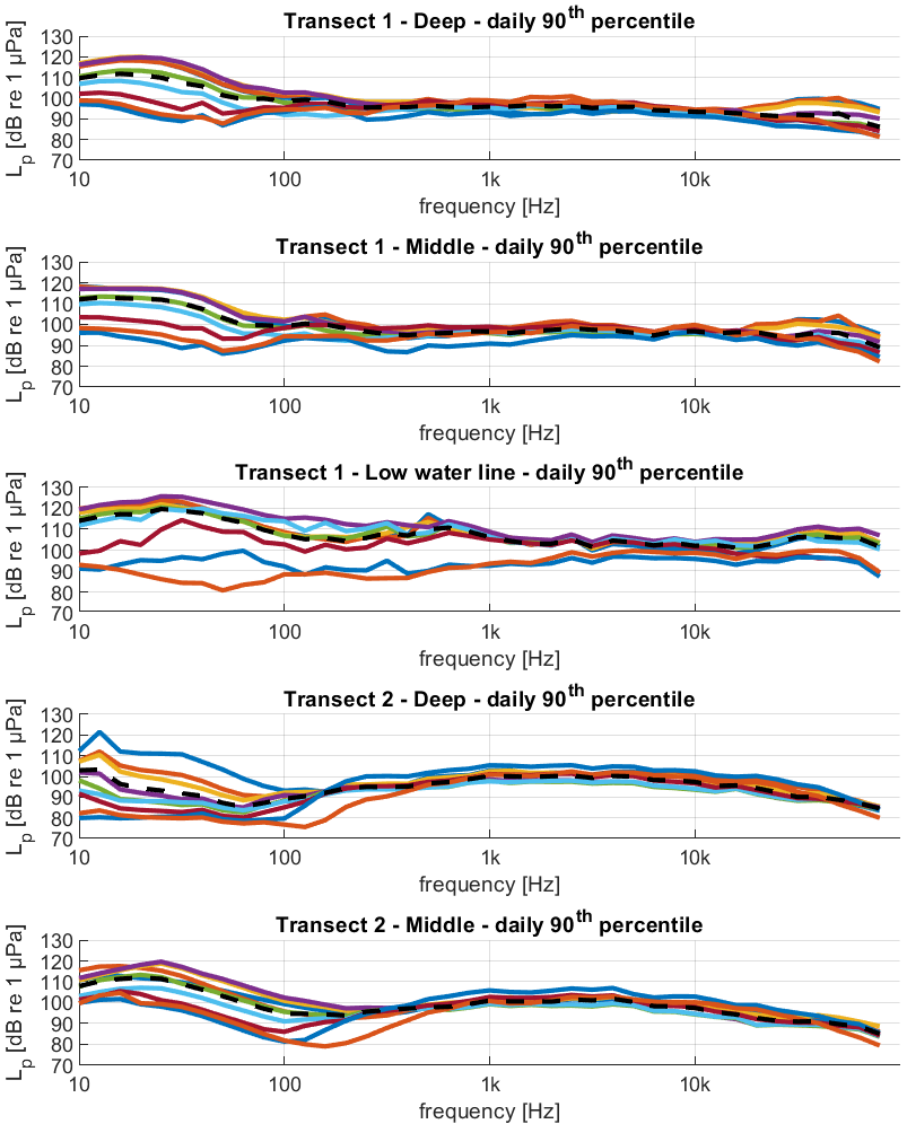

Figure B.3: Daily 90th percentile of the measured SPL_{1s} in decidecade bands at the five measurement stations near the port of Lauwersoog for the 9 measurement days (coloured lines). The black dashed lines give the 90th percentile over the full measurement period.

B.2 Harlingen-Terscheling

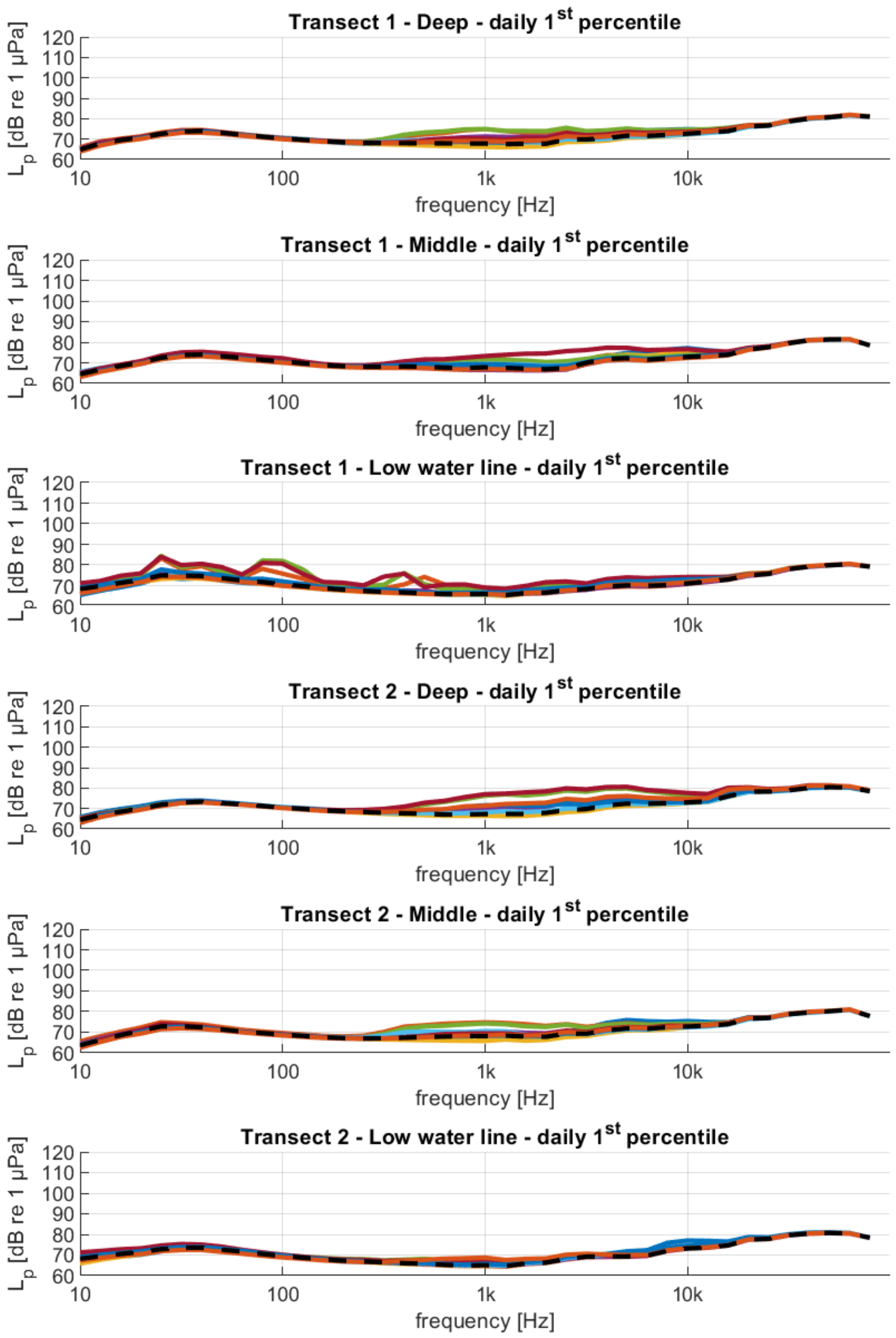

Figure B.4: Daily 1st percentile of the measured SPL_{1s} in decidecade bands at the six measurement stations near the port of Harlingen for the 9 measurement days (coloured lines). The black dashed lines give the 1st percentile over the full measurement period.

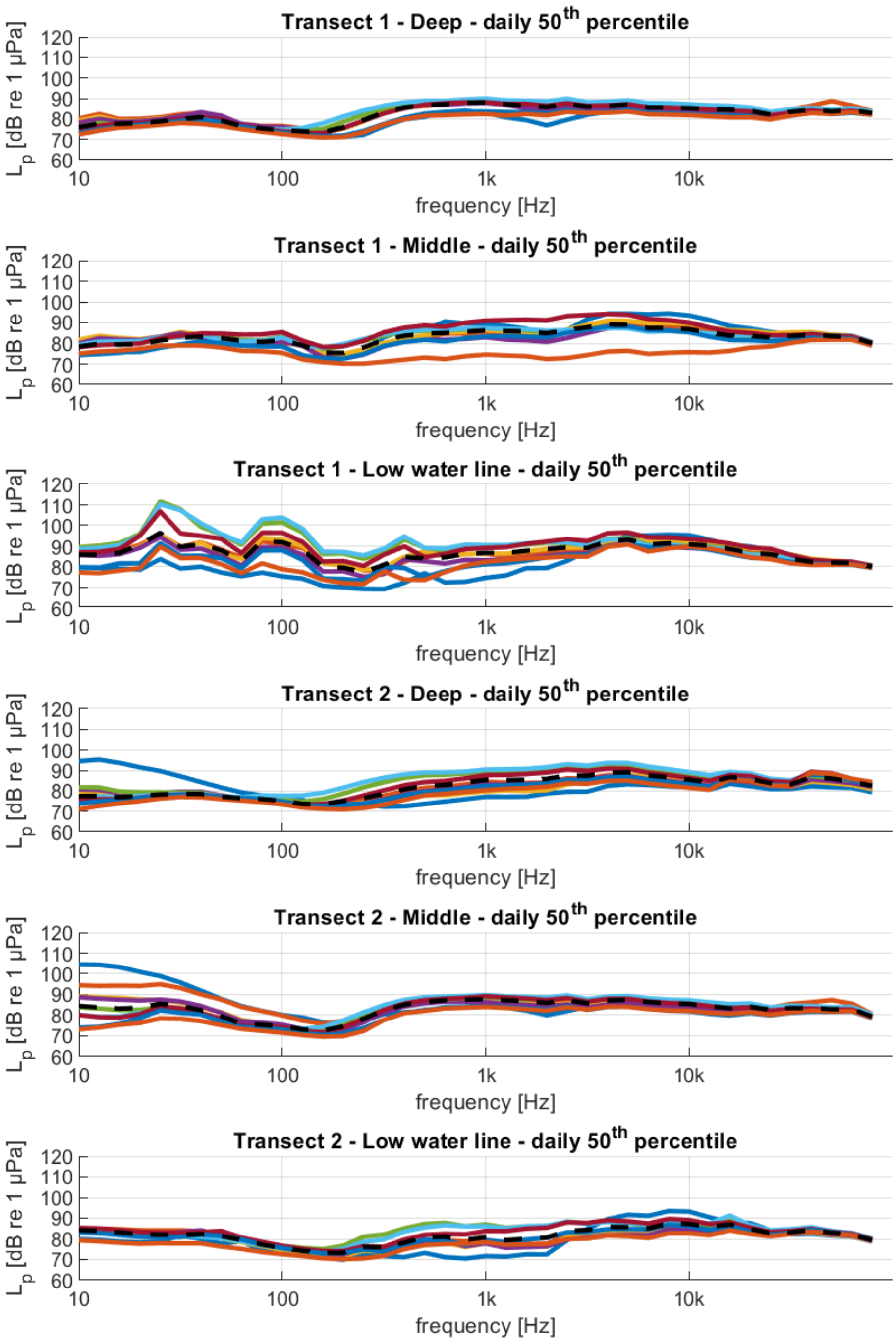

Figure B.5: Daily median (50th percentile) of the measured SPL_{1s} in decidecade bands at the six measurement stations near the port of Harlingen for the 9 measurement days (coloured lines). The black dashed lines give the median over the full measurement period.

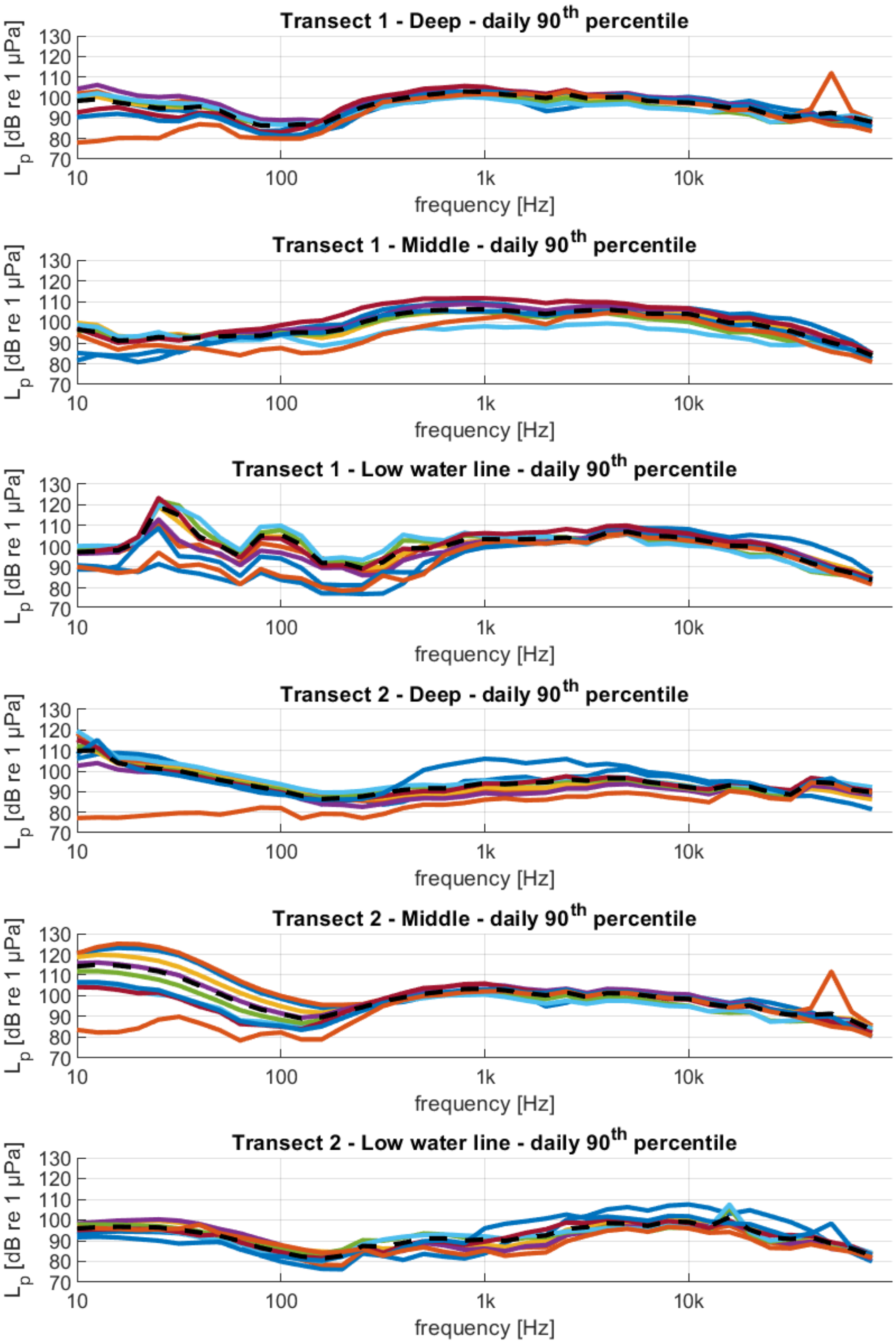

Figure B.6: Daily 90th percentile of the measured SPL_{1s} in decidecade bands at the six measurement stations near the port of Harlingen for the 9 measurement days (coloured lines). The black dashed lines give the 90th percentile over the full measurement period.

Appendix C
Environmental data

Waterproof has collected environmental data for the two measurement periods, see (van Tol, Olivierse, & Brinkkemper, 2022). The following figures provide an overview of the data:

- wind speed;
- wind direction;
- water temperature;
- wave height;
- water height (tidal) above NAP.

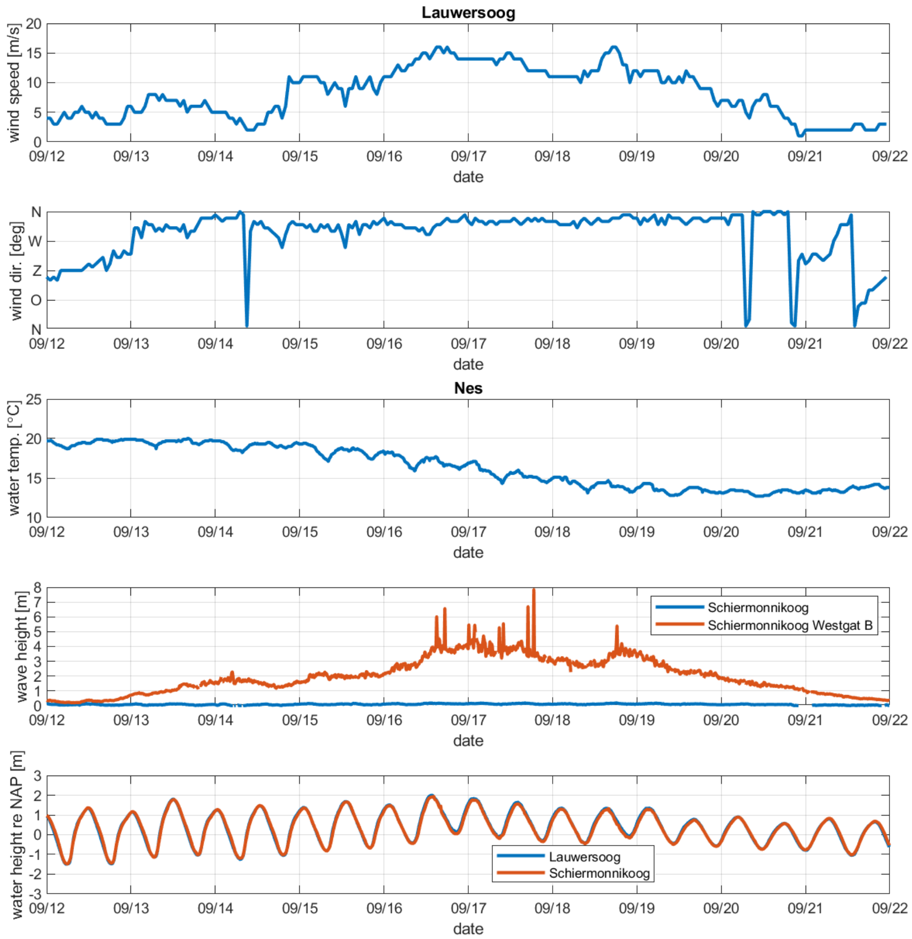

Figure C.1: Wind speed and direction, water temperature, wave height and water height during the period of the measurements between Lauwersoog and Schiermonnikoog. The map shows the two measurement positions for wave height (Schiermonnikoog and Schiermonnikoog Westgat B).

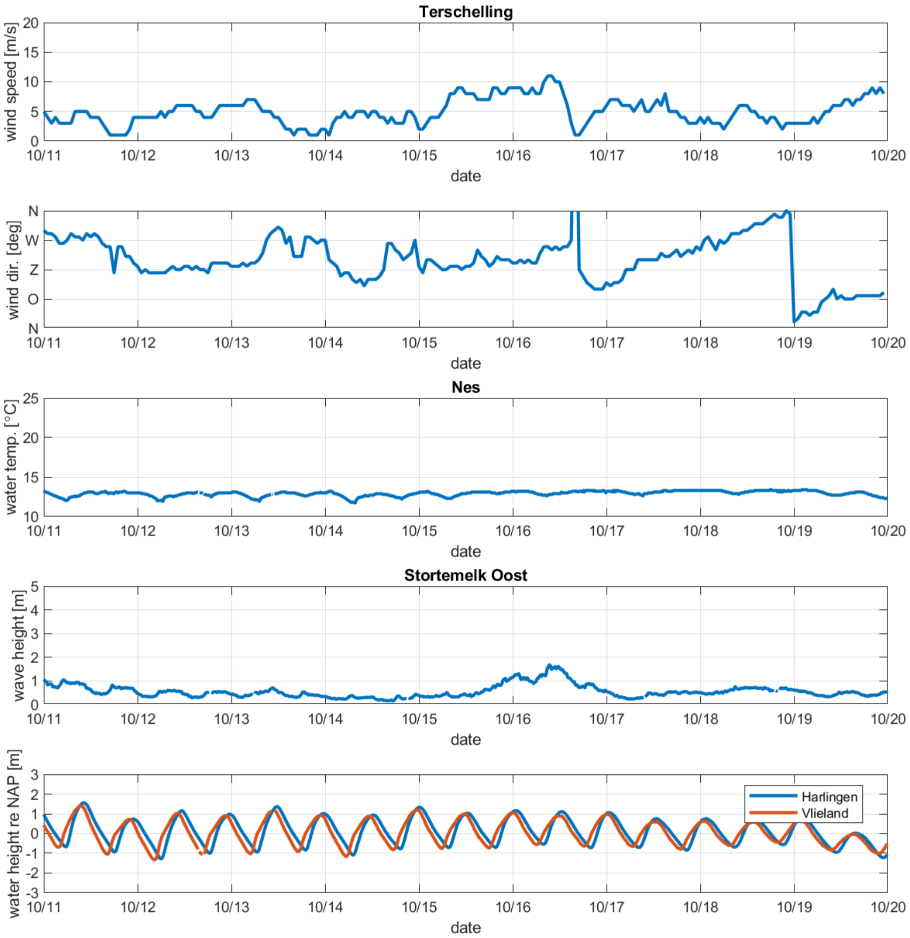

Figure C.2: Wind speed and direction, water temperature, wave height and water height during the period of the measurements between Harlingen and Terschelling. The map shows the measurement positions for wave height (Stortemelk Oost).

Appendix D
Vessel class

The anonymized AIS data give insight in the vessel types that were present during the measurement periods at the two locations, see table D.1. For some vessels also ERI vessel codes were provided, see table D.2.

Table D.1: Overview of the vessel types in the AIS data, and the number of selected measurements of their underwater radiated sound from an undisturbed passage within 500 m from a hydrophone.

Class	Shiptype ID	AIS type summary	Lauwersoog		Harlingen	
			vessels	passages	vessels	passages
Fishing	30	Fishing	44	118	30	57
Dredger	33	Dredger	1	3	6	15
Sailing Vessel	36	Sailing vessel	24	35	25	31
Pleasure craft	37	Pleasure craft	10	14	12	19
Passenger	60	Passenger			6	45
	61	Passenger			1	3
	69	Passenger	8	239	7	10
	94	Other	1	88		
Cargo	70	Cargo	1	1	3	5
	79	Cargo	1	1	2	2
Other	0	Unspecified	1	1	3	9
	34	Dive vessel	2	16	1	11
	40	High-speed craft	1	2	1	4
	49	High-speed craft			1	8
	50	Pilot Vessel	1	6	2	11
	51	SAR	3	36	1	1
	52	Tug	1	6		
	55	Law enforce	2	4	2	4
	57	Local vessel	1	1		
	90	Other	4	9	2	5
	99	Other			1	3
		TOTAL	106	580	106	243

Table D.2: ERI ship codes (source: 'Handboek voor de inbouw van Inland AIS', Vessel Tracking and Tracing Expert Group).

ERI code	Ship type	AIS
0	type unknown	99
1850	Pleasure craft, longer than 20 metres	37
1910	Hydrofoil	49
1920	Catamaran Fast	49
8000	type unknown	99
8010	Motor freighter	79
8440	Passenger ship, ferry, cruise ship, red cross ship	69
8441	Ferry	69
8444	Passenger ship without accommodation	69
8450	Service vessel, police patrol, port service	99
8460	Vessel, work maintenance craft, floating derrick, cable-ship, buoy-ship, dredge	33
8480	Fishing boat	30

Defence, Safety & Security

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