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TNO report

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Underwater noise of Trailing Suction Hopper Dredgers at Maasvlakte 2: Analysis of source levels and background noise

Date	November 2010
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Summary

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The Port of Rotterdam is expanding to meet the growing demand to accommodate large cargo vessels. The construction of Maasvlakte 2 (MV2) started in September 2008. This report describes the monitoring of the underwater sound produced during its construction, in connection with the environmental impact assessment.
Underwater noise measurements were carried out between 22 September and 5 October 2009. During these measurements, seven dredgers were working for MV2. These seven are representative of the dredging fleet working for MV2.

The main aim of the measurements was to determine the acoustic source level of the Trailing Suction Hopper Dredgers during the various activities at MV2: dredging, transport and discharge of sediment. Because of the lack of appropriate standards for characterizing ships as sources of underwater noise, a new analysis methodology was developed for the present study. The highest sound pressure levels were found for large dredgers while transiting. Sand dredging generally produced source levels at a few decibels lower than for transiting dredgers. Pumping and rainbowing resulted in source levels similar to dredging in the frequency range between 500 Hz and 10 kHz and significantly lower levels outside this range. The broadband noise characteristics above 100 Hz are very similar for all dredger activities except sand dumping. It is likely that the noise is dominated by cavitation noise from propellers and bow thrusters.

A second aim of the measurements was to compare the 2009 (25 September to 5 October) background noise levels with those measured in 2008 (8 to 15 September) [TNO-DV 2009 C212: Dreschler et al., 2009]. The background noise at a fixed position, as measured in 2008, before the start of Maasvlakte 2 construction activities, was found to be dominated by noise produced by shipping. The measured noise levels in 2009, at a slightly different fixed position, were generally higher than those in 2008. Because the dredgers passed close by the measurement position, they are responsible for larger variations in the noise levels than was observed in 2008.
Despite the overall increase relative to 2008, in some third-octave bands (close to 3 kHz) the levels in 2009 were lower than in 2008, especially during the night time. This difference could be due to a diurnal variation in the propagation loss, possibly caused by the presence and behaviour of large numbers of small bladdered fish (of length between 3 and 5 cm).

List of abbreviations

AIS	Automatic Identification System
CPA	Closest Point of Approach
CTD	Conductivity, Temperature, Depth
GPS	Global Positioning System
kn	knot
MV2	Maasvlakte 2
OASES	Ocean Acoustics and Seismic Exploration Synthesis (software)
PL	Propagation Loss
PUMA	Projectorganisatie Uitbreiding Maasvlakte
SL	Source Level
SPL	Sound Pressure Level
SSP	Sound Speed Profile
TSHD	Trailing Suction Hopper Dredger
TSHDs	Trailing Suction Hopper Dredgers

Contents

1 Introduction

The Port of Rotterdam is expanding to meet the growing demand to accommodate large cargo vessels. The construction of Maasvlakte 2 (MV2) started in September 2008. The 'Milieueffectrapport Aanleg Maasvlakte 2'provided a preliminary assessment of the underwater sound produced during the construction of MV2. One of the licence conditions for Maasvlakte 2 is the actual monitoring of the underwater sound produced during its construction. Specific activities to be monitored are the dredging, transport, and sand dumping, rainbowing and pumping ashore by the Trailing Suction Hopper Dredgers (TSHDs).

Little is known about the underwater sound produced by dredging and land reclamation. Different dredgers and different activities would have different source levels, different underwater environments lead to differences in sound propagation, and there are differences in the sensitivity of different marine animals to underwater sound. Specific measurements on the MV2 dredging will lead to specific source levels for the MV2 conditions. These source levels can be used in future studies of the influence of the construction noise on marine life in the area, e.g. seals and harbour porpoises.

The objective of the present document is to report on the results of the source level and background noise measurements that were made in the period 22 September to 5 October 2009 in the MV2 dredging activities area. The measurement procedures are described in the Measurement plan underwater sound Maasvlakte 2 [van Walree et al., 2009]. One aim of the Maasvlakte 2 measurements was to determine the acoustic source level of the dredgers during the various activities: dredging, transport, and discharge of sediment. Another was to characterise the 2009 background noise level for comparison with 2008 measurements.

Chapter 2 describes the methodology for the measurements, where during one week the background underwater noise, including the noise of the TSHDs, in front of MV2 was recorded from a fixed position. Simultaneously, the measurement of source level for dredging activities was carried out from various positions using a mobile system. The measurements are described in chapter 3, after which the procedure to estimate the source level from the underwater noise measurements with the mobile system is illustrated by several typical examples in chapter 4 with respect to tracking, underwater noise and propagation loss. The effect of sediment parameters and sound depth are also discussed. Detailed results for the source levels obtained from the mobile system are presented in chapter 5 for the various dredging activities: dredging, rainbowing, direct sand dumping, pumping ashore and transit. Concluding a comparison is made of the maximum underwater noise due to the various activities.

The background noise measurements with the autonomous platform SESAME are described in chapter 6. Starting with a description of the experimental method and data analysis, the results are discussed next including a comparison between the sound pressure levels (SPL) for the 2009 and 2008 campaigns, the effect of TSHDs on the level of the background noise and a comparison of SPL for day and night time. Finally a summary of the results is given.

2 Source level: Methodology

2.1 Measurement equipment

The tug *'Mon Desir'* served as a platform for measuring the underwater sound. The ship was used to deploy the wet equipment and to provide shelter for the dry equipment and work space for the personnel.

Figure 2.1 Measurement platform *'Mon Desir'* (Sleepvaart en Baggerbedrijf J.J.Saarloos, Dordrecht).

The source level measurements are performed with a vertical hydrophone chain, deployed and recovered from the measurement vessel. The wet end of the equipment has the following components, from top to bottom:

- a buoy, floating at the sea surface,
- two hydrophones (B&K 8101),
- a dead weight of about 3 kg (in water), to keep the rope straight.

See Figure 2.2 for a sketch of the set-up. A bundled set of cables connects the hydrophones with data acquisition equipment (B&K PULSE) in the cabin of the ship. This is the dry end of the acoustic measurement system. Other instruments that are used on the measurement ship are:

- AIS recording equipment (SR161, Smart Radio)
- GPS recording equipment (Garmin GPS 12XL)
- A stand-alone sound velocity profiler (DIGIBAR DB1200)
- Meteorological sensors, placed on the deck of the ship.

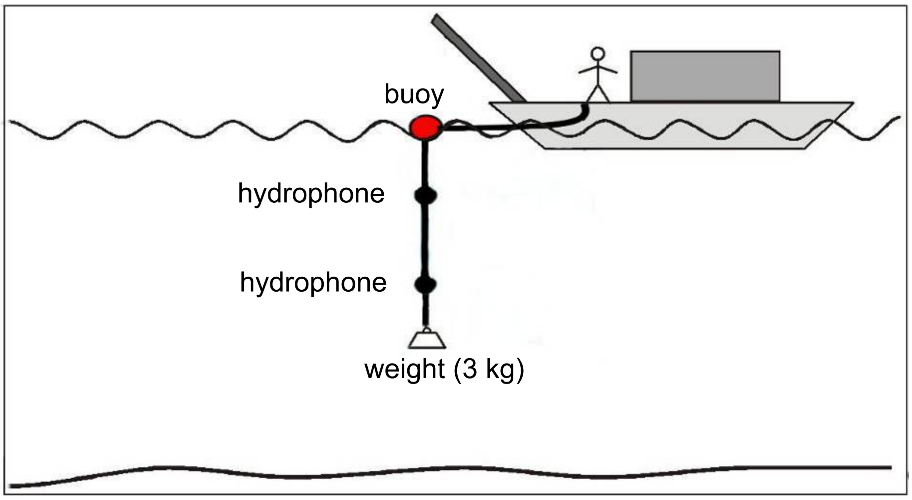


Figure 2.2 Schematic drawing of the source level measurements. The hydrophones are at a fixed distance (6 and 12 metres) from the surface for water depths of more than 14 metres.

2.2 Source level measurements

Figure 2.3 sketches the geometry of the source level measurements. For dredging and transport, measurements at different ranges are obtained by positioning the measurement ship at a given position. The approaching and receding TSHD ensures that the recordings contain ‘many ranges’. The suggested minimum range is d2 ≈ 100 m. The maximum ranges d1 and d3 are determined by the condition that the noise from the TSHD should dominate the recorded sound. As to sand dumping, the measurement ship is moved from one spot to the next, see Figure 2.3. This is only feasible for rainbowing and pumping ashore, because direct dumping lasts only ~10 minutes.

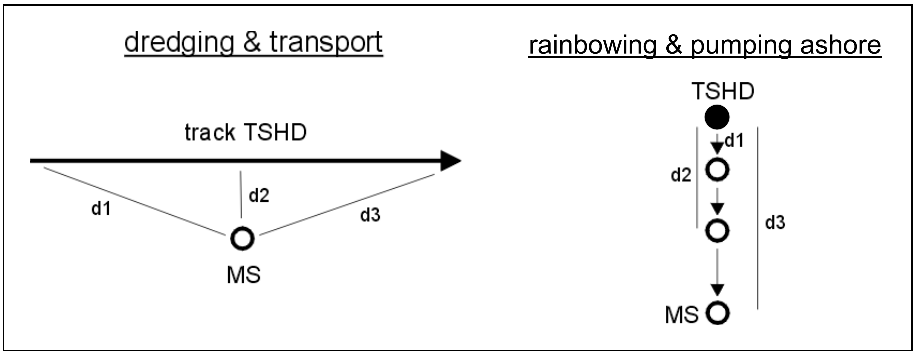


Figure 2.3 Sketch of the source-level measurements for dredging and transport (left), and rainbowing and pumping ashore (right). Different ranges are obtained from the moving TSHD, and by moving the measurement ship respectively.

2.3 Source Level estimation

The measured underwater noise is influenced by the ship and the environment in which the noise propagates. The measure for characterising sources of underwater noise, independent of the environment in which the measurements are taken, is the source level SL [Urick, 1983][de Jong, 2009].

Important initial assumptions are that the noise generation is a stationary process during each run and that the source can be represented as a monopole that radiates equally strong in all directions.

2.3.1 *Source Level definition*

The Source Level expresses the mean square sound pressure p_{rms}^2 [Pa^2] at a distance r [m] in a certain direction in the far field of the source (where the sound pressure and particle velocity are in-phase and decrease inversely proportional to the distance from the source), scaled back to a reference distance r_{ref} = 1 m from the acoustic centre of the source. The acoustic centre is the fictitious point from which the far field sound appears to be radiated. Note that the source level cannot be directly measured at the reference distance of 1 m if that point is not in the far field. The definition of SL can be written as:

$$\mathrm{SL} = \mathrm{SPL}(r) + 10\log_{10}\left(r^2/r_{ref}^2\right) \qquad \text{[dB re 1 μPa}^2\text{m}^2\text{]} \qquad (1)$$

where $\mathrm{SPL}(r) = 10\log_{10}\left(p_{rms}^2(r)/p_{ref}^2\right)$ [dB re 1 μPa^2] is the mean square sound pressure level measured at distance r [m] in a certain direction and p_{ref} = 1 μPa is the reference pressure for underwater sound. The second term in eq.(1) provides the scaling to the 1 m reference distance.

This definition is appropriate for a monopole in free space, i.e. a point source that radiates sound continuously and uniformly in all directions, in a homogeneous, isotropic medium (with equilibrium density ρ_w [kg/m^3] and speed of sound c_w [m/s]), without absorption and free from boundaries. In that case, there is a simple relation between the source power W [W] and the mean square sound pressure p_{rms}^2 [Pa^2] at a distance r [m] from the source:

$$W = \frac{4\pi r^2 p_{rms}^2(r)}{\rho_w c_w} \qquad \text{[W]} \qquad (2)$$

In practice, this equation does not apply to surface ships. Ships exhibit directional radiation patterns and a local hydrodynamic field in their vicinity. The underwater environment in which the noise is measured is complex, due to effects of reflections at the water surface and seabed and of variations of the sound speed across the water depth. Especially the reflections at the water surface, often referred to as *Lloyd's Mirror effect*, have a large impact on the sound radiation by surface ships. When comparing published ship 'source levels', one must be alert for the definition, the measurement conditions, experimental procedures and environmental parameters, as well as for inconsistencies in reference distances, units and bandwidths, which are all given in various ways in the literature. Some present ship 'source levels' based on the correction given in eq.(1), without taking the free-surface and bottom interference effects or absorption losses into account, e.g. [Arveson & Vendittis, 2000]. Others, e.g. [Wales & Heitmeyer, 2002], determine the monopole source level, using a propagation model and an assumption for the effective depth of the acoustic centre of the ship.

The recently issued American National Standard ANSI/ASA S12.64-2009/Part 1 'Quantities and Procedures for Description and Measurement of Underwater Sound from Ships – Part 1: General Requirements' [ANSI S12.64], provides a methodology for the reporting of one-third octave band underwater sound pressure levels from ships at a prescribed operating condition. The resulting quantities are the sound pressure levels normalized to a distance of 1 m, based on a correction as given in eq.(1).
Since the underwater sound pressure levels are affected by the presence of the free

surface (and sometimes by the bottom and by absorption), such quantities are considered '*affected source levels*'.

The choice for the 'source level' definition and the associated measurement and analysis procedure, depends on the intended use of the results. We presume that the source level is to be used as input for sound distribution calculations, so that the source level definition should agree with the definition used in the propagation model.
This propagation model is used to estimate the propagation loss PL (dB re 1 m^2), so that the source level is estimated from:

$$\mathrm{SL}(f) = \mathrm{SPL}(r, f) + \mathrm{PL}(r, f) \qquad \text{(dB re 1 } \mu\text{Pa}^2\text{m}^2\text{)} \tag{3}$$

Different propagation models require different source descriptions. In many of these models the acoustic source is modeled as a monopole, often characterized by its free-field SL according to eq.(1). But the energy flux based model ANOMALY for underwater sound propagation at the North Sea [Ainslie et al., 2009], assumes that the source is remote from all reflecting surfaces and requires as input a source level that represents the acoustic power produced by the source. That means that the source descriptor needs to include the dominant effect of surface image interference, similar to the 'affected source level' according to the ANSI S12.64 standard[1].

Therefore, a dual approach is chosen for this study. First, the monopole Source Level of the dredgers is estimated using eq.(3) and a point-to-point propagation loss model (§2.3.2). An important assumption is the location of the virtual monopole source that represents the vessel. The axial position on the vessel is initially selected at the axial position of the GPS antenna. The choice of source depth is also very important.
As an initial guess, a source depth of 4 m is assumed and the effect of this choice on the 'monopole' and 'dipole' Source Level is investigated (§4.6).

Next, this monopole source level is converted to a 'dipole' Source Level, including the contribution of the surface image. The translation between the monopole and dipole source descriptions is approximately given by [Ainslie, 2010]:

$$\mathrm{SL}_{\text{dipole}} = \mathrm{SL}_{\text{monopole}} - 10\log_{10}\left(\frac{1}{2} + \frac{1}{4k^2 d^2 \sin^2\theta}\right) \tag{4}$$

where k is the wave number, d the source depth and θ the 'depression' angle relative to the water surface. ANSI S12.64 specifies that the 'affected' (or 'dipole') source level shall be reported as the power average of the results of measurements with far field hydrophones at θ = 15, 30 and 45°, hence:

$$\mathrm{SL}_{\text{dipole}} = \mathrm{SL}_{\text{monopole}} - 10\log_{10}\left(\frac{1}{3}\sum_{i=1:3}\left[\frac{1}{2} + \frac{1}{4k^2 d^2 \sin^2\theta_i}\right]\right) \quad , \theta_i = \{1,2,3\} \tag{5}$$

[1] Note that the ANSI S12.64 ignores the effect of absorption on propagation loss, so that the 'affected source levels' depend on the distance at which the measurements have been taken and hence, at higher frequencies, are generally lower than the monopole and dipole source levels as defined here.

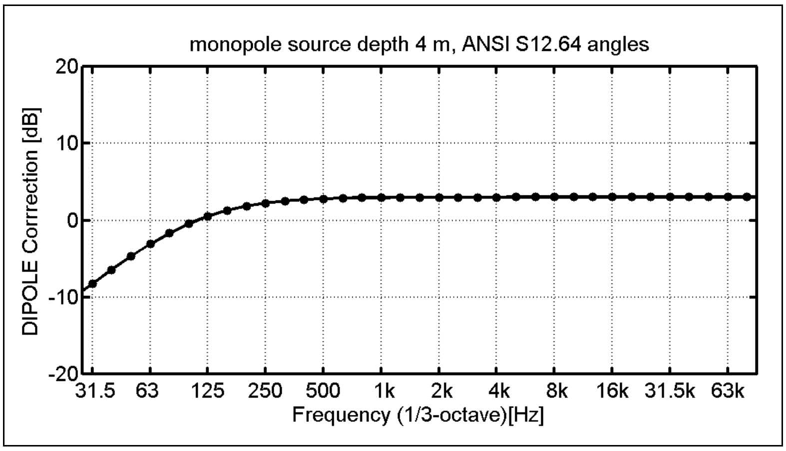


Figure 2.4 Spectrum of the difference between monopole and dipole SL according to eq.(4), for a monopole source at 4 m below the water surface, power averaged over 15, 30 and 45° elevation angles.

2.3.2 *Propagation Loss calculation for the Source Level estimation*

A TNO implementation in Matlab™ of an 'image source ray' model [Urick, 1983] is used to estimate the propagation loss PL between the dredger and the hydrophones. This 'RAYTRACE' model assumes that the water depth and sound speeds in water and sediment are all uniform. The sediment is modelled as a semi-infinite fluid space, characterised by a compressional wave speed, density and loss factor. The water-air interface is assumed to be flat and fully reflecting. The absorption coefficient in seawater is estimated using Urick's modification [Urick, 1983] of Thorp's formula [Thorp, 1967]. As an initial assumption, sediment parameters (compressional sound speed c_b and density ρ_b) were chosen corresponding with 'medium sand' (see also [Ainslie et al.,2009]), with the sediment properties taken from [Ainslie, 2010] (table in §4.4.1.4):

- Sound speed ratio $c_b/c_w = 1.1812$ ($c_w = 1511$ m/s)
- Density ratio $\rho_b/\rho_w = 2.086$ ($\rho_w = 1030$ kg/m^3)
- Bottom absorption coefficient $\alpha_b = 0.88$ dB/λ

2.3.3 *Propagation Model Comparison*

In order to validate the implementation of the 'RAYTRACE' model, calculation results for a selected configuration were compared with results of the more elaborate OASES code for modeling seismo-acoustic propagation in horizontally stratified waveguides, see http://acoustics.mit.edu/faculty/henrik/oases.html.

Calculations were carried out of the propagation loss between a monopole source at a depth of 4 m and a point receiver at a depth of 12 m in a homogeneous environment of 20 m water depth with 'medium sand' properties. Figure 2.5 shows the resulting Propagation Loss as a function of the horizontal distance between source and receiver, averaged over the 80, 160, 320 and 640 Hz 1/3-octave bands. The results are equal for both models at the higher frequencies. The 'ray' model is essentially a high-frequency approximation. At the lower frequencies (in this case 80 Hz), the ray model underestimates the PL by 3 to 6 dB.

The cut-off frequency for propagating normal modes in a shallow water environment can be estimated from [Ainslie, 2010]:

$$f_{cut-off} = \frac{c_w}{2h} \frac{\pi - (\rho_b / \rho_w)}{\pi \sqrt{1 - (c_w / c_b)^2}} \tag{6}$$

For the parameters used in this study, the cut-off frequency for a water depth of 20 m is about 24 Hz. That means that the models start to deviate at frequencies well above cut-off.

Hence, all estimations of low frequency source levels (below 160 Hz) on the basis of the ray model propagation loss calculations have to be treated with some caution.

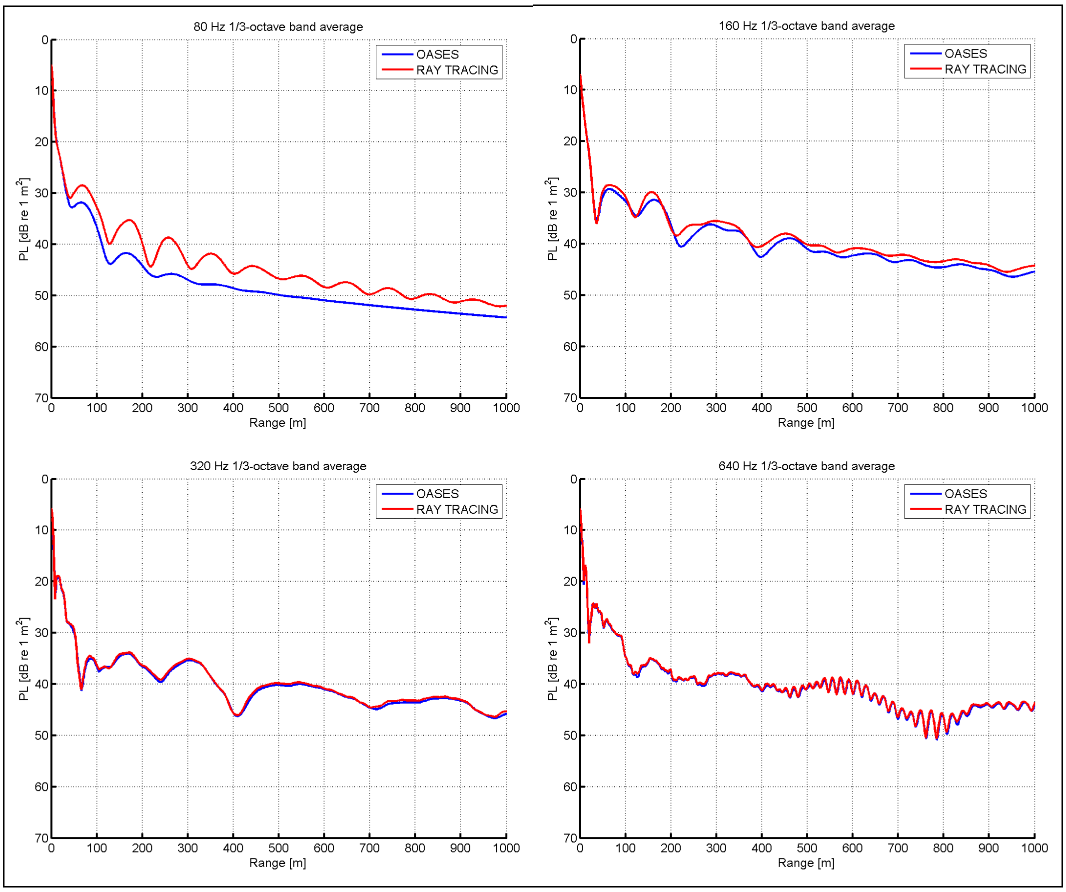


Figure 2.5 Comparison of the Propagation Loss as a function of distance as calculated by OASES and by the TNO 'image source ray' model.

3 Source level: Measurements

The sand for Maasvlakte 2 is delivered by Trailing Suction Hopper Dredgers. Since the start of the offshore sand borrowing activities, i.e. January 2009 up till October 2009, twenty two (22) different TSHDs have been employed by the Contractor PUMA (Table 3.1).

Table 3.1 Overview of all TSHDs that were active at Maasvlakte 2 between January and October 2009.

Name of the TSHD	Owner
Amazone	Baggerbedrijf de Boer
Barent Zanen	Boskalis
Cornelia	Boskalis
Crestway	Boskalis
Geopotes 14	Van Oord
Geopotes 15	Van Oord
HAM311	Van Oord
HAM312	Van Oord
HAM316	Van Oord
HAM317	Van Oord
Hein	Van der Kamp
IJsseldelta	Van der Kamp
Lelystad	HAM
Oranje	Boskalis
Ostsee	Van Oord
Prins der Nederlanden	Boskalis
Seaway	Boskalis
Shoreway	Boskalis
Utrecht	Van Oord
Volvox Olympia	Van Oord
Volvox Terranova	Van Oord
Vox Maxima	Van Oord
Waterway	Boskalis

Underwater noise measurements were carried out between 22 September and 1 October 2009. During these measurements, seven (7) of the above mentioned TSHDs were working for MV2. These seven are representative of the dredging fleet working for MV2, as can be seen in Figure 3.1 below.

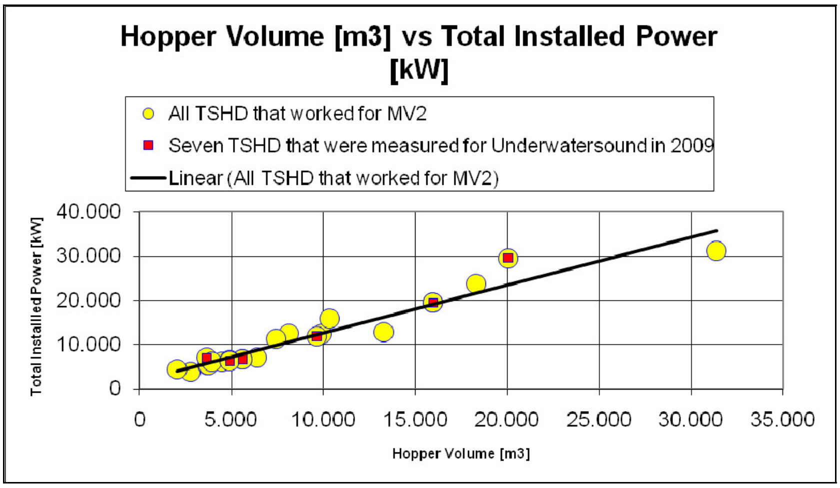
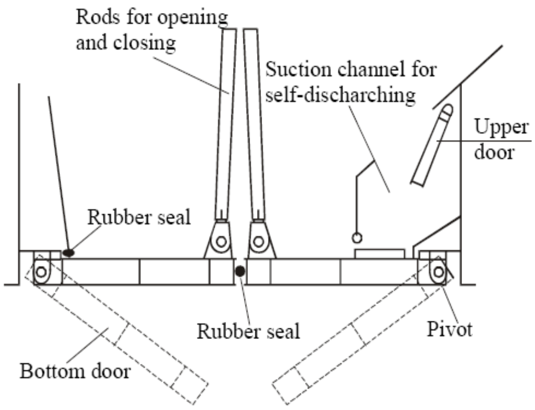


Figure 3.1 Overview of the sizes (hopper volume and total installed power) of the TSHDs that were active at Maasvlakte 2 between January and October 2009, demonstrating that the seven TSHDs of which the underwater noise was measured are representative of a large portion of the active fleet.

The measurements, as will be explained in detail further on in this report, concern the specific activities during a whole dredge cycle, i.e. dredging, transiting, and direct dumping, rainbowing or pumping ashore (see Figure 3.2). In the table below these activities are listed as well as the number of events recorded.

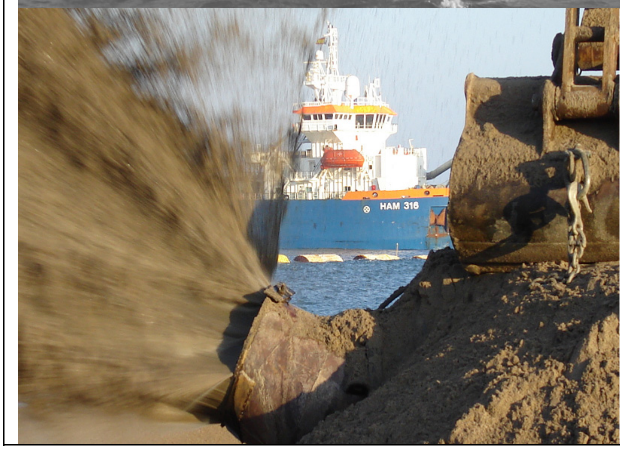
Table 3.2 Overview of the dredger activities for which the underwater noise was monitored in 2009.

Week 39 & 40 in 2009	
Action	**number of events:**
Transit : fully loaded	**16**
Transit : empty	**16**
Dredging port side	**15**
Dredging star board	**10**
Rainbowing	**13**
Pumping ashore	**2**
Dumping	**2**



Direct sand dumping through the opening of bottom doors.
The doors can be hinged as shown, but alternatively sliding doors or conic valves may be used. (Image from [Vlasbom, 2005].)

Rainbowing.
(Image from [Vlasbom, 2005])



Pumping ashore.
(Image courtesy of Van Oord.)

Figure 3.2 Illustration of the three discharge methods: direct sand dumping, rainbowing, and pumping ashore.

3.1 Sound speed

During the measurement period, 14 sound speed profile measurements were taken in the area, see Figure 3.3. It can be seen that the profile is well mixed. The sound speed varies by less than 0.2% (except for some larger deviations near the water surface at one occasion). These variations are insignificant for the source level estimation as applied in this study. In the further processing a uniform sound speed of 1511 m/s is assumed.

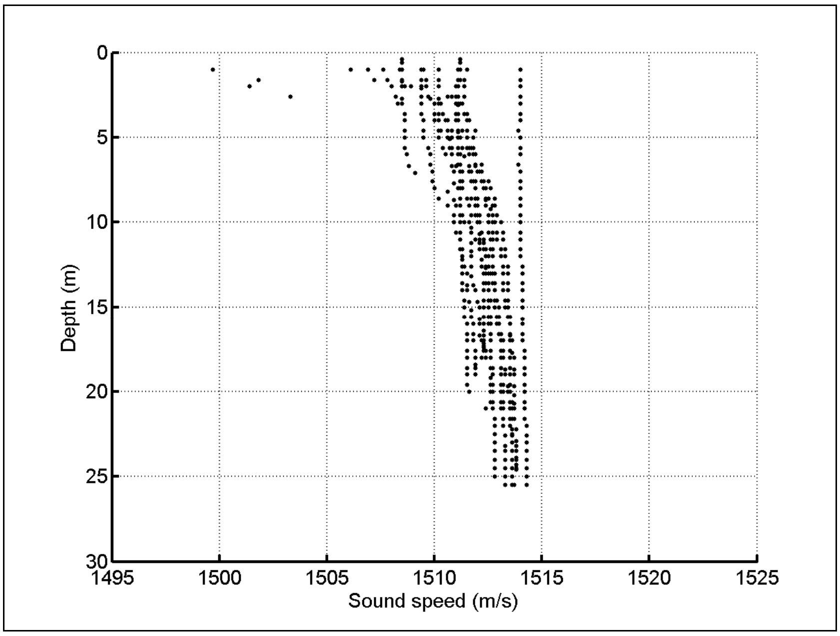


Figure 3.3 Underwater sound speed profiles measured at sea in the Maasvlakte 2 area from 14 Digibar DB1200 casts during the noise measurement period. Every dot represents a measurement point.

3.2 Tracking

The positions of the measurement vessel and the dredgers during the acoustic measurements were monitored by means of on-board GPS systems. The actual position of the antenna on the vessels (relative to the position of the hydrophone array and the acoustical centre of the dredger) is not taken into account in the current analysis.
The GPS antenna positions are taken as representative of the positions of vessel and hydrophone array. The main reason for this is that the orientation of the vessels is not directly recorded, so that the relative (two-dimensional) positions cannot be estimated from the GPS data. The tracking error associated with this assumption may lead to an error in the propagation loss estimation, which decreases rapidly with increasing distance between vessel and hydrophones. Because the Source Levels are estimated from measurements at multiple distances, the error due to incorrect tracking is limited.

3.3 Bathymetry

Recently updated bathymetry data for the dredging area were provided by the Port of Rotterdam.

3.4 Acoustic measurement data

The recorded acoustic data of the two hydrophones were converted to 1/3-octave band spectra of the received Sound Pressure Level (SPL) at the two hydrophones, for each second of the recordings and stored in a Matlab™ data file. The frequency range contained the 12.5 Hz to 160 kHz 1/3-octave bands.

3.4.1 Hydrophone calibration

The B&K PULSE system that is used for the recording stores the data as sound pressures in pascals, based on a single tone pistonphone calibration of the measurement chain at 250 Hz. The frequency response of the hydrophones (4 to 200 kHz) was calibrated by B&K in October 2008 and again in January 2010. The sensitivity of the two hydrophones, relative to the value at 250 Hz, is shown in Figure 3.4. The measured hydrophone data were corrected for this frequency response by subtracting this spectrum from the third-octave band spectra of the measurements.

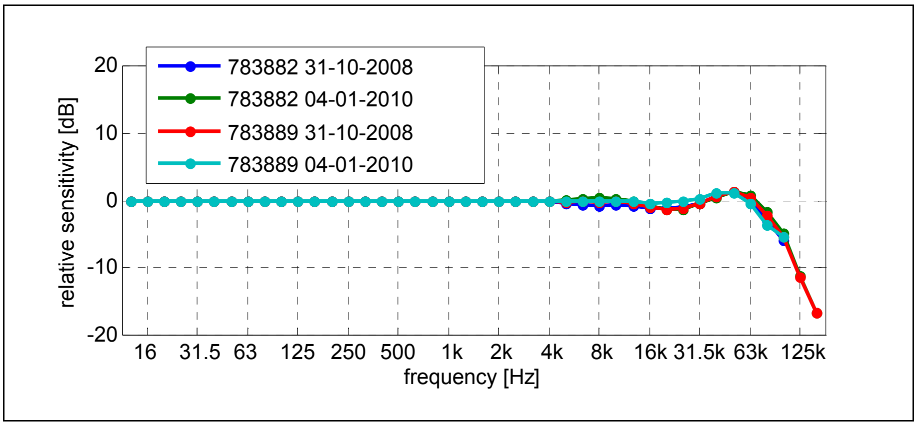


Figure 3.4 B&K 8101 hydrophone calibration curves at 1/3-octave band center frequencies.

3.5 Background noise

The background noise in the area, with no specific target ships present near the measurement platform, is highly variable. This is illustrated in Figure 3.5. Due to this variability it is not possible to get an accurate estimation of the background noise during actual dredger noise measurements. Hence, it is not feasible to estimate the signal-to-noise ratio (SNR) for these measurements or to correct for background noise. However, in most cases the ship noise was clearly larger than the background.

Background measurement number 2 shows a contribution of the diesel generator of the measurement vessel (tonal lines in the 50 and 100 Hz 1/3-octave bands). This generator could not always be stopped during the acoustic measurements.

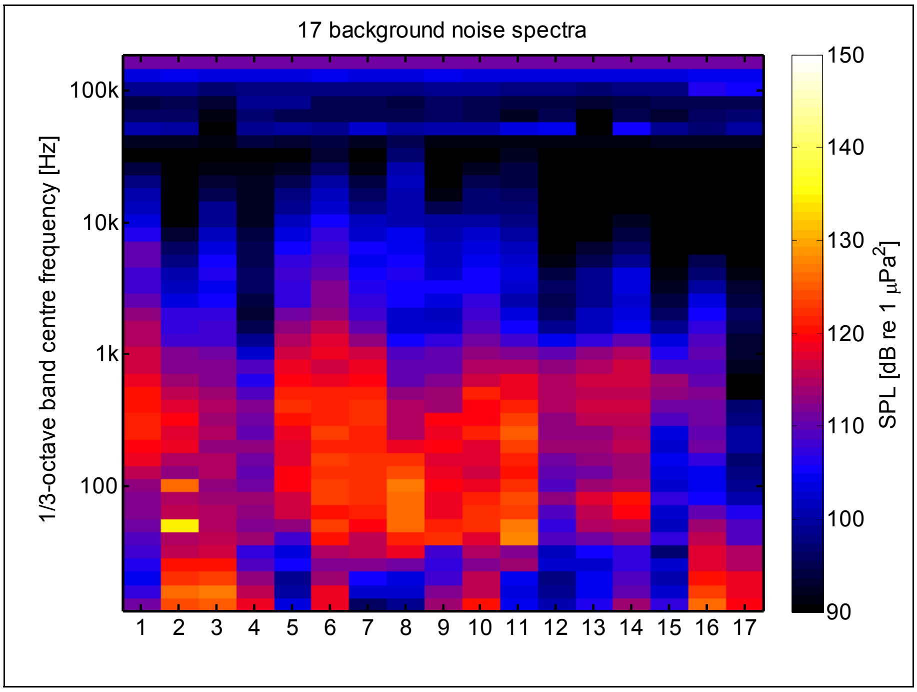


Figure 3.5 Background noise third-octave SPL (10 s average) at 17 different moments during the measurement period

4 Source level: Methodology

The procedure for estimating the Source Level from the underwater noise measurements is illustrated for a single run of a dredger in transit at a speed of 16.6 knots.

4.1 Tracking

The GPS positions of the dredger and the measurement vessel were recorded. Figure 4.1 shows the distance between dredger and measurement vessel during the passage. The distance at the closest point of approach (CPA) in this example is 212 m.

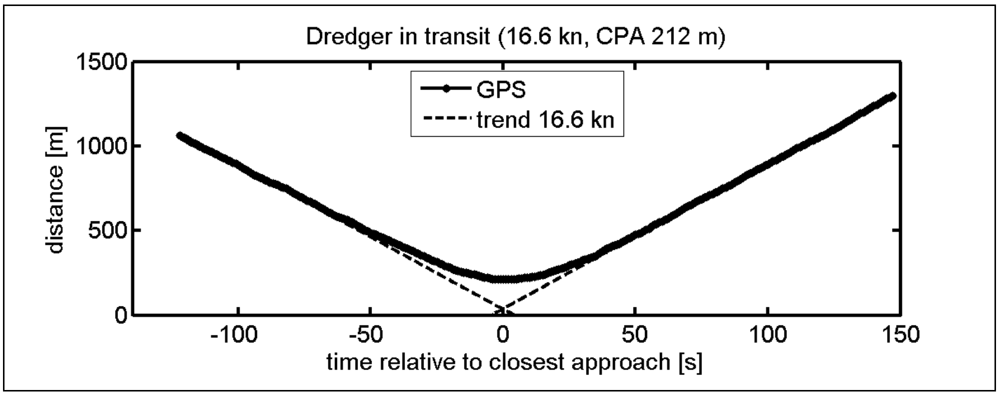


Figure 4.1 The GPS-based distance between dredger and measurement vessel as a function of time.

4.2 Underwater noise

The underwater noise was measured by two hydrophones at 6 and 12 m depth relative to the water surface respectively. The local water depth (bathymetry provided by the Port of Rotterdam) was about 18.7 m. The bottom is approximately flat in the area of this run.

Figure 4.2 shows the recorded total broadband SPL during the run at the two hydrophones. The x-axis is converted from time to distance, incorporating a constant speed of 16.6 kn. The reference position (Closest-Point-of-Approach; CPA) is determined from the moment at which the minimum distance is reached according to the GPS data (Figure 4.1). The maximum received level at the shallower hydrophone (6 m depth from the sea surface) is about 3 dB lower than that at the lower hydrophone (12 m depth). This is due to the stronger interference with sound reflecting from the sea surface.

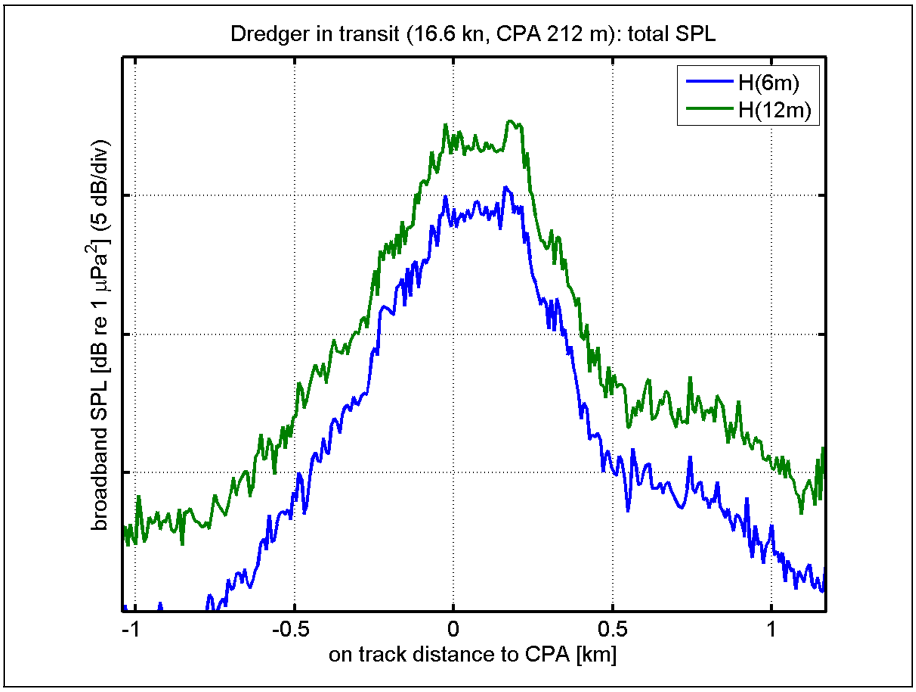


Figure 4.2 The total recorded broadband noise (12.5 Hz – 160 kHz) at the two hydrophones, as a function of the on track position of the dredger relative to CPA. Time runs from left to right on the horizontal axis. At 16.6 knots, the vessel travels 2 km in 234 seconds.

Figure 4.3 shows the corresponding 1/3-octave band spectrograms. Especially the spectrogram of the 6 m deep hydrophone exhibits a typical surface image interference (‘Lloyd Mirror’) pattern. It can also be seen in these plots that the measurements are dominated by background noise in the lowest four and the upper three third-octave bands. Hence the estimation of the source level of the vessel is limited to the frequency bands between 31.5 Hz and 80 kHz.

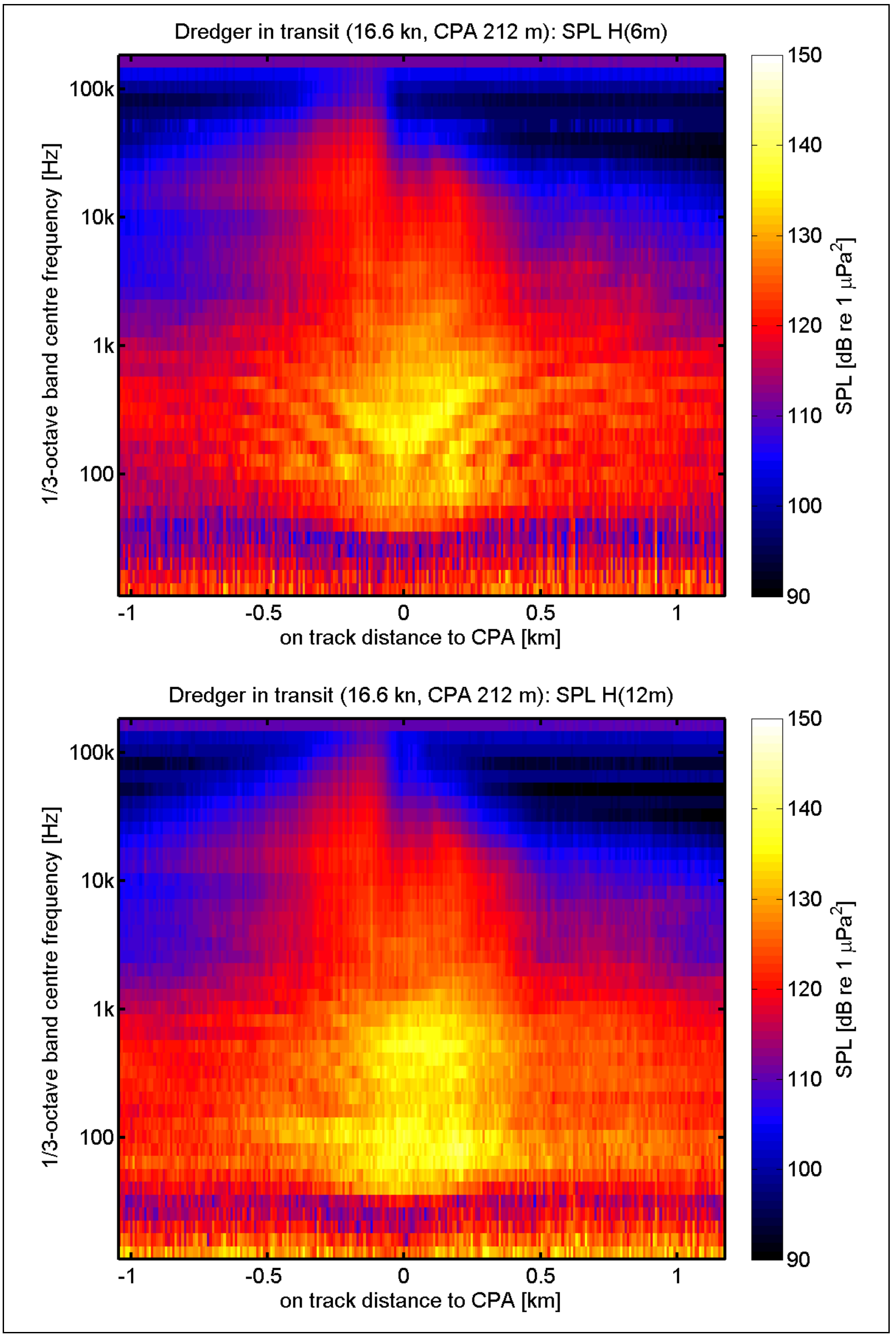


Figure 4.3 1/3-octave spectrogram (1 second steps) of the underwater noise during the passage of the transiting dredger, recorded at the two hydrophones (top: 6 m and bottom: 12 m depth)

4.3 Propagation Loss

Calculations are carried out of the propagation loss (PL) between the source monopole and the hydrophone positions, for each instant during the transit of the dredger.
As an initial guess, a source depth of 4 m is assumed. Narrow band calculations are carried out for 11 logarithmically spaced frequency lines within each third-octave band. The resulting PL per band is determined via averaging of the inverse of the individual PL values. The resulting third-octave spectrograms of the PL are shown in Figure 4.4. These show surface image interference ('Lloyd Mirror') patterns similar, but not equal, to those found in the measured underwater noise (Figure 4.3). Apparently, the actual source depth differs from the 4 m depth assumed for the propagation calculations. In reality, the source depth will be different for the different source mechanisms on the TSHD. At each frequency, the total radiated noise is the sum of contributions due to different source mechanisms, like propeller noise, engine noise, pump noise, etc.
In the far field of the ship, where the Source Level is defined, the locations of the individual source mechanisms can not be distinguished. Instead of attempting to determine the actual source depth, the errors in the propagation loss calculation associated with the assumed source depth are mitigated by averaging over the Source Level estimations at all different ranges between ship and hydrophones (see §4.4).

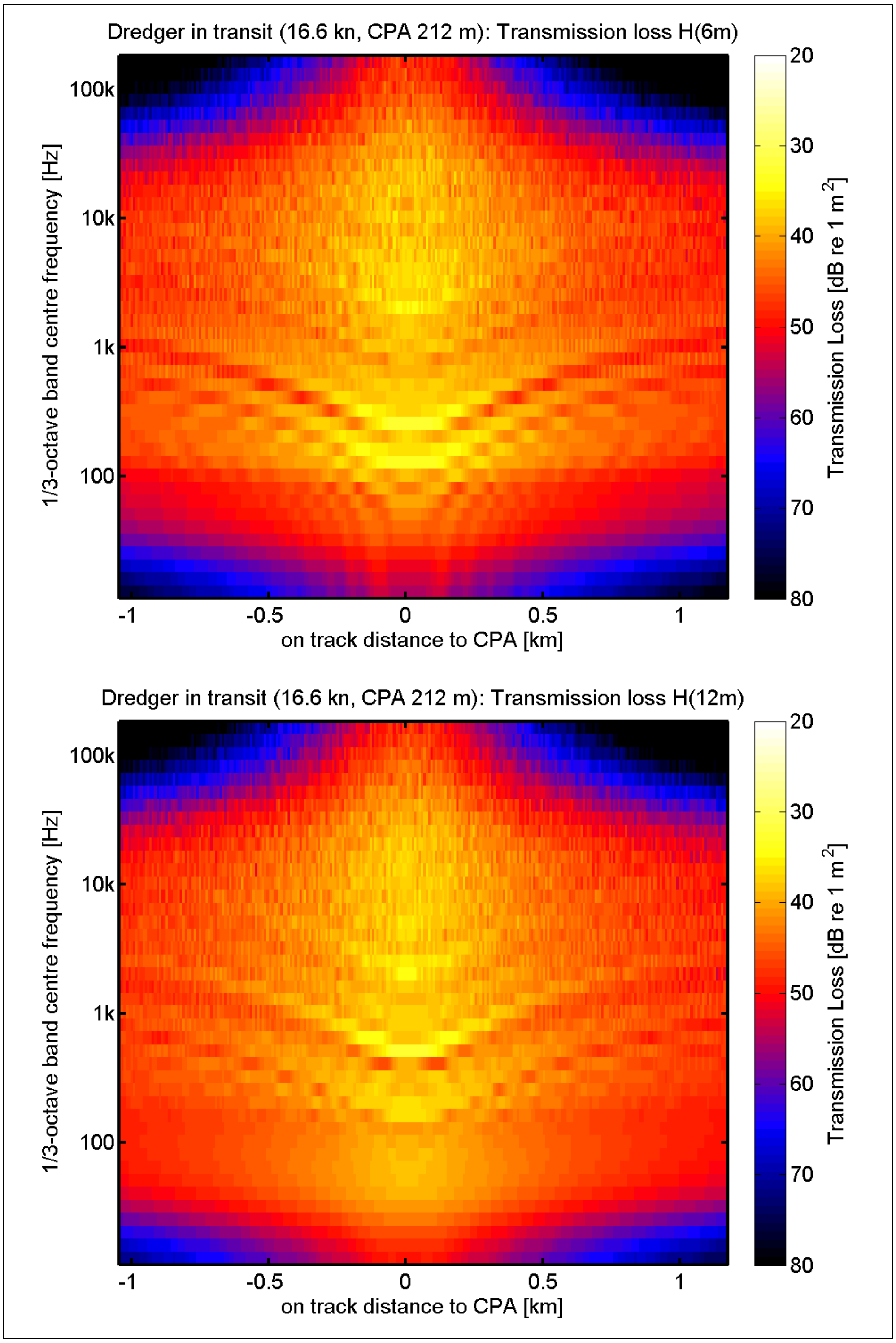


Figure 4.4 1/3-octave band spectrograms of the calculated propagation loss (using an image source model) between the two hydrophones (top: 6 m and bottom: 12 m depth) and the monopole (assumed source depth 4 m) representing the vessel.

4.4 Source Level estimation

As a next step, we use the calculated PL to estimate the source level (SL) from the measured SPL for each track position: SL=SPL+PL. The result is shown in Figure 4.5.

Ideally, the spectrogram of the SL would exhibit the same result for each point along the track. Note that the Lloyd mirror patterns in SPL and PL do not match exactly, so that they are not fully cancelled in the SL spectrogram. The very high source levels at the greatest distances at the lowest and highest frequencies (the four white corners of the spectrogram) are caused by a possible overestimation of the propagation loss due to absorption in combination with an insufficient signal to noise ratio. In these corners the assumption that the received sound is caused by the dredger only is no longer valid.

Important assumptions applied here are that the noise generation is a stationary process during the run and that the source can be represented as a monopole that radiates equally strong in all directions. The asymmetry of the received sound spectra (Figure 4.3) with respect to CPA illustrates that these assumptions are not fully met.

An average Source Level spectrum is estimated from the SL spectrograms of Figure 4.5. The choice of data to use for this averaging is a compromise between obtaining sufficient data for averaging and avoiding the errors that occur in the four corners of the SL spectrograms, where large PL values may lead to an overestimation of the SL in case of insufficient signal-to-noise ratio. After some initial tests, it was decided to take the power average over only those data points in the SL spectrogram where the calculated PL is not more than 10 dB greater than the minimum in the PL (for each frequency). This avoids an eventual amplification of ambient noise with more than 10 dB. The result is shown in Figure 4.6. The standard deviation of the resulting average SL estimation is of the order of ±5 dB.

At the highest and lowest frequencies, the SL estimations show a much larger variability, because of the strong increase of propagation loss with distance due to absorption and waveguide cut-off effects. For the same reason and because the measurement results do not show excessive received noise in these frequency bands, environmental effects of the noise generated by the TSHDs in these frequency bands will be limited to short ranges. Therefore, the presentation of the estimated Source Levels (in Figure 4.6 and in subsequent figures) is limited to the 1/3-octave bands between 25 Hz and 80 kHz (see also §6.2.4).

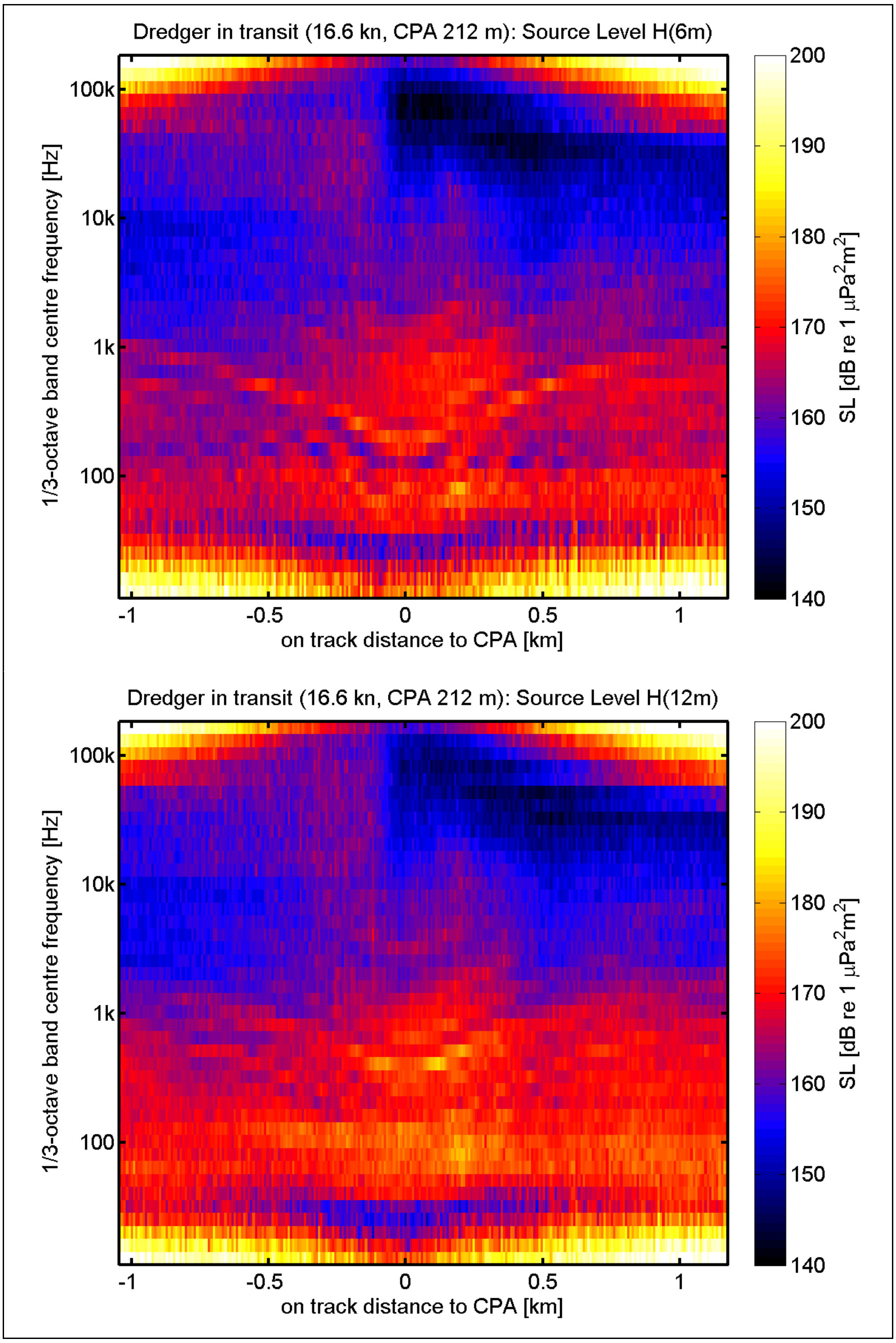


Figure 4.5 1/3-octave band spectrograms of the monopole Source Level, estimated from the SPL received at the two hydrophones (top: 6 m and bottom: 12 m depth) during the passage of the dredger (Figure 4.3) and the calculated propagation loss (Figure 4.4).

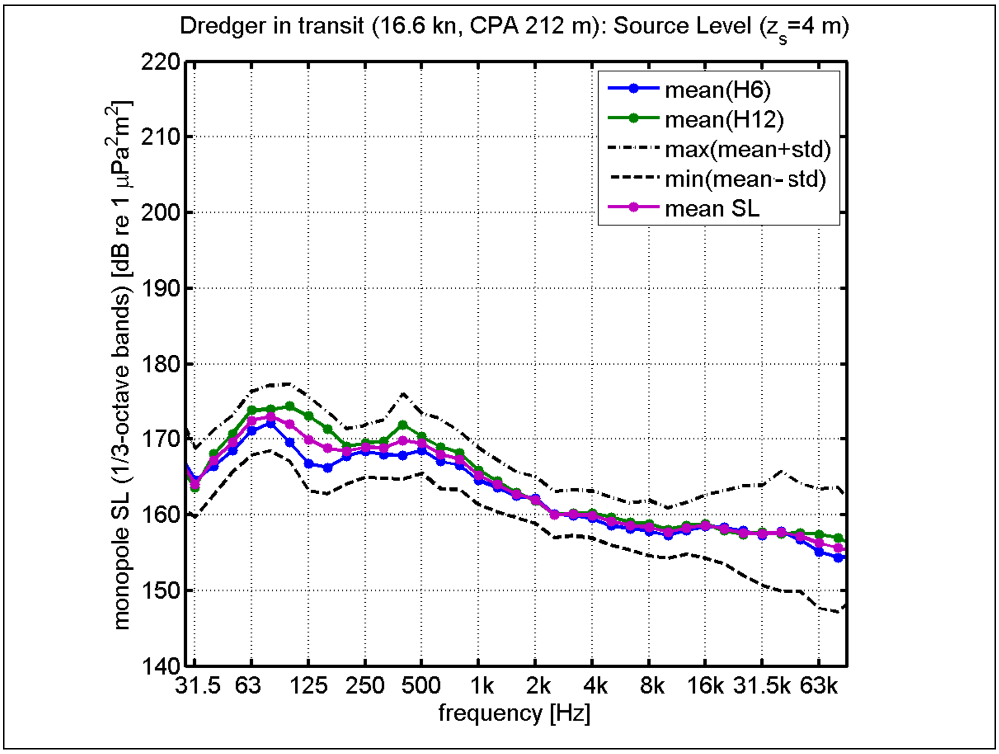


Figure 4.6 1/3-octave band monopole source level spectra of the transiting dredger based on averaging the data in Figure 4.5 over sections of the track where the PL is less than 10 dB higher than the minimum PL (at each frequency), with an indication of the spreading (± one standard deviation).

4.5 Effect of sediment parameters

The above analysis was carried out with the initial assumption that the sediment consists of ‘medium sand’, with the sediment properties taken from Ainslie (2010) (table in §4.4.1.4). The dependence of the results on this assumption was tested by repeating the calculations for two other sediment types: ‘coarse’ and ‘fine’ sand, with the following parameters:

		coarse sand	medium sand	fine sand
Sound speed ratio	c_b/c_w	1.2329	1.1812	1.1362
Density ratio	ρ_b/ρ_w	2.231	2.086	1.945
Absorption coefficient	α_b [dB/λ]	0.87	0.88	0.89
grain size	d [μm]	320	160	80
porosity		23 %	32 %	41 %

Figure 4.7 shows the resulting SL estimations. The differences are small in comparison with the ±5 dB uncertainty in the SL estimation. Hence, further analyses will be all carried out with the parameters for medium sand.

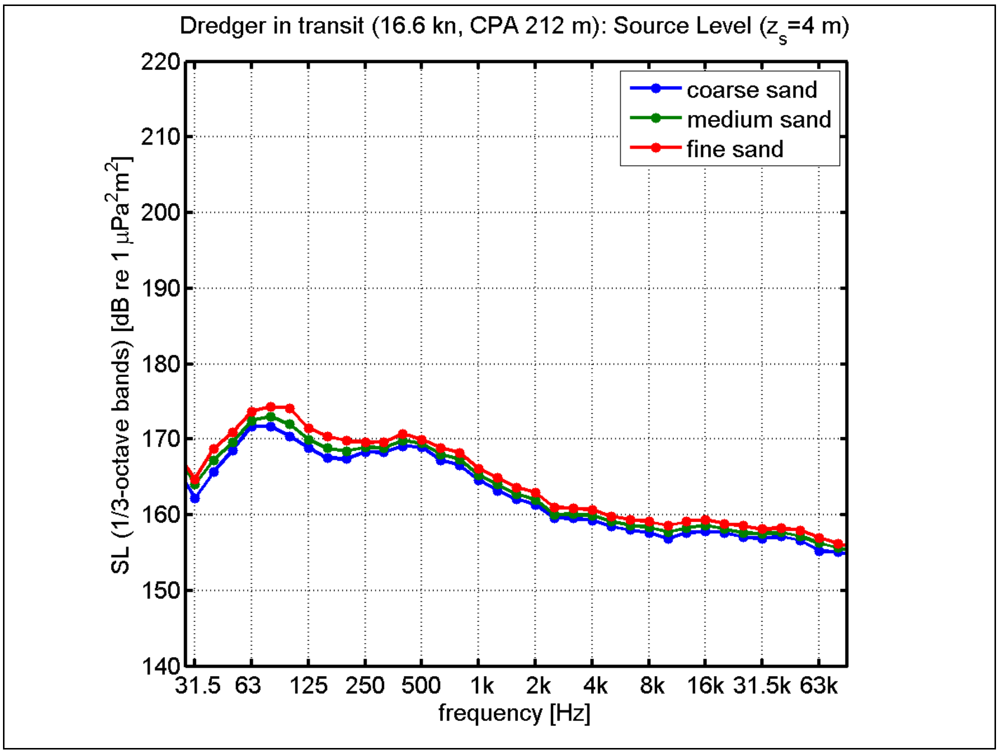


Figure 4.7 Averaged 1/3-octave band monopole source level of the transiting dredger, for three different choices of sediment parameters.

4.6 Effect of source depth

The choice of the source depth (4 m) in the above analyses was rather arbitrary. Due to the surface image interference effect ('Lloyd's Mirror'), this choice may have a large effect on the SL estimation. This effect was tested by repeating the calculations for 6 different source depths (1, 2, 3, 4, 5 and 6 m). Figure 4.8 gives the resulting SL estimations. This confirms that the assumed source depth has a large impact on the result, at frequencies below 500 Hz for this source receiver geometry. The shallower the point source, the higher the PL due to surface interference and the higher the SL estimation. Note that this effect will be compensated when the SL estimation is used in forward estimations of the sound distribution due to this source, if the same source depth is used, because then the PL will also be larger for shallower sources.

The effect of the unknown source depth on the SL estimation can be reduced by reporting the 'dipole' SL, i.e. the SL including the contribution of the surface image. The translation between the monopole and dipole source descriptions is approximately given by eq. (5) (§2.3.1). It depends on the elevation angle under which the dipole source is observed. This angle is chosen on the basis of the recently issued ANSI S12.64 measurement standard for surface ship radiated sound. ANSI S12.64 specifies that the 'affected' source level shall be reported as the power average of the results of measurements with hydrophones at θ = 15, 30 and 45° (called 'beam aspect').

Applying this translation to the spectra in Figure 4.8 leads to the dipole source level spectra given in Figure 4.9. These are approximately independent of the choice of source depth. Notice the large difference between the monopole (Figure 4.8) and dipole (Figure 4.9) source levels for shallow sources. This illustrates the need for a clear definition, when reporting Source Levels (§2.3.1).

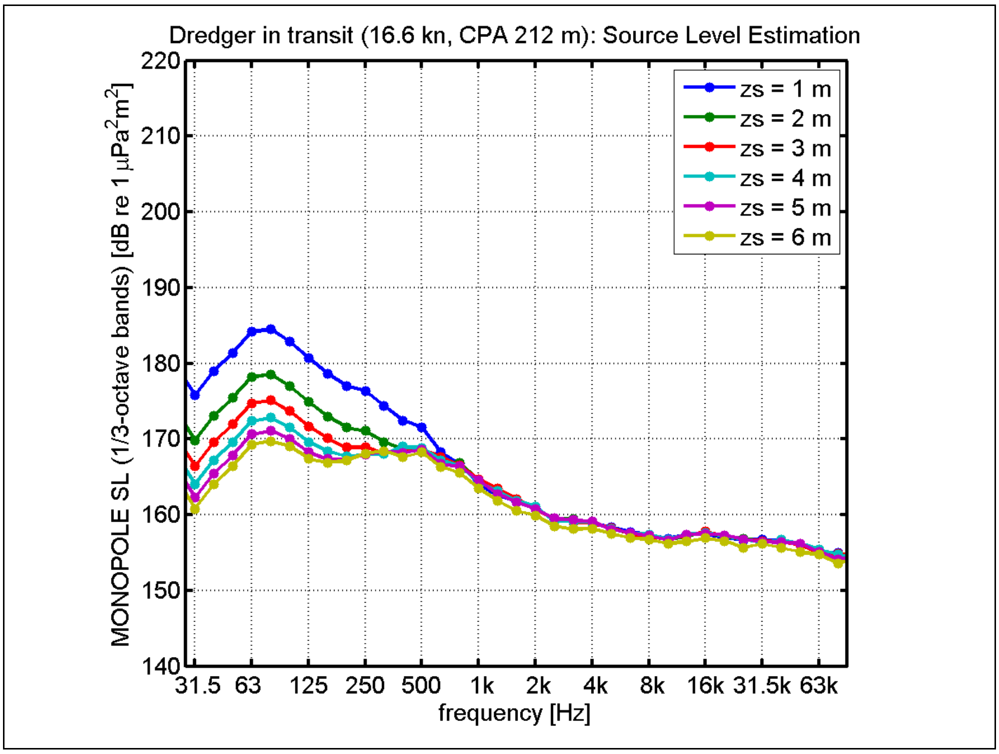


Figure 4.8 Averaged 1/3-octave band monopole source level of the transiting dredger, for six different assumed source depths.

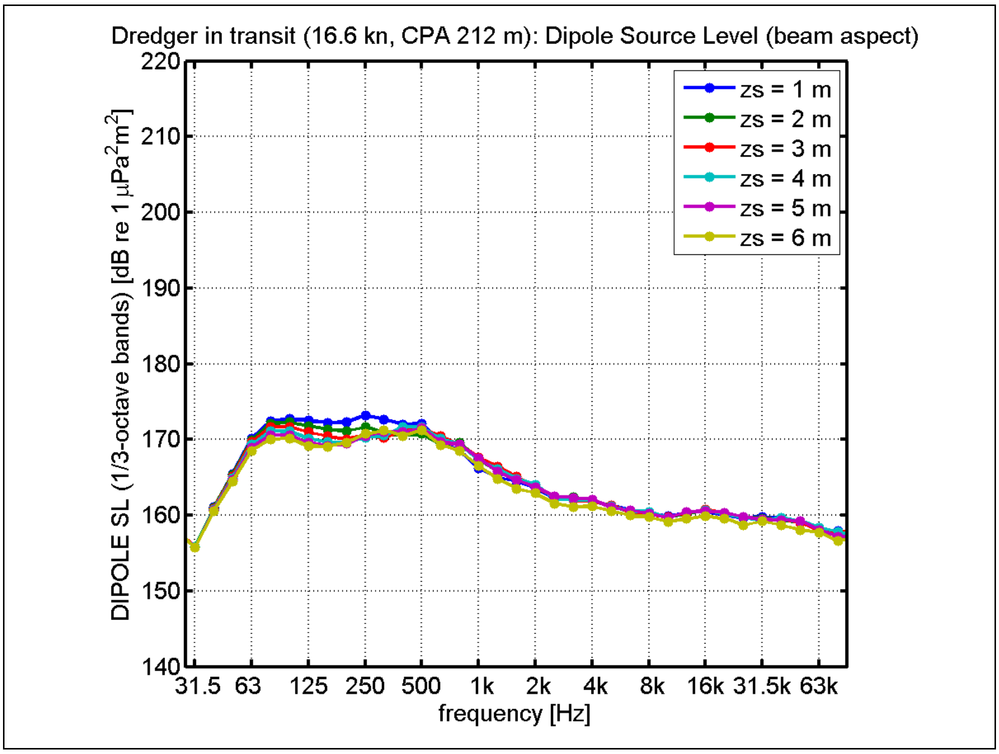


Figure 4.9 Averaged 1/3-octave band dipole source level of the transiting dredger, for six different assumed source depths, calculated from the monopole Source Level by including the effect of the surface image with the angles chosen in accordance with ANSI S12.64

5 Source level: Results

The methodology described in the previous chapter was applied for all measurements described in chapter 3. In the following sections, the resulting estimations of the 'beam aspect' dipole source level for the various activities of the individual dredgers.
The vessels are kept anonymous by reporting results for dredgers 1 to 7. Where possible, the source levels are represented as the power average of the estimations based on the two different hydrophones, using all time-frequency data points where the propagation loss is not more than 10 dB higher than the minimum PL. The standard deviations associated with this averaging are generally of the same order of magnitude as these shown in Figure 4.6 and not shown here.

The legend to the following figures gives the 'Speed' of the dredger, at the closest-point-of-approach (CPA) to the hydrophone array, in knots; the 'CPA' distance in meters and the water 'depth' at the dredger, estimated from the GPS position of the dredger in the bathymetry map provided by the Port of Rotterdam. In the analysis it is assumed that the water depth is constant between the dredger and the hydrophones. The source depth is chosen to be 4 m for all runs in which the water depth is larger than 4 m. For some of the sand dumping runs the water was shallower. In these cases the source depths is chosen at 3 m.

5.1 Dredging

Figure 5.1 until Figure 5.6 show the dipole source level estimations for dredging at Maasvlakte 2 (MV2). The reproducibility of the results for different runs is generally quite good and within the estimated standard deviation of ±5 dB per 1/3-octave band around the average result per run. Each figure also shows the power average of the different runs, which is calculated as a representative source level for the dredging by the individual dredgers at MV2.

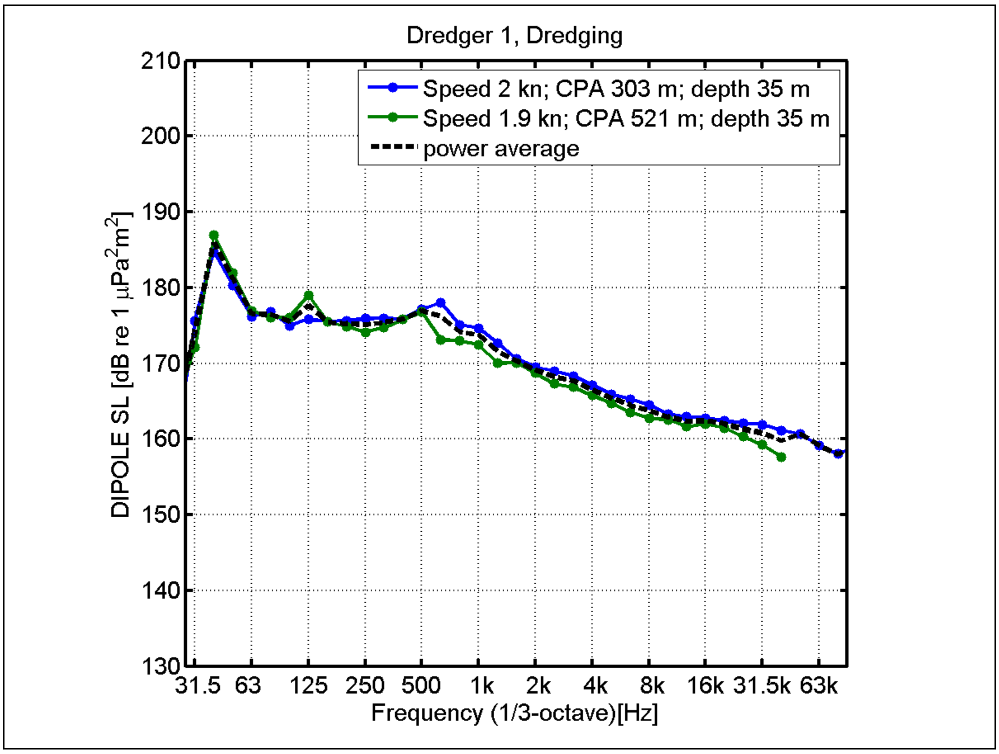


Figure 5.1 Averaged 1/3-octave band dipole source level of the dredger 1, while dredging at about 2 knots (2 runs).

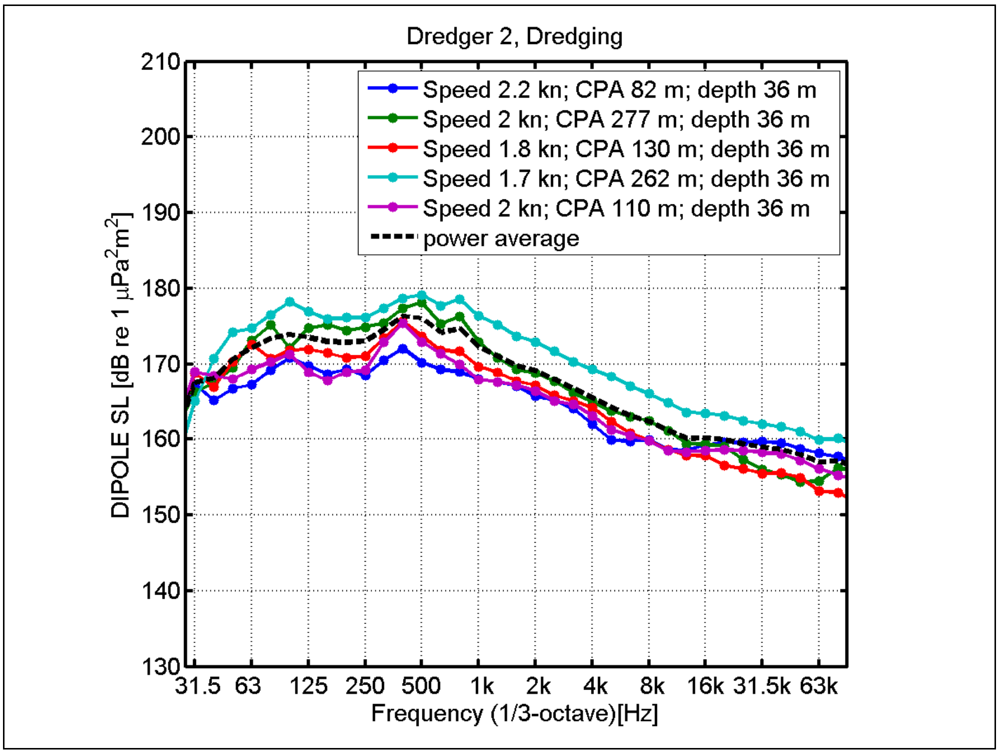


Figure 5.2 Averaged 1/3-octave band dipole source level of the dredger 2, while dredging at about 2 knots (5 runs).

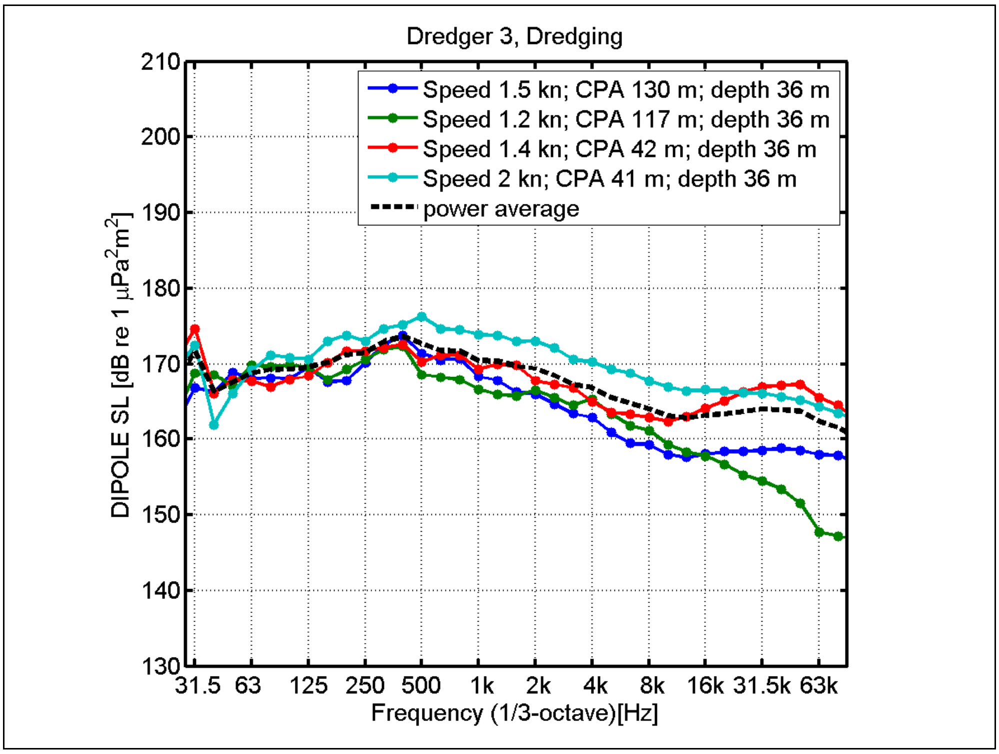


Figure 5.3 Averaged 1/3-octave band dipole source level of the dredger 3, while dredging at about 2 knots (4 runs).

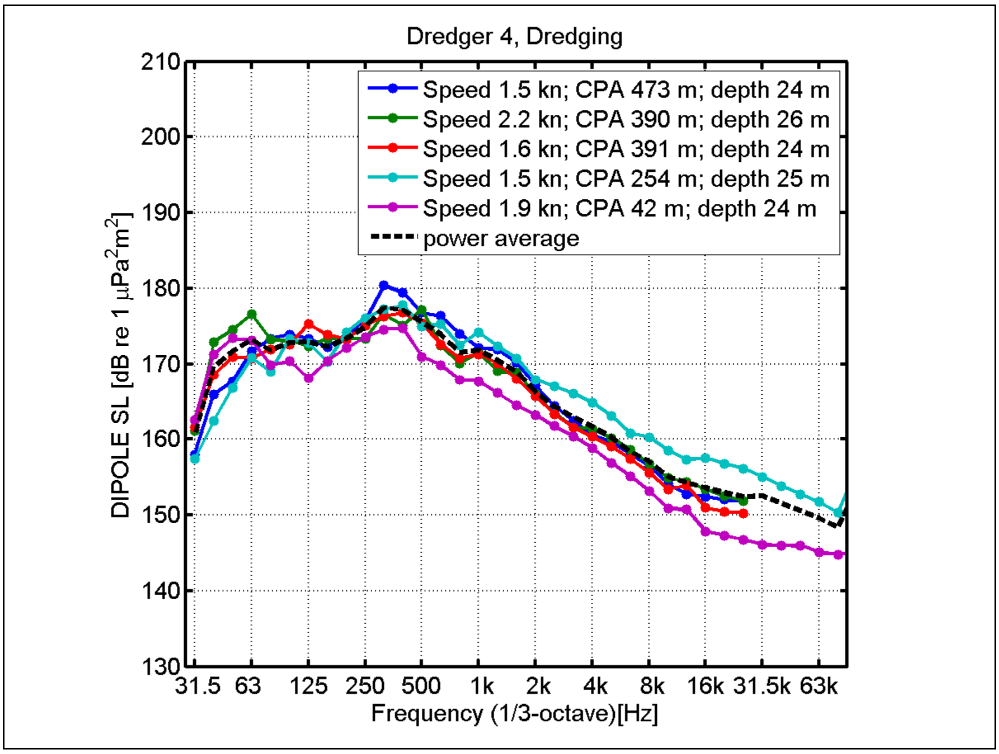


Figure 5.4 Averaged 1/3-octave band dipole source level of the dredger 4, while dredging at about 2 knots (5 runs).

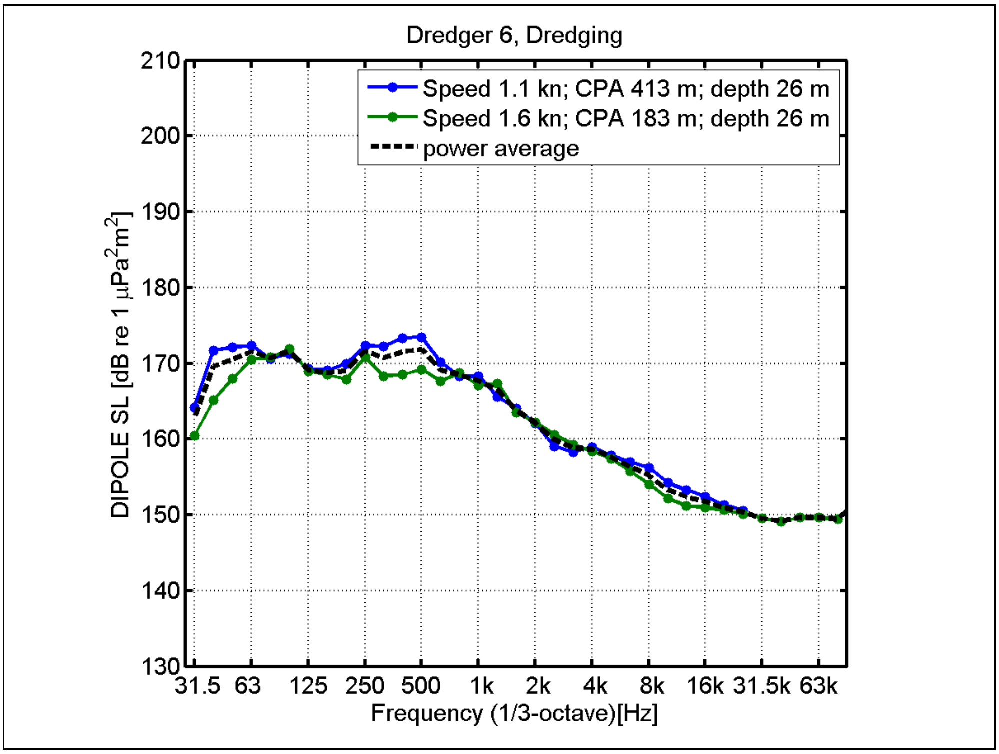


Figure 5.5 Averaged 1/3-octave band dipole source level of the dredger 6, while dredging at about 2 knots (2 runs).

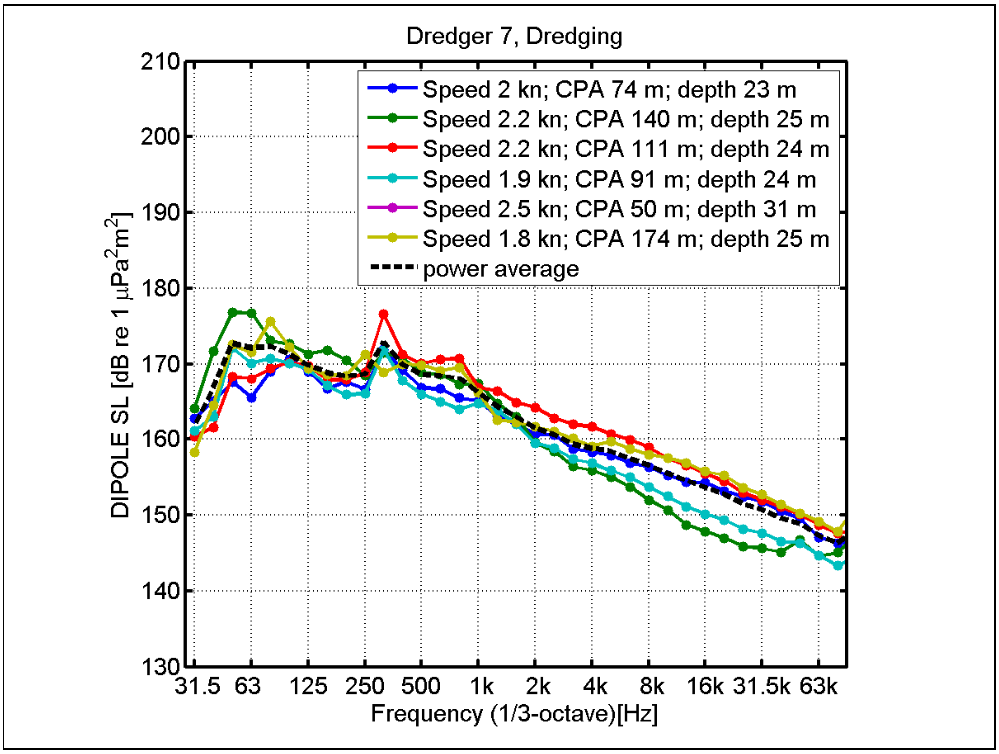


Figure 5.6 Averaged 1/3-octave band dipole source level of the dredger 7, while dredging at about 2 knots (2 runs).

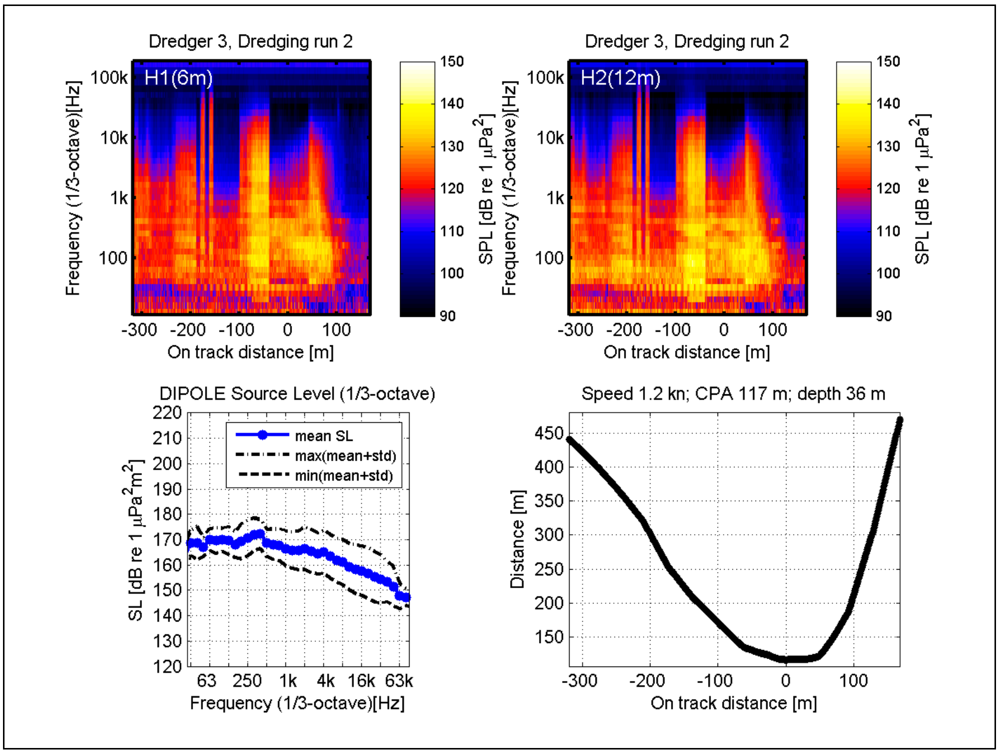


Figure 5.7 1/3-octave band spectrograms (top) of the received sound at the two hydrophones for dredging run 2 of dredger 3, with the estimated dipole source level spectrum (bottom left) and the tracking for this run (bottom right). Note the variations of the received sound with time (track position).

Figure 5.7 shows that the assumption that the dredger is a constant noise source is not always valid. In several runs, the received sound levels vary stepwise in time.
These variations are due to variations in the sound generating mechanisms on board of the dredger. In this and many similar cases, the variations are due to switching (on and off) of the transverse (bow and/or stern) thrusters of the vessel that are used to keep track or position. Cavitation noise of these thrusters appears to be a dominant noise source mechanism. In the data processing, no special treatment has been applied to account for these variations. The source level estimation procedure includes a temporal averaging, that mitigates these variations.

The average dredging noise source levels for the 6 dredgers are compared in Figure 5.8. It can be seen that the levels are generally very similar. Only dredger 1 clearly produces more noise than the others at low frequencies (below 250 Hz). This noise is probably noise related with propeller cavitation.

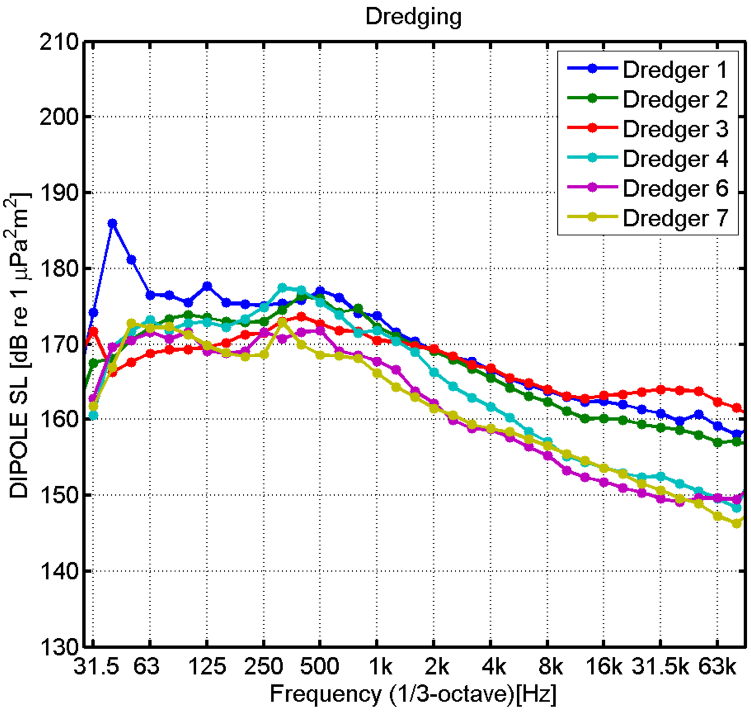


Figure 5.8 Comparison of power averaged dipole source level spectra for 6 TSHDs, while dredging in front of MV2.

5.2 Rainbowing

Figure 5.9 until Figure 5.12 show the estimated dipole source level of four dredgers while depositing sand via 'rainbowing'. The vessels are kept at their location during this activity (speed 0 kn). In some cases the propeller and transverse thrusters are operated to maintain position.

The four averaged dipole source level spectra are compared in Figure 5.13. There is a large difference between two groups of dredgers. A possible explanation for this difference is that the louder dredgers use their thrusters and the quieter dredgers do not.

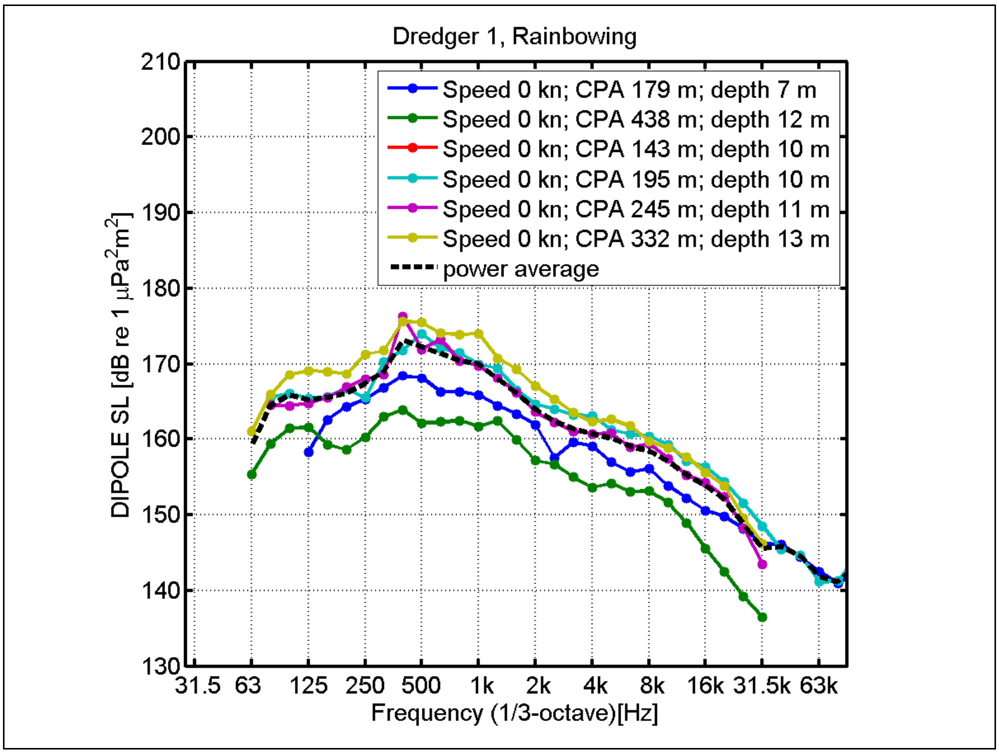


Figure 5.9 Averaged 1/3-octave band dipole source level of the dredger 1, while rainbowing (6 runs).

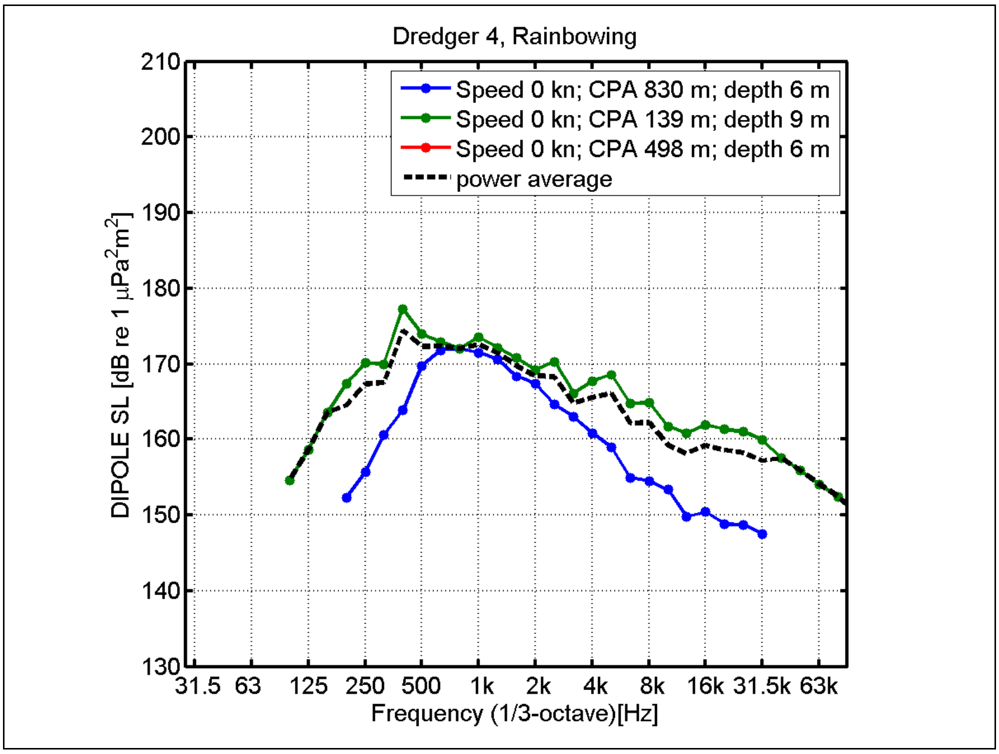


Figure 5.10 Averaged 1/3-octave band dipole source level of the dredger 4, while rainbowing (2 runs).

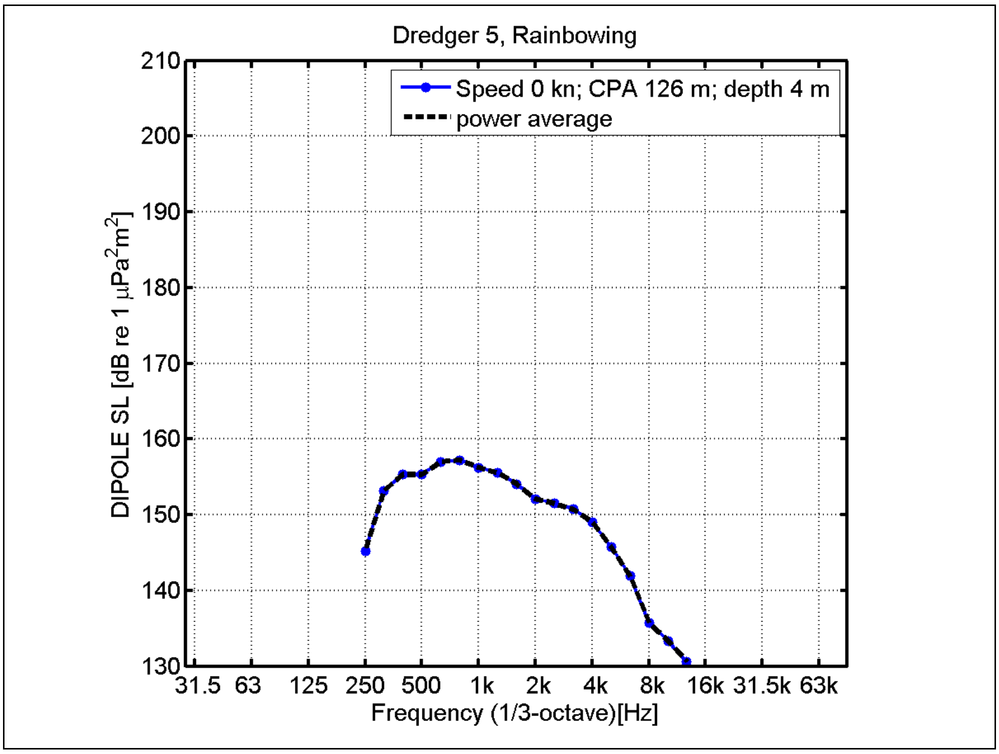


Figure 5.11 Averaged 1/3-octave band dipole source level of the dredger 5, while rainbowing (1 run).

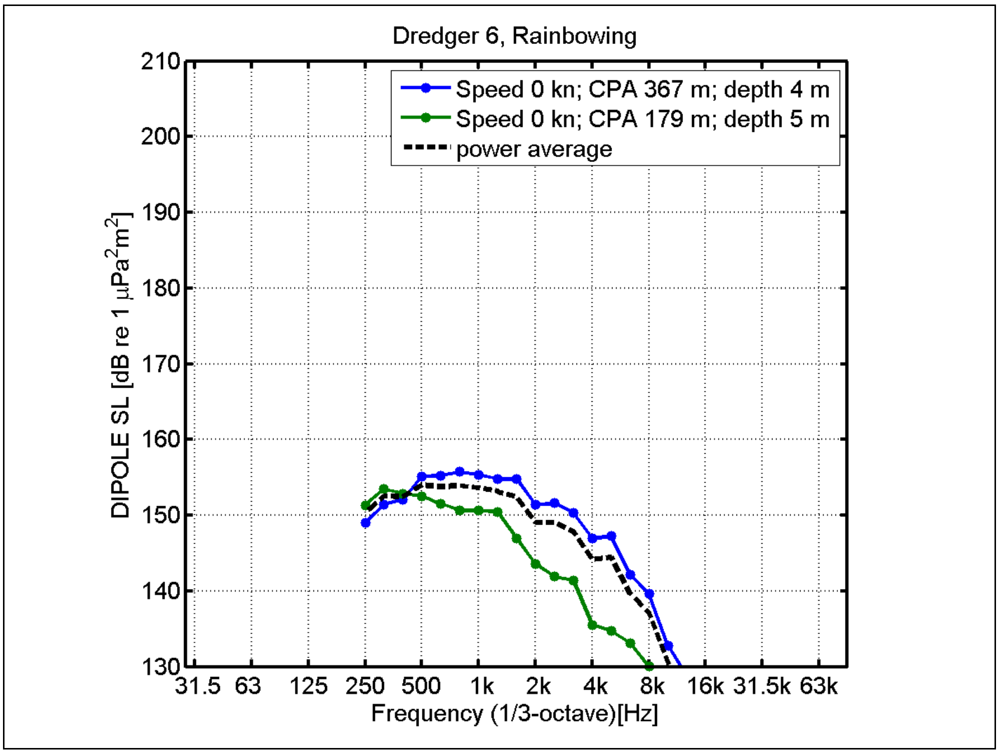


Figure 5.12 Averaged 1/3-octave band dipole source level of the dredger 6, while rainbowing (2 runs).

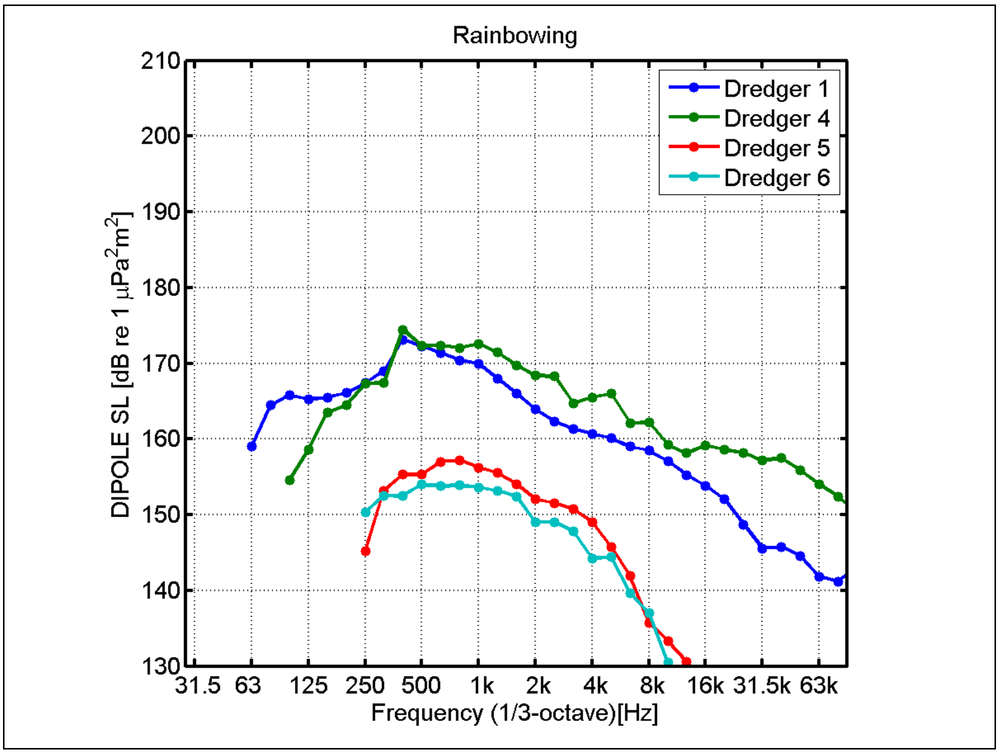


Figure 5.13 Comparison of power averaged dipole source level spectra for 4 dredgers while Rainbowing.

5.3 Direct sand dumping

Figure 5.14 shows the estimated dipole source level of two dredgers while depositing sand via direct sand dumping. The vessels are kept at their location during this activity (speed 0 kn). Just two measurements of sand dumping noise could be made; hence the statistic reliability of the results is somewhat limited. The results are compared in Figure 5.14. In this case, dredger 7 is much quieter than dredger 1, but this may be related to the large difference in water depth.

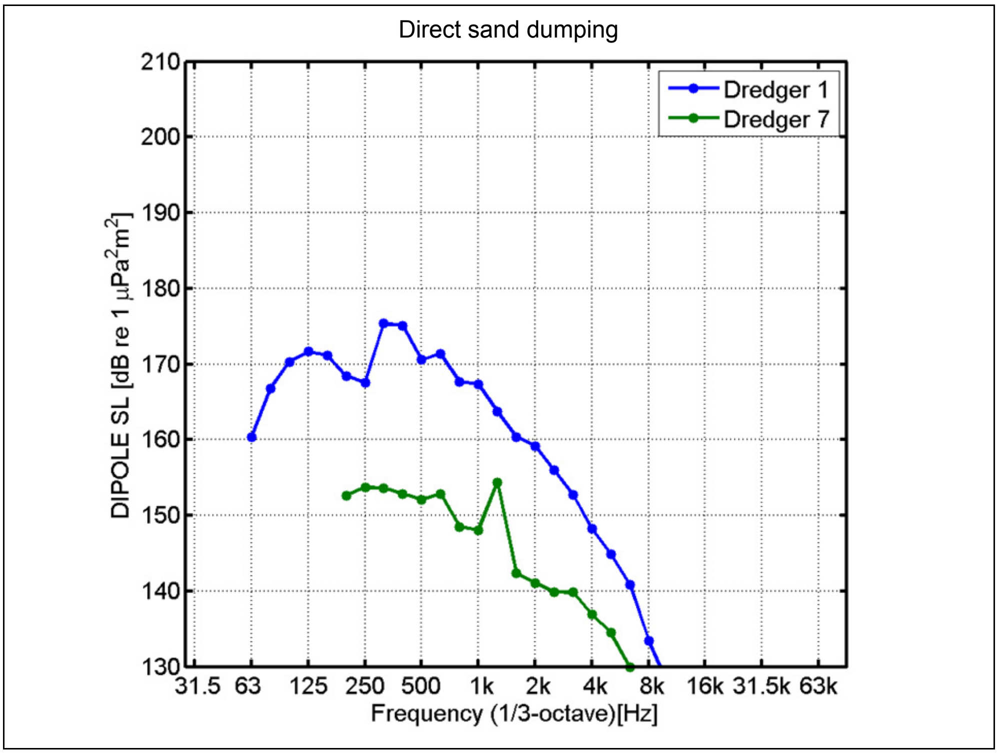


Figure 5.14 Comparison of power averaged dipole source level spectra for 2 dredgers while directly dumping sand. Dredger 1 was measured at a CPA distance of 70 m in 13 m water depth, dredger 7 at 65 m distance in 4 m water depth.

5.4 Pumping ashore

Figure 5.15 shows the estimated dipole source level of two dredgers while pumping sand ashore. The vessels are kept at their location during this activity (speed 0 kn). Just two measurements of pumping noise could be made; hence the statistic reliability of the results is somewhat limited. The results are compared in Figure 5.15. In this case, dredger 3 is quieter than dredger 2. The shape of the spectra is similar to that for other activities in which cavitation is a predominant noise source. A possible explanation for the level difference could be sought in the activity of the thrusters.

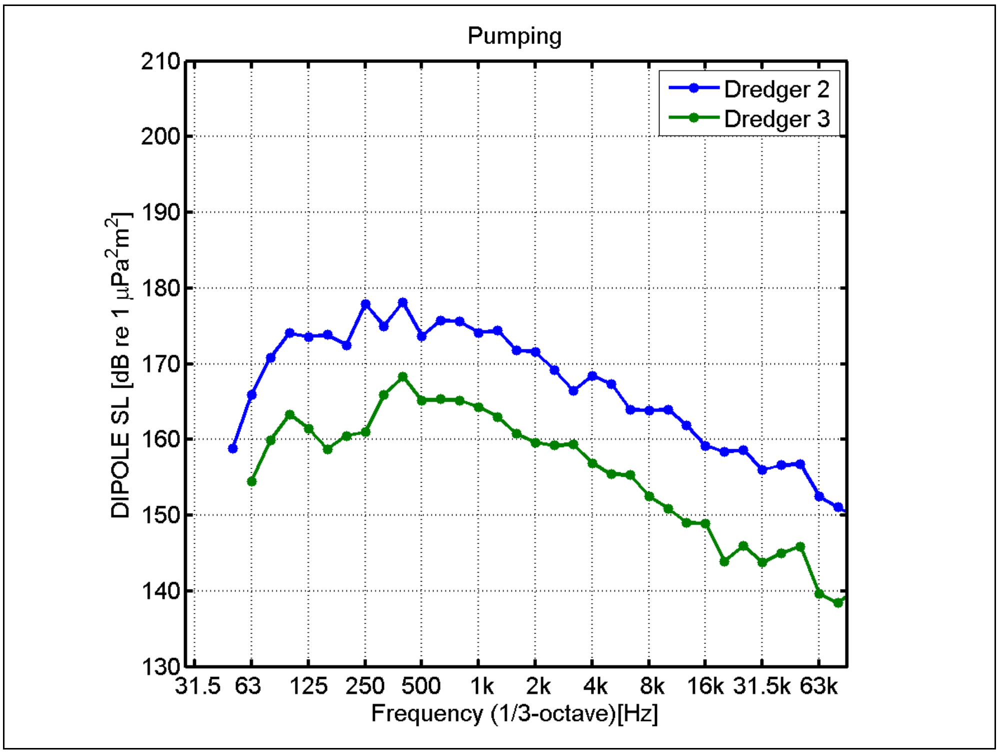


Figure 5.15 Comparison of power averaged dipole source level spectra for 2 dredgers while pumping sand ashore. Dredger 1 was measured at a CPA distance of 157 m in 14 m water depth, dredger 7 at 143 m distance in 14 m water depth.

5.5 Transit

Figure 5.16 until Figure 5.22 show the estimated dipole source level of all dredgers while transiting between the dredging and sand dumping areas. The vessels are 'Loaded' when they transit from the dredging area to the MV2 area and 'Empty' when they return. The transiting speeds are generally quite high (10 to 17 knots).

The repeatability of the measurement and source level estimation results is generally very good. The correlation between source level and speed and loading condition is not always clear, which may partly be explained by the inaccuracies introduced by differences in the CPA distance.

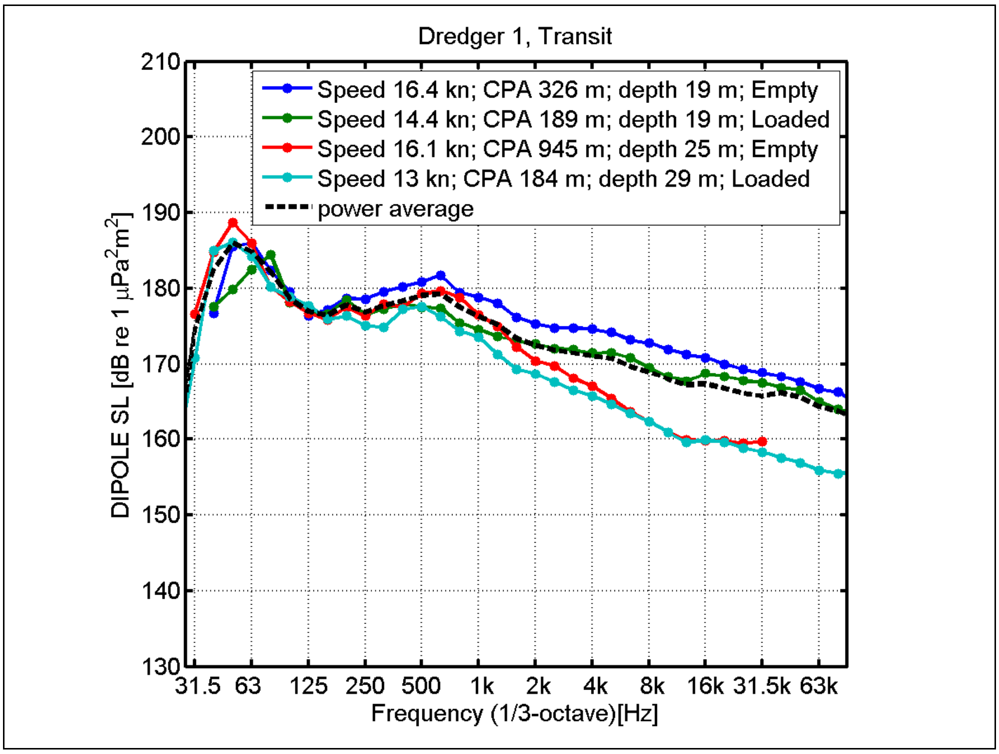


Figure 5.16 Averaged 1/3-octave band dipole source level of the dredger 1, while transiting (4 runs).

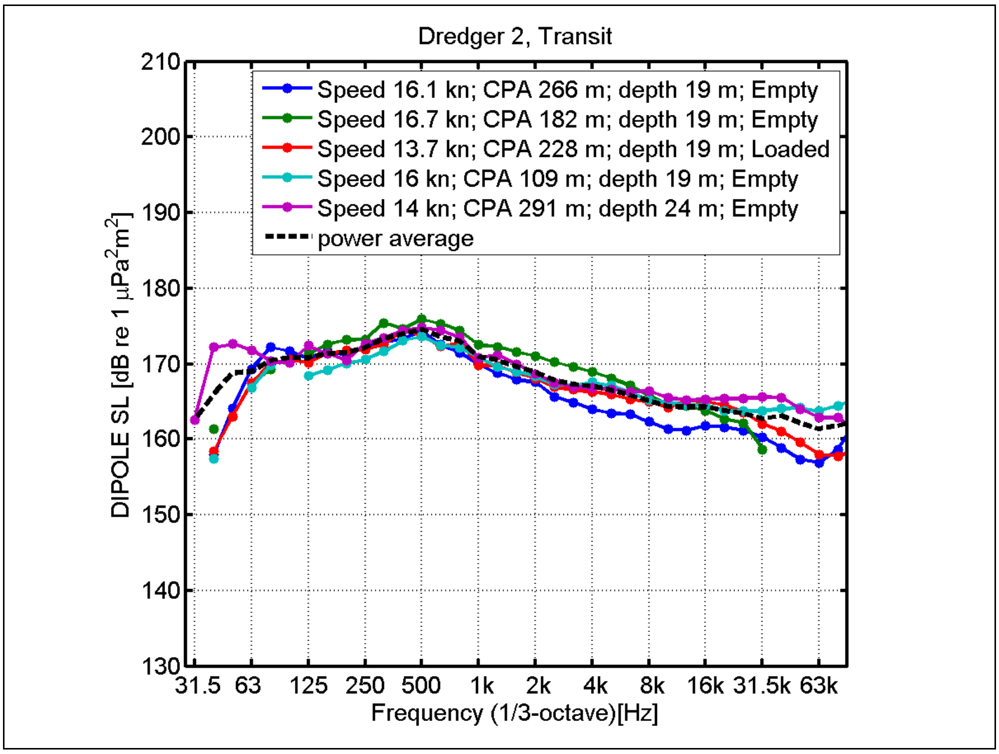


Figure 5.17 Averaged 1/3-octave band dipole source level of the dredger 2, while transiting (5 runs).

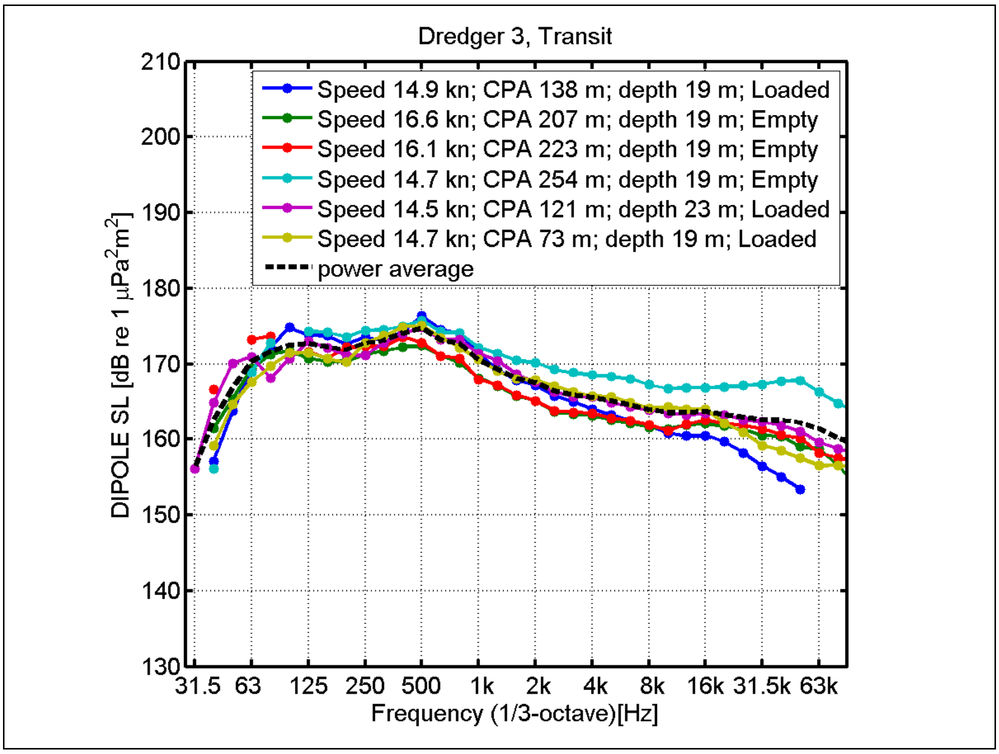


Figure 5.18 Averaged 1/3-octave band dipole source level of the dredger 3, while transiting (6 runs).

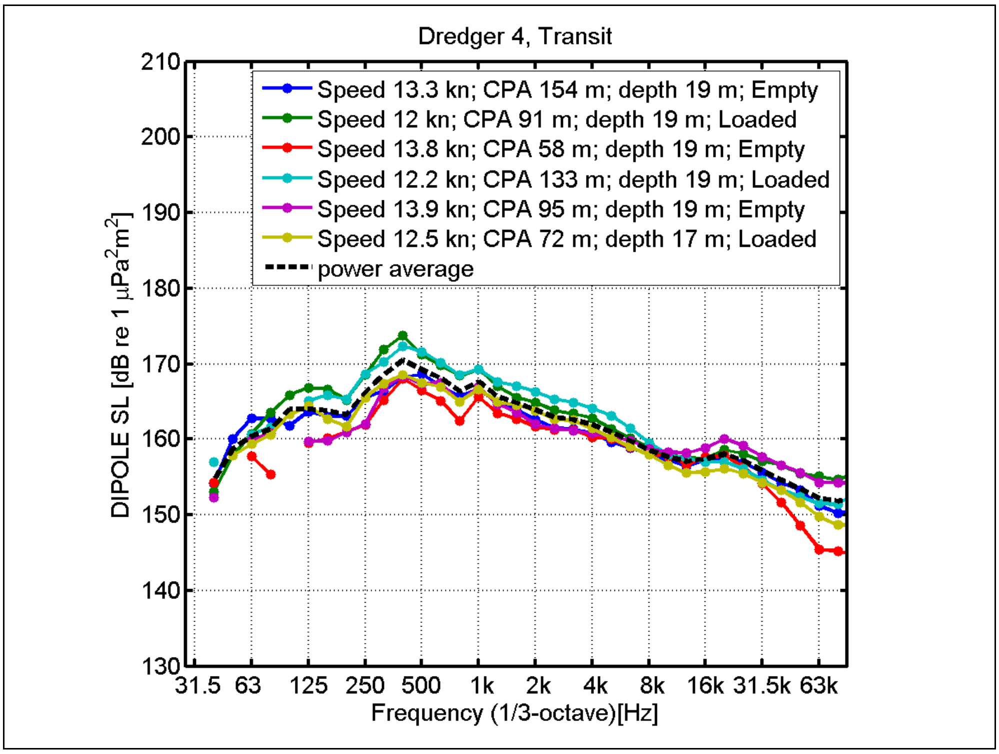


Figure 5.19 Averaged 1/3-octave band dipole source level of the dredger 4, while transiting (6 runs).

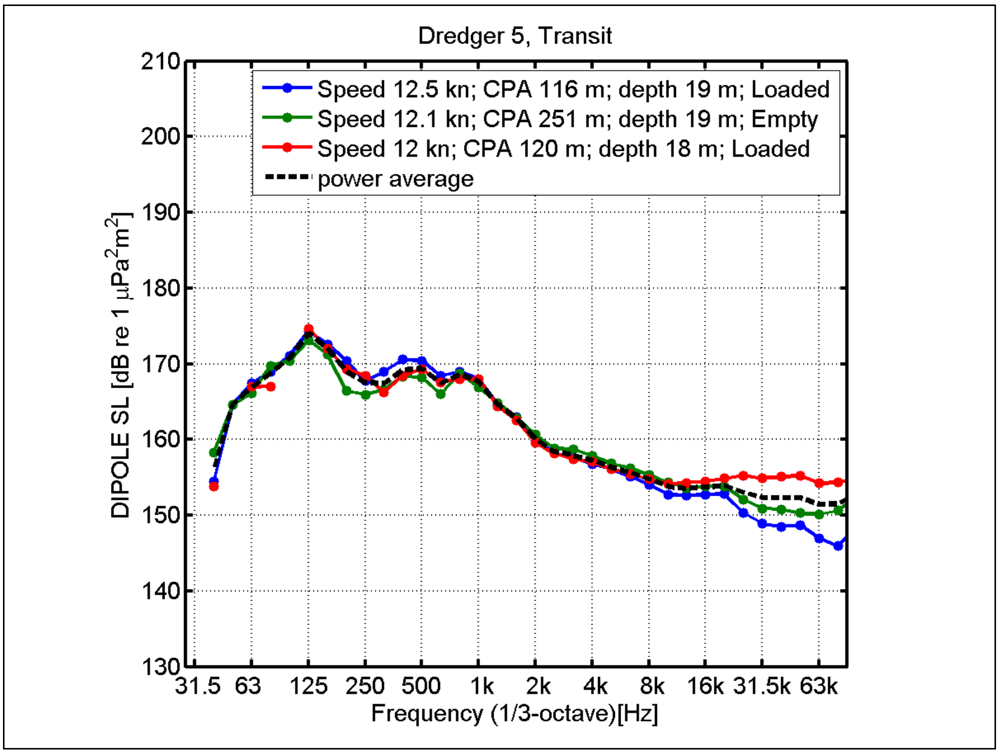


Figure 5.20 Averaged 1/3-octave band dipole source level of the dredger 5, while transiting (3 runs).

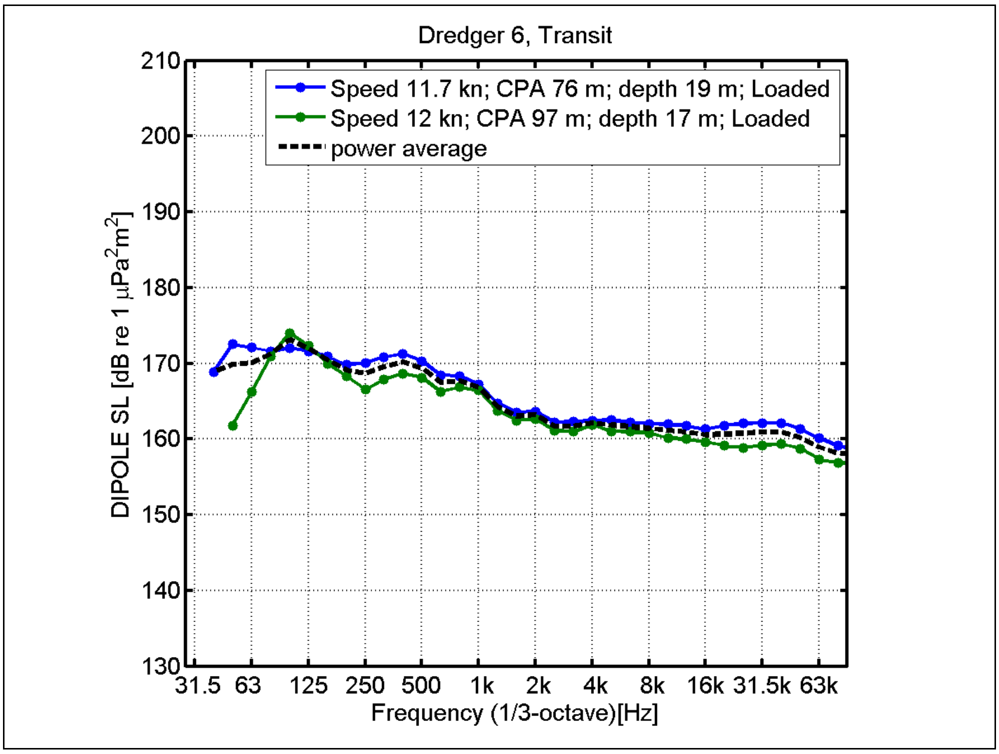


Figure 5.21 Averaged 1/3-octave band dipole source level of the dredger 6, while transiting (2 runs).

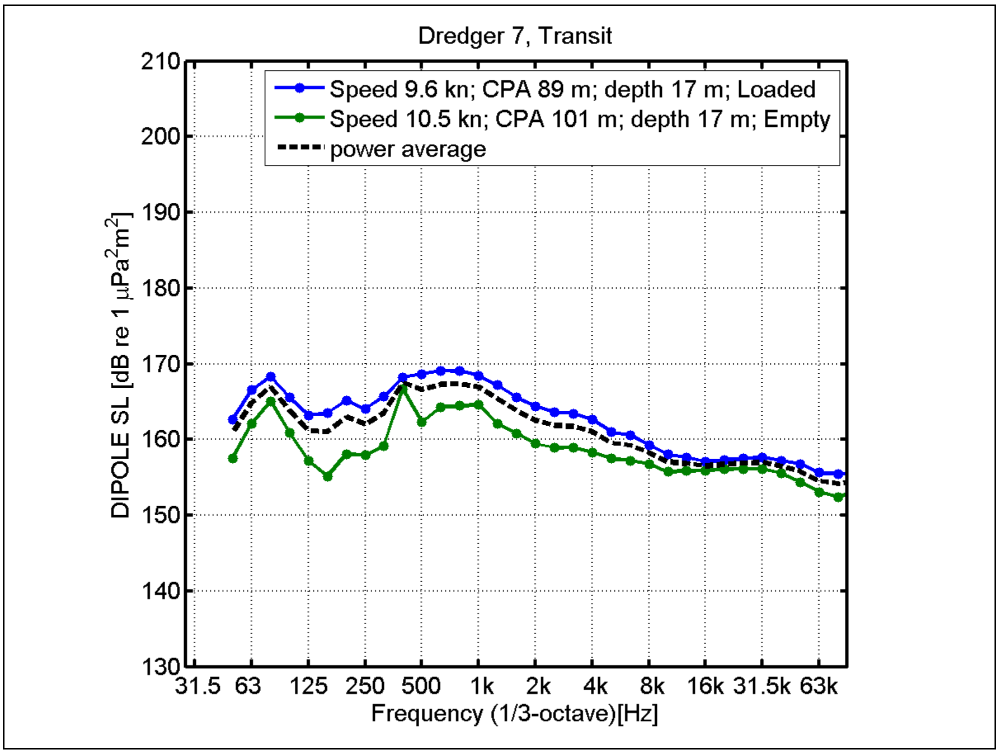


Figure 5.22 Averaged 1/3-octave band dipole source level of the dredger 7, while transiting (2 runs).

Figure 5.23 shows a comparison of the representative underwater dipole source level for the seven dredgers when transiting between the dredging and sand dumping areas. Note that the average speeds for the dredgers are different. During these measurements, dredgers 1 to 3 traveled a larger average speed (14-17 kn) than dredgers 4 to 7 (10-14 kn). Similar to what was observed for the dredging runs, dredger 1 is substantially noisier than the others, especially at low frequency (below 100 Hz).

The dipole source level of the transiting dredgers is compared to the source level of the cargo vessel *Overseas Harriette*, published in [Arveson & Vendittis, 2000], at speeds of 10 and 16 knots. The broadband source level of *Overseas Harriette* is derived from measurements in deep water in 'keel aspect', i.e. with the hydrophones below the vessel. Note that the *Overseas Harriette* source level estimation does not account for absorption loss, so that the high frequency source levels may be underestimated (at 31.5 kHz, for a measurement distance of 460 m the absorption loss is about 4 dB).

For the comparison in Figure 5.23, the *Overseas Harriette* keel aspect source level is translated to a representative beam aspect signature, using equations 4 and 5 (§2.3.1). As explained in [Arveson & Vendittis, 2000], the *Overseas Harriette* noise is dominated by propeller cavitation noise: broadband noise at higher frequencies (>250 Hz) and blade rate tonals at lower frequencies. Only dredger 1 produces more low-frequency noise than this cargo vessel at the same speed (16 kn). The spectrum suggests that the flow around the propellers of this dredger is cavitating more viciously than that for *Overseas Harriette*.

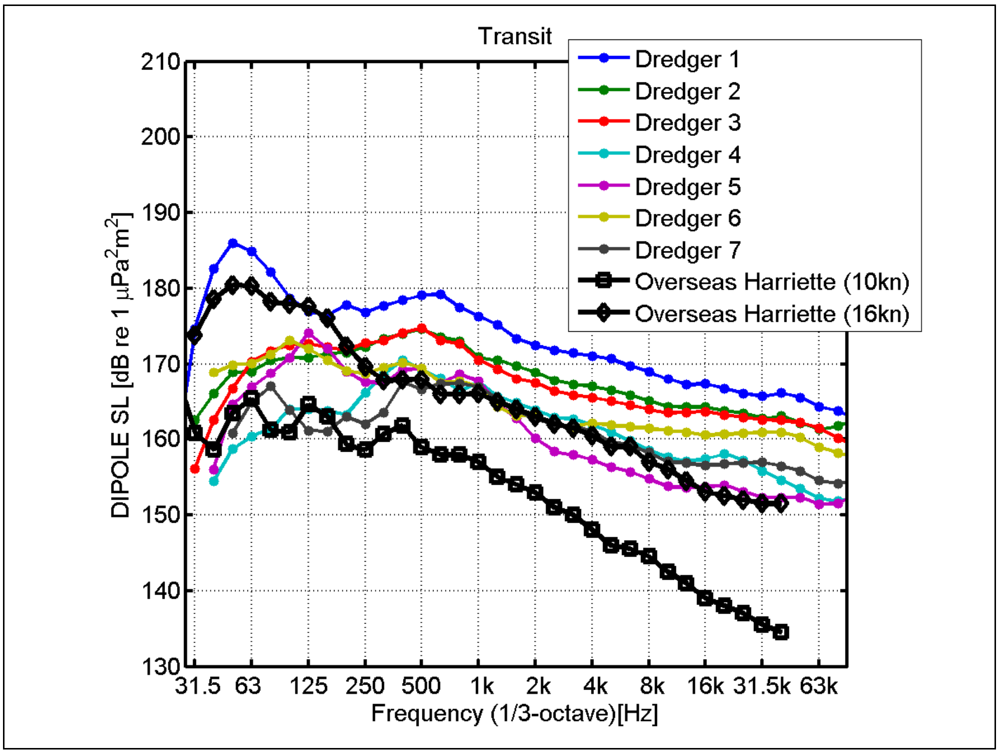


Figure 5.23 Comparison of power averaged dipole source level spectra for the 7 dredgers in transit, with the dipole source level (converted from keel to beam aspect) of the transiting cargo ship *Overseas Harriette* at 10 and16 kn, from [Arveson & Vendittis, 2000].

5.6 Comparison of the maximum underwater noise due to the various activities

In Figure 5.24, the maximum envelope of the estimated dipole source level for the various activities of all dredgers are compared.

This shows that for the dredgers at the Maasvlakte 2 area during the measurement period dredging did not produce more noise than transiting of the dredgers. Note that the sediment here mainly consists of sand. The conclusion could be different for dredging of gravel.

The highest noise levels, below 100 Hz, are probably caused by propeller cavitation of that dredger, which only occurs when the ship is moving.

The maximum broadband noise above 100 Hz is very similar for all activities except 'sand dumping'. It is very likely that this is dominated by cavitation noise from propellers and bow thrusters.

Sand dumping is the quietest activity. Apparently the two measurements of sand dumping vessels were taken in the absence of significant cavitation noise from propellers or transverse thrusters.

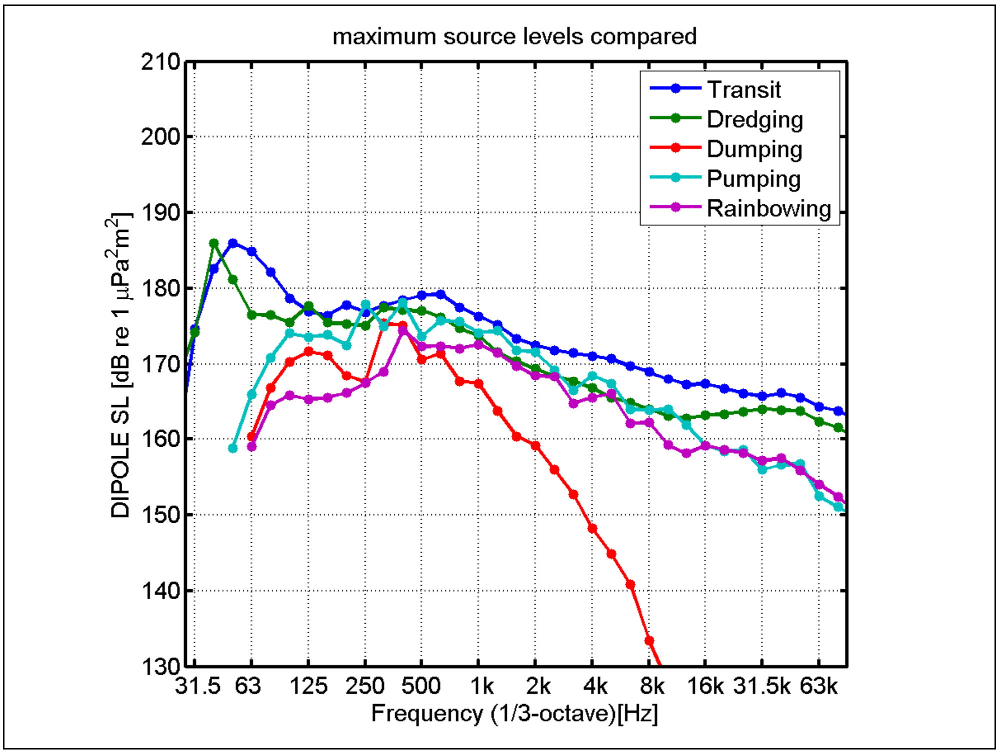


Figure 5.24 Comparison of the upper envelope of the power averaged dipole source level spectra of al TSHDs for the various activities.

6 Background measurements with autonomous platform

6.1 Introduction

In addition to the source level measurements described in section 3.5 background noise measurements were performed between 25 September and 5 October 2009 at a fixed location in the MV2 area. These measurements were carried out in the presence of dredging activities, such as sand dredging, transport, and dumping. During an earlier measurement campaign in September 2008, background measurements were performed in the absence of dredging. Those earlier measurements are described in [Dreschler et al., 2009]. The objective of the two background measurement campaigns is to compare background noise in the presence and absence of dredging. A comparison of the statistics from both campaigns was intended to reveal to what extent the MV2 construction activities affect the underwater noise in the area (see ‘Measurement plan underwater sound Maasvlakte 2’ [van Walree et al.,2009]).

The measurements in both campaigns each covered a time period of about one week, so as to collect enough statistics on the variations in background noise caused by the varying environmental conditions, such as shipping and weather. Contributions to the background noise from these other sources may not have been the same during both campaigns. As described in [Dreschler et al.,2009] shipping noise dominated the low frequency noise levels before the start of dredging activities.
In the analysis of the recent measurements in the presence of dredging activities the shipping conditions were taken into account as well, so that the levels of background noise could be compared with the levels in the absence of dredging activities for similar shipping conditions.

6.2 Experimental method

6.2.1 *Measurement location*

The location of the background measurements was required by the measurement plan [van Walree et al.,2009] to be relevant for seals and porpoises, and to be within a range of 5 km from the sand borrow and reclamation areas, at a site where measurements are allowed. In Figure 6.1 the location specified by the measurement plan is indicated.
The 2009 background measurements were planned to be performed at the same coordinates as for the measurements of background noise in September 2008: *51º 58.0339’ N, 3º 54.9400’ E* (Longitude, Latitude, WGS84). However, the location of the measurement system had to be changed, because small ships such as fishing vessels were passing too close to that location, which would have caused a risk to the system. Eventually, SESAME was moved to the coordinates *51º 57.913’ N, 3º 56.806’ E*, which was about 200 m north of the buoy *‘MV-C’* and about 2 km east from the measurement location of the 2008 campaign.

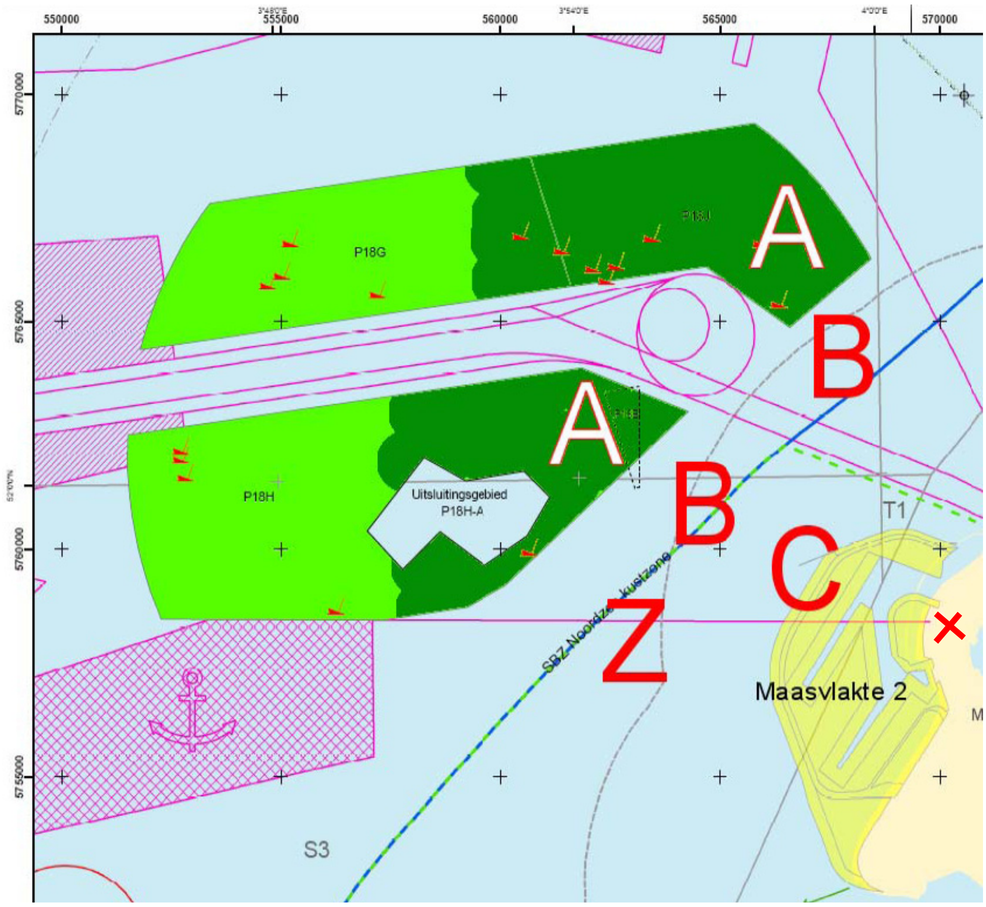


Figure 6.1 Area map with Maasvlakte 2 and the dredging areas (green). The big letters indicate the areas for source level measurements of A) the dredging; B) the transport and C) the dumping of sand. Z denotes the area for the background noise measurements. The approximate location of the meteo system deployed in 2009 is marked with a red cross.

6.2.2 *Time schedule SESAME measurements*

The measurement system SESAME (see 6.2.3) was positioned on the seafloor, and its measurements started on Friday, 25 September 2009. On Friday, 2 October when the measurement session was planned to end, an attempt was made to lift the setup out of the water. While lifting the measurement frame, the cable used to lift the system broke and the system stayed on the seafloor until on Monday, 5 October the system was successfully taken out of the water with the help of divers.

6.2.3 *Experimental setup*

Measurements of underwater acoustic background noise were performed at a fixed location by using a stand-alone measurement system referred to as SESAME (Shallow-water Extendible Stand-alone Acoustic Measuring System). An illustration of the measurement system can be found in Figure 6.2. The electronics and the power supply of the measurement system are housed within a metal container supported by a metal frame. During the full measurement period the frame was positioned at a fixed location on the seafloor.
Sound was recorded by two hydrophones. The hydrophones were attached to the frame by using a vertical cable. The cable was kept vertically above the frame by a buoy providing an upward force. The buoy remained fully below the water surface at about

6–7 m above the seafloor. The hydrophones were fixed at 2 m and 4 m above the seafloor.
The height of the lowest hydrophone from the seabed was the same as that of the lowest hydrophone used in the previous measurements of background noise in 2008.
Motivation for placing the hydrophones in the lower half of the water column was the sound experiences less interference due to reflections at the water surface. Moreover, seals, porpoises and many fish species spend most of the time near the bottom when foraging.

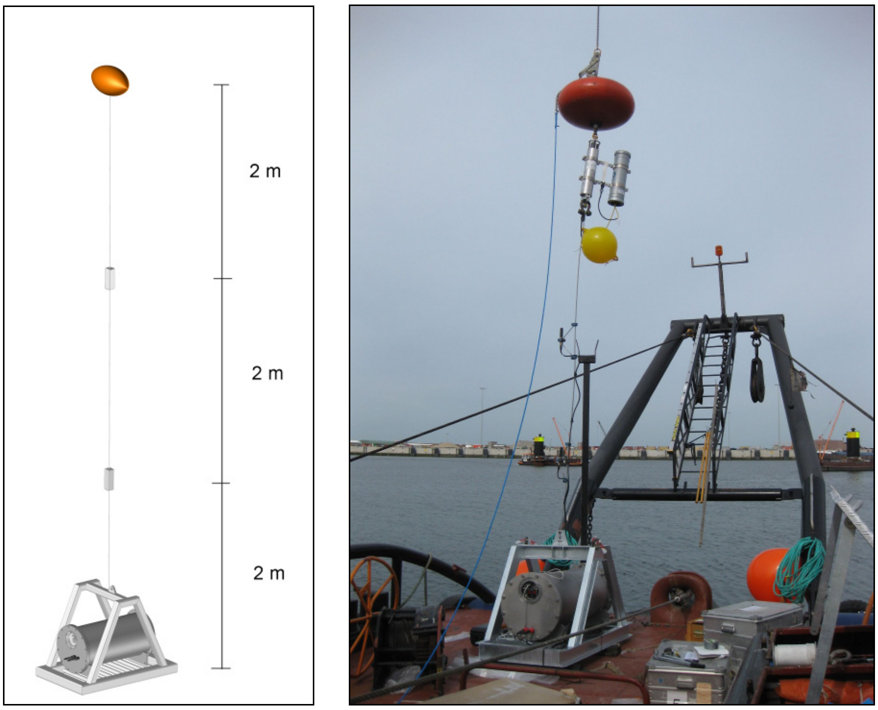


Figure 6.2 The SESAME stand-alone recording system (left: sketch, right: picture on board of measurement vessel *Mon Desir*, prior to the deployment). The buoy providing the upward force for the hydrophone cable remained underwater.

6.2.4 *Frequency range*

The range of frequencies to be covered by the acoustic measurements was considered in the measurement plan [van Walree et al., 2009]. Based on the hearing sensitivity of harbour seals and harbour porpoises and on the effects of increased propagation loss towards higher and lower frequencies (see also §4.3), the frequency range of 25 Hz to 80 kHz provides a sensible coverage of relevant frequencies. In SESAME, the lower frequency was increased to 50 Hz, see §6.2.5.

6.2.5 *Signal conditioning and data acquisition*

The output of the two hydrophones was conditioned by using amplifiers, high-pass filters, and low-pass filters. The resulting signal was converted to 16-bit digital data by an ADC (Analogue-Digital Converter). The applied settings for signal conditioning and data acquisition are listed in Table 6.1.
Recordings were done with a sample frequency of 200 kHz. The -3 dB cut-off frequency of the low-pass filter was set at 80 kHz in order to suppress aliasing effects. A high pass filter with a -3 dB frequency of 50 Hz was used in order to remove the DC voltage component of the signal and to limit the dynamic range of the measured signals

by removing low frequency noise. The gain of the amplifier was varied dynamically. It was automatically set in such a way that the voltage offered to the ADC remained within its input range. The resulting digital data was offered to a data-acquisition system programmed so as to record 6 seconds of data for every minute (i.e., with a duty cycle of 10 %). The raw data were stored on a hard disk in binary format.

Table 6.1 Signal conditioning and data acquisition settings applied by SESAME system during the noise measurements.

Sample frequency	200 kHz
low-pass filter -3 dB frequency	80 kHz
high-pass filter -3 dB frequency	50 Hz
gain	automatically set between 0 dB and 60 dB, in steps of 6 dB
ADC resolution	16 bit
Duty cycle	10 % (6 s every minute)

6.2.6 *Monitoring of environmental conditions*

Information on all shipping including the active dredgers in the vicinity of the MV2 area was logged by using an AIS (Automatic Identification System) receiver. Since the AIS data was only logged in combination with the mobile source level measurements, the log files did not cover the full measurement period of the SESAME recordings. The Port of Rotterdam provided information on shipping for the full measurement period. The shipping information could be used to investigate possible effects from shipping on the levels of background noise (see section 6.2.3).
Weather conditions such as wind speed and direction were monitored by using meteo systems at two locations. One meteo system was positioned at a fixed location in the Maasvlakte area (see Figure 6.1 and Figure 6.3). The other meteo system was positioned on board of the ship 'Mon Desir', used as a measurement ship for the mobile measurements. On most days the air temperature was between 13 and 17 ºC and water temperature between 18 and 20 ºC, so on average the water temperature exceeded the air temperature by about 4 ºC.

Figure 6.3 The land-based meteo system, placed on top of a cotaniner in the Maasvlakte area (see Figure 6.1 for the location).

6.3 Data Analysis

6.3.1 *Determination of sound pressure levels*

Sound pressure levels were determined from the recorded data stored in 16-bit binary format by the following steps:

- The 16-bit data were converted to time series of voltages by using the information on the voltage range of the ADC and the sample frequency. Since recordings were done with a duty cycle of 10 %, for each minute the resulting time series cover a duration of 6 seconds.
- A discrete Fourier transform was applied to each of the time series of voltages, which resulted in the corresponding electrical power spectral densities. In the Fourier transform a time weighting was performed by using a Hann window.
- The electrical power spectral densities were converted to acoustic power spectral densities by accounting for the applied amplification factor, filter characteristics, and the frequency dependent hydrophone sensitivity.
- From the to acoustic power spectral densities the 1/3-octave sound pressure levels were determined. Each determined SPL value is based on a time interval of about 6 seconds. An overview of the obtained SPL's is presented in section 6.4.

6.3.2 *Measures of shipping conditions*

During the previous measurement campaign in 2008, which was performed prior to the start of dredging activities associated with the construction of Maasvlakte 2, noise produced by shipping was found to be the dominant contribution to the measured background noise levels (see [Dreschler et al.,2009]). In order to evaluate to what extent dredging activities affect the background noise levels in the analysis of the 2009 campaign, it is relevant to distinguish between effects from dredging activities and effects of regular shipping. For both the 2008 and the 2009 measurement campaigns shipping density measures were determined, so that background levels could be obtained and compared for specific shipping conditions.
Shipping density measures were determined from the available information on the positions, speeds, and identification numbers of ships obtained from AIS logs and from the additional information provided by the Port of Rotterdam. From this information the distances relative to the measurement location were determined for each ship as a function of time. By using these distances, the following shipping density measures were determined for each minute of the recording period (in both 2008 and 2009):

- The distance to the nearest ship (ND^{ships})
- Weighted sums N_2^{ships} over a selection of ships:

$$N_n^{ships} = \Sigma_i \; r_i^{-n}, \qquad \text{with } n = 0, 1, 2, 3, \ldots$$

where i labels the selected ships, and r_i is the distance of each ship relative to the location of the measurement. The weighting factors used are equal to $1/r_i^n$. These measures take into account the number of ships in the vicinity of the measurement as well as the distances of these ships relative to the measurement location.
In the analysis of the background noise measurements of 2008 [Dreschler et al.,2009]), it was found that the N_2 measure, with r_i^{-2}-weighting, exhibited the strongest correlation with the measured noise. The N_2 measure gives a rough estimation of the potential contribution of ships to the measured background noise, based on the assumption that

all ships have the same source level and the propagation loss is due to spherical spreading only.
For the 2009 measurement campaign the shipping measures were determined separately for dredgers and for other types of ships:
- $ND^{dredgers}$, $N_2^{dredgers}$: measures for dredgers only
- ND^{ships}, N_2^{ships}: measures for other types of ships, excluding dredgers

Specific selections of ships were included in the determination of the measures. Only moving ships, outside the harbour, were included (selected ships were required to have a speed higher than 1 m/s). Dredgers that were clearly shielded by the walls of sand between the ship and the measurement system were not included in the determination of $ND^{dredgers}$, $N_2^{dredgers}$. Moreover, in the determination of ND^{ships} N_2^{ships} the following (types of) ships were excluded:
- Measurement ship '*Mon Desir*'
- Fishing ships
- Sailing ships or pleasure yachts
- Dredging-related ships / workboats
- Survey vessels
- Ships without operating AIS

During the 2009 campaign these types of ships were more frequently active in the vicinity of the background measurements than during the 2008 campaign. For measurements included in the comparison of background levels from the 2009 and the 2008 campaign it was required that ships of these types were further away from the measurements than 4 km (an exception was made for ships that were clearly shielded by the walls of sand between the ship and the measurement system).

Trajectories of dredgers relative to the location of the SESAME measurement system are displayed in Figure 6.4. In the same figure also the trajectories of ship of which the presence is related to the dredging activities are displayed. The trajectories of ships during the 2009 also the 2008 campaigns are displayed relative to the position of the measurement systems in Figure 6.5 and Figure 6.6, respectively (trajectories of the measurement ship '*Mon Desir*', fishing ships, sailing ships, pleasure yachts, dredging-related ships, or survey vessels are excluded from these figures).

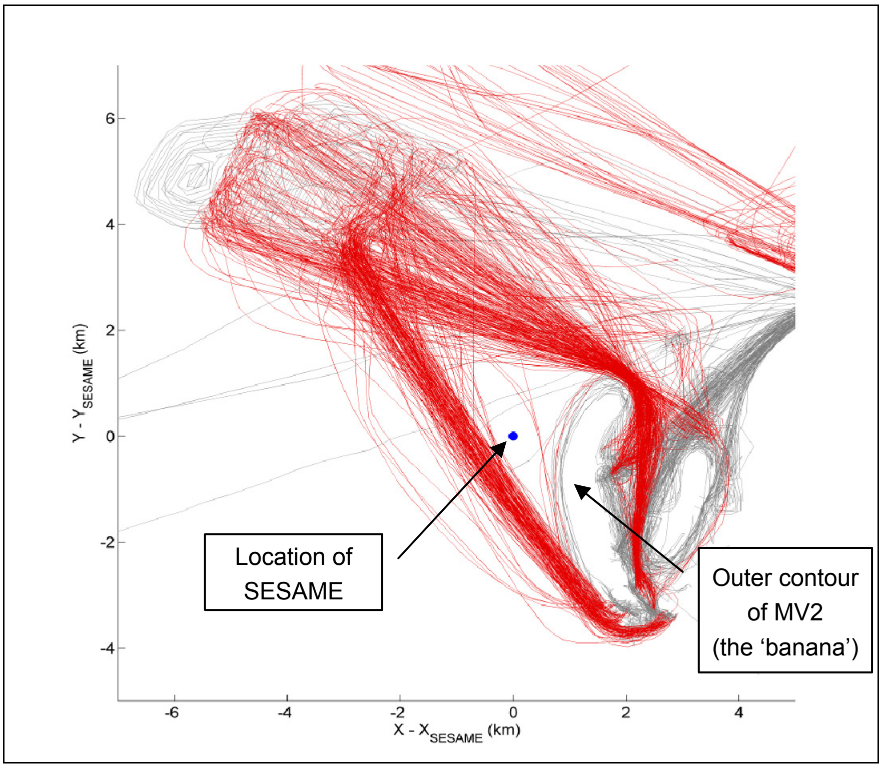


Figure 6.4 Trajectories of dredgers (red) and dredging related ships (grey). The blue filled circle marks the position of the SESAME measurement system.

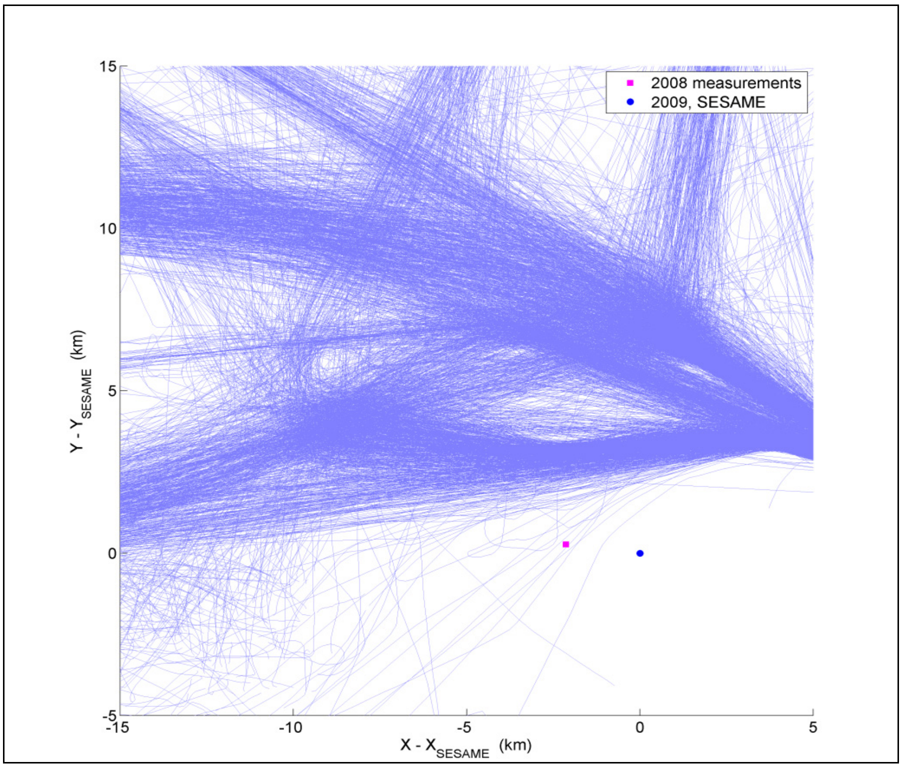


Figure 6.5 Trajectories of ships during the 2009 measurement campaign relative to the location of the SESAME measurement system. The locations of the measurement systems for both campaigns are indicated. The trajectories of dredgers are not displayed in this figure.

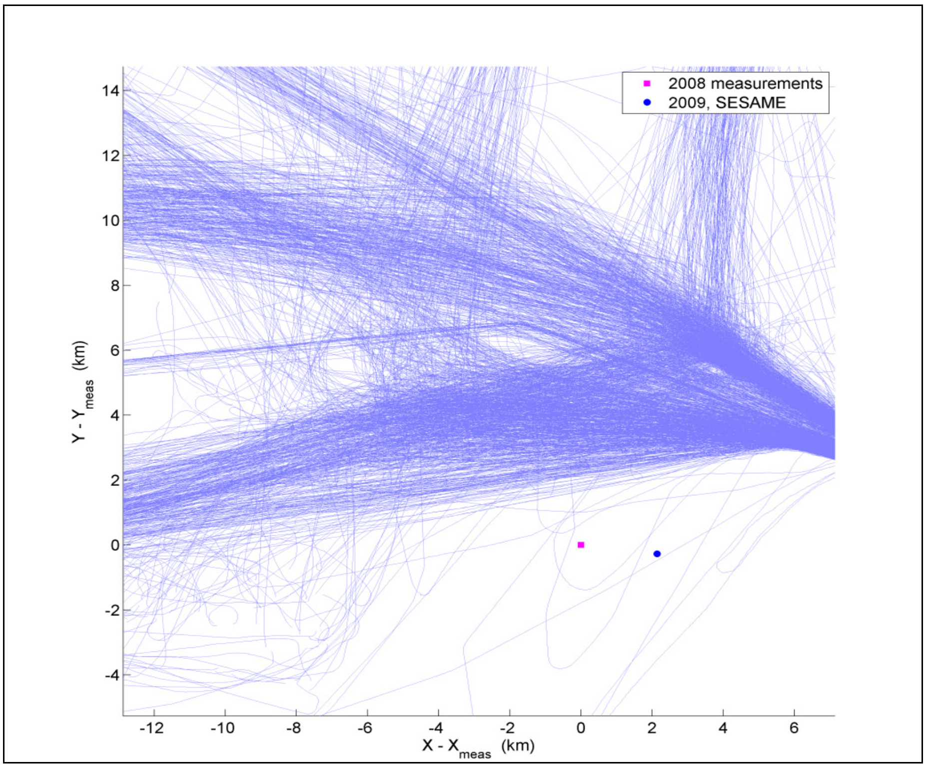


Figure 6.6 Trajectories of ships during the 2008 measurement campaign relative to the location of the 2008 measurement system. The locations of the measurement systems for both campaigns are indicated.

Several differences between the shipping conditions for the 2009 and the 2008 measurement campaigns were observed. The location of the measurement platform was changed and, as a result, also the distance relative to shipping lanes. The shipping lanes also changed as a result of the dredging activities, since the ships avoided the sand winning areas north-west to the location of SESAME. During the 2008 campaign north from the measurement location effectively a broad lane at a distance between 2 and 6 km was present in that area, whereas during the 2009 campaign two more confined lanes were present north and south from the sand winning area. Moreover, also the behaviour of nearby ships changed. During the 2009 campaign less tanker and cargo ships large were manoeuvring (i.e. turning) near to the measurement system.

6.3.3 *Effects from wind*

It was investigated to what extent the factor wind had affected the measured background noise by determining correlations between the wind speed and the measured noise levels. For this purpose, weather information obtained with the meteo system in the Maasvlakte area was used (see section 6.2.6), at an estimated measurement height of 4.5 m. The wind speed information was updated by the meteo station every 10 seconds. From these data the wind speed at the time of each noise measurement occurring each minute was determined. The distribution of the wind speed for the full period of the noise measurements is displayed in Figure 6.7. Coefficients representing the correlations between wind speed and sound pressure levels were determined. This was done for various subsets obtained by imposing different requirements on the measure $N_2^{dredgers}$ in order to account for varying distances of the dredgers relative to the measurement location. The results obtained from this analysis are presented and discussed in section 6.4.6.

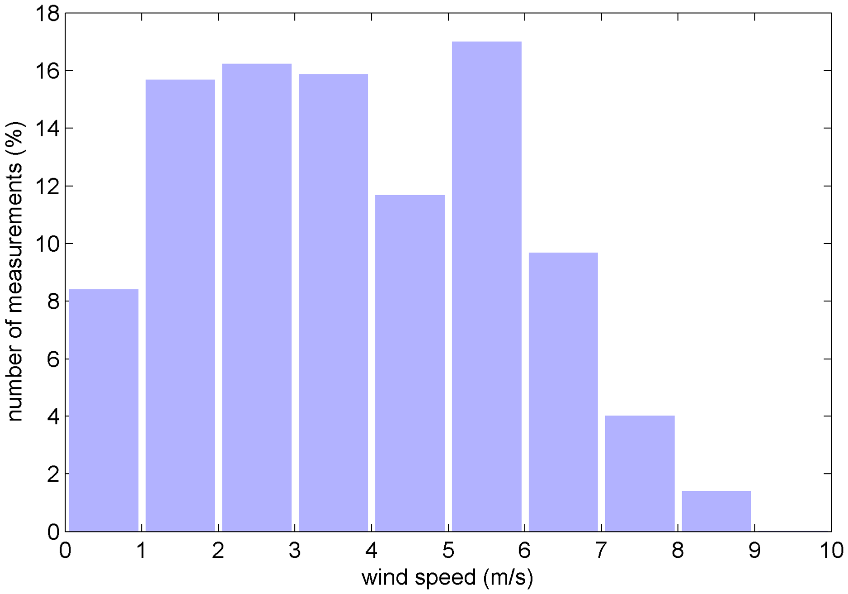


Figure 6.7 Histogram of the wind speed measured with the meteo system (height 4.5 m) in the Maasvlakte area during the time period of the background noise measurements, averaged in one minute intervals.

6.4 Results

Sound Pressure Levels (SPLs) of underwater background noise were determined in 1/3-octave frequency bands for every minute. In the analysis the data for the lower hydrophone was used. An overview of the sound pressure levels during the measurement period of the 2009 campaign is given by the spectrogram in Figure 6.8.

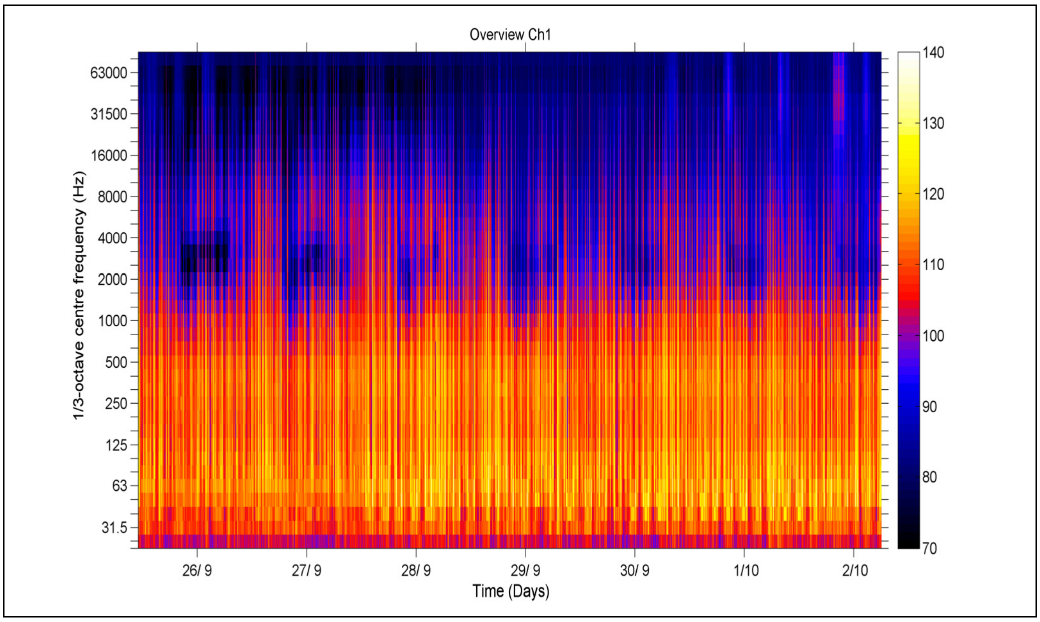


Figure 6.8 Sound pressure levels [dB re 1 μPa²] in 1/3-octave bands versus time for the selected data taking period, with a time resolution of one minute. The ticks on the time axis specify the beginning of each day at 00:00 local time (UTC + 2 hours).

The SPLs are plotted versus frequency in Figure 6.9. The results for all individual measurements are plotted in light grey. In the same figure the corresponding percentiles P5, P16, P50, P84, and P95 are drawn. Each percentile indicates the percentage of measurements for which the levels were below the value of the percentile: 5%, 16%, 50%, 84%, and 95%, respectively. Per 1/3-octave band average SPLs were determined in two different ways. One way was to determine the mean squared pressure for the complete set of measurements and then the corresponding SPL. The other way was to determine the mean of the SPLs determined first for all measurements[2]. The mean values determined in both ways are displayed in Figure 6.9.
From the percentiles P5 and P95 it follows that for a subset containing 90% of the measurements the levels vary over 15 to 25 dB. Except for the frequency bands at and around 2500 and 3150 Hz, where the middle 90% of the levels vary up to about 30 dB.

In the case of normally distributed sound pressure levels the median level (i.e., the percentile P50) would coincide with the mean level, which is indicated in Figure 6.9 by the green solid line. Moreover, in that case the levels at one standard deviation below or above the mean (green dotted lines) would coincide with the percentiles P16 or P84, respectively. The mean SPLs agree reasonable well with the median levels and the

[2] The difference between both approaches is that the former approach uses the arithmetic mean of the mean square pressures per measurement, whereas in the latter approach uses the geometric mean of the mean square pressures per measurement, i.e., the arithmetic mean of their logarithms.

levels at one standard deviation from the mean are close to the percentiles P16 and P84. In this respect the shape of distributions levels per frequency band are close to that of a normal distribution. At frequencies between 20 and 40 kHz, the largest differences between median and mean levels are observed, which are up to about 1-2 dB.
These differences result from the fact that the variations from median towards higher levels are larger than the variation towards lower levels.

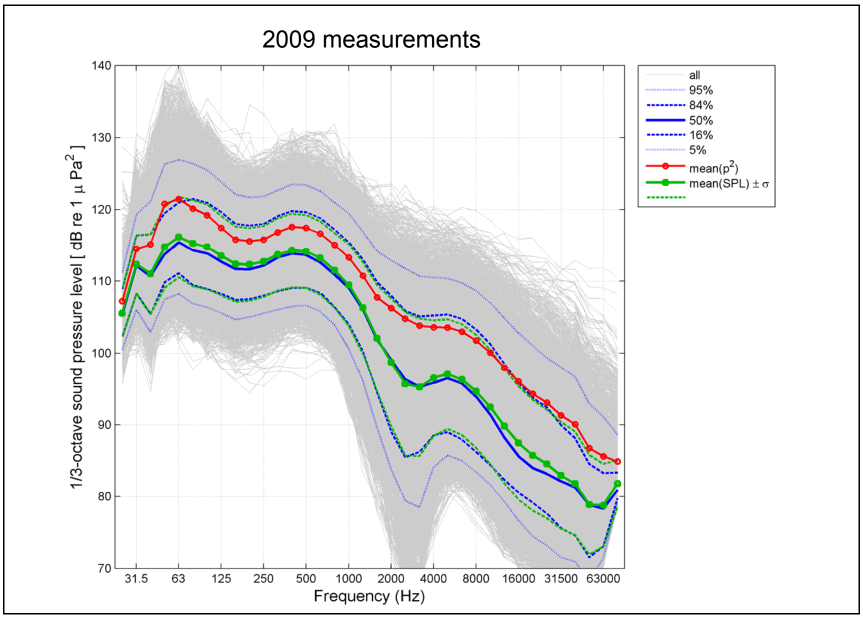


Figure 6.9 Sound pressure levels in 1/3-octave bands. The results of all individual measurements are represented by the light-grey lines. The blue dotted, dashed, and solid curves represent the percentiles P_5, P_{16}, P_{50}, P_{84}, and P_{95}. The red and green curves represent average values of the noise levels for, respectively, averaging over the mean square pressures and averaging over corresponding SPLs. The green dashed curves represent the levels at ±1 standard deviations from the latter average.

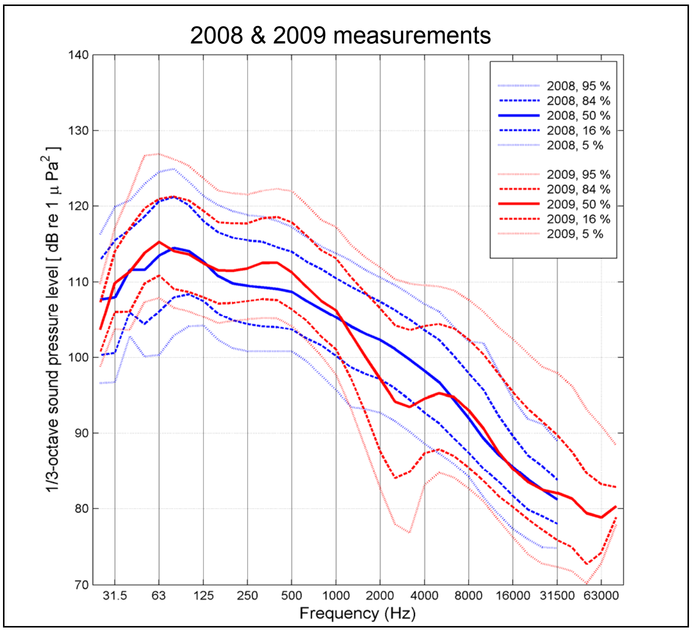


Figure 6.10 Comparison of percentiles of the sound pressure levels of the 2009 and the 2008 measurement campaigns. Clear differences between the shapes of the spectra for both campaigns are observed.

6.4.1 *Comparison of sound pressure levels for the 2009 and 2008 campaigns*

The percentiles of the sound pressure levels measured during the 2009 campaign were compared with those of the 2008 campaign. The percentiles for both campaigns are displayed in Figure 6.10. The median sound pressure levels for the 2009 campaign were generally about equal to or, in the frequency intervals 40-80 Hz and 200-800 Hz, up to 2-3 dB higher than those for the 2008 campaign. An exception is observed in the 1600-5000 Hz frequency bands, in which the levels are lower for the 2009 campaign. At frequencies of 5000 Hz and higher the median levels agree within 1 dB, but larger variations towards higher values are observed for the levels of the 2009 campaign.
The percentiles of the sound pressure levels measured during the 2009 campaign were While for the 2008 campaign the levels of the middle 90 % of the measurements vary over 15-20 dB, for the 2009 campaign they vary over 20-25 dB above 5000 Hz. For frequencies below 1000 Hz, where the median levels are equal to, or a few dB higher than those of the 2008 campaign, the variation of the levels of the 2009 campaign are comparable or smaller.
Between the spectra for the 2009 and the 2008 measurement campaigns a clear difference in shape is observed. In the frequency interval between about 1600 and 5000 Hz dips are present in the percentiles for the 2009 campaign, whereas such dips were not present in the percentiles for the 2008 campaign. The dip has a minimum in the 2500 or 3150 Hz band. In these frequency bands the median levels of the 2009 campaign are about 6 dB lower, whereas the percentile for 5 % is even up to 15 dB lower compared to that of the 2008 campaign.

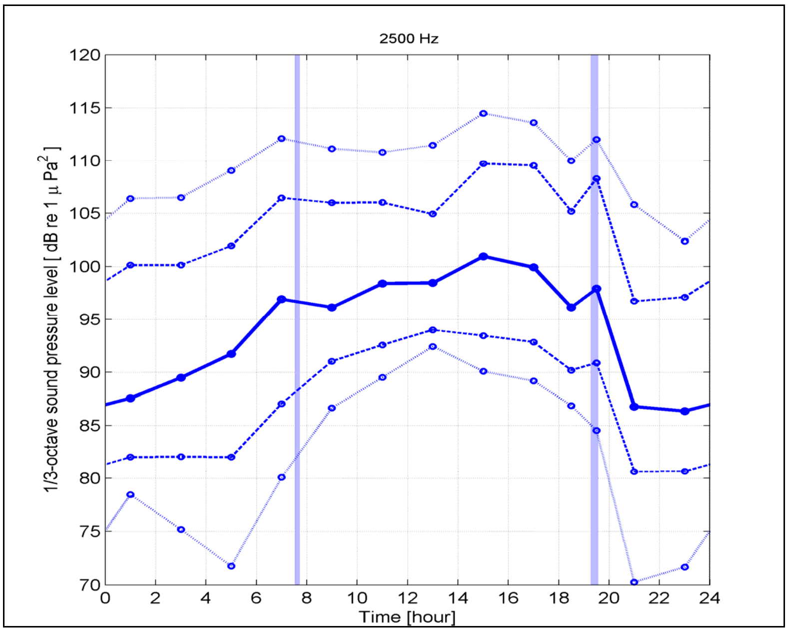


Figure 6.11 Percentiles of sound pressure levels in the 2500 Hz band as a function of the time during the day (2009 campaign). The curves represent the percentiles P_5, P_{16}, P_{50}, P_{84}, and P_{95}. The percentiles are determined for time intervals of two hours combined from all days of the measurement period. The vertical light-blue bands indicate sunrise and sunset. The time is given in Amsterdam local time, which at the time of the measurements was UTC plus 2 hours.

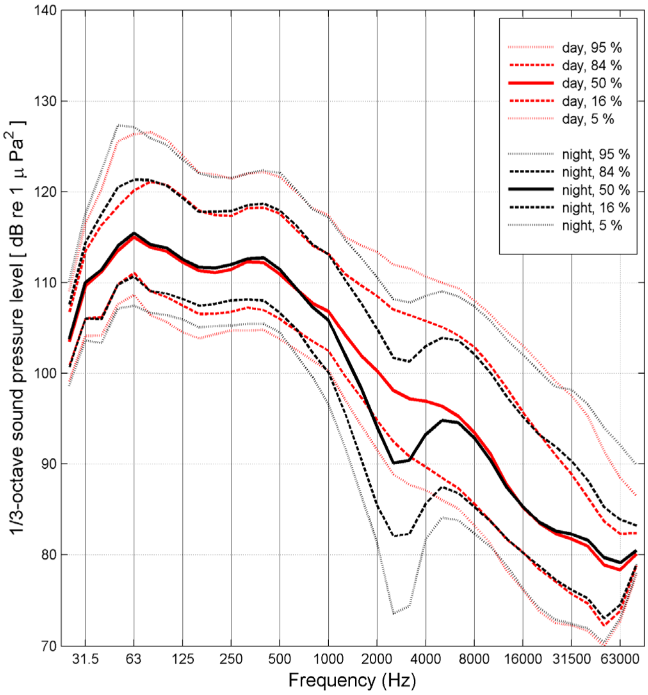


Figure 6.12 Comparison of the percentiles of day-time and night-time sound pressure levels during the 2009 campaign. At frequencies around 2500 Hz the night-time percentiles are consistently lower than the day-time percentiles.

6.4.2 *Comparison of day-time and night-time sound pressure levels*

For the 2009 campaign, diurnal variations were present in the percentiles of the sound pressure levels in the 1600-5000 Hz bands. This time dependence is illustrated for the 2500 Hz band in Figure 6.11. Every day the levels are seen to increase around sunrise and to decrease around sunset. The rapid decrease between 19:30 and 21:00 is particularly striking.

The percentiles for day-time and night-time measurements were compared (see Figure 6.12). Measurements between sunrise and sunset are categorized as day-time measurements, and measurements between sunset and sunrise are categorized as night-time measurements. The dip around the 2500 Hz and 3150 Hz bands was clearly present during the night and not clearly during day time. For lower and higher frequencies the percentiles for day-time and night time sound pressure levels agreed reasonably well.

The diurnal variations in sound pressure level could be caused by variations in propagation loss in this frequency interval.

A possible cause for diurnal variations in propagation loss is the presence of large numbers of fish. The characteristic signature of absorption due to (bladdered) fish is a marked diurnal variation (due to their aggregation into shoals during the day and dispersal at night) and a broad absorption line around the bladder resonance frequency [Weston, 1972; Weston, 1970; Weston, 1992; Diachok, 1999; Diachok & Wales, 2005], both of which are present in the observed data. The presence of fishing vessels in the area provides circumstantial evidence that fish were indeed present, but it is not known what type of fish was caught.

The quietest period occurs between 21:00 and 23:00, during which time the median level is 5 dB lower than the quietest noon measurement (P_5). There are noise peaks that coincide approximately in time with dawn (07:00) and dusk (19:00).

The resonance frequency of a fish of length *L* at depth *z* (both in metres), for a bladdered fish, can be estimated using [Ainslie, 2010]

$$f_0(L) \approx (0.079\ \text{kHz}) \frac{\sqrt{0.1z + 1.75}}{L}.$$

Therefore, for a given resonance frequency f_0 (in kilohertz), the corresponding fish length is

$$L(f_0) \approx (0.079\ \text{m}) \frac{\sqrt{0.1z + 1.75}}{f_0}.$$

For example, in the depth range 0 to 20 m, the length of fish that would resonate at 3 kHz is between 3 and 5 cm. Candidate species of the right size and likely to have been present, although not necessarily in sufficient numbers, include sprat, juvenile whiting and juvenile herring. Figure 6.13 and Figure 6.14 show distributions of herring, sprat and whiting from a population survey carried out between April 2007 and October 2007. The length distributions corresponding to the fish population of October 2007 is shown in Figure 6.16 and Figure 6.17. A long term (1977-2005) average for sprat is shown in Figure 6.18 for quarter 1, indicating that this species is regularly present, at least in the spring.

It has been suggested that (passive) sound measurements can be used to classify fish [Weston, 1972; Diachok et al., 2005]. However, despite the considerable literature on the absorption of sound by fish, the authors are unaware of any previous measurement of an absorption line in ambient noise associated with fish.

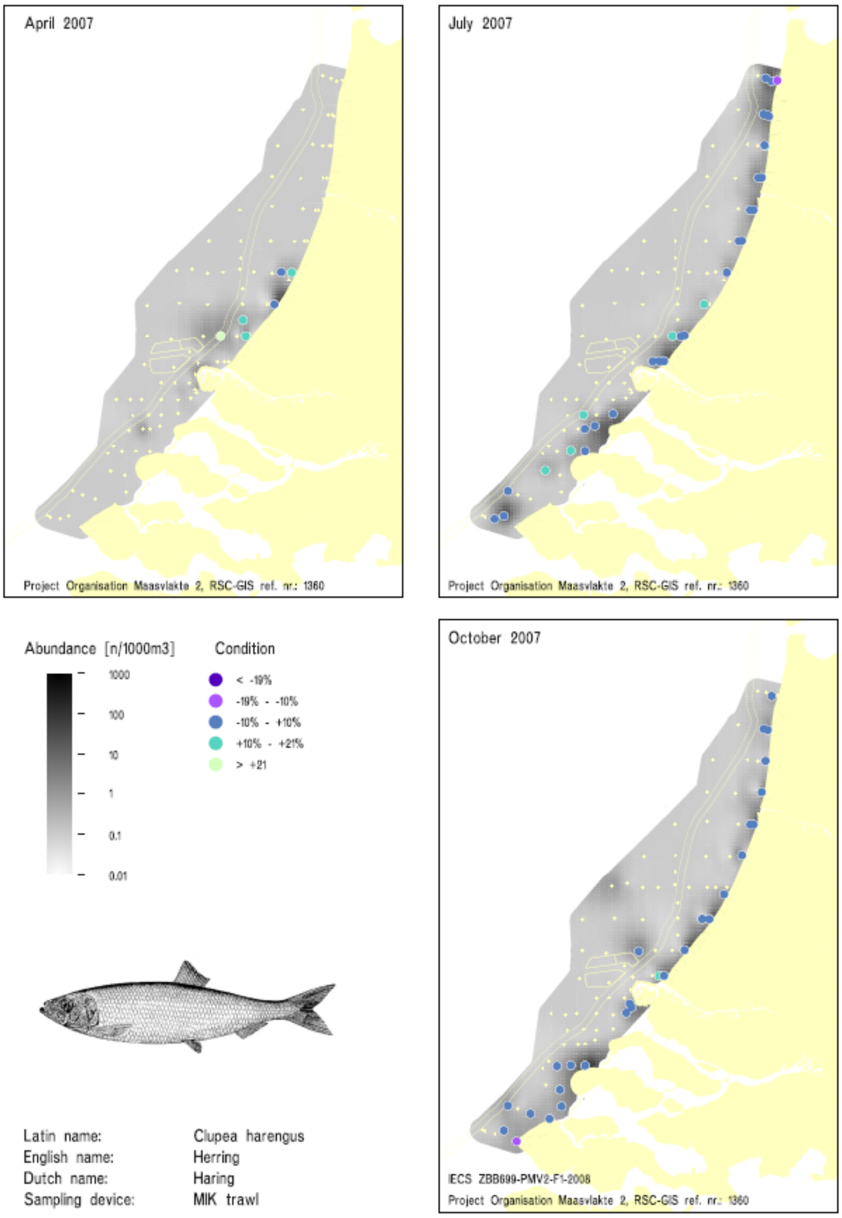


Figure 6.13 Measured distribution of herring between April 2007 and October 2007 [Pérez Domínguez, 2008].

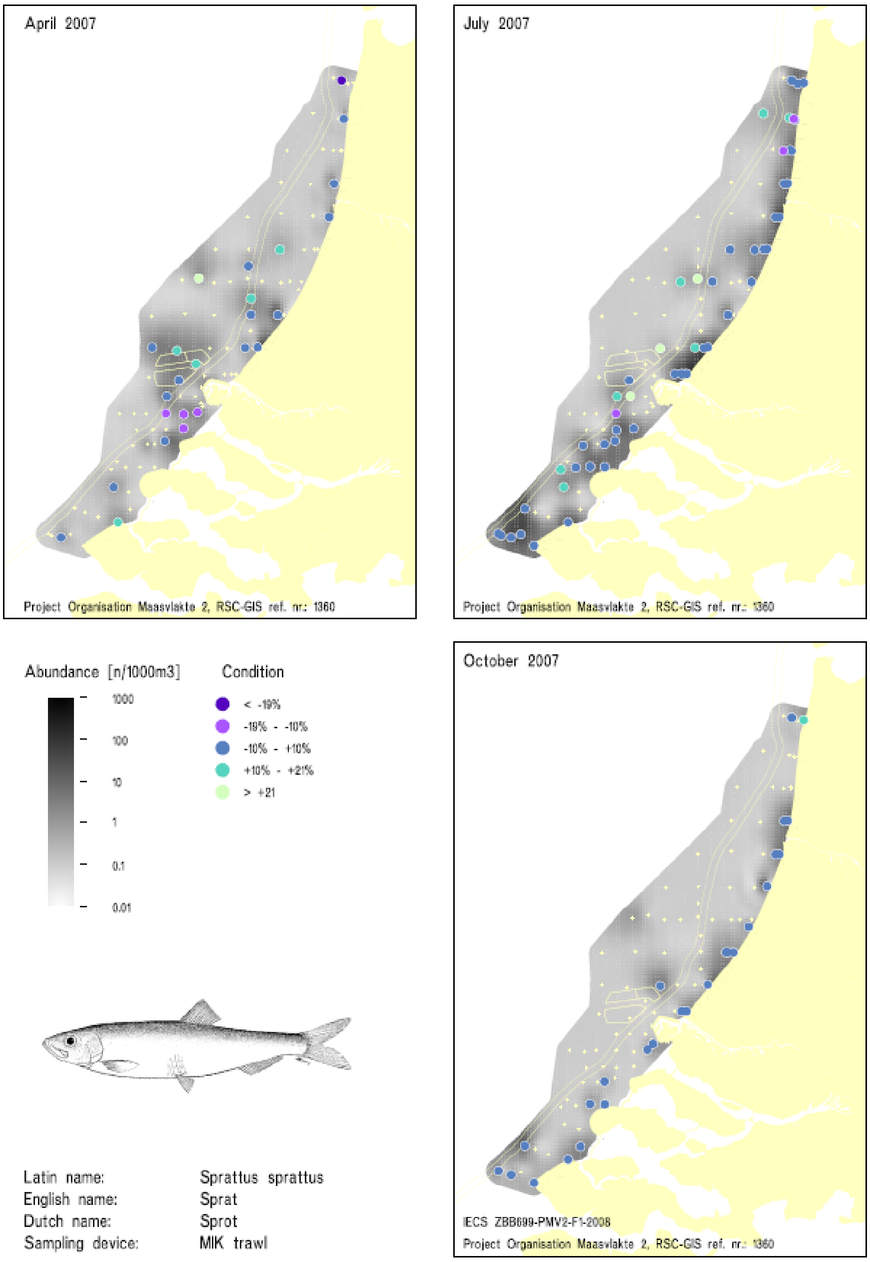


Figure 6.14 Measured distribution of sprat between April 2007 and October 2007 [Pérez Domínguez, 2008].

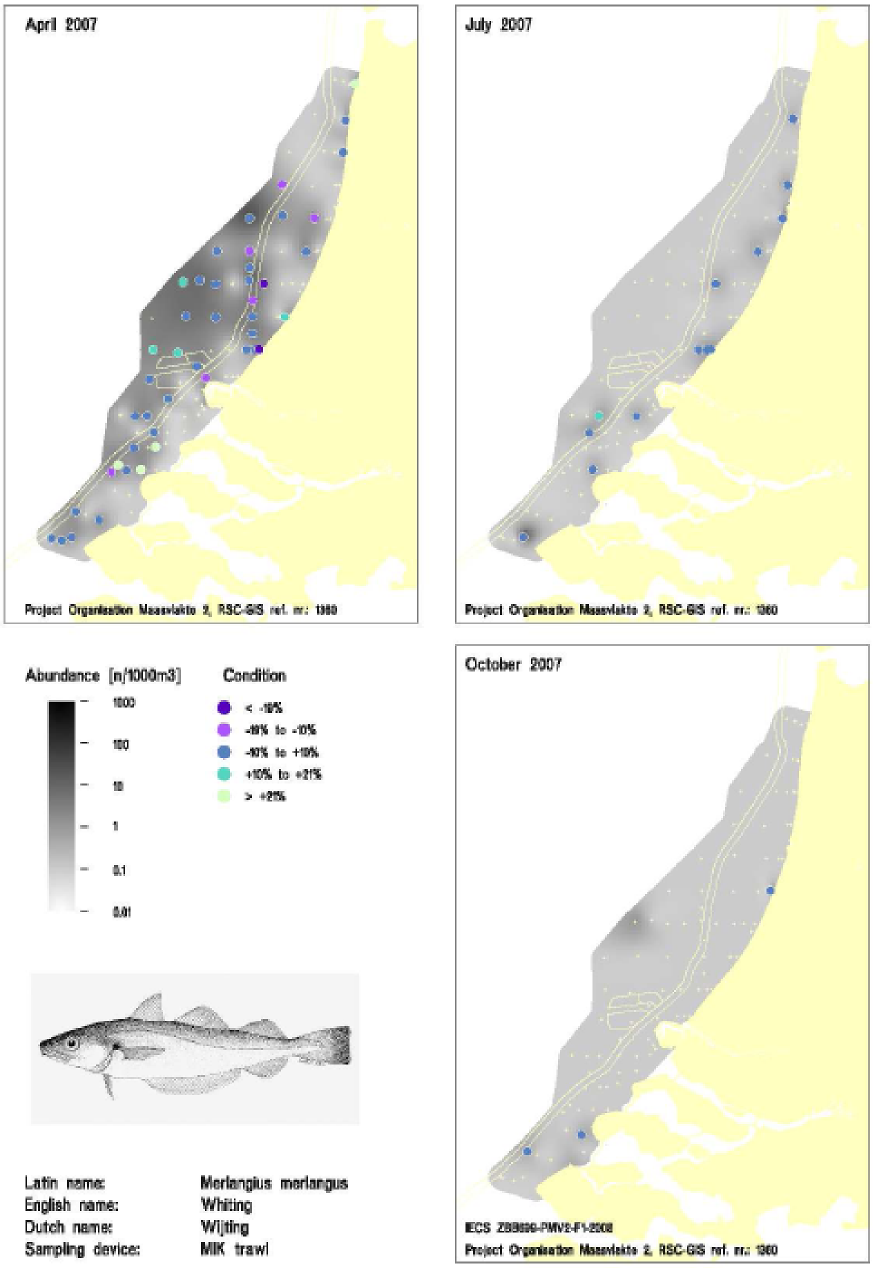


Figure 6.15 Measured distribution of whiting between April 2007 and October 2007 [Pérez Domínguez, 2008].

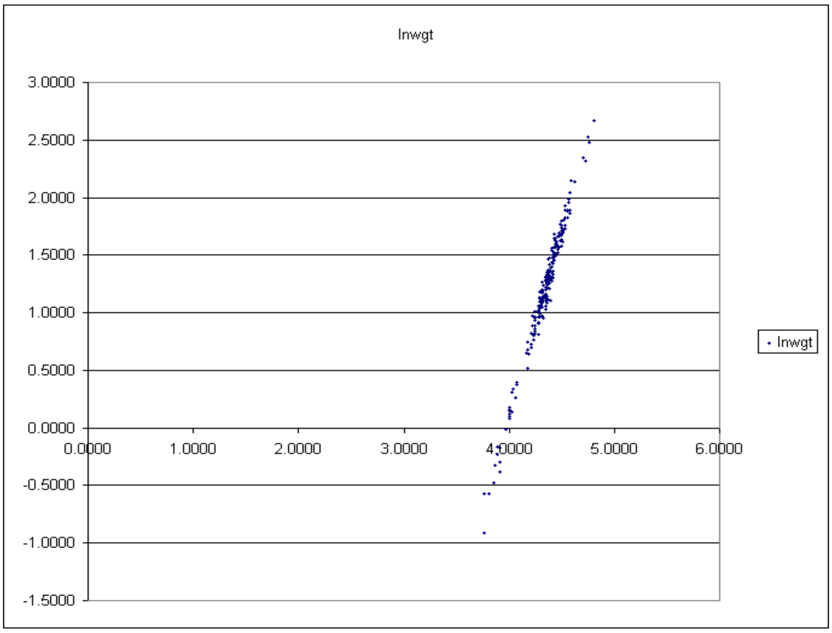


Figure 6.16 Graph of ln(weight/g) vs ln(length/mm) for (juvenile) herring, October 2007 [Borst, 2010]. Most of the herring are in the length range 60 to 100 mm. Length guide: ln(55) = 4; ln(90) = 4.5; ln(148) = 5.0.

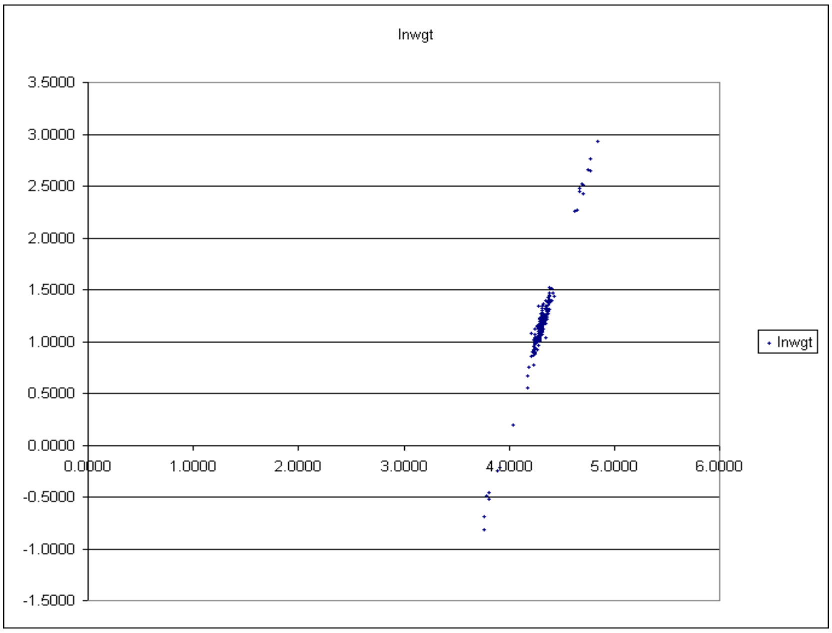


Figure 6.17 Graph of ln(weight/g) vs ln(length/mm) for sprat, October 2007 [Borst, 2010]. Most of the sprat are in the length range 70 to 90 mm. Length guide: ln(55) = 4; ln(90) = 4.5; ln(148) = 5.0.

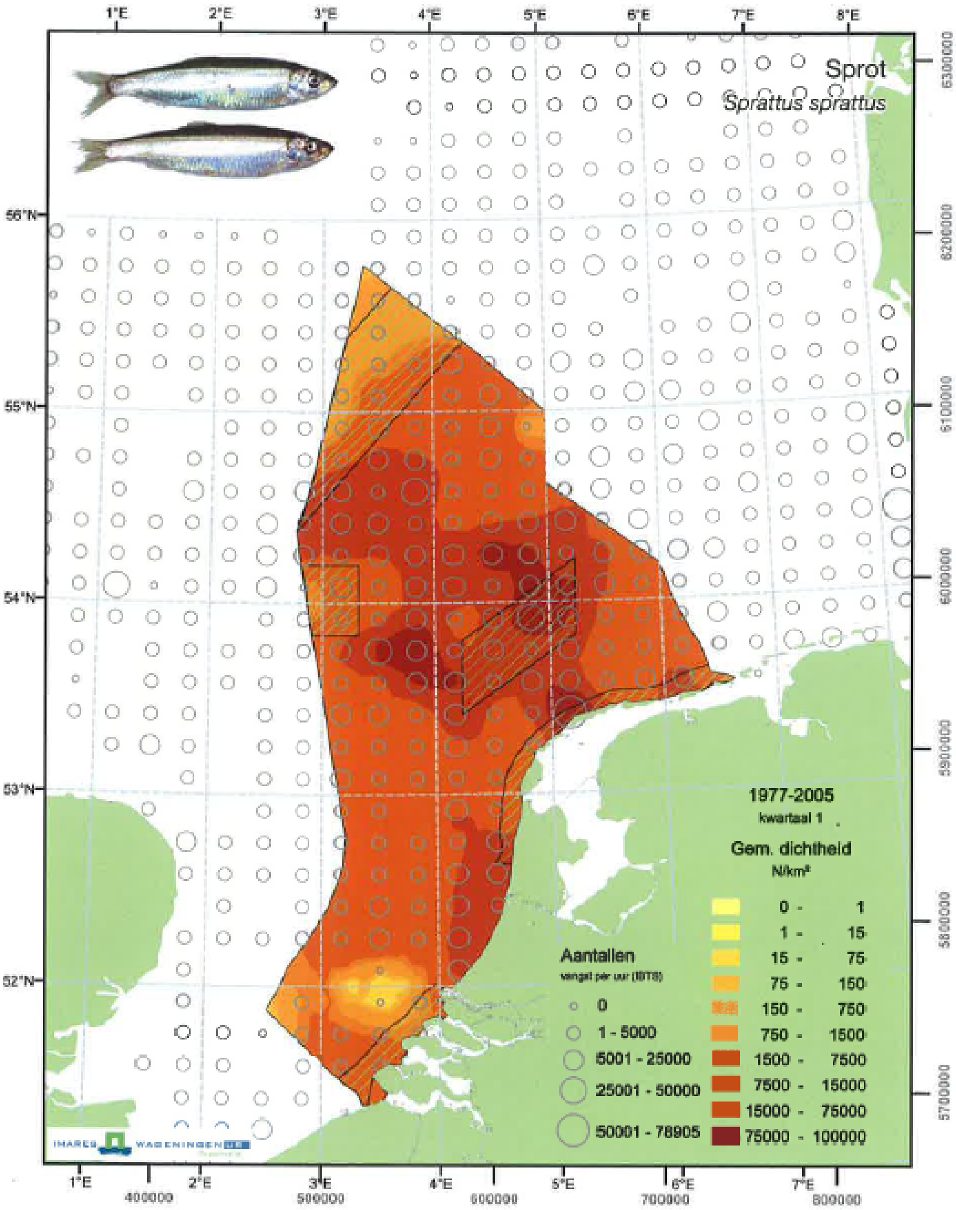


Figure 6.18 Average distribution of sprat in quarter 1 between 1977 and 2005 [Lindeboom et al., 2008]. (Note that the acoustic measurements were carried out in quarter 4 (October) of 2010).

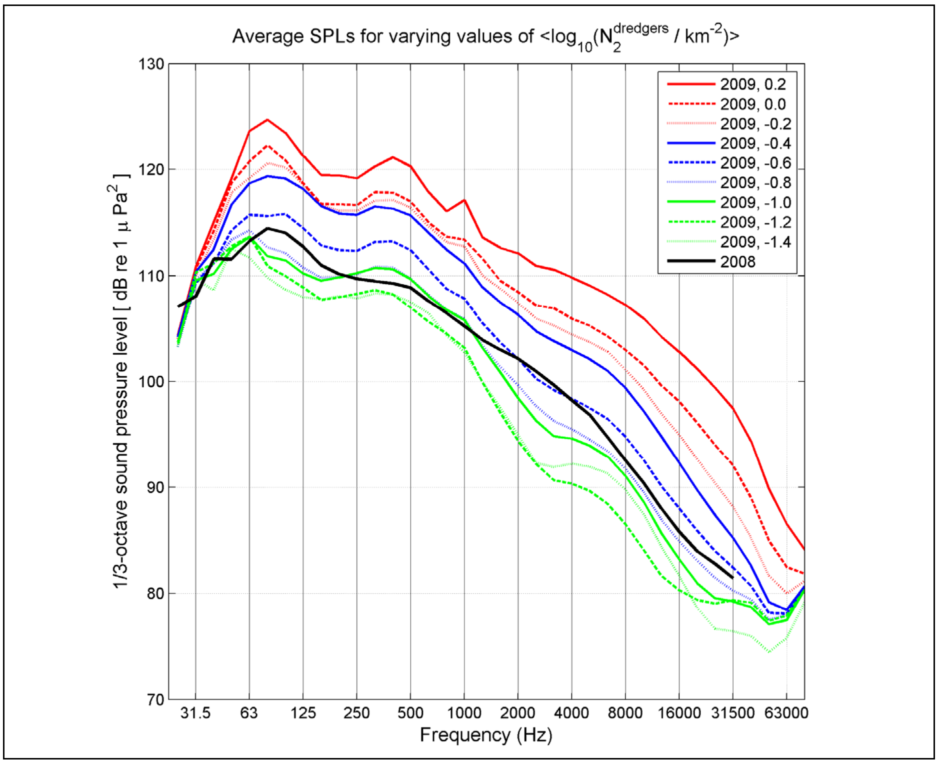


Figure 6.19 Average sound pressure levels in 1/3-octave bands. The curves represent the average levels for distinct subsets, which have been selected by imposing requirements on the value of $\log_{10}(N_2^{dredgers})$. For each subset the average value of $\log_{10}(N_2^{dredgers}/\text{km}^{-2})$ is indicated in the legend. The average levels of the 2008 campaign are drawn as well for reasons of comparison.

6.4.3 *Effects of dredgers on the levels of background noise*

During the 2009 campaign the sound pressure levels were strongly correlated with the measures for dredgers introduced in section 6.3.2. The dependence of average levels on $\log_{10}(N_2^{dredgers})$ is illustrated in Figure 6.19, which displays the average day-time levels for subsets each for a different interval of $\log_{10}(N_2^{dredgers})$. Clear differences between the average levels for selections of nearby and far away dredgers are observed.
For frequencies between 50 and 1000 Hz differences up to 12 dB are observed.
Above 1000 Hz up to about 20000 Hz the differences increase. Around 20000 Hz differences of more than 20 dB are observed. Because of the strong dependence of the levels on the distances of the dredgers relative to the measurement location, noise produced by transiting dredgers is most likely the dominant contributor to the levels of background noise during the 2009 measurement campaign. The variation of the distances of transiting dredgers most likely causes the strong variations observed earlier for the levels of the background noise.

For subsets where $\log_{10}(N_2^{dredgers}/\ \text{km}^{-2})$ is about -0.6 or larger the average levels are above the average levels of the 2008 campaign (the latter levels are drawn in Figure 6.19 for comparison). The higher background levels observed for the 2009 campaign may be caused by the presence of the dredging activities.

For subsets of measurements with dredgers sufficiently far away (the subsets for which $\log_{10}(N_2^{dredgers}/\ \text{km}^{-2})$ is smaller than about -0.8) the average levels are lower than the average levels of the 2008 campaign for a large part of the spectrum in spite of the fact that during the latter campaign no dredging activities were present. The decrease of noise levels could be caused by a decrease of the noise levels produced by regular shipping. Effects of regular shipping on the levels of background noise are discussed in section 6.4.5.

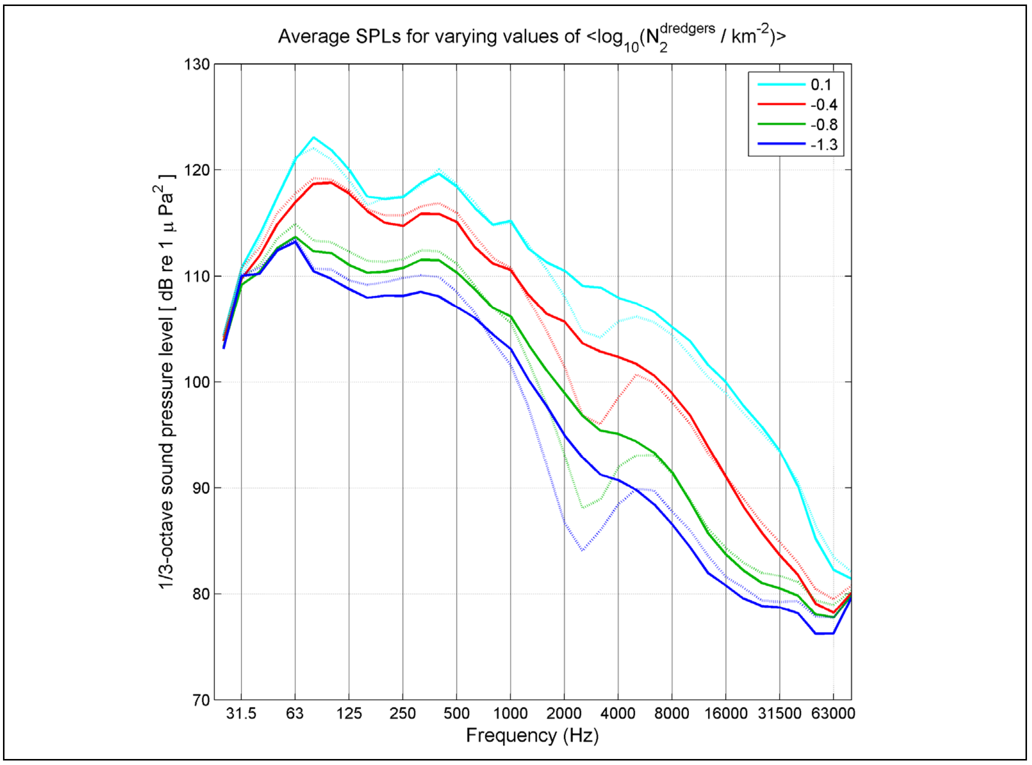


Figure 6.20 Average sound pressure levels in 1/3-octave bands. The curves represent the average levels for distinct subsets, which have been selected by imposing requirements on the value of $\log_{10}(N_2^{dredgers})$. For each subset the average value of $\log_{10}(N_2^{dredgers}/\mathrm{km}^{-2})$ is indicated in the legend. Curves are plotted separately for day-time and night-time measurements (solid and dotted curves, respectively).

6.4.4 Day-night comparison of the effects of dredgers on the levels of background noise

The average day-time and night-time levels, when compared in the same intervals of $\log_{10}(N_2^{dredgers})$, agree within a few dB expect for frequencies between 1500 and 5000 Hz (see Figure 6.20). In this frequency interval the difference between night-time and day-time levels decreased from about 10 dB to 4 dB with increasing $\log_{10}(N_2^{dredgers})$. This dependence indicates that the day-night difference is larger if dredgers are further away. As discussed in section 6.4.2 the dip observed for night-time measurements in this frequency interval might be caused by an increase in propagation loss during the night.[3] Such an increase of propagation loss during the night is consistent with the observation that the day-night difference is larger if dredgers are further away.

[3] As discussed in section 6.4.2 such a day-night difference of propagation loss in the frequency range between 1500 and 5000 Hz could be caused by a diurnal variation of the distribution of fishes in the water column.

6.4.5 *Comparison of sound pressure levels for the 2009 and 2008 campaigns for similar shipping conditions*

The fact that for cases where dredgers are sufficiently far away the average levels of the 2009 campaign are lower than those of the 2008 campaign could be caused by differences in shipping noise between the two campaigns. As was discussed in the report of the 2008 campaign [Dreschler et al., 2009] in the absence of dredging activities the levels strongly depended on the measures for shipping, in particular with the measure $\log_{10}(N_2^{ships})$. In order to compare the noise levels of both campaigns for similar shipping conditions the measurements were divided into subsets corresponding to varying sub-intervals of $\log_{10}(N_2^{ships})$. The levels of both campaigns were then compared for the same intervals of this shipping measure. As an illustration, for both campaigns percentiles of sound pressure levels in the 400 Hz and 20000 Hz bands are plotted versus the shipping measure $\log_{10}(N_2^{ships})$ in Figure 6.21.

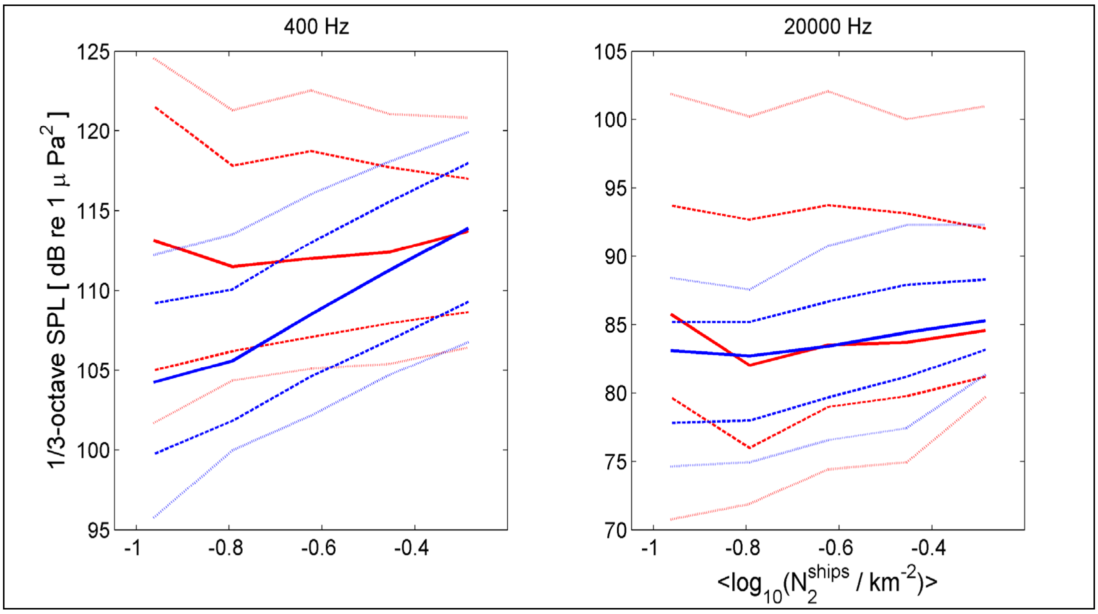


Figure 6.21 Percentiles of sound pressure levels in the 400 Hz and 20000 Hz bands versus the shipping measure $\log_{10}(N_2^{ships}/\mathrm{km}^{-2})$. The red curves represent the percentiles for the 2009 campaign and the blue curves the percentiles for the 2008 campaign. The curves represent the percentiles P_5, P_{16}, P_{50}, P_{84}, and P_{95} for both years.

For distant shipping (with $\log_{10}(N_2^{ships} / \mathrm{km}^{-2})$ smaller than -0.8) the median levels of the 2009 campaign are about 2-8 dB above those of the 2008 campaign in the frequency interval between 20 and 10000 Hz. Above 10000 Hz the differences between the median levels decrease until they are about the same above 20000 Hz. The differences between the higher percentiles (e.g. those for 84 % or 95 %) of both campaigns are about 8-12 dB in the frequency range between 200 and 20000 Hz. For higher frequencies these differences decrease with increasing frequency. For distant shipping the median levels are higher and larger variations towards higher levels are present for the 2009 campaign.

For intermediate shipping conditions (with $\log_{10}(N_2^{ships} / \mathrm{km}^{-2})$ around -0.6) the median levels of the 2009 campaign are comparable to, or (at frequencies between 40 and 1000 Hz) up to 2-3 dB higher than those of the 2008 campaign. However, for the higher percentiles the differences between the two campaigns are larger. Below 1000 Hz the higher percentiles of the 2009 campaign are up to about 5 dB higher. For frequencies above 10000 Hz the higher percentiles of the 2009 campaign are about 5 to 10 dB above those of the 2008 campaign. For intermediate shipping conditions the median levels of both campaigns are comparable, but larger variations towards higher levels are present for the 2009 campaign.

In the case of nearby shipping (with $\log_{10}(N_2^{ships}$ / km^{-2}) larger than -0.4) at frequencies below 10000 Hz the median levels for the 2009 campaign are up to 5 dB lower than those of the 2008 campaign. An exception is observed at frequencies between 200 and 500 Hz where the median levels of both campaigns are practically the same.
At frequencies above 10000 Hz the median levels are also practically the same, but for the 2009 campaign larger variations in level up to a few dB higher values are present. The fact that in the case of nearby shipping the median levels of the 2008 campaign below 10000 Hz are higher is remarkable, since the comparison was performed for similar shipping conditions, and during the 2009 not only noise produced by regular ships, but also noise produced by dredger activities was present.

For the 2009 campaign the sound pressure levels are less strongly correlated with the measures for shipping than for the 2008 campaign. Consequently, the percentiles of the levels for the 2009 increase less with increasing $\log_{10}(N_2^{ships})$. In fact, a slight increase with $\log_{10}(N_2^{ships})$ is observed for the lower percentiles, but the higher percentiles decrease with increasing $\log_{10}(N_2^{ships})$. The difference in the dependence of noise levels on shipping conditions can be explained by the interpretation that, at least in the cases of intermediate and distant shipping, for the 2009 campaign the noise levels are mostly dominated by noise produced by dredgers. The lower percentiles correspond to those cases for which dredger noise is less likely to be dominant, which could explain why the lower percentiles seem more affected by the presence of nearby shipping.
For the upper percentiles it is likely that the levels are dominated by dredger-related noise. The decrease of the upper percentiles with increasing shipping measures could indicate that the noise levels produced by dredgers are correlated to the presence of other ships. This explanation is supported by the observation that for nearby shipping the presence of nearby dredgers is anti-correlated with the presence of regular ships.

For frequencies above 20000 Hz the median noise levels from both campaigns agree within a few dB, independently on the selected shipping conditions. This is partly because in this frequency range the 2008 levels are less dependent on the shipping conditions compared to lower frequencies. Other types of noise, such as wind related noise are more dominant in this frequency range (see [Dreschler et al., 2009]).
An explanation for the agreement of the levels of the 2009 and the 2008 campaigns in this frequency range is that the median levels of noise produced by dredgers are comparable to, or lower than, the levels of other sources of background noise.
For the 2009 measurement campaign larger variations in noise levels are present leading to higher values of the upper percentiles (e.g., the percentiles for 84 % and 95 %). This indicates that above 20000 Hz part of the time the noise produced by dredgers is still 5-10 dB higher than the other sources of background noise.

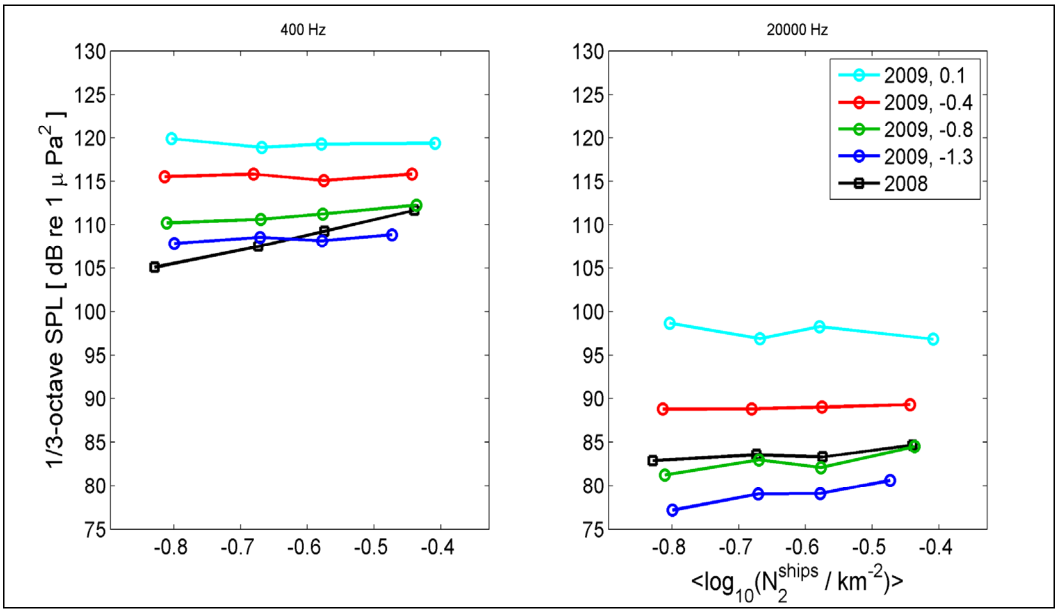


Figure 6.22 Average 1/3-octave sound pressure levels in the 400 Hz and 20000 Hz bands for distinct subsets, which have been selected by imposing requirements on the values of both $\log_{10}(N_2^{dredgers})$ and $\log_{10}(N_2^{ships})$ for the 2009 campaign and only for $\log_{10}(N_2^{ships})$ for the 2008 campaign. The levels are plot against the average value of $\log_{10}(N_2^{ships})$. Each curves for the 2009 campaign corresponds to a specific interval for $\log_{10}(N_2^{dredgers})$. In the legend the average value of $\log_{10}(N_2^{dredgers}$ / km^{-2}) is indicated.

As observed earlier the presence of dredgers near the measurement location is in some cases (anti-)correlated with the presence of other ships. As a result, also the noise levels caused by dredgers can be correlated with the measures for shipping. The comparison of the results of the 2009 and 2008 campaigns is intended to be for similar shipping conditions, and to distinguish the effects from dredgers and regular ships. In order to distinguish these effects for the 2009 campaign subsets corresponding to varying sub-intervals of $\log_{10}(N_2^{dredgers})$ were further divided into smaller subsets for varying intervals of the measure $\log_{10}(N_2^{ships})$. The levels of background noise from both campaigns were then compared for subsets for comparable values of both measures. In Figure 6.22 the average levels for various subsets are compared for the 400 Hz and 20000 Hz frequency bands.

For the 2009 campaign the average levels depend clearly on the measure $\log_{10}(N_2^{dredgers})$. This is the case for the various intervals of the measure $\log_{10}(N_2^{ships})$. The average noise levels corresponding to a specific interval of $\log_{10}(N_2^{dredgers})$ depend less on the shipping the measure $\log_{10}(N_2^{ships})$ than the levels of the 2008 campaign. These observations are consistent with the interpretation that for the 2009 campaign, noise produced by dredgers is more dominant than noise from regular ships. However, it is remarkable that for those cases where dredgers are further away ($\log_{10}(N_2^{dredgers})$ smaller than about -0.8) the average levels are lower than those of the 2008 campaign even when these levels are compared for similar intervals of the shipping measure $\log_{10}(N_2^{ships})$. The lower levels may be caused by a combination of factors, for instance, the propagation loss could have been higher, e.g., due to an increase of absorption or reflection loss, or the source levels of noise produced by nearby ships could have been lower, e.g., due to slower or less severe manoeuvring ships, or quieter types of ships.

6.4.6 *Effects of wind on the levels of background noise*

As discussed in section 6.3.3, correlations between wind speed and background noise levels measured during the 2009 campaign were investigated by using wind speed information obtained with a meteo system in the Maasvlakte area. Coefficients representing the correlations between wind speed and sound pressure levels were determined. This was done for various subsets obtained by imposing different requirements on the measure $N_2^{dredgers}$ in order to account for varying distances of the dredgers relative to the measurement location. For the subsets used in this analysis the requirements on $N_2^{dredgers}$ were the same as for those used in the investigation of effects from regular shipping (see section 6.4.5). Because the day-time and night-time spectra of were found to differ in the frequency bands at 1600 to 5000 Hz (see section 6.4.2) the correlation coefficients were determined separately for day-time and night-time measurements. The resulting correlation coefficients for each 1/3-octave band are displayed in Figure 6.23 and Figure 6.25, respectively.

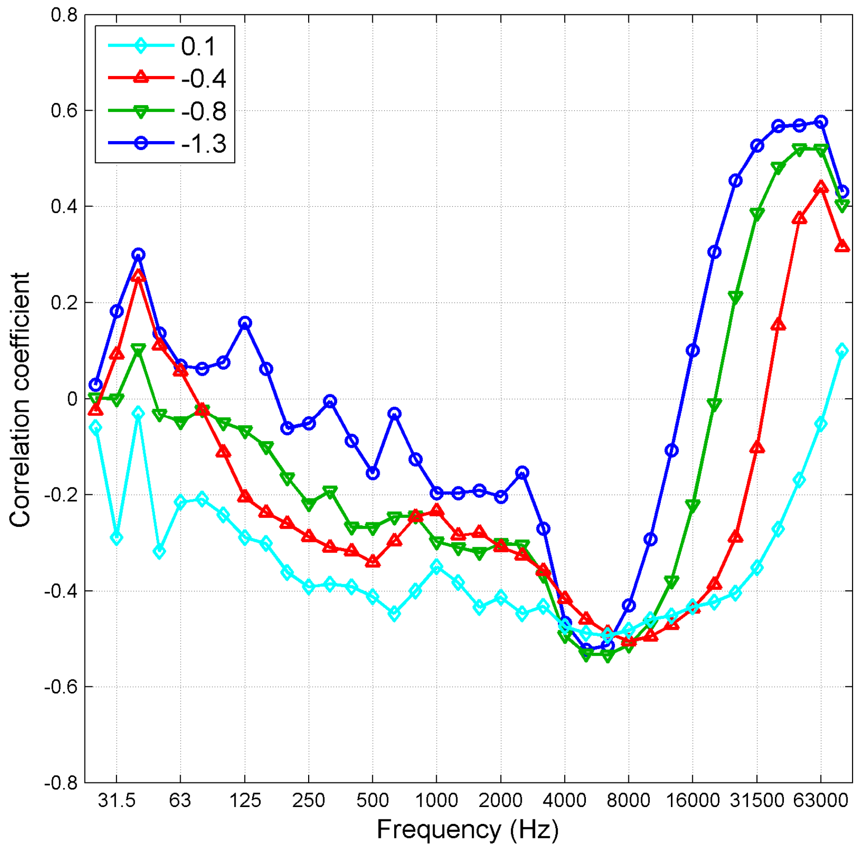


Figure 6.23 Coefficients representing the correlations between wind speed and sound pressure level for day-time measurements. In the legend the average value of $\log_{10}(N_2^{dredgers}$ / km$^{-2})$ for each subset is indicated.

For the day-time measurements the correlation coefficients at frequencies between about 100 Hz and 10000 Hz are mostly negative. These negative correlation coefficients are largest in magnitude in the frequency range between 4000 Hz and 10000 Hz.

In this frequency range the coefficients are about -0.5 for all subsets with varying requirements on $N_2^{dredgers}$. At frequencies below 4000 Hz the negative correlation coefficients are larger in magnitude for the subsets for nearby dredgers in comparison to those for the subsets of further away dredgers.
A possible explanation for the negative correlation between about 100 Hz and 10000 Hz is that the attenuation due to surface scattering of sound produced by dredgers increases as a result of increasing wind speed leading to a decrease of the sound pressure levels. In order to evaluate the actual dependence between sound pressure level and wind speed each subset was subdivided into smaller subsets for different wind-speed intervals. For each wind-speed interval the corresponding average sound pressure levels were determined. In Figure 6.24 the average levels for the 125 Hz, 500 Hz and 8000 Hz 1/3-octave bands are displayed versus wind speed.

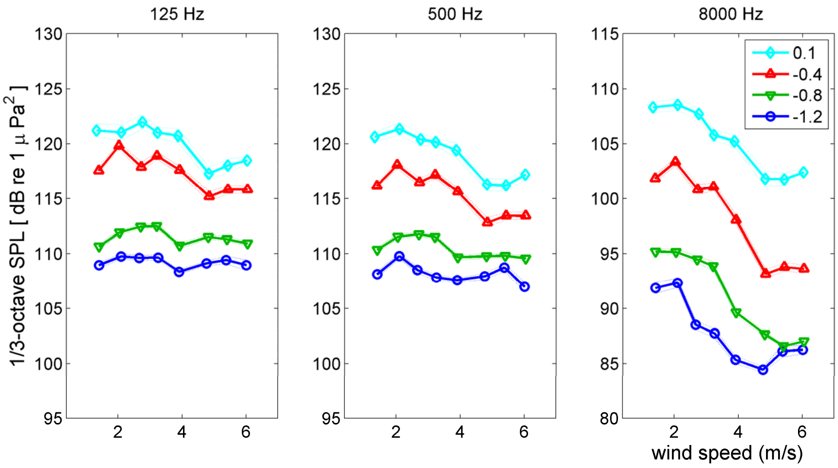


Figure 6.24 Average sound pressure levels in 125 Hz, 500 Hz, and 8000 Hz 1/3-octave bands versus wind speed for subsets with different requirements on the measure $N_2^{dredgers}$. In the legend the average value of $\log_{10}(N_2^{dredgers}$ / km^{-2}) for each subset is indicated.

At frequencies between about 100 Hz and 1000 Hz the average levels were found to decrease slightly with increasing wind speed for the cases where the dredgers were near to the measurement location.
This trend was observed in the wind speed interval between approximately 2 m/s and 5 m/s. In this interval a decrease in sound pressure level of about 2-4 dB was observed. At higher frequencies stronger dependences were observed. These dependences were also observed for the cases where dredgers were further away. For instance, at frequencies around 8000 Hz in the wind speed interval between approximately 2 m/s to 5 m/s the average levels decreased by about 6-10 dB. These wind speed values are not measured at sea, but on land (see Figure 6.1), at an estimated height of 4.5 m.
It is expected that the wind speed over open water at a height of 10 m would be higher than this, but the difference is expected to be small because the water was several degrees warmer than the air, leading to am unstable boundary layer.
A possible explanation for the decrease in level between 2 and 5 m/s is the onset of whitecaps, which is expected between Beaufort force 3 (“perhaps scattered white horses.”, wind speed 4.3 to 6.4 m/s at 10 m height) and 4 (“fairly frequent white horses.”, wind speed 6.4 to 9.2 m/s at 10 m). [Ainslie, 2010]

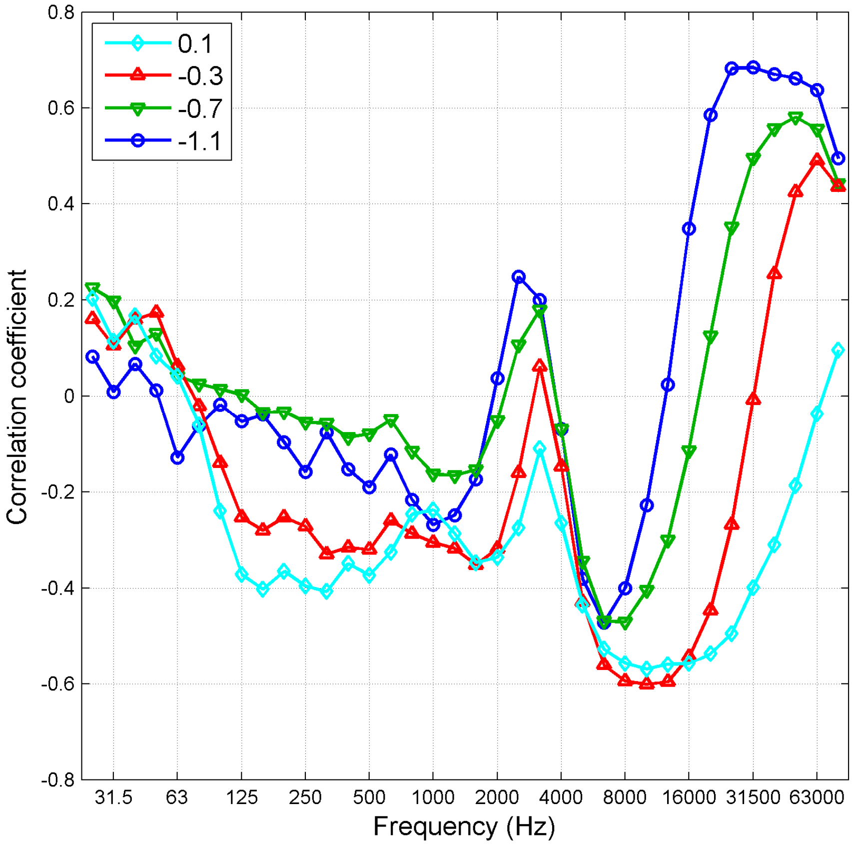


Figure 6.25 Coefficients representing the correlations between wind speed and sound pressure level for night-time measurements. In the legend the average value of $\log_{10}(N_2^{dredgers}$ / $km^{-2})$ for each subset is indicated.

Compared to the correlations of the day-time noise levels the correlations of the night-time noise levels with wind speed behave clearly differently at frequencies between 2000 and 4000 Hz. At these frequencies the correlation coefficients of the night-time measurements are less negative or in some cases even positive. Moreover, for the night-time noise levels the correlation coefficients are larger for subsets for which dredgers are further away from the measurement. These differences between night-time and day-time measurements may be consistent with the earlier interpretation that during the night there is an increase in propagation loss in the frequency range between 1600 and 5000 Hz, possibly due to the diurnal behaviour of fish (see section 6.4.2). The resulting increased sound attenuation during the night would cause the dredger noise to be less dominant, leading to less negative correlations, in particular for dredgers further away. Both for the day-time and the night-time noise levels the correlation with wind speed increased with frequency above a frequency of about 8000 Hz. In this frequency range the largest correlation coefficients were observed for the subset for which the dredgers are furthest away from the measurement location. For this subset the correlation coefficients are positive at frequencies above 10000 Hz. The frequency at which the transition from a negative to a positive correlation occurs is larger for the subsets for which dredgers were closer to the measurement location. For the subset with the closest dredgers the correlation coefficient increases with increasing frequency, but remains negative up to 63000 Hz.

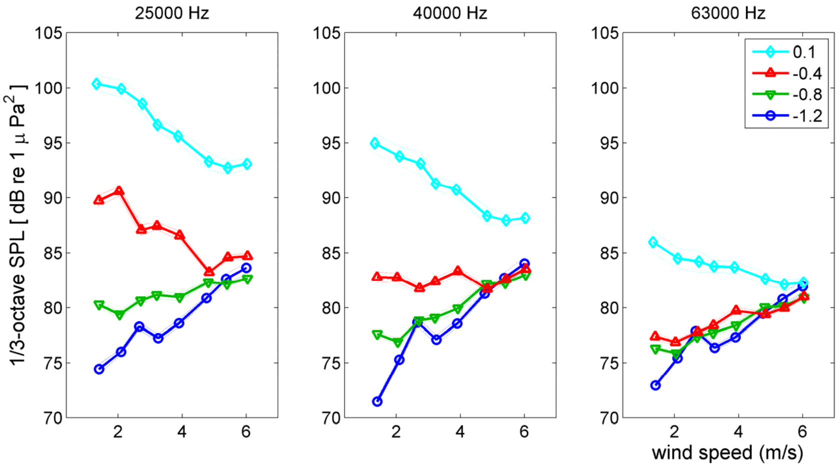


Figure 6.26 Average sound pressure levels in 25 kHz, 40 kHz, and 63 kHz 1/3-octave bands versus wind speed for subsets with different requirements on the measure $N_2^{dredgers}$.In the legend the average value of $\log_{10}(N_2^{dredgers}$ / km^{-2}) for each subset is indicated.

For frequencies above about 8000 Hz, as frequency increases, decreasing trends of the sound pressure levels versus wind speed change into increasing trends. For the subset for which the dredgers ships are farthest from the measurement location the levels increase with increasing wind speed at frequencies above 12500 Hz. However, for the subset for which the dredgers ships are closest to the measurement location the levels decrease with increasing wind speed at frequencies up to 63000 Hz. In Figure 6.26 average levels are displayed versus wind speed for the 25000 Hz, 40000 Hz and 63000 Hz 1/3-octave bands. For instance, in the 25000 Hz frequency band in the wind speed interval between approximately 2 m/s to 5 m/s the average level decreased with about 8 dB for the subset with nearby dredgers, whereas the average level for far away dredgers increased with about 7 dB in the same wind speed interval.
The levels of wind generated noise, for instance, noise produced by wind generated breaking of waves, are expected to increase with increasing wind speed, thus to be positively correlated with wind speed. Since the levels of noise produced by dredgers decrease with increasing frequency, wind generated noise was likely to be more dominant for higher frequencies. Therefore, the increase of the correlation coefficient with increasing frequency, and the observed increase of sound pressure levels with increasing wind speed is expected to be caused by wind generated noise.

6.5 Summary

Background noise measurements were performed at a fixed location in the MV2 area in the presence of dredging activities during a period of about one week between 25 September and 5 October 2009. For every minute, sound pressure levels were determined in 1/3-octave frequency bands in the frequency range between 20 Hz and 80 kHz. In order to investigate to what extent the MV2 construction activities affected the underwater noise in the area these noise levels were compared with the noise levels measured during an earlier campaign in 2008 in the absence of dredging activities.

In the frequency bands below 1600 Hz the median levels of the 2009 campaign are mostly comparable to the median levels of the 2008 campaign, and in the frequency bands between 40-80 Hz and 200-800 Hz those of the 2009 campaign are up to 2-3 dB higher. At frequencies above 5000 Hz the median levels agree within 1 dB, but larger variations towards higher values are observed for the levels in the presence of dredging activities.
In the frequency interval between about 1600 and 5000 Hz the spectra of both campaigns are clearly different as a clear dip in the spectrum of the 2009 campaign is present. This dip was clearly present during the night and not clearly during day time. These diurnal variations in sound pressure level could be caused by variations in propagation loss in this frequency interval. Such a day-night difference of propagation loss could be the result of diurnal variations of the distribution of fish in the water column.
The noise levels in the presence of dredging activities depend strongly on the distances of the dredgers relative to the measurement location. Noise produced by nearby transiting dredgers is most likely the most dominant contribution to the levels of low frequency background noise during the 2009 measurement campaign
The levels of both campaigns were compared for similar conditions of regular shipping, represented by the measure N_2^{ships}. For the case of distant shipping the median levels of the 2009 campaign are about 8-12 dB higher at frequencies between 20 and 10000 Hz. For intermediate shipping conditions the median levels of the 2009 campaign are comparable to, or between 40-1000 Hz up to 2-3 dB higher than those of the 2008 campaign. For the case of nearby shipping at frequencies below 10000 Hz the median levels for the 2009 campaign are up to 5 dB lower than those of the 2008 campaign except for frequencies between 200 and 500 Hz where the median levels of both campaigns are practically the same. For frequencies above 20000 Hz the median noise levels from both campaigns agree within a few dB, independently of the shipping conditions. However, in particular for these frequency bands larger variations in noise levels were measured in the presence of dredging activities even for the case of nearby shipping.
A comparison of the results of the 2009 and 2008 campaigns for similar conditions for dredgers and regular ships, represented by the measures $N_2^{dredgers}$ and N_2^{ships}, confirmed that during the 2009 campaign the noise levels were dominated by the noise produced by dredgers. The noise due to nearby regular ships was most likely louder in the absence of dredging activities, which would explain why for the case of nearby shipping the median levels in the absence of dredging activities are higher than those in presence of dredging activities at frequencies below 10000 Hz. The larger variations in noise level occurring at higher frequencies in the presence of dredging activities are most likely caused by the noise from nearby transiting dredgers.
Coefficients representing the correlations between wind speed and sound pressure level were determined. The correlation coefficients for frequencies between about 100 Hz and 10000 Hz were mostly negative. A possible explanation for the negative correlation is that the attenuation of sound produced by dredgers increased as a result of increasing wind speed. At frequencies around 8000 Hz in the wind speed interval between approximately 2 m/s to 5 m/s the average levels decreased by about 6-10 dB. Below 1000 Hz in this wind-speed interval a decrease in sound pressure level of about 2-4 dB was observed for the subsets of nearby dredgers.
For the 2008 campaign negative correlations with wind speed were observed only for subsets for which ships were sufficiently far from the measurement location, whereas for subsets of nearby shipping the correlation coefficients were slightly positive.

The correlation coefficients for night-time noise levels were less negative or even positive at frequencies between 2000 and 4000 Hz. This deviation is consistent with the earlier interpretation that during the night there is an increase in propagation loss in the range between 1600 and 5000 Hz, possibly due to the diurnal behaviour of fishes.

Above a frequency of about 8000 Hz the correlation with wind speed increased with frequency. A transition from a negative to a positive correlation coefficient occurred at a frequency that was larger for subsets for which dredgers were closer to the measurement location. Consequently the relation between noise level and wind speed depended strongly on the distances relative to the dredgers ships. For the 2008 campaign a comparable transition to positive correlations occurred only for subsets for which regular ships were sufficiently far from the measurement location. The increase of the correlation coefficient with increasing frequency, and the observed increase of sound pressure levels with increasing wind speed is expected to be caused by wind generated noise, for instance noise produced by wind generated breaking of waves.

7 Conclusions and recommendations

7.1 Source Level

The main aim of the Maasvlakte 2 measurements was to determine the acoustic source level of the Trailing Suction Hopper Dredgers (TSHDs) during the various activities: dredging, transport and discharge of sediment.

Due to the lack of appropriate standards for characterizing ships as sources of underwater noise, an analysis methodology had to be developed by TNO for the present study. The various activities are characterised in terms of a ‘dipole source level’, which describes the power radiated by the vessel and its surface image under an angle of about 30 degrees with the sea surface, consistent with the current ANSI standard applicable to deep water (S12.64).

The highest sound pressure levels were found for large dredgers while transiting (at speeds up to 16 knots). Sand dredging in the Maasvlakte 2 area produced similar source levels, a few decibels lower than for transiting dredgers in most third-octave bands. Pumping and rainbowing resulted in source levels similar to dredging in the frequency range between 500 Hz and 10 kHz and significantly lower levels outside this range. The lowest source levels measured at high frequency (above 1 kHz) was for sand dumping and at low frequency (below 500 Hz) for rainbowing. The broadband noise spectra above 100 Hz are very similar for all dredger activities except sand dumping. It is likely that the noise is dominated by cavitation noise from propellers and bow thrusters.

Note that the source levels found in this study are only representative for dredging activities similar to these at Maasvlakte 2. Deviating source levels may be expected for activities in different sediment (e.g. gravel instead of sand) and at different water depth.

7.2 Background noise

A second aim of the measurements was to compare the 2009 (25 September to 5 October) background noise levels with those measured in 2008 (8 to 15 September) [TNO-DV 2009 C212: Dreschler et al., 2009].

Because of the changed traffic lanes due to the Maasvlakte 2 project and the need to avoid risks to the new autonomous measurement system SESAME, the 2009 measurement location was shifted to about 2 km east of the 2008 measurement location. Consequently, also the distance between the measurement position and the traffic lanes was different. In both cases, underwater noise measurement results were analysed in correlation with synchronous recordings of ship traffic (AIS) and weather conditions (wind speed).

The background noise measured in 2008, i.e., before the start of Maasvlakte 2 construction activities, was found to be dominated by noise produced by shipping. The measured noise levels in 2009 were generally higher than those in 2008 and show a strong correlation with the distance to the dredgers, which means that the noise produced by transiting dredgers is most likely the dominant contribution. Because these dredgers pass the measurement position relatively closely, they are responsible for larger variations in the noise levels than observed in 2008.

Despite the overall increase relative to 2008, in some third-octave bands (close to 3 kHz) the levels in 2009 were lower than in 2008, especially during the night time. This difference could be due to a diurnal variation in the propagation loss, possibly caused by the presence and behaviour of large numbers of small bladdered fish (of length between 3 and 5 cm).

Lower levels, relative to the average levels measured in 2008, were also observed in 2009 at times when no dredgers were active close to the measurement position (see Fig6.19). This could be caused by differences in general shipping noise between both campaigns. No clear correlation could be found between this difference and differences in the distance to the shipping lanes. Hence, no conclusive explanation can be given for this difference. Possible causes are differences in propagation loss, due to different environmental conditions at the two different positions in two different years, or differences in the source levels of the distant shipping, e.g. due to changes in the speed and manoeuvring of the ships, perhaps related with the Maasvlakte 2 activities.

Wind generated surface noise dominated the background noise at frequencies above 10 kHz except in the presence of transiting dredgers. At frequencies between about 100 Hz and 10 kHz, a negative correlation is observed between wind speed and background noise. This is probably caused by the increased propagation loss due to increased scattering of sound associated with increased surface wave height.

7.3 Recommendations

The background noise measurements in the present study suggest that dredger activities (especially transiting dredgers) cause a significant increase of the background noise at the chosen measurement location. It is recommended to investigate whether this conclusion can be confirmed on the basis of the measured source levels and a suitable propagation loss model. Synchronous measurements of background noise and source level can be used to check the validity of these calculations.

It is recommended to use the observed source levels of the various activities in combination with a noise mapping tool (ANOMALY) to investigate the spreading of noise to other locations.

The background noise measurements exhibit noise ‘events’ that cannot be directly explained from the AIS data. It is recommended to further investigate some of these events, to check whether these can be explained from either synchronous source level measurements or from logged events related with dredging activities.

8 Acknowledgements

The authors thank the Port of Rotterdam Authority for assigning this project and Albert Gerrits and Wil Borst for guiding our activities. We acknowledge the cooperation that we have received from PUMA and from the operators of the dredgers. We thank all colleagues who were involved with the preparation of SESAME and have carried out the actual measurements. Benoit Quesson has carried out the OASES calculations to validate the propagation modelling for the source level determination. Floor Heinis has been of great help with the interpretation of the biological effects that were observed in the background measurements.

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10 Signature

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