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TNO report

TNO-DV 2008 C302

Measurement plan underwater sound Maasvlakte 2

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Pipe dumping. Image courtesy of Boskalis.

Contents

List of abbreviations

AIS	Automatic Identification System
CSD	Cutter Suction Dredger
CTD	Conductivity, Temperature, Depth
DC	Direct Current
GPS	Global Positioning System
MER	MilieuEffectRapport (Aanleg Maasvlakte 2)
MV2	Maasvlakte 2
PUMA	Projectorganisatie Uitbreiding MAasvlakte
SSP	Sound Speed Profile
TNO	Netherlands Organisation for Applied Scientific Research TNO
TSHD	Trailing Suction Hopper Dredger

1 Introduction

The Port of Rotterdam is expanding to meet the growing demand to accommodate large cargo vessels. A new harbour and industry area "Maasvlakte 2" (MV2) will be built, with the construction expected to start in September 2008. The "Milieueffectrapport Aanleg Maasvlakte 2", henceforth abbreviated as MER[1], provides a preliminary assessment of the underwater sound produced during the construction of MV2 [1].
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 laying.
Little is known about the underwater sound produced by dredging and land reclamation. Spectral noise levels of Cornelis Zanen and Geopotes X, two 8000-m^3 trailing suction hopper dredgers (TSHDs), are found in [2]. Loading, transport, and discharge activities were monitored. The same paper also presents noise measurements on Aquarius, a cutter suction dredger (CSD). An online document [3] presents 1/3-octave source levels for Gerardus Mercator, an 18 000-m^3 TSHD, Taccola, a 4400-m^3
TSHD, and J.F.J. de Nul, the most powerful CSD in the world. Furthermore there are some relevant references [4,5,6] for which only an abstract is available. In a playback experiment, bowhead whales proved sensitive to dredging and drilling noise at distances of 3–11 km from the source [4]. A study of the influence of dredging noise on manatee is presented in [6]. It is found that high noise levels from dredging can mask the sounds of other boats and vessels, increasing the risk of manatee-boat collisions up to a range of 4 km from the dredger. The "aanvulling MER Eemshaven" mentions a dredger disturbance range (worst case scenario) of 1.5 km for seals [7], but does not provide a reference or explanation for this number.
Different dredgers and activities have different source levels, different underwater environments lead to differences in sound propagation, and there are differences in the sensitivity of different marine mammals to underwater sound [8, 9].
Specific measurements on the MV2 dredging will lead to specific source levels for the MV2 conditions. These source levels can be used to study the influence of the construction noise on seals and harbour porpoises.
The objective of the present document is to plan and describe these measurements.
It follows the strategy "strategic measurements and modelling" [10], a decision made in consultation with Havenbedrijf Rotterdam N.V. and the competent authority (Rijkswaterstaat). This report is further organized as follows. Section 2 describes the dredging process from sand borrowing to land reclamation, and discusses potential sources of construction noise. Section 3 discloses preliminary dredging and reclamation plans, and indicates areas where underwater sound is to be measured. Section 4 describes two types of acoustic measurements, a time schedule, and discusses the acoustic frequency range in relation to marine mammals and shallow-water sound propagation. Section 5 treats several aspects of acoustic modelling, needed for the determination of source levels and wide-area forecasts.

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[1] Dutch abbreviation similar to the English EIA, "Environmental Impact Assessment".

2 The dredging process

2.1 Trailing suction hopper dredger

Dredging, sand transport, and sand laying for MV2 are contracted to Royal Boskalis Westminster nv and Van Oord, working together under the name PUMA (project organisation for the expansion of the Maasvlakte). The type of dredging vessel for the offshore dredging is a so-called trailing suction hopper dredger (TSHD). An overview of the PUMA fleet is found online [11, 12], but the specific names of the ships for MV2 are not yet known. The present idea is that there will be four TSHDs active during the first phase of the MV2 construction, two 16,000-m^3 vessels, one 8,000-m^3 vessel, and one 4,000-m^3 vessel, where the volumes give the capacity of the hopper—an onboard space in which the dredged material settles. Although these figures may change, the principle of operation is the same for all TSHDs. It uses no anchors or cables and dredges while sailing.

2.2 Suction

A TSHD is a sea-going vessel with one or more suction tubes provided with suction mouths called dragheads [13]. Surficial sediment is broken up with the help of teeth on the draghead, or water jets. One or more dredge pumps suck material from the seabed, and transport a mixture of soil and water to the hopper. Figure 1 illustrates the TSHD dredging process. When the TSHD starts dredging the majority of the soil will settle in the hopper, whereas a fraction of the particles will leave the hopper together with the water via an overflow. As the dredging continues the soil settling rate will gradually decrease, and the soil fraction that leaves the hopper via the water overflow increases. At some point it is no longer economical to continue, and the dredging is stopped. The suction tubes are recovered and the TSHD sails from the sand borrow area to the discharge area to deliver the soil.

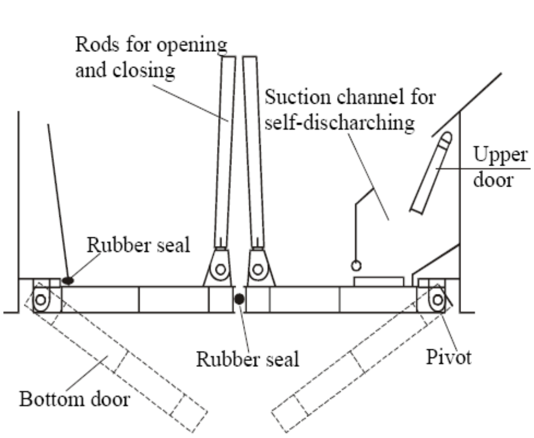
Figure 1 Illustration of a trailing suction hopper dredger in operation. (Image taken from [13].)

2.3 Discharge of sediment

There are three distinctly different methods to unload the sediment at the destination site. The first method will be called "direct dumping". This is the preferred way for sand laying when the water is sufficiently deep. The TSHD opens a set of bottom doors or valves and lets the dredged material slip out of the hopper. In relatively shallow waters the procedure may be performed with a (slowly) moving ship, and according to a predefined dump plan, to prevent the TSHD from getting stuck. Direct dumping is the fastest discharge method, and a hopper may be emptied within 5–10 minutes.
When the water depth has become too shallow for direct dumping, there are alternative discharge options. "Rainbowing" is the name of the process whereby the TSHD fluidizes the sand in the hopper and pumps it through a nozzle at the bow of the ship. The dredged material travels through the air before it falls on the reclamation area. Alternatively a pipeline may be used for discharging over still longer distances, or for controlled filling of submerged dumps. This process is called "pipe dumping".
The discharge time for rainbowing and pipe dumping is normally of the same order as the suction time, unless the hopper is equipped with an installation that improves breaching by means of water jets. Figure 2 illustrates the three distinct discharge methods. All these dumping procedures will be used for the MV2.
As pumping ashore is a time consuming operation, common practice on large projects is to employ a suction dredge with enough installed pump power to take over this part of the operation. The TSHD dumps its load in a transfer pit and another (cutter suction) dredger pumps it further ashore through floating and land pipelines. A cutter suction dredger (CSD) normally has a cutter head at the front end of the suction tube, to mechanically loosen the soil and transport it to the suction mouth. Loosened material is normally sucked up by a centrifugal pump and pumped ashore via a pipeline.
Several types of cutter heads may be installed for different purposes. However, the sand for MV2 that has just been deposited by a TSHD is loosely packed and does not require cutter action. For MV2 construction a cutter will not be used, except perhaps for deepening of the harbour and initial creation of the transfer pit where the TSHDs deliver sand by direct dumping. CSD action is expected after the outer seawalls (see Figure 6) have been established. These walls strongly dampen the underwater sound and construction activities within the seawalls require no acoustic monitoring.

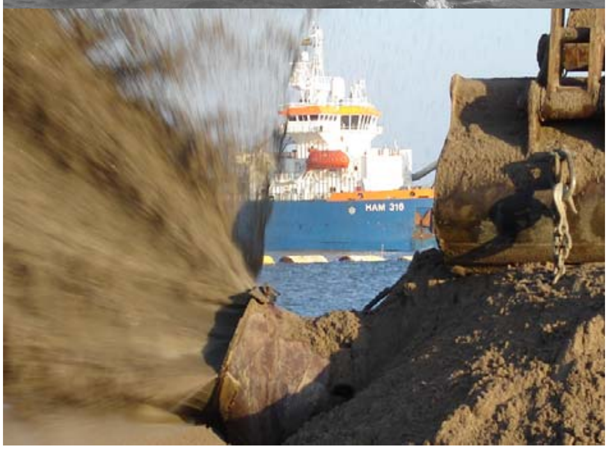
2.4 Noise generation

TSHDs use various kinds of machineries, both for dredging and for more general naval activities such as sailing and navigation. Measurements of underwater noise should focus on noisy operations which are specific for the acquisition, transport, and discharge of sand during the MV2 construction [10]. Subsections 2.4.1–2.4.3 below identify mechanisms which most likely dominate the production of underwater sound. However, since little quantitative information is available on underwater noise due to dredging processes, the text unavoidably contains assumptions and expectations.
Noise which is not identified below may manifest itself during the MV2 measurements. It is recommended to have a close coordination between the TSHD under observation and the acoustic measurement team, so that particular noises can be ascribed to particular actions or pieces of machinery.



Direct 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 taken from [13].)

Rainbowing.
(Image taken from [13].)



Pumping ashore.
(Image courtesy of Van Oord.)

Figure 2 Illustration of the three discharge methods: direct dumping, rainbowing, and pumping ashore.

2.4.1 *Dredging*

A suction mouth that is dragged over the seafloor is probably not the dominant noise source; it is the centrifugal dredge pumps that produce most of the underwater sound during dredging. These pumps are normally located on the ship in shallow waters, and somewhere in the suction tube if the water depth exceeds a value of ~35 m. It is possible that only ship-based pumps will be used during the dredging for MV2, which would imply that the ship hull will act as the primary noise source. However, this remains to be confirmed. Centrifugal pumps are prone to cavitation if they are operated at high speed, in which case they are likely to produce more noise. Note: [6] mentions cavitation from dredge propellers (navigation), draghead vacuuming, and noise from submerged slurry pipelines as discernible noise sources.

2.4.2 *Transport*

During transport the TSHD sails with a full hopper from the sand borrow site to the reclamation area, and with an empty hopper on the return trip. Machines specific for dredging are switched off and the main source of underwater noise are the propulsion engines. There are no a priori reasons why sailing TSHDs would make more noise than other vessels of the same proportions, but they do off course contribute to the underwater soundscape. Sailing ships can produce high peak noise levels with cavitating propellers [14, 15]. In a study of various dredge and drilling sounds in the Beaufort Sea, the strongest sounds came from an underway hopper dredge with a damaged propeller [2].

2.4.3 *Reclamation*

It is expected that most underwater noise produced during the discharge is not caused by the actual deposition of the sand, but by the pumps used for rainbowing and pumping ashore. These concern pumps for the actual transport, as well as water jet pumps used to fluidize the soil and facilitate the outflow. For direct dumping one can expect mechanical noise connected to the opening and closing of the bottom doors or valves. The underwater outflow of fluidized soil itself is unlikely to generate much noise. With pumping ashore the soil travels through a pipeline, with some noise produced at the open end, where the soil flows out. This is above water though.
Only with rainbowing is there reason to believe that the actual deposition of dredged material could generate substantial noise. Soil and water fly through the air and arrive at the destination site in a splashing manner. Note that the pumps of the CSD will also generate noise when it dredges and delivers sand.

3 Construction of Maasvlakte 2

3.1 Dredging plans and locations for acoustic measurements

The construction of MV2 is scheduled to start in September 2008. Figure 3 shows the existing Maasvlakte, the extension called Maasvlakte 2, and the allocated dredging areas in green. The present expectation is that these areas only need to be partially exploited to supply sufficient sand for MV2. Only the easternmost parts of the allocated area, tentatively coloured dark green, would then be dredged by the TSHDs.
In Figure 3, the letters A, B, C and Z indicate the areas for particular acoustic measurements. These letters are only rough indications; more precise positions for measurements rely on daily or weekly dredging schedules during construction. Source level measurements for the underwater dredging noise take place at A, source level measurements for sand transport at B, and source level measurements for the various discharge methods at C.

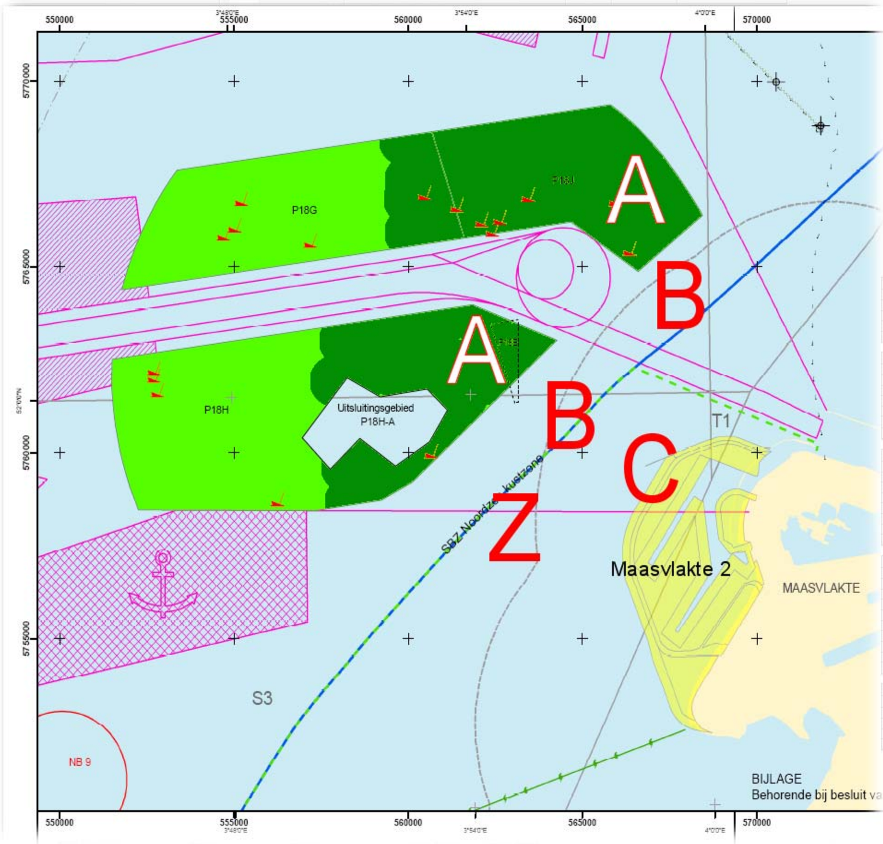


Figure 3 Area map with Maasvlakte 2 and the dredging areas (green). The big letters indicate the areas for source level measurements of A) the dredging; B) the transport and C) the dumping of sand. Z denotes a tentative location for the noise background measurements.

In addition to the source level measurements, background noise measurements are planned at a fixed location to compare received sound pressure levels in the presence and absence of dredging. There are several considerations that are relevant for the location of these measurements. First, it should not be too far from the construction

activities, say 5 km or less, in order to be able to distinguish the construction noise from the ambient noise. Broadband TSHD source levels of 180–190 dB re 1 $\mu Pa^2 m^2$ mentioned in [3] indicate that dredging sound should be sufficiently loud at distances of several kilometres from the source. Note that the background measurements will be performed on three occasions, once in the absence of dredging, and twice in the presence of construction noise. Second, the location should be relevant for seals and porpoises. According to IMARES these mammals occur in the Maasvlakte area. Seals are occasionally spotted on the Hinderplaat, just south of the Maasvlakte, and are also known to migrate between the Scheldt Delta and the Wadden Sea. There is no indication of preferred foraging spots or migration routes in the Maasvlakte area. Finally, the position of Z should be such that permission can be obtained from the authorities to moor a ship or barge for these measurements.
The conclusion thus is that Z should be located within a range of 5 km from the sand borrow and reclamation areas, at a site where measurements are allowed. A tentative position is given in Figure 3, but there is some degree of flexibility so long as the above conditions are met.
The TSHDs operate 24 hours a day, cycling through a periodic schedule of dredging, transit, discharge, transit, dredging, etc. A diagram of this cycle is presented in Figure 4, together with the approximate time required for each step. The vessels sail at a speed of 2–4 knots while dredging, sucking up a thin layer of order 10 cm with their dragheads. In the course of time they will pass repeatedly over the same locations, removing 10–20 m of sediment in total. The pit may reach depths of 10 m in the northern section, and 20 m in the southern section of the allocated dredging area (Figure 3).

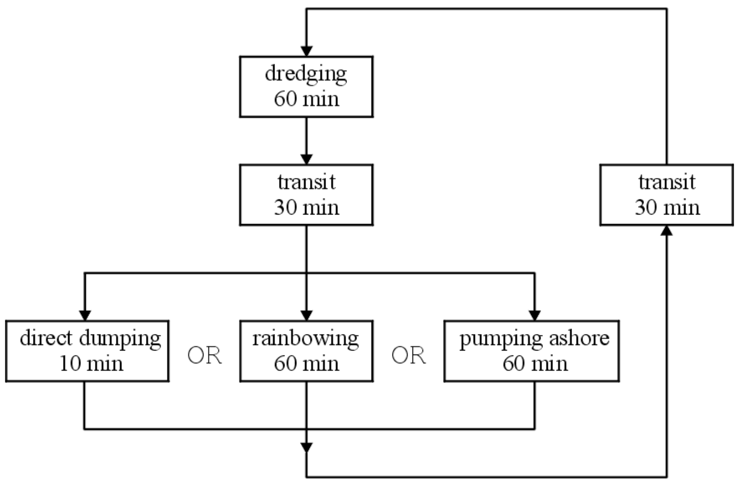


Figure 4 Flow diagram for the MV2 dredging cycle. Tentative durations for each activity are included.

3.2 Sand laying plans

PUMA has issued a preliminary schedule for the construction of seawalls and harbour works. Figure 5 offers a large-scale perspective of the planned progress for the spring of 2009. Figure 6 zooms in on MV2 and shows the progress from the autumn of 2008 to the summer of 2011. The construction time schedule is important, both for the planning of the acoustic measurements and for the acoustic modelling.

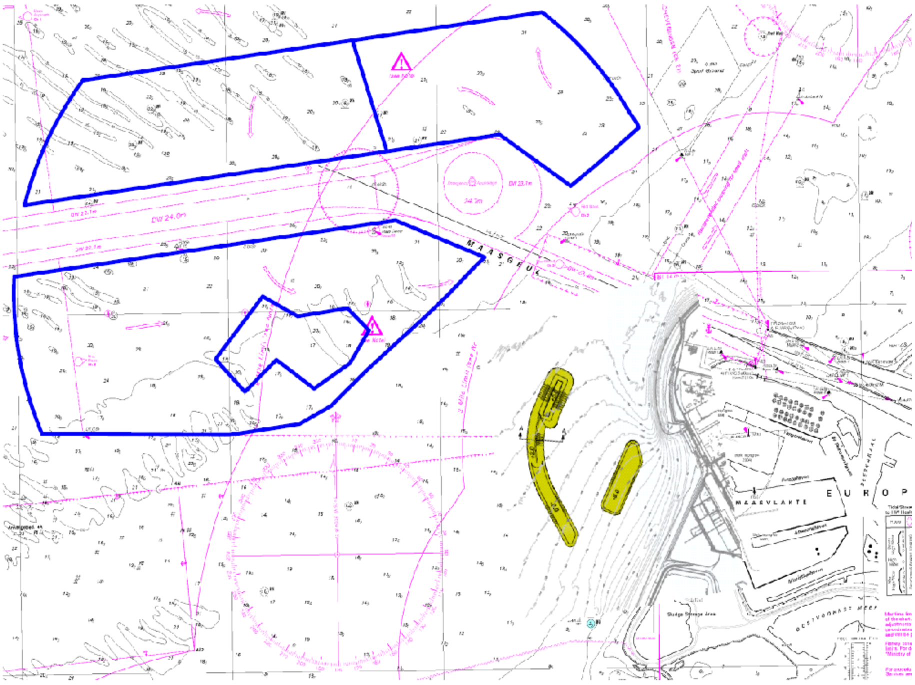


Figure 5 Area map including the present Maasvlakte (bottom right), allocated dredging areas (blue contours), and the spring 2009 land reclamation of MV2 (green areas).

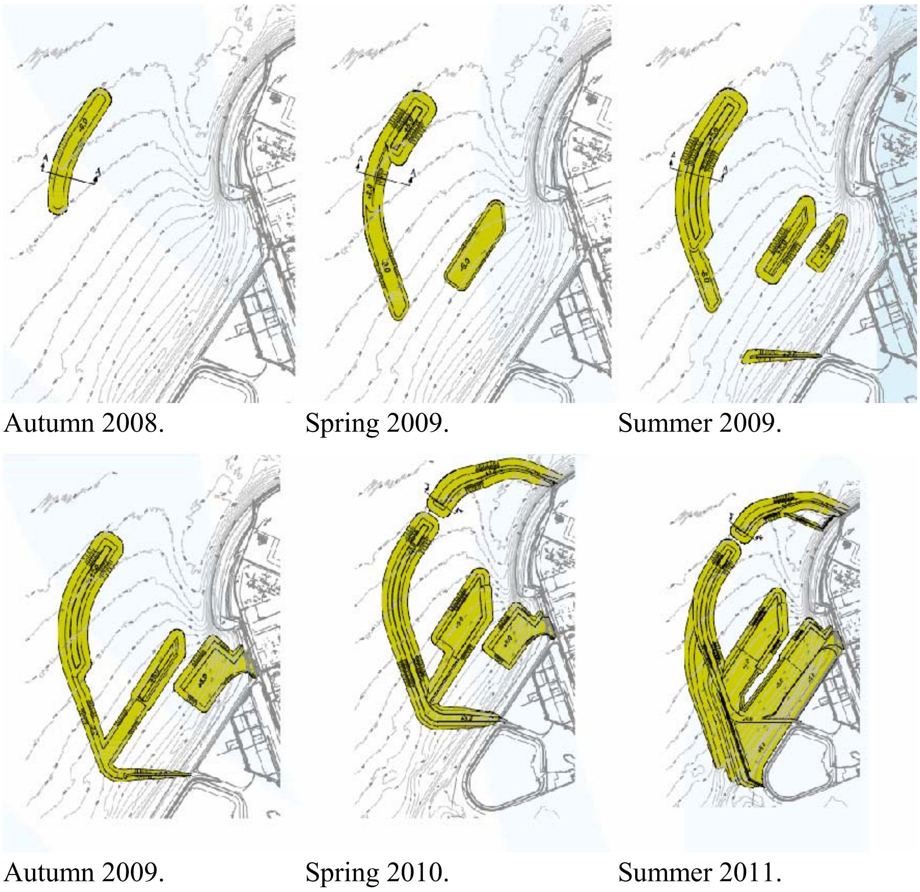


Figure 6 Preliminary plans for the progress of MV2 land reclamation.

4 Acoustic measurements

4.1 Time schedule

It is anticipated that three measurement campaigns will be carried out [10], as summarized in Table 1. The first campaign concerns one week of continuous background noise measurements in the absence of construction noise (i.e. sand dredging, transport, and laying). The second campaign repeats the measurements of the first campaign, but in the presence of construction noise. In parallel, source level measurements are performed on the dredging, transport, and discharge of sediment.
The third campaign is similar to the second one, with background noise and source level measurements. Compared with the second campaign the construction activities are more intense with more TSHDs being operated. Experience and lessons learned from the second sea trial can be put into practice. It is also anticipated that the acoustic modelling will start after the second campaign, so that the third campaign can also better concentrate on the interrelation between measurements and modelling. This includes validation of the model by comparison of source level measurements at A, B, C, and the simultaneously recorded underwater sound at position Z.
Since the MV2 construction covers several years, there is flexibility in the planning of source-level measurements. On the other hand, opportunities are limited for noise background measurements in the absence of dredging. Table 1 summarizes the main features of the sea experiments.

Table 1 Summary of measurement campaigns.

	Campaign 1	Campaign 2	Campaign 3
Purpose / to measure	1. Background noise.	1. Background + construction noise. 2. Source level.	1. Background + construction noise. 2. Source level.
When	2008–2009. Choose period when there are no construction activities.	2009 Measure in the presence of construction activities.	2009–2013 Measure in the presence of construction activities.
	NB1. The concentration of harbour porpoises near the coast is larger in the period November–April than in summer. Seasonal variation is not known for seals. NB2. Background measurements may also be planned to include a transition from construction activity to no activity, or vice versa. Switching on/off effects are normally easier to detect.		
Conditions	Absence of construction noise (in particular no TSHDs active for MV2)	2–4 TSHDs active for MV2	5–7 TSHDs active for MV2
Duration[2]	one week	one week	one week

[2] Time available for measurements, excluding installation and dismantling of equipment.

4.2 Background (and construction) noise measurements

Noise is recorded at a fixed position and during one week, including the weekend.
The sound should be recorded at a rate that is comparable to, or faster than, the time scale of the expected noise processes. Considering the sound produced by waves, rain, industry on land, (distant) shipping, suction of sand, transport of sand, discharge, etc., the underwater soundscape will not change from one second to the next but rather vary on a time scale of minutes or longer. Therefore the sound may either be recorded continuously (if storage capacity allows) or in regular intervals, where a minimum duty cycle of 5% is adopted. The objective of these measurements is to collect statistics, which, for example, can be used to extract hourly, daily, or weekly noise averages in different frequency bands. Comparison of such statistics between Campaign 1 and Campaigns 2 and 3 will then reveal to what extent the MV2 construction activities contributes to the underwater noise in the area. Here it is assumed that noise contributions from mechanisms unrelated to the MV2 construction are similar between Campaigns. The extended period of one week helps to average out weather influences in a statistical comparison. Furthermore it ensures a spread of conditions, so that the probability increases of finding sub-periods with conditions in common between campaigns.
As to the measurement location, it would be convenient to use an existing platform. Lichtschip Goeree has been mentioned, but unfortunately it is too far from the construction site (20 km). Another candidate, the Europlatform, is even further away. A bottom mounted frame would provide a solution, but a complicated and risky one without possibilities for regular data checks. A temporary surface station is therefore preferred. A moored ship or barge (if allowed by the authorities) seems to be the most convenient solution. A large buoy may be considered too, if there is room inside for recording hardware and power supply. Table 2 lists several conditions and requirements for the background noise measurements.

Table 2 Comparison between the two types of measurements.

	Background measurements	Source level measurements
To do	Measure underwater sound for an extended period.	Measure sound in the vicinity of TSHDs during suction, transport, and discharge of sand.
Analysis	Extract statistics (hourly, daily, ...) for noise levels at various frequencies in 1/3 octave bands or smaller.	Invert for source level of the noise source in 1/3 octave bands or smaller. (Involved, see Section 5.)
Purpose	Comparison of overall noise levels in the presence and absence of dredging	Input for sound propagation models. Wide-area prediction of noise levels.
Location	Fixed at Z. Tentative coordinates: X = 563000 m; Y = 5758000 m (See Figure 3.)	Variable in the A, B, C areas. The Competent Authority requests that the noise caused by the discharge of sand is measured as far south as possible.

Table 2 Comparison between the two types of measurements (continuous).

	Background measurements	Source level measurements
Array	Vertical chain with two hydrophones and a bottom weight against tilting.	Vertical chain with two hydrophones and a bottom weight against tilting.
Number of hydrophones	2 (calibrated)	2
Hydrophone depths	7 m Near bottom, depending on water depth at Z. NB. When foraging, seals and porpoises spend most of the time near the bottom.	7 m 14 m
Frequency range	20 Hz – 150 kHz	20 Hz – 50/150 kHz (See Figure 11 and its discussion).
Sampling frequency	≥ 384 kHz	≥ 128/384 kHz
Dynamic range data acq.	≥ 16 bit	≥ 16 bit
Filters	Remove dc components (falloff below 20 Hz); anti-alias filter in accordance with sampling frequency.	Remove dc components (falloff below 20 Hz); anti-alias filter in accordance with sampling frequency.
Recording time	Continuous or continual (at least 3 s every minute).	Irregularly spaced intervals, recordings are typically between a few tens of seconds and a few minutes.
Platform	Moored ship / barge / large buoy.	Mobile ship (stationary during measurement).
Platform requirements	Room for data acquisition hardware, power supply, 2 persons. Possibility to deploy vertical hydrophone chain. **Quiet throughout: no engines; avoid metal sounds, e.g. due to anchor chains.** (Power generator may be needed though ...)	Room for personnel, power amplifier, PCs, data acquisition system, batteries. Possibility to deploy vertical hydrophone chain. Quiet for brief periods (typically a few minutes, during source level measurement).

Table 2 Comparison between the two types of measurements (continuous).

	Background measurements	Source level measurements
Human supervision	No. (Periodic checks or battery recharge may be needed.)	Yes.
Coordination with dredgers	No. (Normal dredging operations taking place.)	Yes.
(Minimum) distance from noise sources	No choice (fixed location).	100 m
Logging	Must-have Wind speed (height of wind measurement must be known). Temperatures of air and sea. Shipping log (either logs made by port authorities and/or separate AIS receiver). Nice to have TSHD black boxes. Environmental data from existing monitoring stations (RWS).	Must-have GPS (positions of measurement ship and TSHD). Event log (connecting specific recordings to specific construction activities). Local seabed information. Nice to have Sound speed profiles. AIS receiver. TSHD black boxes. Shipping logs made by port authorities Wind speed. Temperature of air and sea.

4.3 Source level measurements

The source level measurements are strategic recordings of dredging, transport, and discharge noise. To clearly separate the noise under examination from the background, the distance between noise source and recording hydrophone should not be too large. For inversion of the recorded data for the source level, multiple distances are preferred, but all close enough for the construction noise to dominate the soundscape. On the other hand there should be a safety margin. A minimum range of 100 m is presently specified, but this may be overruled by the captains of the involved ships. Safety of ships and personnel comes first. It may also be decided at sea that it is safe to use shorter ranges. However, if a range of 100 m is too long to separate suction/transport/discharge noise from ambient noise, that observation alone is already valuable information.
Note that 100 m is a minimum distance. The measurement ship will choose a position and record the sound of an approaching TSHD, which passes at the minimum distance before moving off again. A sound recording thus lasts several minutes and covers a range of distances between the noise source and the receiver. On the assumption that the radiated noise is constant during the track of a TSHD, the source level can be deduced from the measurements. When 100 m cannot be considered far field, this strategy

ensures that measurements are available also for longer ranges. Use of multiple distances increases the reliability of the source-level inversion. During the discharge of sand, the TSHD is stationary. In this case the measurement ship will need to be positioned at different positions from the TSHD to obtain sound recordings at different distances from the source. For rainbowing and pipe dumping, which last approximately one hour, it is estimated that four ranges can be covered. The measurement ship starts at a distance of 100 m, measures for a few minutes, sails to a distance of 200 m, measures for a few minutes, sails to a distance of 400 m, etc. Recovery and deployment of equipment in between transits may limit the number of distances that can be covered. Figure 7 sketches the geometry of the source level measurements. For dredging and transport, measurements at different ranges are obtained by positioning the measurement ship (MS) at a given position. The approaching and receding TSHD ensures that the recordings contain 'many ranges'. The 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 laying, the measurement ship is moved from one spot to the next in Figure 7. This is only feasible for rainbowing and pipe dumping, because direct dumping lasts only ~ 10 minutes.

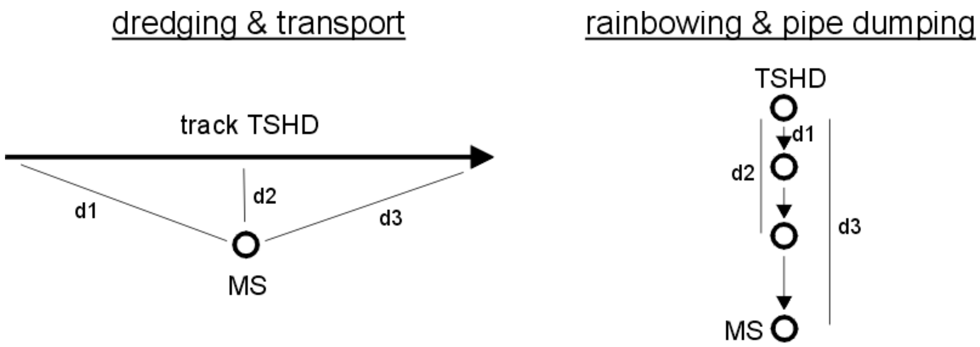


Figure 7 Sketch of the source-level measurements for dredging and transport (left), and rainbowing and pipe dumping (right). Different ranges are obtained from the moving TSHD, and by moving the measurement ship (MS) respectively.

The measurement team will consult dredging schedules and prepare a daily measurement plan. Typically the measurement ship will moor (or drift) at positions close to planned dredging actions. The TSHDs will be sailing during suction and transport, and the measurement team needs to anticipate. During discharge the TSHD remains at a certain spot for an extended period and there is more time for acoustic measurements. Coordination between the measurement team and the dredgers is of great importance. The measurement team should know which actions take place at what time, and the dredgers should be aware of the presence and intentions of the measurement ship.

Figure 8 sketches the data acquisition chain, in this case for a high-frequency limit of 150 kHz. Figure 9 illustrates an example deployment of a vertical chain with two hydrophones and a floating buoy. This measurement plan only specifies the depths of these hydrophones. It is the responsibility of the contractor to minimize self-noise of the measurement platform. A solution may be considered with hydrophones deployed at some distance from the platform, using long cables.

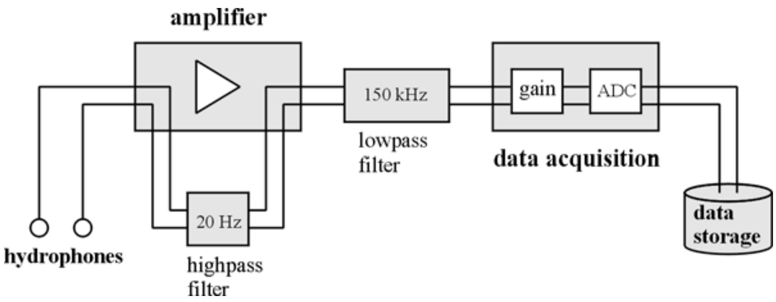


Figure 8 Flow diagram for the data acquisition chain.

Figure 9 Example deployment of a chain with two hydrophones and a surface buoy.

4.4 Frequency range

The range of frequencies to be covered by the acoustic measurements is an important consideration. A number of publications are available which address the hearing threshold of harbour porpoises [19,20] and harbour seals [21–25]. Figure 10 combines results from these publications. Specifically, at each frequency the shown curves show the minimum threshold found in these papers. For both species the sensitivity falls off towards low and high frequencies, i.e. the audibility threshold increases. The seal is the more sensitive species at low frequencies, the porpoise at high frequencies.
Between 150 and 200 kHz, the sensitivity of the porpoise falls off rapidly.
The specified frequency range of 20 Hz –150 kHz in Table 2 thus provides a reasonable coverage for the source level measurements. The low-frequency cut-off at 20 Hz serves to eliminate pressure fluctuations due to variations in hydrophone depth. The high limit is probably overspecified, but measurements are needed to confirm this.

For the background measurements the situation is different. Measured TSHD source levels are only shown up to 10 kHz in the few available references [3,26]. One third octave levels are strongest at frequencies of 100–200 Hz, and reveal a falloff towards 10 kHz. This fall-off normally continues towards still higher frequencies. Moreover, high-frequency sound is strongly attenuated with distance as sound absorption in the sea increases rapidly with the frequency. To obtain an estimate of the highest frequency that still makes sense to measure at a long distance from the source, Figure 11 was produced. It is based on reasonable estimates of the environment (which is not critical for this computation) and spectral source levels derived from [3]. However, since [3] does not give source levels beyond 10 kHz, we used an average value below 10 kHz. This translates as a spectral source level of ~ 130 dB re 1 $\mu Pa^2 m^2/Hz$; the true source level at high frequencies could be much lower. In that case the graph is a ``worst case scenario''. The transition between orange and purple specifies the range where, depending on the frequency, the assumed construction noise is as loud as ambient noise corresponding to a wind speed of 2 m/s (light breeze). For example, if Z is at least 4 km away from the TSHDs, one would not need to measure beyond 40 kHz. If the distance is at least 2 km, the limit is 80 kHz. Note that there is no construction noise during the first measurement campaign, and that an upper limit of 80 kHz is certainly sufficient. Campaigns 2 and 3 can be used to confirm the presumption that no significant construction noise is produced at frequencies of order 100 kHz or higher. If there is, the frequency range for the background measurements may be increased.

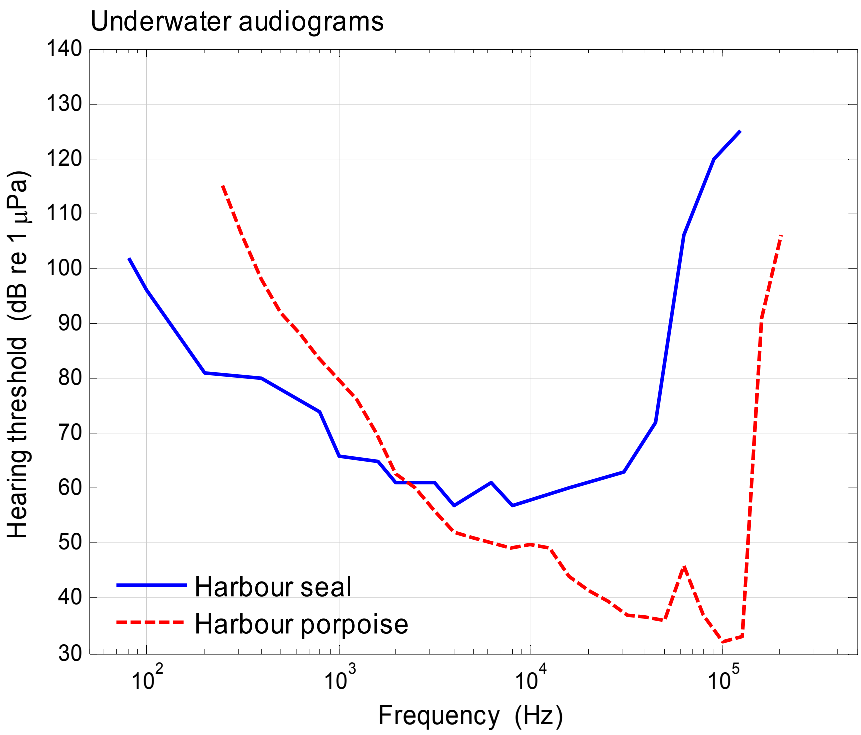


Figure 10 Hearing threshold for harbour seals and harbour porpoises, obtained by combining data from [19,20] for the porpoise and [21–25] for the seal.

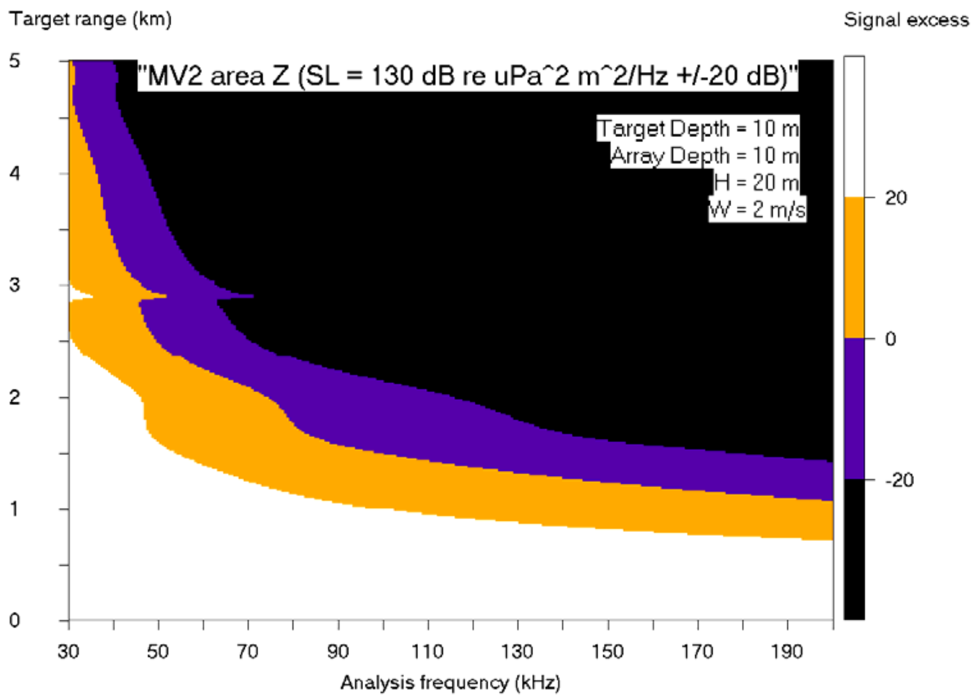


Figure 11 Look-up table to determine the high-frequency limit for the background noise measurements, computed for a water depth of 20 m using the Insight model The transition between orange and purple gives the range where construction noise falls below the ambient noise, computed for a wind speed of 2 m/s and a spectral source level of 130 dB re 1 $\mu Pa^2m^2/Hz$. The transition between white and orange does the same for a spectral source level of 110 dB re 1 $\mu Pa^2m^2/Hz$ and the transition between purple and black for 150 dB re 1 $\mu Pa^2m^2/Hz$.

Acoustical concerns about the chosen frequency range are the near/far field regimes and the cut-off frequency of a shallow-water environment. For a given coherent sound source, the far field starts at a certain distance from the source and this distance increases with the frequency. If the entire hull of a TSHD is considered as the sound source, far-field conditions at frequencies of 10 kHz or higher would require ranges of many kilometres. However, at high frequencies a TSHD is an incoherent source and in this case any near-field effect is negligible. At very low frequencies there could be some coherence of the radiated sound along the TSHD and near-field effects may occur during the source level measurements. However, no problems are expected at frequencies where the seals and porpoises are most sensitive. The background measurements, which take place at several kilometres from the action, are not subject to the near-field effect at any frequency.

In any waveguide there exists a minimum frequency for which sound can propagate effectively, known as the waveguide cut-off frequency. For the waveguide formed by acoustic reflections from the sea surface and seabed, the cut-off frequency is determined by the water depth and the bottom type. For a sand seabed the wavelength of sound at the cut-off frequency is approximately equal to twice the water depth. If the water depth is 30 m, the corresponding wavelength is about 60 m, corresponding to a cut-off frequency of 25 Hz. As with any other propagation effect, the propagation loss can be predicted for a waveguide whether the frequency is above or below its cut-off frequency (the propagation loss is needed to relate the measured level to the source level of the sound producer). However, the accuracy with which propagation loss can be predicted is much greater if the frequency is above cut-off. For this reason, accurate source level measurements are likely to be limited to frequencies above 25 Hz.

5 Acoustic modelling

In an early phase of measurement planning it was decided to combine measurements of construction noise with acoustic propagation modelling for prediction of noise levels over a wide area. The modelling is twofold. First, noise measured in the vicinity of its source must be inverted for the source level, which is a measure of the acoustic power of an underwater sound source. Source level measurements are the primary objective of this measurement plan. The next step is to assume the presence of one or more noise sources at given positions and depths, and compute the sound pressure levels of the noise in the three-dimensional underwater space. In the end a third step may be needed, whereby predicted sound pressure levels are weighted per animal hearing in order to derive sea life disturbance contours. These three steps are henceforth denoted as inversion, forecasting, and weighting.

5.1 Inversion

Following the measurements, the recorded data and log files are used to invert the measured acoustic data for the source levels. For inversion the emphasis is on making accurate predictions close to the source, at the location where the measurements are made. Propagation models that would be considered for this purpose include the existing models KRAKEN, OASES, RAM, and Insight. Table 3 summarizes the measurements and parameters that are needed.

Table 3 Measurements and parameters required for inversion.

Description	Remark
Calibrated noise recordings	Calibration of the entire measurement chain is required.
Mechanism of sound production	Notes by the measurement team concerning the origin of the sound. Not strictly necessary for inversion, but for correct labelling of the sound.
Information about the geometry.	Positions of measurement ship and noise source (tracks if moving) are required. Use TSHD black boxes, AIS log files, GPS.
Depth of noise source and hydrophones	Depth of noise source, e.g. within ship for an engine, near seafloor for a draghead, etc. Depth of the hydrophone(s) used for the noise measurement.
Nominal water depth	Water depth at the location of the noise measurement.

Table 3 Measurements and parameters required for inversion (continuous).

Description	Remark
Sound speed profile	Can be measured by measurement team.
Seabed characteristics	Type of sediment at the location of the noise measurement. For measurements close to the source (say 50 m) a rough indication is sufficient (e.g. clay, sand, gravel). If it is not possible to get close, more detailed information may be required. (Influence on sediment on sound propagation increases with range.)
Weather conditions	Wind speed, rain.
Information on transient sounds.	To avoid inadvertent inversion of polluted data due to, for example, close shipping, overflying aircraft, noise produced onboard measurement ship.

5.2 Forecasting

After determination of the source levels, and model set-up, contour maps of sound pressure levels can be produced for particular combinations of TSHDs and activities. For forecasts of noise over a wide area there is a greater emphasis on accuracy of long-range predictions, for which the effects of sound speed profile (SSP) and bathymetry are more important. Models that would be considered for this purpose include ALMOST, FELMODE, Marsh-Schulkin and RAM. Table 4 summarizes the measurements and parameters that are needed. The models can be applied for a few different realizations of sound speed profiles and other environmental conditions. Extreme values can be entered in order to obtain the worst case scenario.

Table 4 Measurements and parameters required for forecasting.

Description	Remark
Position and depth of noise source(s)	Enable simultaneous modelling of different noise sources at different locations.
Source level of noise source(s)	Source levels as determined by inversion, in bands of 1/3 octave or smaller.
Two-dimensional map of the bathymetry	Of the area for which forecasting is considered relevant. Multibeam echo sounder surveys exist and can be made available.
Seabed characteristics	Type of sediment along the propagation path(s) between the sound source(s) and the point of interest. See for example [16].
Sea surface conditions	Can be inserted through wind speed
Sound speed profile	

5.3 Weighting

Once sound pressure levels are obtained, the next step is to match these with the hearing thresholds of seals and porpoises. The result is a map with contours, which can be used to check the fidelity or otherwise of the contours shown in the MER. The method of the MER [1] may be used, but alternatively more sophisticated methods can be used, such as weighting noise levels per animal hearing [18]. Here, the sound exposure experienced by the animal is weighted according to its hearing characteristics and behavioural thresholds.

5.4 Running the forecasting model

Once the chosen model has been set up for the MV2 area and conditions, it can be run for an arbitrary number of noise sources and environmental conditions. When the underwater environment changes, only the environment needs to be updated in the modelling. There is no need for new acoustic measurements. Constant environmental parameters are the overall bathymetry and bottom type of the area. Environmental parameters that are most likely to vary with time are the SSP, the sea surface, and local currents. Moreover, sand borrow pits in the dredge areas will alter the local bathymetry. The SSP can be measured on location or could be obtained from historical databases. Different sea surface conditions can be included in the modelling through insertion of the wind speed. It is also possible to run the model for various hypothetical SSPs and wind speeds in order to obtain indications of their importance.

5.5 Validation of the model

Validation of the inversion model alone is difficult, unless a calibrated sound source is used instead of unknown construction noise sources. However, what counts is the predicted sound pressure level away from the source. The combination of inversion and forecasting modelling is amenable to validation. One option is to use several hydrophones for the source level measurements described in Section 4.3.
If one hydrophone is used for inversion, a second one at a different depth can be used for validation purposes. The availability of measurements at different distances from the source (see Figure 7) offers more validation options. Furthermore, if the background and source level measurements coincide in time, data from the former may allow for a consistency check.

5.6 Availability of models

The models which are suggested in Sections 5.1 and 5.2 are listed in Table 5, which also addresses their availability. Note that this is not a complete list and that other candidate models may exist. Also note that the presence of a model on the list does not imply that it *is* suitable for a particular task, only that it may be suitable. Regardless of which model is finally used, the modelling should have a proper physical basis. One should not just extrapolate the measurements using an empirical data fit.

Table 5 Candidate sound propagation models and availability.

Model name	Available at
ALMOST	TNO
FELMODE	TNO
KRAKEN	http://oalib.hlsresearch.com/Modes/
Marsh-Schulkin	JASA [27]
OASES	http://oalib.hlsresearch.com/FFP/index.html
RAM	http://oalib.hlsresearch.com/PE/index.html
Insight	BAE Systems

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7 Signature

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