



Field testing the efficiency of the FaunaGuard Porpoise Module (FG-PM) in the Marsdiep area

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Geert M Aarts

CONFIDENTIAL

Wageningen University &
Research Report C076/17

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Publication date: 29 September 2017

Wageningen Marine Research
Den Helder, September 2017

CONFIDENTIAL

Wageningen Marine Research report C076/17

Geelhoed SCV, von Asmuth R, Al Abbar F, Leopold MF & Aarts GM, 2017. Field testing the efficiency of the FaunaGuard Porpoise Module (FG-PM) in the Marsdiep area. Wageningen, Wageningen Marine Research (University & Research centre), Wageningen Marine Research report C076/17 Confidential 35 pp.; number of tables 3; number of figures 17; number of ref. 21.

Keywords: deterrent, Phocoena, Fauna Guard, Safe distance.

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BTW nr. NL 806511618

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Summary

SEAMARCO and Van Oord Dredging and Marine Contractors have developed the FaunaGuard-PM (FG-PM) to deter harbour porpoises from localised offshore anthropogenic activities in order to minimize potential negative effects of these activities on porpoise hearing. The efficiency of the FG-PM was tested in a pool and the distance up to which it would deter porpoises in the field has been modelled, but was not tested at sea. The aim of this study was to test and evaluate the efficiency of the FG-PM to deter porpoises under field conditions. Porpoise behaviour was studied by simultaneous visual observations and passive acoustic monitoring in the vicinity of a periodically active FG-PM in the Marsdiep, Western Dutch Wadden Sea, in February-April 2016.

Visual observations and passive acoustic monitoring took place during a series of pre-exposure (at least 1 h FG-PM off), exposure (15 min FG-PM on) and post-exposure experiments (up to 2 hrs FG-PM off). Visual observations and continuous video recordings were made from a vantage point on the southern tip of Texel. CPODs were stationed at different distances from the FG-PM to record unseen underwater activity of harbour porpoises acoustically.

The visual observations showed that the FG-PM deterred harbour porpoises up to distances of at least 1000 meters. Most of the acoustic monitoring data during FG-PM exposure experiments corroborated the expected results, but due to equipment failure most of these data were of limited value. During post-exposure, shortly after the FG-PM was turned off, harbour porpoises were detected again in the vicinity of the FG-PM.

This study confirms that the FG-PM is successful in deterring harbour porpoises up to at least 1000 m in the field conditions studied, and that porpoises were seen in the exposed area shortly after the FG-PM was deactivated.

1 Introduction

The most abundant cetacean species in the North Sea, the harbour porpoise (*Phocoena phocoena*), has sensitive hearing. The species is therefore susceptible to noise-induced effects from anthropogenic activities at sea. Impacts can range from altered behaviour, including avoidance, temporary or permanent hearing thresholds shifts, physical trauma or even death. Since the harbour porpoise is a protected species there is an obligation to prevent harm to these animals.

Harbour porpoises use echolocation as an active sensory system for information about their environment, and as a means of communication. These echolocation signals contain virtually no energy at frequencies below 100 kHz. The main proportion of the energy is around 132 kHz in a narrow band between 120-150 kHz (Au et al., 1999). Porpoise hearing are most sensitive in this range.

Acoustic Deterrent Devices (ADDs, also called acoustic harassment devices or pingers) are designed to protect marine fauna from localised anthropogenic dangers by temporarily deterring the animals away from the zone of impact. Many ADDs are available, but their effectiveness is rarely scientifically validated. SEAMARCO and Van Oord DMC have developed the FaunaGuard, an ADD that aims to deter specific species of marine fauna safely and temporarily from danger zones, such as marine construction sites, by means of species-specific underwater sounds. Four different modules have been developed, tailor made to deter either porpoises, seals, fish or turtles. The development of the FaunaGuard is based on behavioural response studies both ex situ and in situ for these different fauna groups (Van der Meij et al., 2015).

An experimental ex situ study in a quiet basin (Kastelein et al., 2014) showed that the FaunaGuard Porpoise Module (FG-PM) triggered porpoise behaviour such that the animal would distance itself from the device. Based on the dose-response relationship found in the pool study, the distance up to which the FG-PM would deter porpoises in the field has been modelled, but not tested.

The aim of this research project was to field test (in situ) the efficiency of the FG-PM. To do this, porpoise behaviour was studied in the vicinity of an active FG-PM to determine its effect on free-ranging harbour porpoises. This field study focusses on the avoidance behaviour of porpoises in situations when the FG-PM was active, and on the minimum range from the deterrent device where avoidance occurred.

2 Assignment

The aim of this research project was to test and evaluate the efficiency of the FaunaGuard-PM to deter porpoises under field conditions. This study was commissioned by Van Oord Dredging and Marine Contractors bv, Rotterdam, The Netherlands.

3 Materials and Methods

3.1 Study design

Although harbour porpoises may respond in a variety of ways to anthropogenic sound (e.g. an increase in respiration, swim speed, heart rate or stress hormone levels, or a change in diving behaviour), for the FG-PM to be effective, it should at least lead to displacement away from the sound source within a limited amount of time. Hence the main objective of this study is to measure if porpoises move away from the FG-PM, how they do so, how soon the area is vacated, and how soon the area is re-populated by the same, or by different individuals after the deterring sounds stop.

A study by Kastelein et al. (2014) showed that reactions by captive porpoises to the FG-PM were instantaneous and also that the response did not last long after cessation of sound production. In the field, however, porpoises have the option to move great distances from the source and to have a delayed return to the area. Based on porpoise reaction SPL (the highest sound pressure level) threshold and local environmental parameters influencing propagation loss, the theoretical effective range of the FG-PM was modelled, for a wind farm development site (Luchterduinen) in the Dutch sector of the North Sea, to be 1.3 km for conditions with little wind (de Jong & Binnerts, 2014), i.e. conditions similar to those under which the field experiments were conducted.

To study actual porpoise responsive behaviour in the field we used both visual and acoustic methods. These methods potentially allow monitoring of a number of behaviours of harbour porpoises before, during, and after the exposure to the FG-PM sounds. The two methods cover different aspects. Porpoises – as all cetaceans – spend the majority of time under the water surface. Under favourable conditions surfacing animals can be followed visually over considerable distances (>1000 m), whilst acoustic methods can quantify their underwater activity, albeit at small distances from acoustic detectors only.

For field testing, the FG-PM was deployed in an area known for its relatively high densities of harbour porpoises during a particular period of the year and at incoming tide. The area is easily accessible for study. Therefore, porpoises, and their reactions to FG-PM deployment, could be followed visually, from the shore, as well as under water by recording porpoise sounds. The FG-PM was only deployed for a limited amount of time per day, allowing studying porpoise presence at the test site both in “quiet” (FG-PM off, control) conditions and in situations when the device was active. This limited deployment also allowed porpoises to come back into the affected area, in between successive experimental trials.

3.2 Study area

The study site is the Marsdiep, the tidal inlet between Den Helder and Texel. The Marsdiep area has been used in previous research projects to investigate the small-scale habitat use of porpoises (Figure 1; Boonstra et al., 2013; Hoekendijk et al., 2015; IJsseldijk et al., 2015). Porpoises occur here in highest densities in winter and early spring, particularly in March and the dikes and dunes on Texel can be used as vantage points for visual observations. Previous work (IJsseldijk et al., 2015) has shown that porpoises mostly enter the Marsdiep tidal inlet during flood and return to the adjacent North Sea during ebb. The Marsdiep connects the North Sea to several sea ports, most importantly the Ports of Den Helder and the fishing port and marina of Oudeschild, Texel. The inlet is thus also used by shipping and traffic intensity can be high. However, as the experiments were timed to high porpoise abundance, i.e., in late winter-early spring, vessel traffic was comparatively low as there was little recreational movement. Also, most shipping, including that of fishing vessels with final destination Oudeschild, was directed at the Port of Den Helder. This meant that most ships would take a route across the southern half of the tidal inlet (close to Den Helder), leaving the northern half, where the FG-PM experiments were conducted, relatively undisturbed. Still, when ambient underwater

noise was measured in the study area in September 2016, noise levels were found to be considerable, as Low-frequency underwater sound travels over great distances (Jansen & de Jong, 2016; see below).



Figure 1 The Marsdiep area (Google Inc. 2016). Numbers indicate the CPOD locations. O= observation point, F= is FG-PM position, A= visual observation area.

3.3 FaunaGuard experiments

The FaunaGuard Porpoise Module (FG-PM) was developed for safe and effective deterrence of porpoises. Unlike other ADDs, the FG-PM only produces higher frequencies within the best hearing frequency range of harbour porpoises. FG-PM uses variable sounds. It produces eight sound tracks (varying in duration between 9 and 18 s) at random intervals varying between 3 and 10 s. The sounds are between approximately 60 and 150 kHz in frequency (Kastelein 2014) to trigger deterrence and have a 3 minute ramp up period to give animals an opportunity to leave the area before sounds are emitted at the highest sound pressure level (SPL). Maximum source level is 172 dB re 1 μ Pa at 1m. Observations in the SEAMARCO basin showed avoidance behaviour by harbour porpoises at received SPLs of the FG-PM signals above 90 dB re 1 μ Pa. According to the propagation loss calculations by TNO this level is exceeded at distances up to 1.2 km from the FG-PM in the Marsdiep (Jansen & de Jong, 2016). Thus no deterrent effect was expected beyond 1.2 km from the FG-PM.

3.3.1 Experimental set-up

Visual observations and passive acoustic monitoring took place during a series of exposure (FG-PM on), and control experiments (FG-PM off). The FG-PM was deployed from the Zilvervis, a small research vessel (10x3m), moored to a pole in the study area (Figure 2), with the engine turned off prior to the onset of observations. Exposure experiments were only conducted when at least one porpoise was seen within the experimental area, after at least one hour of pre-exposure observations (Figure 3). All exposure experiments (FG-PM on), and control experiments were conducted under favourable weather conditions only; no rain, wind and sea state <4 Bft, good visibility and low glare.

Control experiments represented undisturbed conditions. During the control experiments, the vessel deploying the FG-PM and CPODs was not operating within the study area.



Figure 2. The research vessel 'Zilvervis' moored to the yellow pole. In the background is the skyline of Den Helder. The red circle shows a harbour porpoise in the vicinity. Photo: Fadia Al Abbar.

The FG-PM was switched-on in the period between 1.5 hour before and 1 hour after high water at Den Helder (source www.getij.nl). For the Marsdiep area, porpoises enter during upcoming tide, and the majority leaves the area during outgoing tide (e.g. Boonstra et al., 2014, IJsseldijk et al., 2015). Figure 3 describes the time schedule followed.

The start of the experiment is defined as the start of the pre-exposure period, which is at least 60 minutes prior to the exposure. Approximately 1.5 hours before starting the experiment, land-based observations commenced. After that, approximately 1 hour before the pre-exposure, the temporary CPODs were deployed, one after the other, from the research vessel, 15 minutes before pre-exposure, the vessel was attached to the pole, the engine was turned off, and the FG-PM was deployed into the water. At the start of the exposure, the FG-PM was turned on for 15 minutes. The presence and distribution of harbour porpoises was continuously registered for up to 2 hours post-exposure. After the post-exposure period, the temporary CPODs were removed from the water. During the entire experiment (pre-exposure, exposure and post-exposure) continuous camera recordings were made. Table 1 gives the dates of FG-PM and control experiments.

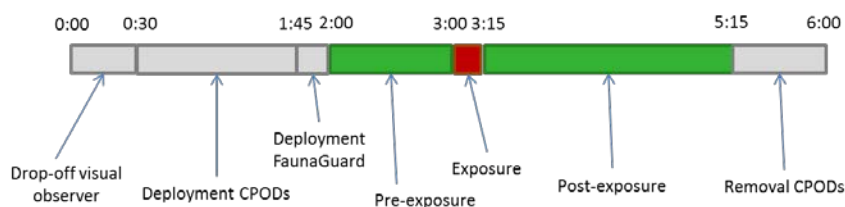


Figure 3. Time schedule of each individual experiment with single exposure. Times are relative.

3.3.2 Visual observations

Visual observations were made from an observation point on the shore, 10.39 meters above NAP (Figure 1 & 5). The FG-PM was activated next to a stationary pole in the Marsdiep, 302.4 meters from the observation point (Figure 1 & 2).

Observations were made using a Telescope, Swarovski 95mm ATX 70x95, mounted on a tripod, binoculars, Leica 7x42 BDA, mounted on a monopod and binoculars (Swarovski 10 X 42 EL), mounted on a tripod together with a video camera. Video recordings were made using a DSLR (digital single

lens reflex) camera, Canon 600d with 1:4 L IS 300mm lens, mounted on a tripod together with binoculars (the "tracking camera"). This combination of binoculars and video camera could be rotated horizontally while tracking a moving harbour porpoise. In addition, an array of five stationary DSLR cameras: two Canon EOS 70d with 70-200mm Canon IS UMD lens, two Canon EOS 70d Mark II with 70-200mm IS UMD Canon lens and one Canon 600d with 70-300mm lens, Sigma APO DG, jointly mounted on a custom-made stand, set to a 200mm focal length, was monitoring the sea around the FG-PM (Figure 4). The video recordings were used for photogrammetry to determine the locations of the sightings.

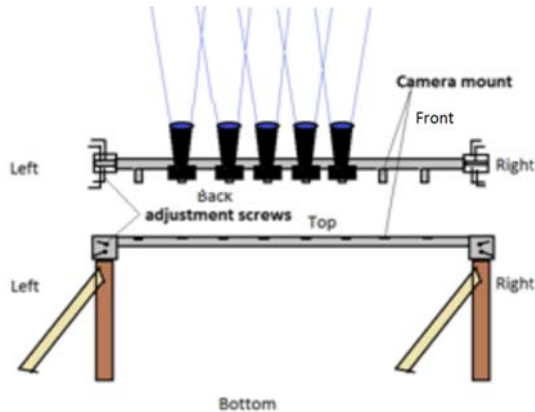


Figure 4. Schematic overview of the camera stand. The poles had been driven into the ground and kept there for the entire length of the study. The horizontal bar with the cameras put on top for each observation session and removed in between sessions.

The elevation of the cameras was determined using a Real-time kinematic GPS, a Trimble R6 Model 3, with a Trimble TSC3 controller using Trimble Access Field Software version 2013.00 (4617). The devices were attached to a 2.00 meter tall, carbon fibre pole. The reference height used was the national standard NAP (Normaal Amsterdams Peil, Amsterdam Ordnance Datum). Two measurement poles were placed in the sea within the survey area, at different locations, to measure the sea level during observations.

Table 1. Dates and times of FG-PM-active periods and of control experiments (FG-PM not turned on).

Date	FG-PM on	FG-PM off	Observation time		Comments
			Start	End	
17-Feb	not turned on	not turned on			Test run
26-Feb	8:39:00	8:54:00	6:30:00	10:10:00	
29-Feb	8:04:30	8:19:30	7:30:00	10:20:00	
3-Mar	not turned on	not turned on	10:00:00	12:30:00	
5-Mar	not turned on	not turned on	10:00:00	13:40:00	
7-Mar	14:30:45	14:45:45	13:30:00	15:40:00	
12-Mar	11:14:50	11:29:50	8:30:00	12:00:00	
17-Mar	not turned on	not turned on	9:20:00	11:40:00	
22-Mar	15:40:45	15:55:45	14:20:00	16:50:00	
31-Mar	10:29:30	10:44:30	9:10:00	11:50:00	
1-Apr	not turned on	not turned on	8:00:00	10:50:00	
2-Apr	12:45:14	13:00:50	9:50:00	13:40:00	
5-Apr	not turned on	not turned on	13:00:00	16:00:00	
8-Apr	6:42:06	6:57:06	5:30:00	8:20:00	
8-Apr	16:57:45	17:12:45	15:50:00	18:10:00	
9-Apr	not turned on	not turned on	5:50:00	9:00:00	



Figure 5. The observers at their observation point in the Texel dunes. Left: the stationary camera stand plus observer. Right: two observers with telescopes and video camera. Photo: Steve Geelhoed.

Field work

To observe and track the porpoises, the research area was being filmed continuously and also observed with binoculars. Every 10 minutes the environmental conditions were recorded. The stationary cameras were aimed in such a way that they gave a slightly overlapping panoramic view of the entire study area (Figure 4), so that porpoises could be tracked over the entire study area. The observers noted on which cameras porpoises were likely visible when they observed them through binoculars and also recorded the swimming direction, the time, any notable behaviour and an indication of the position, to facilitate subsequent analyses of the video footage. To make it easier to trace porpoises on the video recordings (with sound on), the observers said “porpoise” loudly every time they spotted a new porpoise, and “cue” for every subsequent surfacing of a particular animal.

Data processing

The video recordings, at the time when porpoises were sighted in the field, were watched and a single frame was extracted for each surfacing. If the porpoise was first seen well inside the research area (Figure 1: ‘A’) or it was lost with the tracking camera, it was tracked back or forward to the edge of the recorded area using the stationary camera images. Using R (R core team 2016) and a previously developed R script (Hoekendijk et al., 2015), the geographical position of each surfacing could be determined, from the video frame, the height of the observation point (from the centre of the lens to the sea), the geographical position of the observation point, the geographical position of known landmarks across the Marsdiep visible in the background of the frame, the distance to the centre of the earth (from NAP), and the actual water level. We used Google Earth (Google Inc 2016) and street view to determine the geographical locations of 55 visible reference points, across the Marsdiep in the city of Den Helder.

The direction of travel and the travel speed (ground speed) of an animal was determined using the time and position of subsequent sightings. The hypothetically maximum travel speed, direction, surface interval, directness (deviations from a straight line), field notes, and tidal phase were used to determine which surfacings belonged to which porpoise. The researcher was unaware which phase (control, test or recovery) the sightings belonged to when determining these parameters in order to avoid biased data interpretation. Whenever the decision was difficult, the researcher always was careful not to assign surfacings to different animals, keeping estimates of group size conservative. Once the surfacing was assigned to a certain animal being tracked, further data were calculated. The

tracks that were recorded during FG-PM exposure periods were split into four phases: before deployment, ramp up, full power, recovery.

For each tracked animal, the travel speed, distance to FG-PM (for each surfacing), and direction and speed relative to the FG-PM were determined. Direction relative to the FG-PM was taken as the length of the track divided by the difference in distance to the FG-PM between the first and the last surfacing. Relative direction is a dimensionless figure, between 1 for moving directly towards the FG, via 0 for moving parallel to the FG-PM to -1 for moving directly away from the FG. The relative speed to the FG-PM is the mean speed ($\text{m}\cdot\text{s}^{-1}$) of the porpoise multiplied by the direction relative to the FG.

Statistical analyses

The statistical analyses were done using R (R core team 2016). A chi square test was used to determine whether or not the FG-PM successfully caused the porpoises to distance themselves from the active device to a distance of at least 1000 meters. This required a cut-off distance to compare "near" and "far" surfacings. This distance was conservatively set at 1000 meters. The data collected during the ramp up phase was excluded since the chi square test cannot show whether or not the porpoise had time to swim away from the FG.

To determine whether the porpoises were actually moving away from the FG-PM when it was activated, differences in relative speed to the FG-PM were compared. Porpoises with only one observed surfacing were excluded from the analysis since their speed and direction could not be determined. The data from porpoises not exposed to FG-PM sounds that were within 1000 meters from the FG-PM (during control and recovery phase) and the porpoises during the ramp up phase, that were still within 1000 meters from the FG-PM (porpoises outside 1000 meters do not necessarily show a reaction, even if the device works), were compared, using a Wilcoxon ranked sum test.

A Generalized Additive Mixed Model (GAMM) was fitted to test if there is a difference between the mean distances to the FG-PM during the control, test (ramp up and full power) and recovery phase. Because the FG-PM was relatively close to the observation point, the number of porpoises observed per unit area decreased with increasing distance to the FG; the further the porpoises are away from the observation point the harder it was to see them. This decrease in detectability was larger than the increase in area covered with increasing distance. The distribution of distances was described by a Gamma distribution, with log as the link function. Because porpoises often move in groups, in which the individuals are not independent, and the porpoises also clustered at certain locations, a mixed effects model was used to account for the correlation between individual observations (of the same individuals or other members of the 'group'). This GAMM was used to estimate the influence of the explanatory variable, phase (control, test or recovery), on the mean distance to the FG.

3.3.3 Passive acoustic monitoring: CPODs

Passive acoustic monitoring was conducted by using CPODs. A CPOD is a small self-contained data-logger that logs echolocation clicks made by harbour porpoises and other cetaceans. It has been developed by Nick Tregenza (Chelonia, UK) and is widely used in monitoring the occurrence of porpoises acoustically. A CPOD consists of a hydrophone, an amplifier, a number of band-pass filters, and a data-logger that logs echolocation click-activity. It processes the recorded signals in real-time and only logs time and duration sounds fulfilling a number of acoustic criteria set by the user during post-processing. These criteria relate to click-length (duration), frequency distribution and intensity, and are set to match the specific characteristics of echolocation-clicks. These are distinctive in lasting about 50-150 microseconds, and containing virtually no energy below 100 kHz. The main proportion of the energy is in a narrow band between 120-150 kHz, peaking at around 132 kHz.

The CPOD does not provide the data in real-time, so it has to be retrieved from the field to obtain the collected data. CPODs used in this study are calibrated by the German Meeresmuseum in Stralsund to ensure that all CPODs used in the study have a comparable detection probability for porpoises. However, upon retrieval of the CPODS, most of the recorded data appeared to be of dubious quality. No mid-terms controls were performed on the data that could possibly have prevented further loss of data. There were problems with the recorded relative times and there was massive data loss, making a full analysis of these data difficult (Appendix).

4 Results

4.1 Land-based visual observations

Between 26 February and 9 April 1086 surfacings were recorded during a total of 43 hours and 50 minutes of observations (Table 1). Weather conditions in the second half of April were not good enough to continue with the observations. The 1086 surfacings were linked to 281 harbour porpoises. An example of a porpoise track is given in Figure 6.

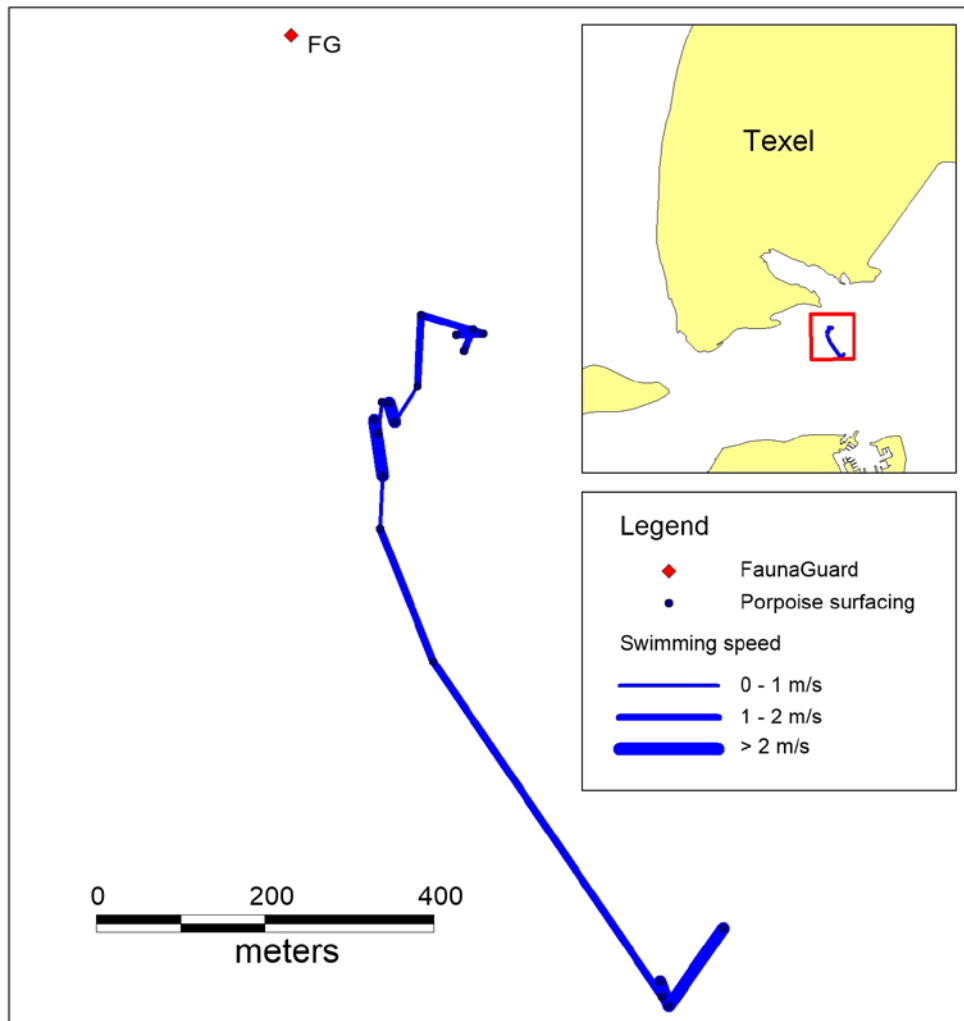


Figure 6. Track of a single porpoise, relative to the position of the FaunaGuard (FG). This particular track shows a porpoise that was near the FaunaGuard when this was turned on. When the FaunaGuard was turned on the porpoise probably dove down and swam a large distance underwater in a south-easterly direction (i.e. was not recorded). It only surfaced once while it distanced itself from the device and resumed apparently normal behaviour at about 1200m from the FG.

After some tracks were divided into different time frames 305 data points were available for analysis (for example: the porpoise with id 214, of which the track is visible in Figure 6, that surfaced during different time frames, was divided and later referenced to as 214a, 214b and 214c).

The nearest surfacing recorded during the time the FG-PM was active at full power was 1006 m from the device, while porpoises were always much closer at the onset of FG-PM deployment, as this was a pre-determined situation for starting an experiment (see sections 4.1.3 and 5.3).

4.1.1 Different distances to FG

The ratios of distances of porpoises inside and outside 1000 meters, between the time the FG-PM was on, at full power, and the time the FG-PM was off ($n=290$) were significantly different from each other ($\chi^2 = 39.45$, $df = 1$, $p = 3.367e-10$). No porpoises were ever seen within a distance to the FG-PM of 1000 meters, when the FG-PM was on at full power.

4.1.2 Relative swimming speed

Porpoises within a 1000 meters from the FG-PM ($n=152$) had a lower speed relative to the FG-PM when it was ramping up than during the control phase (Figure 7, $W = 424$, $p = 0.008067$), indicating that they were swimming away from the device during ramp up.

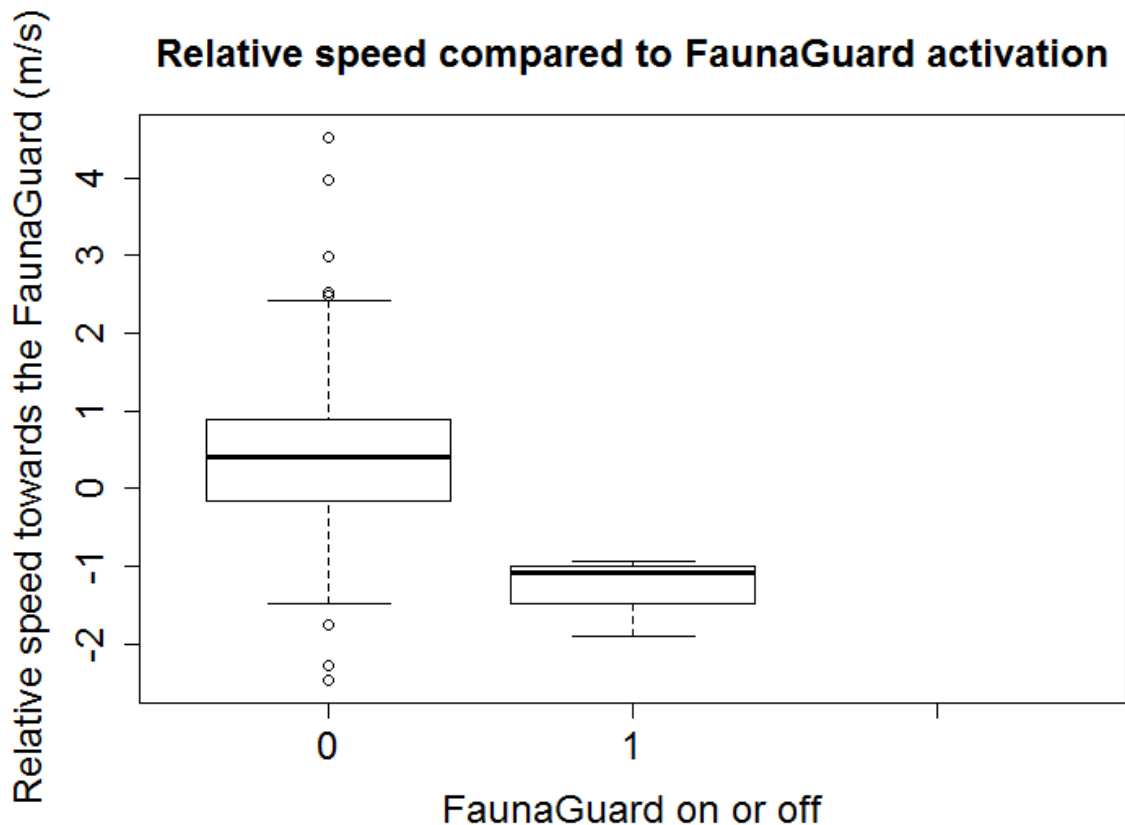


Figure 7. Boxplot of mean relative speed to FG-PM during ramp up (on) and off phases, showing median values (thick lines), the first and third quartiles (the boxes), one standard deviation above and below the mean of the data (the whiskers) and outliers within the dataset (circles). The data show that when the FG-PM was on, the porpoises swam away from it.

4.1.3 Distance to FG

A GAMM analysis shows a highly significant difference in the mean distance to the FG-PM between the control, test, and recovery phases (t -value = 5.088, $p = 8.53e-07$). To show this difference in mean distance to FG, three separate GAMMs were fitted to the data, one for every phase, with time since the onset of FG-PM deployment as the explanatory variable, with a smoothing penalty to reduce the noise in the highly variable data. Four knots were used in all three GAMMs to let the models show the variability in the data, but still prevent overly flexible models to be fitted. These GAMMs were used to predict the mean distance of a porpoise to the FG-PM for every minute in a time slot from 80 minutes

before the FG-PM was activated until 60 minutes after it was activated (this time interval complies with the actual observed data). The smooth functions were plotted for the three different phases in the same graph, over the actual mean (per track) distances to the FG-PM of the observed porpoises. Figure 8 clearly shows that there was not a single porpoise track with a mean porpoise distance to the FG-PM within 1000 meters when the FG-PM was active at full power (3-15 minutes after activation).

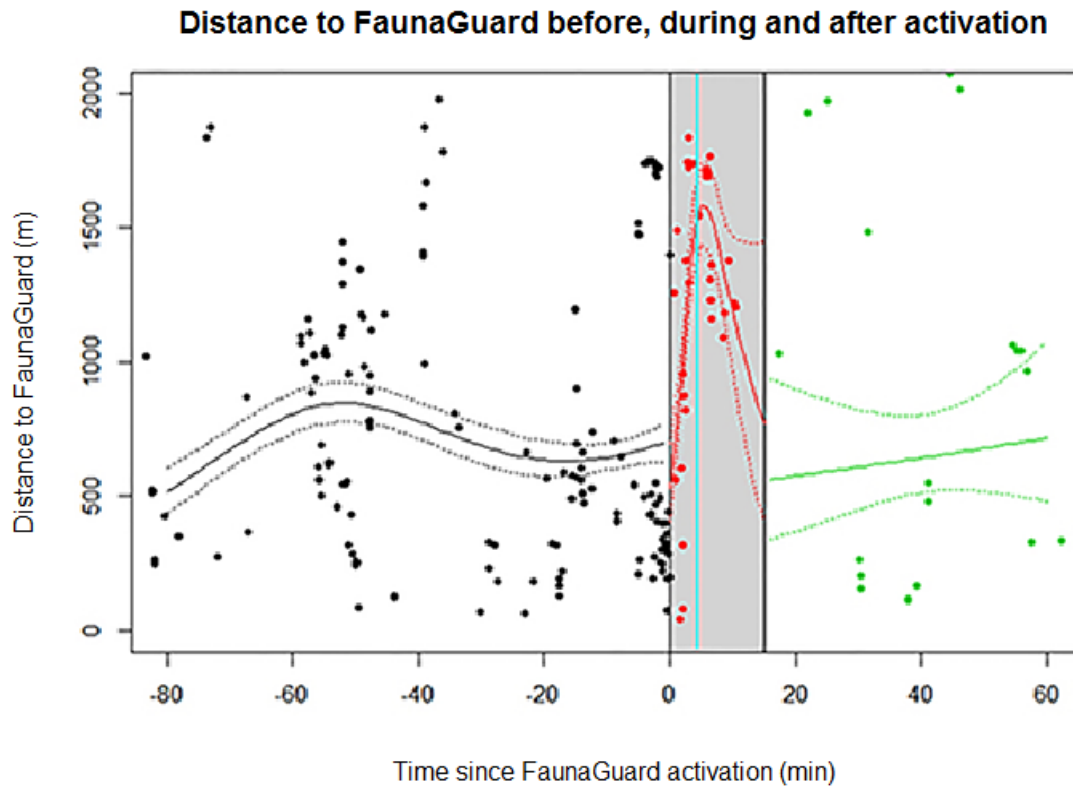


Figure 8. The distance to the FG-PM as a function of time since deployment. Black plot: smooth through predicted values from the GAMM model of the control phase. Red plot: smooth through predicted values from the GAMM model of the test phase. Green plot: smooth through predicted values from the GAMM model of the recovery phase. All models: family = gamma, link function = log, $K=4$. Black dots: mean distance values of porpoises in the control phase. Red dots: mean distance values of porpoises in the test phase. Green dots: mean distance values of porpoises in the recovery phase. Grey area: test phase, FG-PM active; with the vertical blue line within this period indicating start of emissions at full power. Dotted lines indicate the 95% confidence interval of the functions.

5 Discussion

5.1 Visual observations

The detection of 281 harbour porpoises in 44 hours of video observations in a relatively small research area (about 3 km²) shows that the recently developed method of detecting and geo-referencing harbour porpoises (Hoekendijk et al., 2015) is an effective one. Not only does it provide an effective means to discover harbour porpoises, the method of constant filming also makes that one can track the animals and always look back on the different behavioural traits one wants to focus on. This provides a large advantage over traditional methods using visual observations or theodolites, but the method only works if sufficient background orientation points are available, and if they are visible in the video images.

5.2 Swimming speed and distance to the FG-PM

The large difference in porpoise distances from the FG-PM, before, during and after the deployment of the FG-PM, shows that the device successfully deterred wild harbour porpoises to distances of at least 1000 meters.

The differences in relative speed towards the FG, between the ramp up phase and during FG-PM inactivity, shows a strong and fast reaction to the FG-PM being turned on. The mean speed directional component of around -1m/s (away from the FG-PM) during the ramp up clearly shows that harbour porpoises moved away from the sound source when it started. A swimming speed of 1m/s, however, is well below porpoise top speed, which is thought to be 1.4 m/s by Otani et al. (2001), but which may easily be three times this value, while burst speeds up to 6 m/s (Lucke et al., 2000). Note, however, that between successive surfacings porpoises did not necessarily swim in a straight line, so actual swimming speeds may have been higher. With the FG-PM switched on, animals that were nearby did swim away with an effective speed of about 1 m/s. During the full power phase, the animals continued to swim away until a certain evasion distance was reached. In the experiments we found that this evasion distance was at least 1000 m. Note that no porpoises were visually detected at close range (<1000 from the FG-PM) after the ramp up period, but sample sizes per tracked porpoise are not very large (Figure 6) and with most movement occurring under water, swimming speeds and tracks during evasive movements were not always exactly known.

The mean distances, for each track, from the FG-PM as plotted in Figure 6 show highly erratic, rather than clear directional swimming. The net movement of porpoises with the FG turned on was clearly away from the device. The GAMM analyses show a strong effect of the FG-PM's activity on the distance from the FG-PM porpoises are observed. The predicted values show that porpoises were seen at any distance from the FG-PM in the control phase. After the FG-PM was activated, the mean distance increased steeply to a mean distance over 1000 meters. In this phase the distance to FG-PM decreased after the device was active for a while. This decrease, however, is probably the result of the large mean distance (a lot further than the effect area) just after the device had been active for a while and the lack of data at the later period of the test phase (meaning that datapoints for the most distant animals were lost). The confidence interval around this smooth is very wide. It is also clear that there were no porpoises within 1 km from the FG-PM that was within view, when the device was on at full power.

The last smooth, for the recovery phase, shows a mean around the same distance as the first smooth, during the pre-exposure period. The confidence intervals and the actual mean distances show that there is less data available in this last, recovery, phase. It is unclear if most porpoises left the area altogether after FG-PM deployment, and that the porpoises visible in the recovery phase were new porpoises, that entered the area after the FG-PM was turned off. It is also possible that the number of

porpoises was just naturally lower at these times because the control phase started with the incoming tide, and the recovery phase was usually when the currents were weak (towards high tide). Porpoises swim into the Marsdiep from the North Sea with the incoming tide (IJsseldijk et al., 2015) and may use the current to travel and forage, as is shown in other locations (Benjamins et al., 2016). So, numbers in the study area may have dropped naturally towards the turning of the tide.

The cluster of visually observed porpoises in the vicinity of the FG-PM just before FG-PM deployment was the result from the method of only turning the FG-PM on when there was at least one porpoise close by. The fact that most of these porpoises were not visually observed again after the FG-PM was turned on, is because harbour porpoises may dive for a long period and swim away at high speed (3 minutes underwater at 3 m/s for example = 540 m) when being subjected to ADD sound, as is shown by a study on captive harbour porpoises (Teilmann et al., 2006). The required swim speed is well within the capabilities of harbour porpoises as shown by field measurements of a free-ranging animal fitted with a transmitter that sends out its position deduced from satellite telemetry (Lucke et al., 2000). Therefore, even though the porpoises that were not seen again after FG-PM activation cannot be used to measure distance to the FG, or relative swim speed to the FG, during the test phase, they do provide additional evidence for the strong effect of the FG-PM even though their tracks could not be monitored. These porpoises are expected to have left the area.

5.3 FG-PM has expected effect

The analysis of the relative speed of harbour porpoises towards the FG-PM proves that the FG-PM is effective; it causes harbour porpoises to move to distances at least 1000 m away from it. The fact that not a single porpoise was visually observed within 1000 meters of the FG-PM when it was at full power indicates that the FG-PM affected all or nearly all harbour porpoises present within a 1000 meter radius.

The fact that many porpoises, that were close to the FG-PM when it was turned on, were not observed again after the FG-PM was activated, indicates that the porpoises reacted with prolonged diving, which was expected in response to ADD sounds (Teilmann et al., 2006). However, because we did not observe most affected porpoises again, animals may also have moved east or west, disappearing from the area that was in view (Figure 1). In summary, the FG-PM provides an effective and consistent means to deter all or nearly all harbour porpoises from its effect area, which is at least 1000 meters in the Marsdiep, and keeps them away. This distance is of the same order as the predicted distance for a site further offshore in the North Sea (de Jong & Binnerts, 2014), but exact deterrent distance are dependent on the acoustical properties of the environment.

In September 2016, TNO made sounds measurements, in a bandwidth between 63-125 kHz, at several distances up to 1 km from an active FG-PM in the study area. The measured Sound Pressure Level (SPL) ranged between 159 dB re $1\mu\text{Pa}^2$ at 5 m distance to about 95 dB re $1\mu\text{Pa}^2$ at 1 km distance. This distance matches well with a predicted maximum distance of 1.2 km for startle response behaviour, based on a 90 dB re $1\mu\text{Pa}^2$ behavioural response threshold SPL (Jansen & de Jong, 2016). Based on the TNO-measurements an SPL of 90 dB re $1\mu\text{Pa}^2$ is expected to be reached between 1.0 and 1.2 km, the predicted maximum distance for startle response behaviour. The avoidance distance of at least 1000 m our visual observations yielded, falls within this range.

The FG-PM works with higher frequencies than standards ADDs, and is more likely to induce a response in harbour porpoises as the perceived SPL (Sound Pressure Level) is higher at these frequencies, TTS (Temporal Threshold Shift) onset SPL's are also depending on frequency, though above 7 kHz the precise TTS onset SPLs for each frequency have not yet been described for harbour porpoises (Wensveen et al., 2014). This makes it probable that this porpoise-specific FG-PM is more effective at preventing TTS in harbour porpoises due to anthropogenic sounds, than ADDs that work with lower frequencies. Because of the inbuilt ramp-up, and the FG-PM's frequencies are most effective at deterring harbour porpoises, before the SPL's get dangerously high, the FG-PM is likely to

be safe for porpoises. No comparative studies with other ADDs have been done yet though. However studies on previous ADDs have shown occurrences of porpoises that were deterred to a much lesser extent by the lower frequency level ADDs (Brandt et al., 2013a,b; Hermannsen et al., 2015). None such occurrences were observed in this research, testing the FG-PM porpoise module, which indicates that this device has species-specific effect that is more reliable and safe, most likely due to the frequencies used. In addition, this device is specifically developed not to be audible by seals.

To increase safety for marine mammals when causing very loud underwater noise, one should take multiple factors into account, like where the activity is taking place, which animals will be effected, what the properties are of the specific area and how far the animals need to be deterred, to prevent harm. With such knowledge, a grid of multiple specialised FG-PMs can be used to deter as many individuals of the important impacted species to a safe distance. One can, for example, in the case of underwater explosions that have no ramp-up (Aarts et al., 2016), align multiple FG-PM's and activate them in sequence to increase the deterring distance for harbour porpoises.

The development of species' specific ADDs such as the different FG-PM Modules offers an excellent opportunity to improve the safety of the use of such devices. This is especially important for odontocetes, as they are vulnerable to sound. The FG-PM works well on harbour porpoises, but may be less effective on other odontocetes. The species-specific frequency dependent perceived SPL will be different in other odontocetes (Tougaard et al., 2015). Species specific hearing range and frequency dependent hearing sensitivity (when available) should always be taken into account when deciding on a sound mitigation method.

6 Conclusions and recommendations

The FG-PM successfully deterred wild harbour porpoises up to distances of at least 1000 meters. Video observations never detected porpoises at the water surface within this distance, during activation of the FG-PM, while during the ramp-up period preceding full power deployment animals were seen swimming away towards this distance.

Shortly after exposure ceased harbour porpoises were seen and heard again in the study area even in the vicinity of the FG-PM. Either porpoises that were deterred returned, or other animals entered the area.

The experimental set up with visual observations worked very well.

The procedure for the retrieval of acoustic monitoring data, as well as the number of C-PODS that need to be deployed, must to be improved in future studies.

7 Quality Assurance

Wageningen Marine Research utilises an ISO 9001:2008 certified quality management system (certificate number: 187378-2015-AQ-NLD-RvA). This certificate is valid until 15 September 2018. The organisation has been certified since 27 February 2001. The certification was issued by DNV Certification B.V.

Acknowledgements

We want to thank our Commissioners, Luuk Folkerts, of Gemini Windpark; Remment ter Hofstede, Bernard Westen and Heidi van der Meij, of Van Oord Dredging and Marine Contractors; and their scientific advisor, Ron Kastelein of SEAMARCO, for their cooperative, pleasant and critical interactive participation in this project and improvements to earlier versions of this report. The help of Sophie Brasseur, Piet Wim van Leeuwen, André Meijboom, Evert Mul, Jessica Schop, Hans Verdaat and Simon de Vries with the field work is also gratefully acknowledged.

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9 Appendix: Passive acoustic monitoring Results

9.1 Fieldwork

Two CPODs were placed permanently throughout the entire study period at the (yellow) pole to which the research vessel Zilvervis was moored for FaunaGuard experiments and at a second (green) pole, located near the Texel TESO harbour from 26 February until 25 April. Five other CPODs were deployed at increasing distances from the FG-PM for the duration of individual observation sessions (Figure 1). The coordinates of the CPOD locations are given in table 2.

Table 2. Coordinates of CPOD locations. *P* are the permanent CPODs and *T* are the temporary CPODs.

CPOD	Perm./Temp.	Latitude	Longitude	Distance to FG (m)	Comments
1	P	52°59'39.68	4°46'22.41	0	Yellow pole
2	T	52°59'27.72	4°46'04.34	500	
3	T	52°59'15.70	4°45'46.14	1000	
4	T	52°59'03.88	4°45'28.20	1500	
5	T	52°59'07.09	4°44'49.78	2000	
6	P	53°00'00.00	4°47'00.00	942	Green pole
7	T	52°59'34.309	4°46'17.10	581	

Data processing

After recovery of the CPODs, the raw data were downloaded onto a PC. Version 2.024 of the software CPOD.exe (Chelonia, UK) was used to analyse the data. During validation, doubtful data were disregarded. Data were considered doubtful if:

- 1) the total duration of the retrieved data did not match the total duration recorded by the observers;
- 2) the timing (actual time and duration) of deployment periods did not match the recorded times;
- 3) the interval between subsequent deployments did not match.

Harbour porpoise echolocation click(train)s were extracted from the background noise using an algorithm that filters out non-porpoise clicks such as cavitation noise from boat propellers, echo sounder signals, and similar high frequency noise. The CPOD software used a KERNO classifier to do this. The settings for the classifier were the same as used in previous wind farm studies (e.g., Geelhoed et al., 2015).

Analysis of harbour porpoise acoustic activity as proxy for porpoise's presence is based on the fundamental unit of clicks-per-minute. This consists of many zero observations (minutes without click trains), as well as porpoise positive minutes (minutes with click trains).

9.2 Passive acoustic monitoring

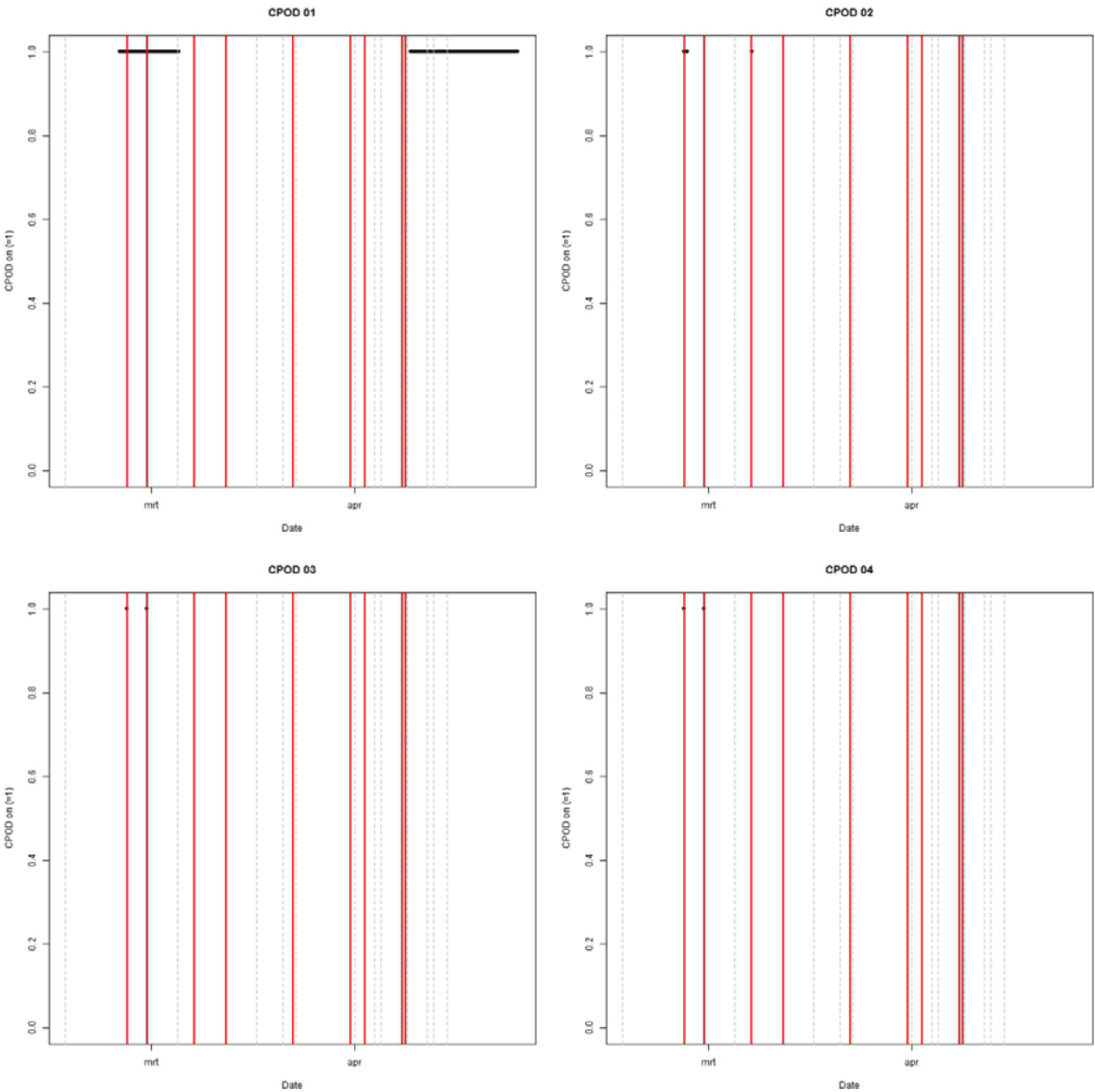
9.2.1 Effort

Between 26 February and 25 April 2016 the CPODs collected data during 2351 hrs. The permanent CPODs 01 and 06 collected the majority of the data (2240 hours between them). CPOD 06, near the TESO harbour, collected data for the whole period, but CPOD 01, near the FG-PM, showed a gap in

recorded data between 5 March and 9 April. The CPODs 02, 03 04, 05, and 07 were deployed only during the exposure and control experiments and this repeated handling of the CPODs and retrieving and deploying them without switching them off apparently has led to major loss of data. Apart from CPOD 07 which was deployed in March and April and collected data during all experiments within these months, the other temporary CPODs did not function properly and recorded data during a few experiments. CPODs 02, 03, and 04 recorded data in February, whilst CPOD 05 collected data in February and in the last 10 days of April (Table 3, Figure 9).

Table 3. CPOD recordings during FG-PM exposure experiments. N/A CPOD not deployed.

Date	01	02	03	04	05	06	07
26-Feb	+	+	+	+	+	+	N/A
29-Feb	+	-	+	+	+	+	N/A
7-Mar	-	+	-	-	-	+	+
12-Mar	-	-	-	-	-	+	+
22-Mar	-	-	-	-	-	+	+
31-Mar	-	-	-	-	-	+	+
2-Apr	-	-	-	-	-	+	+
8-Apr	-	-	-	-	+	+	+
8-Apr	-	-	-	-	+	+	+



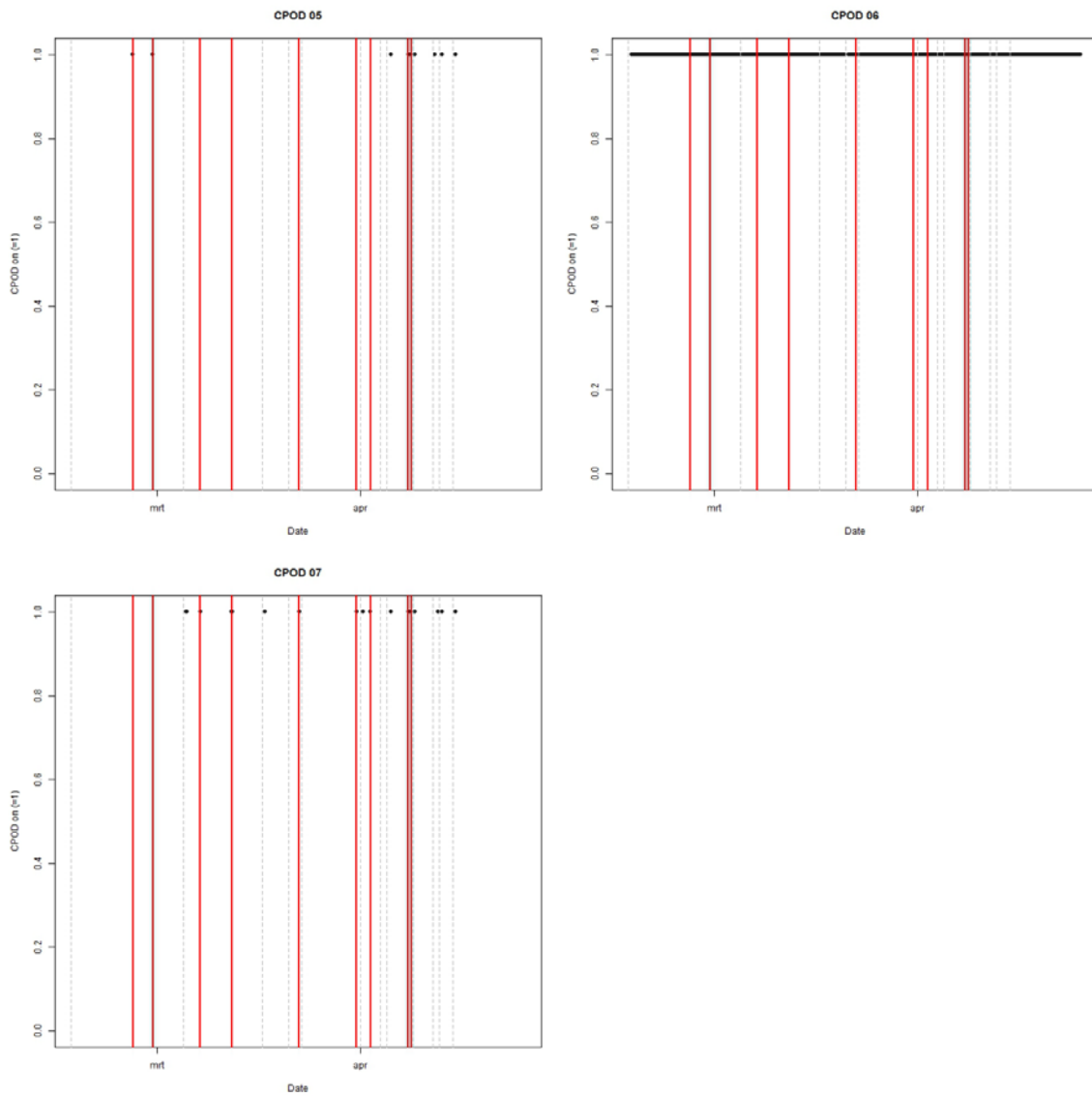


Figure 9. Recordings per CPOD. Horizontal black lines represent CPOD recordings. Red lines represent FG-PM exposure experiments, dotted lines control experiments.

9.2.2 Results

Porpoises were detected daily during the entire study period. Acoustic activity fluctuated daily. It was lowest and irregular in February and increased gradually towards the end of April (Figure 10).

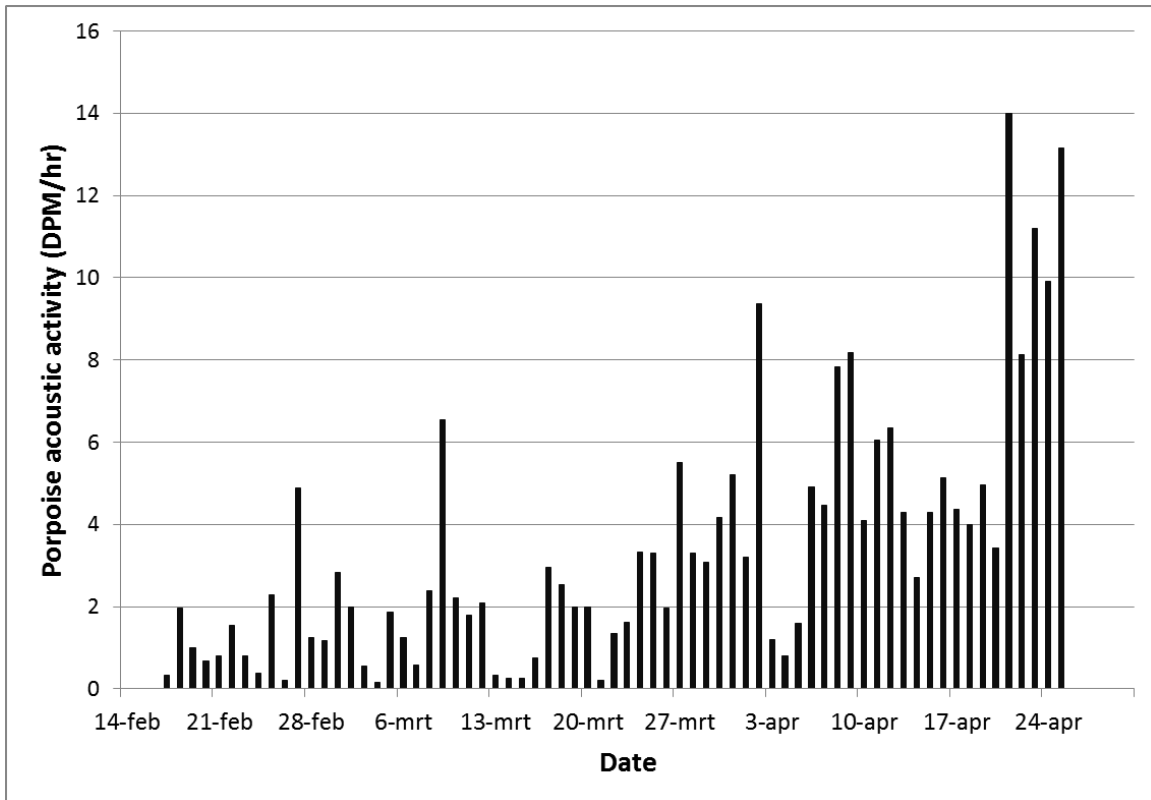


Figure 10. Seasonal pattern in the recordings of harbour porpoise acoustic activity in the Marsdiep area as detected by permanent CPOD 06 (near the TESO harbour at Texel, at 942 m from the FG-PM). Acoustic activity is expressed as hourly detection positive minutes per day.

The results of the FG-PM exposure experiments are shown in Figures 11-17. CPOD 01 collected acoustic data during two exposure experiments. On 26 February the FG-PM was turned on whilst porpoises were detected by the CPOD. Acoustic activity ceased initially but was detected again in the last minutes of the exposure period and continued post-exposure. On 29 February no porpoise activity was detected for a longer time span during pre-exposure, exposure and post-exposure period.

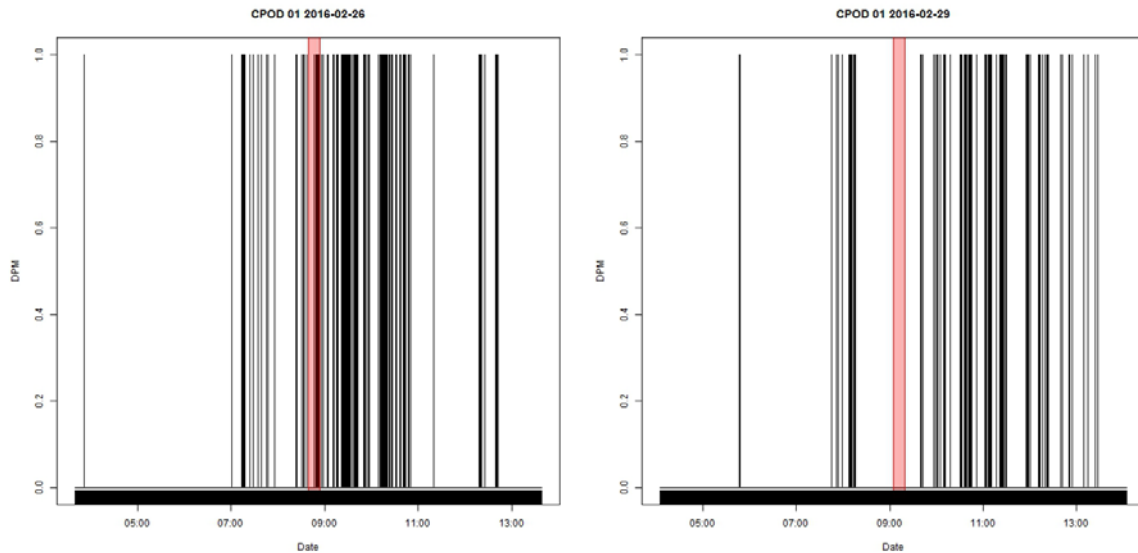


Figure 11. Acoustic activity of harbour porpoises (black lines) during FG-PM exposure experiments (red column), CPOD 01.

CPOD 02, at 500 m from the FG-PM, showed different patterns during exposure experiments on 26 February and 7 March. During the first experiment porpoise activity was not detected in the pre-exposure and exposure period, whilst some acoustic activity was recorded post-exposure. On 7 March acoustic activity was recorded during pre-exposure, exposure and post-exposure. During the first seven minutes of exposure three porpoise positive minutes were recorded. No acoustic activity was detected in the remainder of the exposure period (figure 12).

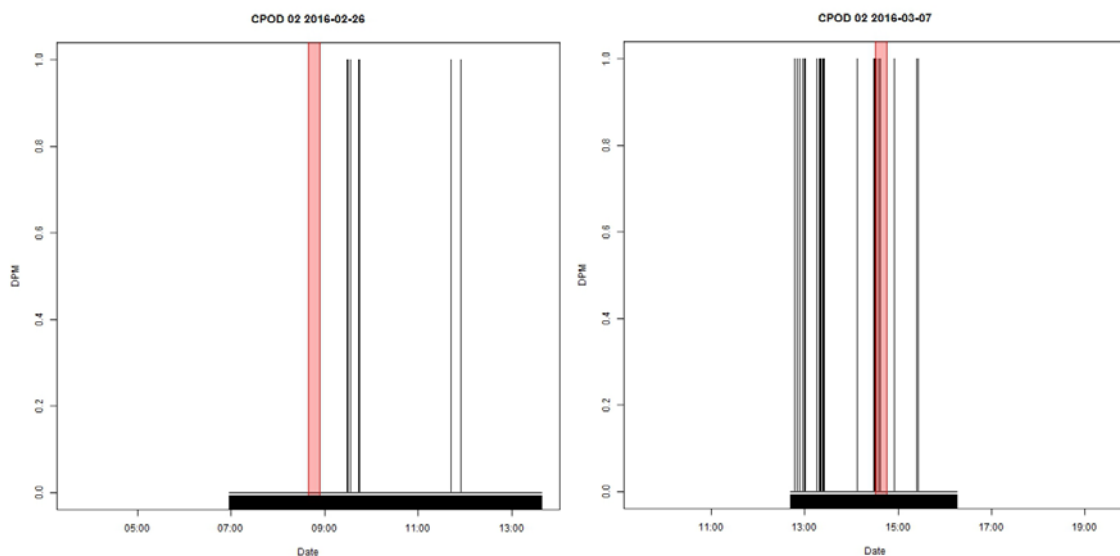


Figure 12. Acoustic activity of harbour porpoises (black lines) during FG-PM exposure experiments (red column), CPOD 02.

CPOD 03, at 1000 m from the FG-PM, showed the same patterns during exposure experiments on 26 and 29 February: acoustic activity was detected during pre-exposure, and none during exposure and post-exposure (figure 13).

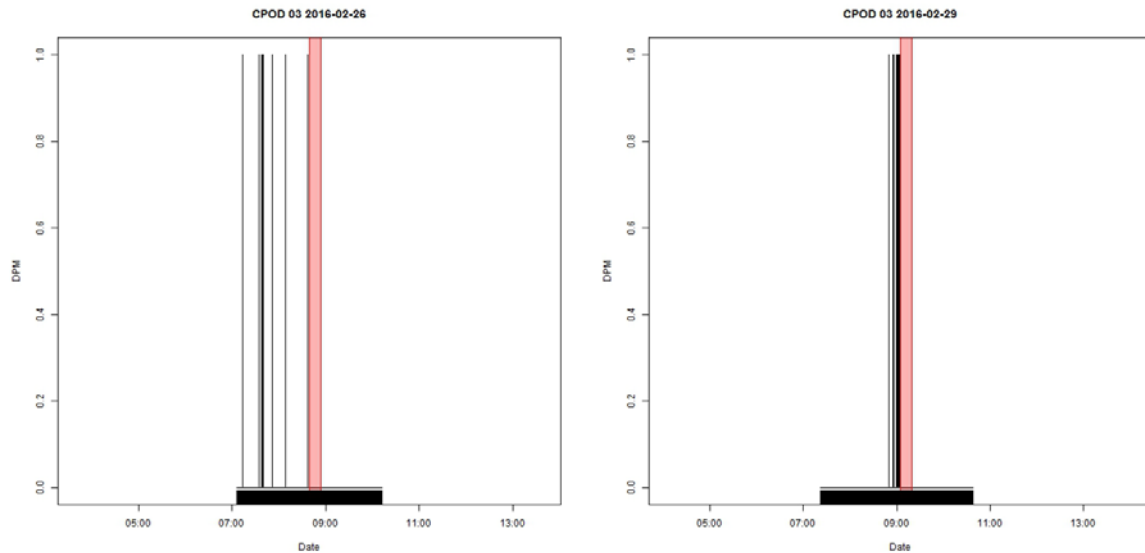


Figure 13. Acoustic activity of harbour porpoises (black lines) during FG-PM exposure experiments (red column), CPOD 03.

CPOD 04, at 1500 m from the FG-PM, showed acoustic activity on 26 February during pre-exposure, and none during exposure and post-exposure. On 29 February acoustic activity was detected during pre-exposure, and during exposure (figure 14).

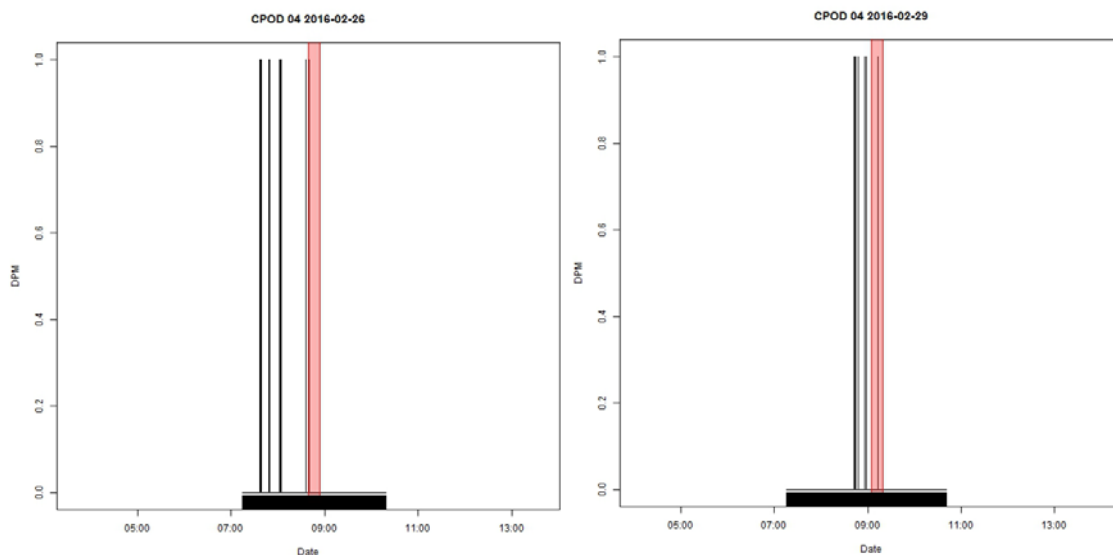


Figure 14. Acoustic activity of harbour porpoises (black lines) during FG-PM exposure experiments (red column), CPOD 04.

CPOD 05, at 2000 m from the FG-PM, never detected porpoise acoustic activity during exposure. Porpoise clicks were recorded both on 26 and 29 February, during pre-exposure and on 26 February also during post-exposure. No porpoise acoustic activity was found on 8 April (figure 15).

CPOD 06 detected acoustic activity during pre-exposure and post-exposure experiments on 26 and 29 February, 7, 12, 22 and 31 March, and 2 and 8 April. With the exception of 8 April no porpoise activity was detected during exposure (figure 16).

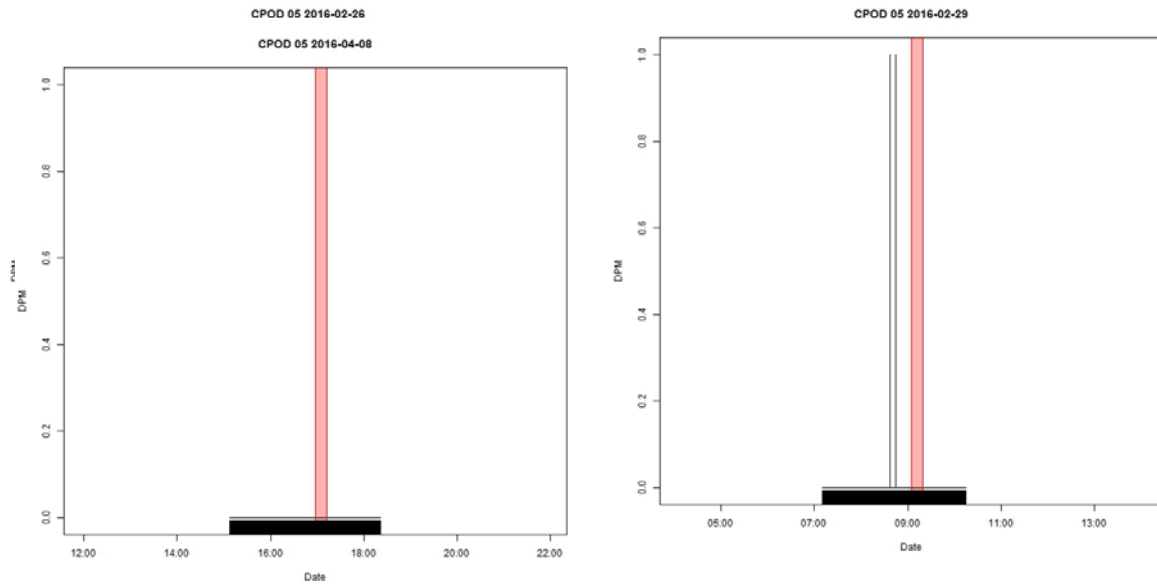


Figure 15. Acoustic activity of harbour porpoises (black lines) during FG-PM exposure experiments (red column), CPOD 05.

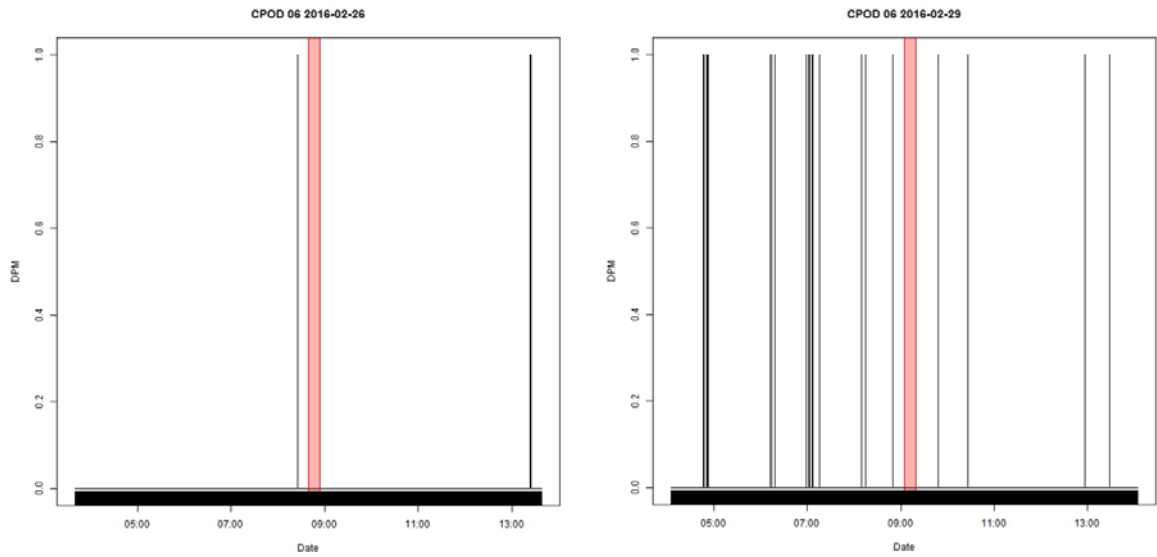


Figure 16. Acoustic activity of harbour porpoises (black lines) during FG-PM exposure experiments (red column), CPOD 06.

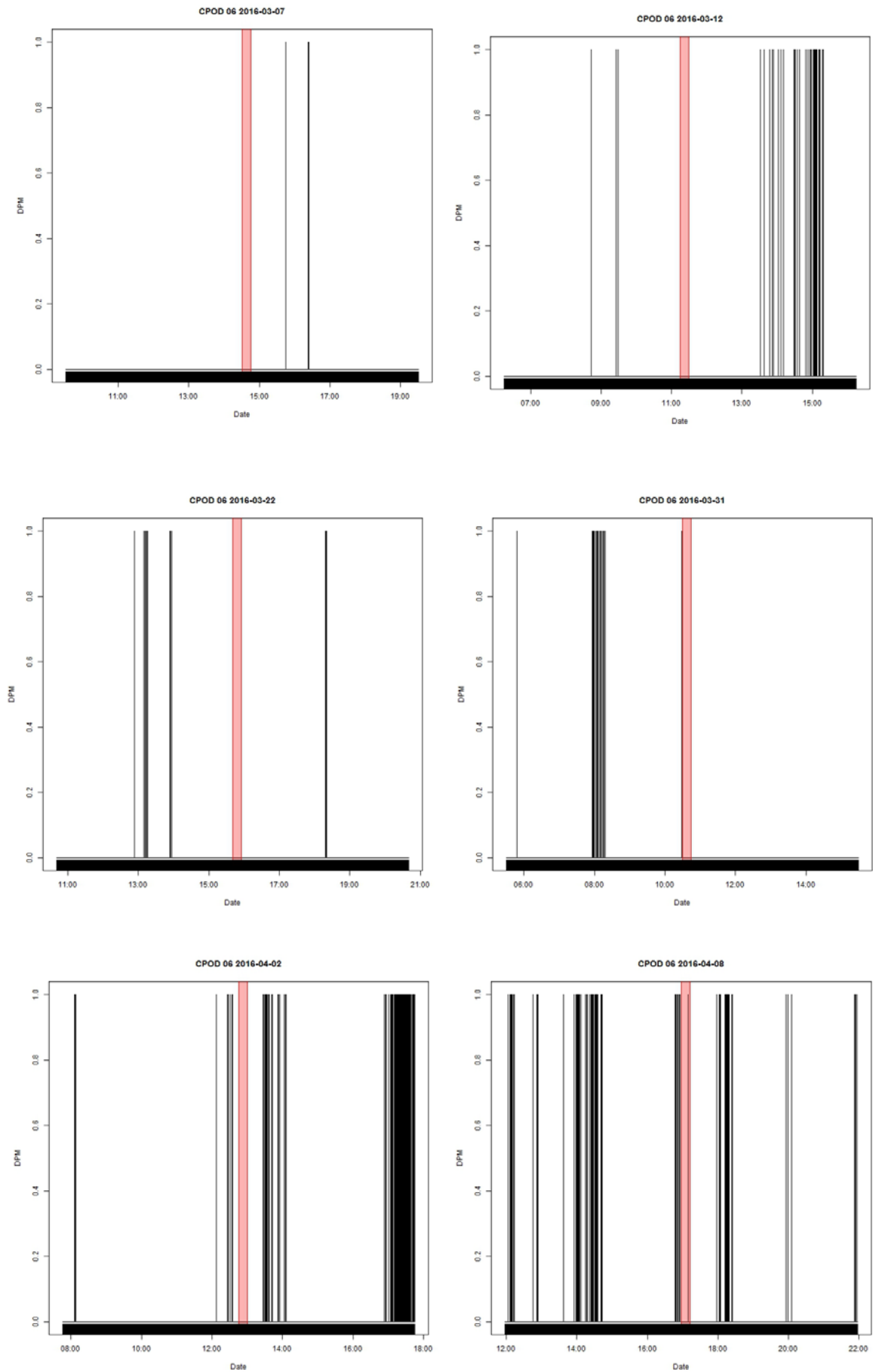


Figure 16 continued. Acoustic activity of harbour porpoises (black lines) during FG-PM exposure experiments (red column), CPOD 06.

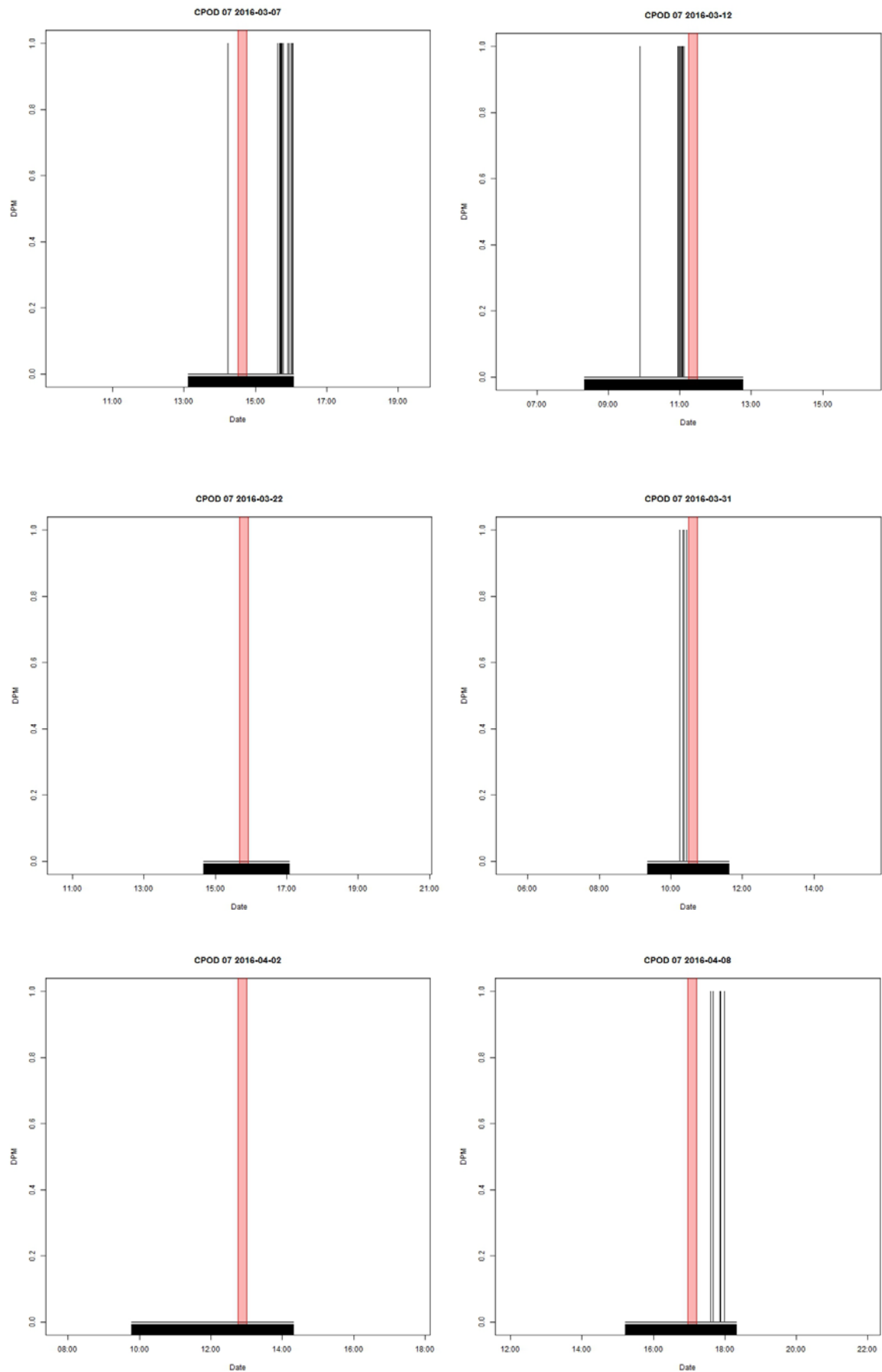


Figure 17. Acoustic activity of harbour porpoises (black lines) during FG-PM exposure experiments (red column), CP0D 07.

CPOD 07 showed different patterns during exposure experiments on 7, 12, 22 and 31 March, and 2 and 8 April. No acoustic activity was detected during exposure (figure 17).

Five of the seven CPODs (01 to 05) recorded acoustic data during 2 out of 10 FG-PM experiments, whilst two CPODs (06 & 07) recorded acoustic data during almost every FG-PM experiment (table 3). During the FG-PM experiments the FG exposure started when a porpoise was observed in the vicinity of the FG-PM/CPOD 01. This makes it feasible that CPOD 01 could record porpoise activity before the FG-PM is turned on, and possibly during ramp-up if not all porpoises swim away from the FG-PM immediately. CPODs at distances between 500 and 1000 meters could record porpoise activity during ramp-up and possibly during early full exposure, of animals swimming past these devices, while CPODs at greater distances could record porpoise clicks at any moment in time. Given the densities of porpoises in the study area, any CPOD could also record no activity during any phase of any experiment. Most importantly, therefore, CPOD 01 should never record porpoises after ramp-up and CPODs 01, 02, 07, 06 and 03 (in order of increasing distance to the FG-PM) should not record porpoise presence in their vicinity during full exposure. This makes a comparison of pre-exposure, exposure and post-exposure situations challenging. Most CPOD data are not in disagreement with expectations, but porpoise clicks were logged by CPOD 01 during exposure at 26 February and during ramp-up at CPOD 02 at 7 March and during full exposure at CPOD 06 at 8 April.

9.3 Understanding of acoustic monitoring result

Most of the acoustic monitoring data during FG-PM exposure experiments that were considered usable were not in disagreement with the results of the visual observations. During ramp up to full power (3 mins) not all porpoises are expected to swim away immediately from the sound source. Animals situated very close to the FG-PM may experience deterring noise levels sooner than animals further away from the FG-PM. Initially, animals in the vicinity of the FG-PM may even turn their heads towards the device, to investigate. This could explain some of the porpoise detections made by CPOD 01, situated right next to the FG-PM, during ramp up (Figure 11). However, later detections by this CPOD, with the FG-PM at full power cannot easily be explained. At that stage, animals should be swimming away from the device, which would render detections, especially at larger distances, impossible. Two possible explanations may be offered. The first is, that the times of this CPOD were slightly off, and that these detections were in fact outside the window with the FG-PM turned on at full power. The other explanation would be that the detections were false positives. Both explanations cast doubt on the overall results gained from the CPODS. Note that no porpoises were ever visually detected in the vicinity of the FG-PM when the device was active, neither by the observers on land, nor by the crew on the research vessel and no animals were ever captured by video at those times. Any animal still present in close proximity to the FG-PM must therefore have been under water for a long time, or must have moved East or West, out of the field of vision (Figure 1). To be detected by the CPOD 01, they should have been facing the FG-PM, while in order to surface at nearly a kilometre away a few minutes later, they should rather have been swimming away fast. Therefore, the 'detections' logged by CPOD 01 with the FG-PM active at 26 February are probably not genuine.

Other CPODS, situated further away from the FG-PM could, theoretically detect porpoise clicks longer, as animals fleeing from the active FG-PM could pass such a CPOD on their way to less noisy areas. However, note that usually only a single porpoise, or pod of porpoises was used to start the experiment and such animals could flee in any direction. Detection probabilities of these animals by CPOD 02 (at 500 m), CPOD 03 (at 1000 m), CPOD 06 (at 942 m) or CPOD 07 (at 581 m) were thus low. Few detections were made by these CPODS during FG-exposures, which is probably what was to be expected.

Also detections at CPOD 04 (at 1500 m) and CPOD 05 were as expected, with detections during all phases of the experiments. With porpoises probably not fleeing (much) beyond 1000 m, animals may have lingered at such distances from the FG-PM, or they were simply not affected by the FG-PM sounds at that location, as the received SPL will have been low.

Justification

Report C076/17

Project Number: 4312100027

The scientific quality of this report has been peer reviewed by a colleague scientist and a member of the Management Team of Wageningen Marine Research

Approved: Dr. ir. T.P. Bult
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Wageningen Marine Research is the Netherlands research institute established to provide the scientific support that is essential for developing policies and innovation in respect of the marine environment, fishery activities, aquaculture and the maritime sector.

Wageningen University & Research:

is specialised in the domain of healthy food and living environment.

The Wageningen Marine Research vision

'To explore the potential of marine nature to improve the quality of life'

The Wageningen Marine Research mission

- To conduct research with the aim of acquiring knowledge and offering advice on the sustainable management and use of marine and coastal areas.
- Wageningen Marine Research is an independent, leading scientific research institute

Wageningen Marine Research is part of the international knowledge organisation Wageningen UR (University & Research centre). Within Wageningen UR, nine specialised research institutes of the Stichting Wageningen Research Foundation have joined forces with Wageningen University to help answer the most important questions in the domain of healthy food and living environment.
