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

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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.

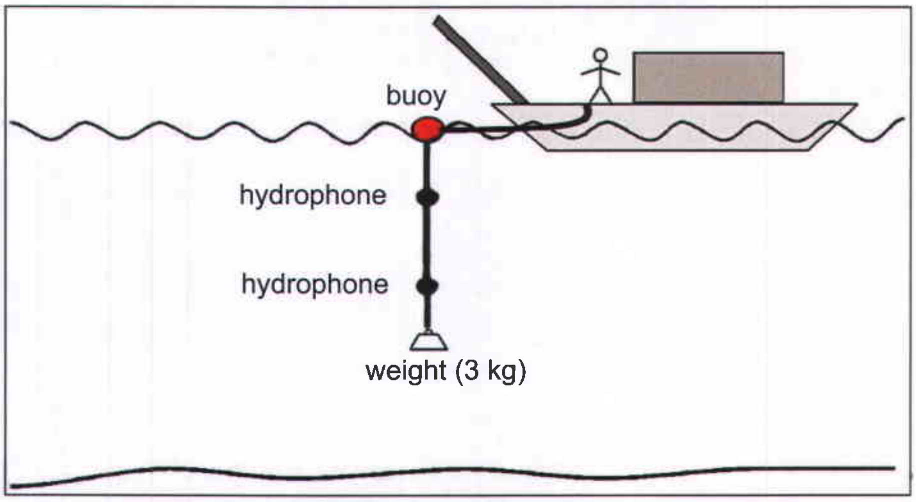

Figure 2.2 Schematic drawing of the source level measurements. The hydrophones are at a fixed distance (6 and 12 metres) from the surface for water depths of more than 14 metres.

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.

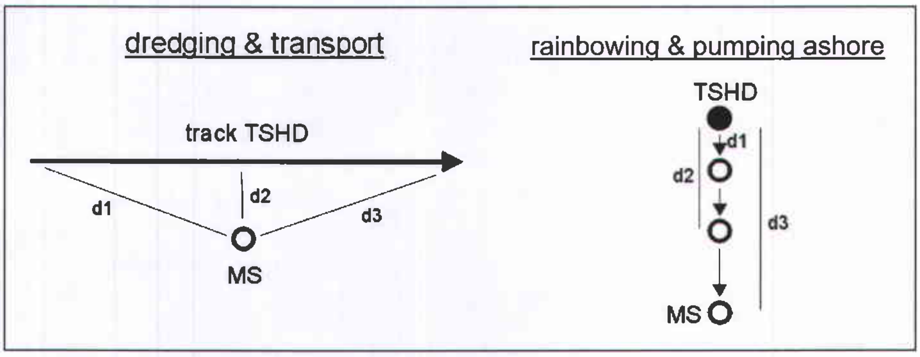

Figure 2.3 Sketch of the source-level measurements for dredging and transport (left), and rainbowing and pumping ashore (right). Different ranges are obtained from the moving TSHD, and by moving the measurement ship respectively.

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:

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

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:

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

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:

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

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]:

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

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:

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

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[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.

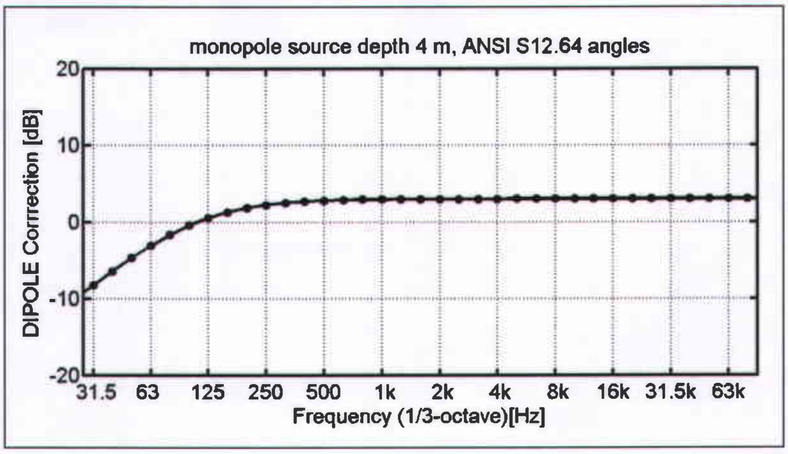


Figure 2.4 Spectrum of the difference between monopole and dipole SL according to eq.(4), for a monopole source at 4 m below the water surface, power averaged over 15, 30 and 45° elevation angles.

2.3.2 *Propagation Loss calculation for the Source Level estimation*

A TNO implementation in Matlab^{TM} 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.

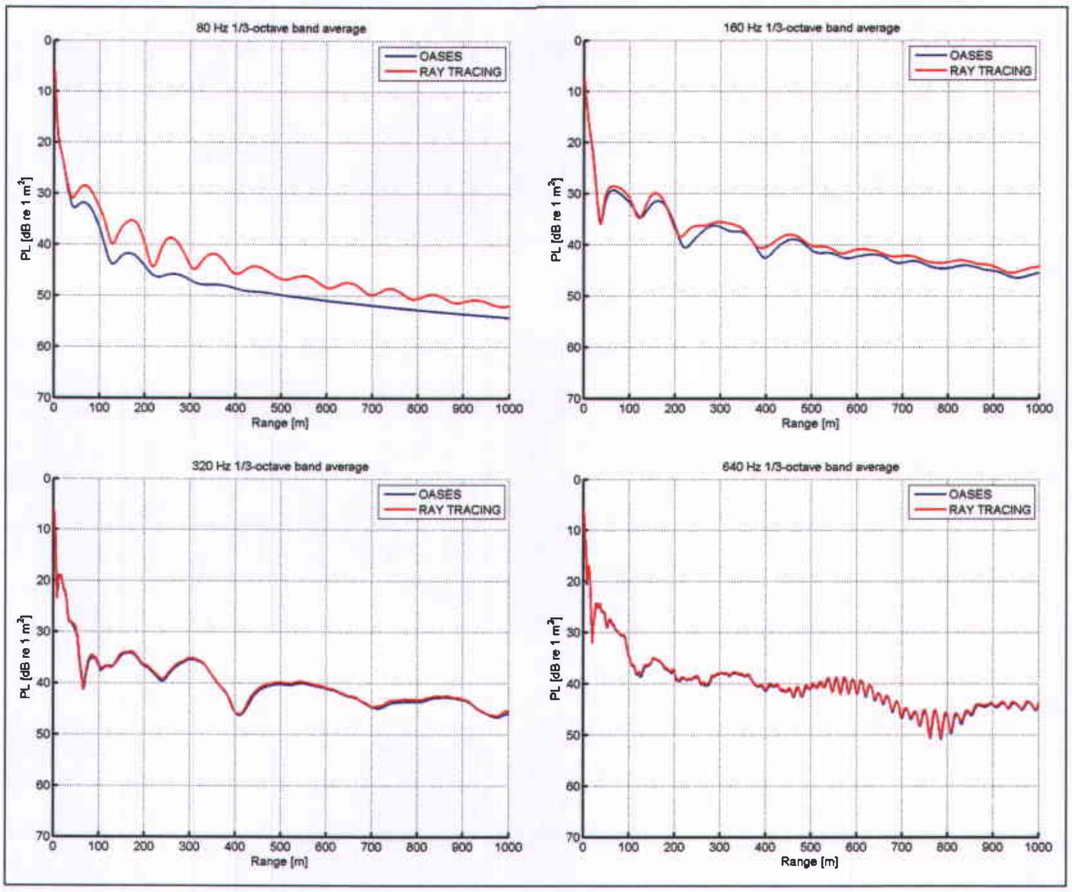


Figure 2.5 Comparison of the Propagation Loss as a function of distance as calculated by OASES and by the TNO 'image source ray' model.

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.

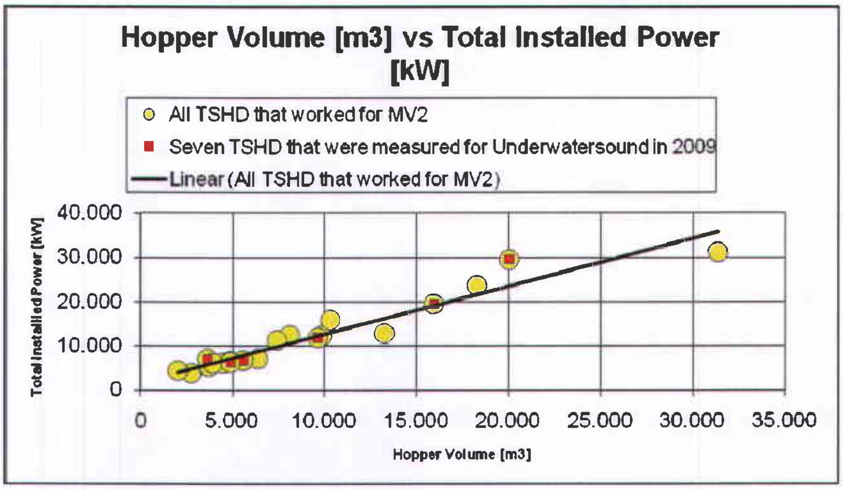
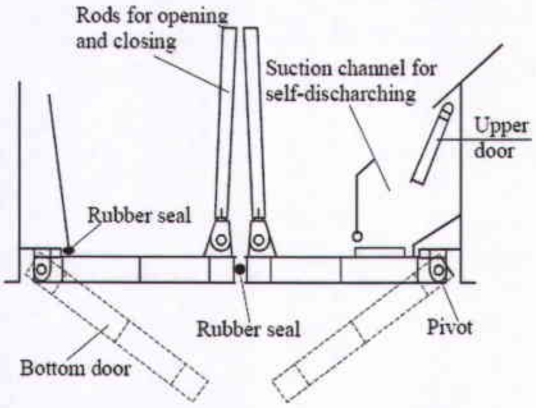


Figure 3.1 Overview of the sizes (hopper volume and total installed power) of the TSHDs that were active at Maasvlakte 2 between January and October 2009, demonstrating that the seven TSHDs of which the underwater noise was measured are representative of a large portion of the active fleet.

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.

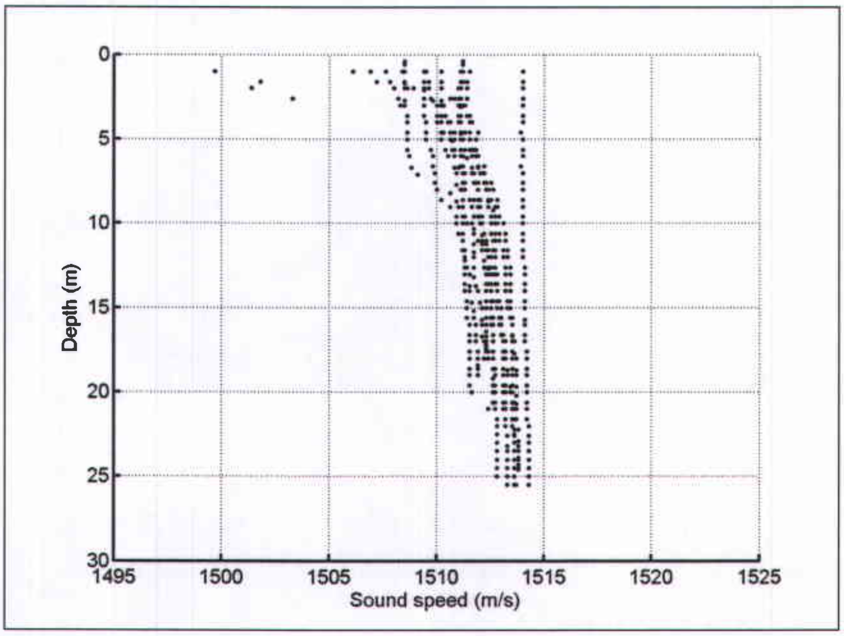


Figure 3.3 Underwater sound speed profiles measured at sea in the Maasvlakte 2 area from 14 Digibar DB1200 casts during the noise measurement period. Every dot represents a measurement point.

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^{TM} 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.

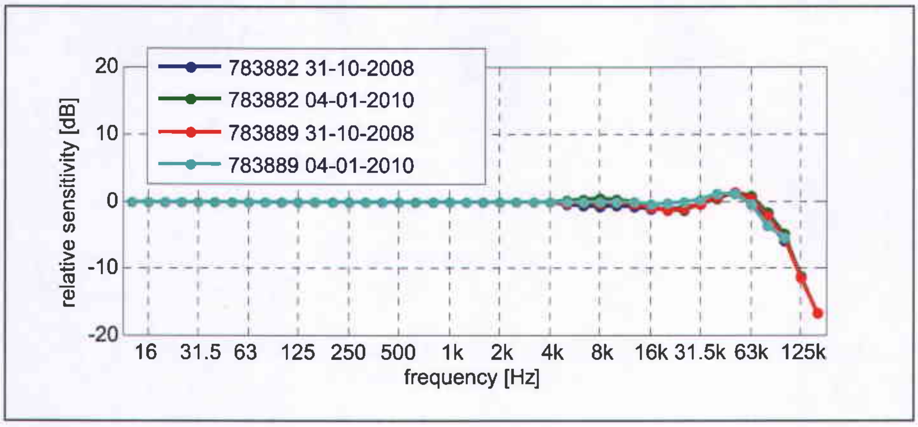


Figure 3.4 B&K 8101 hydrophone calibration curves at 1/3-octave band center frequencies.

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.

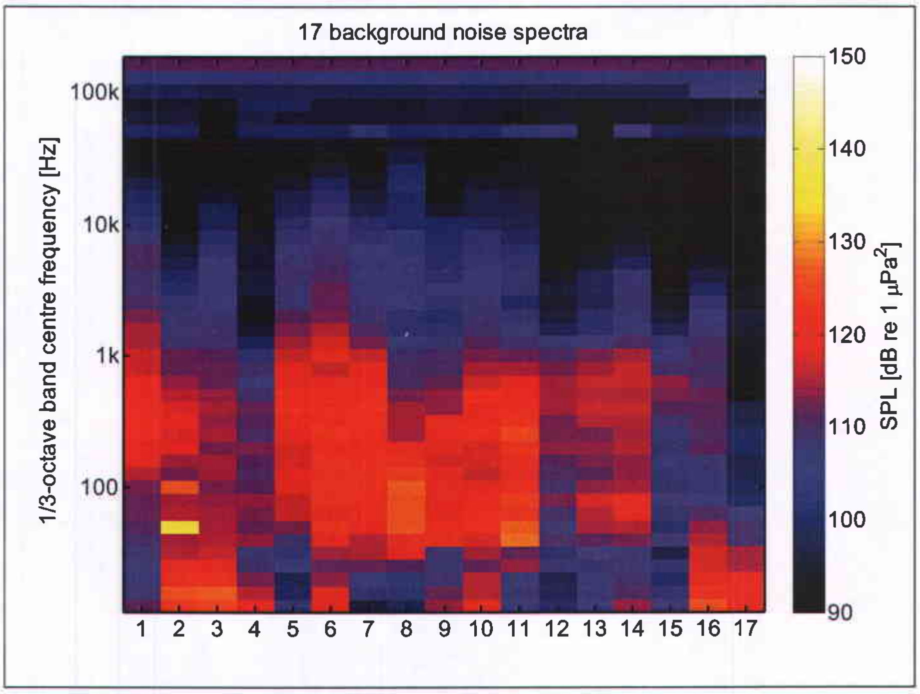


Figure 3.5 Background noise third-octave SPL (10 s average) at 17 different moments during the measurement period

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.

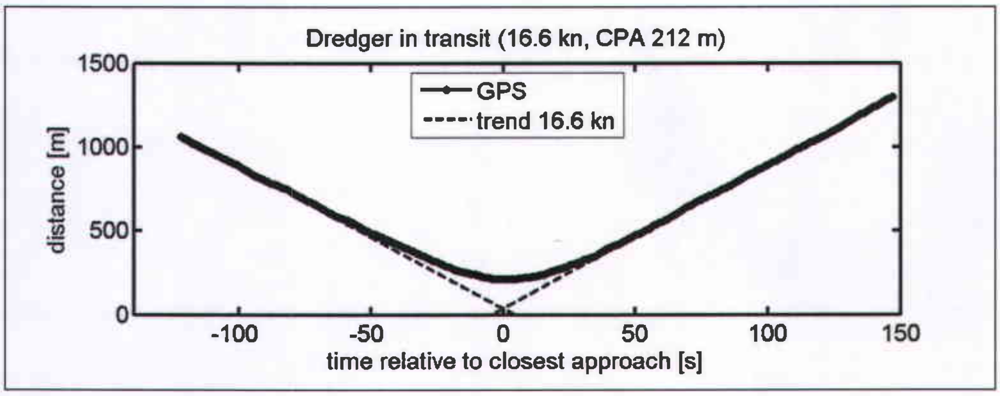


Figure 4.1 The GPS-based distance between dredger and measurement vessel as a function of time.

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.

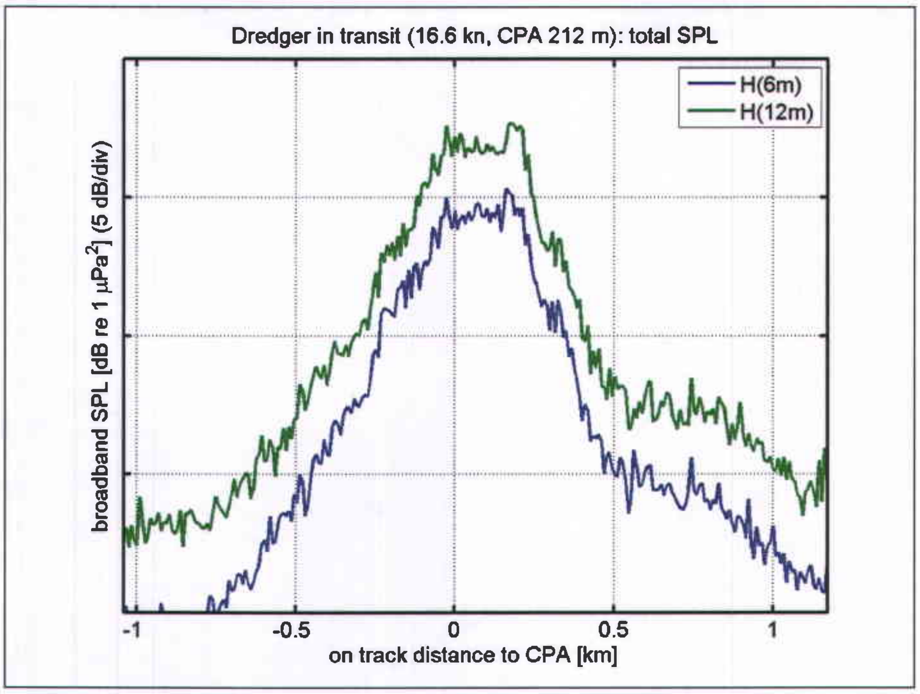


Figure 4.2 The total recorded broadband noise (12.5 Hz – 160 kHz) at the two hydrophones, as a function of the on track position of the dredger relative to CPA. Time runs from left to right on the horizontal axis. At 16.6 knots, the vessel travels 2 km in 234 seconds.

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.