



UNDERWATER NOISE FROM THE DRILLSHIP STENA FORTH IN DISKO WEST, BAFFIN BAY, GREENLAND

NERI Technical Report no. 838 2011

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Line Anker Kyhn
Jakob Tougaard
Signe Sveegaard



Data sheet

Series title and no.: NERI Technical Report No. 838

Title: Underwater noise from the drillship Stena Forth in Disko West, Baffin Bay, Greenland

Authors: Line A. Kyhn, Jakob Tougaard & Signe Sveegaard
Department: Department of Arctic Environment

Publisher: National Environmental Research Institute ©
University of Aarhus - Denmark
URL: <http://www.neri.dk>

Year of publication: June 2011
Editing completed: May 2011
Referee: Professor Peter Teglberg Madsen, Aarhus University

Financial support: Bureau of Minerals and Petroleum, Government of Greenland.

Please cite as: Kyhn, L.A., Tougaard, J. & Sveegaard, S. 2011: Underwater noise from the drillship Stena Forth in Disko West, Baffin Bay, Greenland. National Environmental Research Institute, Aarhus University, Denmark. 30 pp. – NERI Technical Report No. 838. <http://www.dmu.dk/Pub/FR838.pdf>

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Keywords: Underwater noise, oil and gas, drillship, environmental impact.

Layout: NERI Graphics Group, Silkeborg

Cover photo: Signe Sveegaard

ISBN: 978-87-7073-248-2
ISSN (electronic): 1600-0048

Number of pages: 30

Internet version: The report is available in electronic format (pdf) at NERI's website <http://www.dmu.dk/Pub/FR838.pdf>

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Preface

This report was commissioned by the Government of Greenland, Bureau of Minerals and Petroleum. The recordings were undertaken in cooperation with the Bureau of Minerals and Petroleum and Capricorn Greenland Exploration 1 Limited, Edinburg, Scotland and financed jointly by the two parties. The report present results from underwater noise recordings from the drillship *Stena Forth* during operation in Baffin Bay, NW of Disko Island in September 2010. The report is accompanied by a separate, brief evaluation of the potential effects of the Stena Forth noise emissions on marine mammals in the area.

Summary

Capricorn Greenland Exploration 1 Limited made the first drillings for oil in Greenland in the license block *Sigguk* in summer-autumn 2010. To accurately assess the effect a drill operation may have on the surrounding environment, the emitted noise levels must be taken into account, since noise potentially may affect marine life, such as fish, seals and whales. NERI was therefore asked to make sound recordings in order to quantify the emitted noise from the drill ship *Stena Forth* during operation.

The recordings represent a random sample of the noise emitted by *Stena Forth* during both active drilling and during maintenance activities on the drillship. The noise levels were recorded at two depths and at distances from 500 m to 38 km from the rig. Ambient noise recordings were made at a distance of 316 km from *Stena Forth* and 211 km from the semisubmersible *Stena Don*.

Both drilling and maintenance noise were readily discernable underwater, and resulted in marked increases in sound pressure levels throughout the entire frequency spectrum 20 Hz to well above 10 kHz and with clearly discernible peaks below 500 Hz out to 38 km from the rig. The *Stena Forth* is thus a substantial noise source in Baffin Bay both during maintenance work in relation to typical vessel types and during drilling where the source level corresponds to that of a large tanker.

Naalisagaq

Capricorn Greenland Exploration 1 Limited-ip Kalaallit Nunaanni uuliasiorluni qillerinerit siulliit akuersissuteqarfimmi *Siggummi* ingerlappai 2010-mi aasakkut ukiakkullu. Uuliasiornerup avatangiisinut sunniutai nalilersorneqarsinnaassappata qillerinerup nalaani nipiliornerup qanoq annertutiginnissaa ilisimasariaqarpoq. Tamatumunnga pissutaavoq nipi immami uumasunut, pingaartumik aalisakkanut, puisinut arfernullu, ajoqutaasinnaamat. Taamaattumik DMU umiarsuup qilleriffiusup *Stena Forth*-ip qillerinerata nalaani nipiliornermik immiusseqqullugu qinnuigineqarsimavoq.

Nipimik immiussinerit taakkua nipit *Stella Forth*-ip qillerinerani aammalu aserfallataaliilluni umiarsuarmi sulinermit immiutaapput sorliit immiunneqarnissaat siumut aalajangerteernagu. Pisorpaluk itissutsini ungasissutsinilu assigiinngitsuni marlunni 500m aamma 38 km umiarsuaq qillerivik qimallugu immiunneqarpoq. Nipi ungataaniittoq immiunneqarpoq *Stena Forth* qimallugu aamma qilleriveqarfik *Stena Don* 211 km qimallugu.

Qillerinermi aserfallatsaaliinermilu nipiliorneq immap iluani erseqqissorujussuovoq frekvensspekterimilu 20 Hz-imiit 10 kHz-imut erseqqissunik nipitunerpaaffeqartarluni 500 Hz ataallugu sakkortussusilinnik. Taamaalilluni *Stena Forth* Qeqertarsuup Tunuani qarsupiinnagassaanngitsumik nipiliorfiuvoq immakkut angallannermi nipiliornerusartumit nipitunerulluni aserfallatsaalilluni sulinermi qillerinermilu nipiliorneq uuliamik assartuuterujussuup nipiliorneratut sakkortussuseqartarluni.

Resume

Capricorn Greenland Exploration 1 Limited lavede de første prøveboringer efter olie i Grønland i licensblokken *Sigguk* i sommeren og efteråret 2010. For at kunne vurdere virkninger for miljøet af olieefterforskning kræver det, at man tager højde for den støj, der udsendes under boreoperationen. Det skyldes, at støj kan have negative effekter for det marine liv, i særdeleshed for fisk, sæler og hvaler. DMU blev derfor bedt om at lave lydoptagelser under boringerne udført af boreskibet *Stena Forth*.

Optagelserne repræsenterer et tilfældigt udvalg af den støj *Stena Forth* udsendte både under boring og vedligeholdelsesaktiviteter på boreskibet. Støjen blev optaget i to dybder og på afstande mellem 500 m og 38 km fra boreskibet. Baggrundsstøj blev optaget på en afstand af 316 km fra *Stena Forth* og 211 km fra boreriggen *Stena Don*.

Både borestøj og støj fra vedligeholdelsesarbejdet var tydeligt under vandet og gav sig til udtryk som forøgede lydtryk over hele frekvensspektret fra 20 Hz til over 10 kHz med tydelige toppe under 500 Hz. *Stena Forth* er altså en betydelig støjkilde i Baffinbugten, hvor kildestyrken er højere end almindelig skibstrafik under vedligeholdelsesarbejde og under boring hvor kildestyrken svarer til en stor tanker.

1 Introduction

Very few studies have been published on the underwater noise emitted during drilling operations (Greene 1987; Richardson et al. 1990; Hall and Francine 1991; Blackwell et al. 2004; Blackwell and Greene 2006) and of these, only two reports on the noise levels emitted from drillships (Greene 1987; Richardson et al. 1990). Since oil exploration noise generally contain most energy at low frequencies (Richardson et al., 1995), it attenuates little with distance, and the ranges out to which drill operation noise is above the background noise levels is thus potentially very large. To accurately assess the effect a drill operation may have on the surrounding environment, the emitted noise levels must be taken into account. Underwater sound recordings of the drilling operations taking place in West Greenland are therefore highly needed for evaluating the overall effect the operation may have on the environment and to answer the concerns raised by the Greenland Hunting Organisation, KNAPK, on the potential effects on marine mammals.

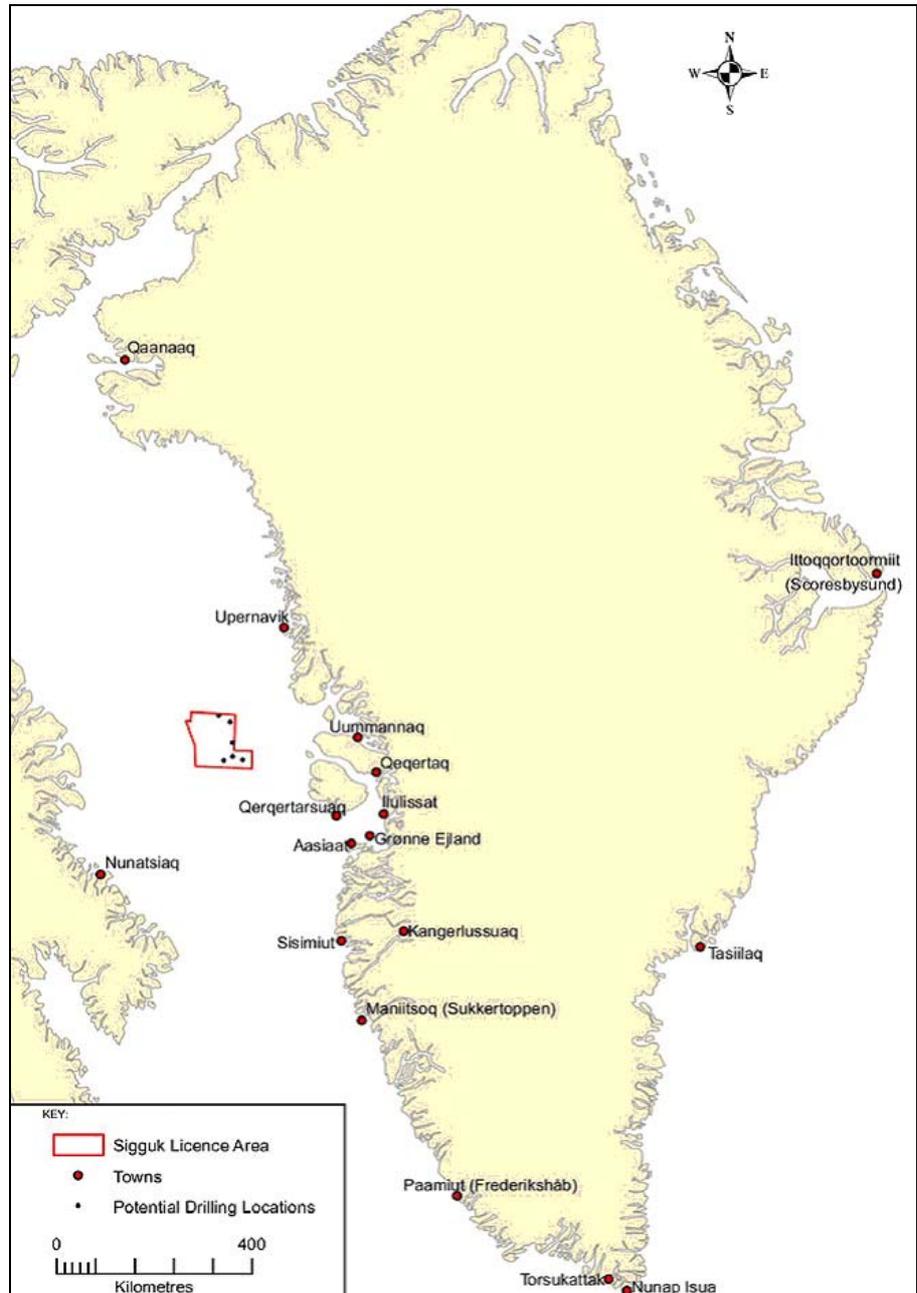
The effects of noise on marine mammals have been reviewed several times, among others Gales (1982); Richardson et al. (1995); National Research Council (2000; 2003; 2005); Hildebrand (2005) and Southall et al. (2007). Only a few studies have looked specifically at the actual and potential effects of drilling operation associated noise (excluding seismic surveys) on marine mammals (Richardson et al. 1985, 1987, 1990).

Recordings of noise from Stena Forth were made when weather permitted (sea state below 2) and no special actions were taken by the Stena Forth during recordings. The recordings as such thus represent a random sample of the noise emitted by Stena Forth, and by chance recordings were made during both active drilling and during maintenance activities on the drillship. The noise levels were recorded at two depths and at distances from 500 m to 38 km from the rig. Due to limiting weather conditions no recordings could be obtained from the semi-submersible rig Stena Don operating at the same time in the same area. Ambient noise recordings were made at a distance of 316 km from Stena Forth and 211 km from Stena Don.

Noise levels are reported both as broadband levels (5 Hz-44 kHz) and frequency-weighted levels (M-weighting, sensu Southall et al. 2007) for all classes (low-frequency cetaceans, mid-frequency cetaceans, high-frequency cetaceans and pinnipeds in water). The M-weighting is a frequency selective weighting of sound pressure or energy in a specific frequency band, with emphasis or de-emphasis on particular frequencies as a function of the estimated sensitivity of the particular species group to sound at those frequencies. Although the M-weighting relies on many unproven assumptions, it has quickly gained status as a de facto standard and is thus included for comparability with other recent studies.

2 Materials and methods

Figure 2.1. The Sigguk oil exploration block. Figure from the EIA (ERM 2010).



2.1 Stena Forth

Stena Forth (see picture on front cover) is a double hulled drillship from 2008 under Bermudan flag. Length overall is 228 m, 42 m wide and displacement 96,000 Mt. It is equipped with six 5,500 kW fixed pitch azimuth thrusters (Rolls Royce Aquamaster AQM UUC 455 L-Drive), sixteen drill motors and six 7,430 kW diesel generators (Wartsilla/16V32) (Specifications obtained from the Environmental Impact Assessment made by ERM consulting services). Stena Forth was positioned at location T-4 (71°7' 45"N 59°54'10" W) in the Sigguk oil exploration block in

Baffin Bay, located approx. 175 km west of Disko Island, Greenland (figure 1). The depth to seabed at the site is 484 m. Further specifications of the site can be found in the Environmental Impact Assessment made for the project (ERM, 2010).

2.2 Recording chain

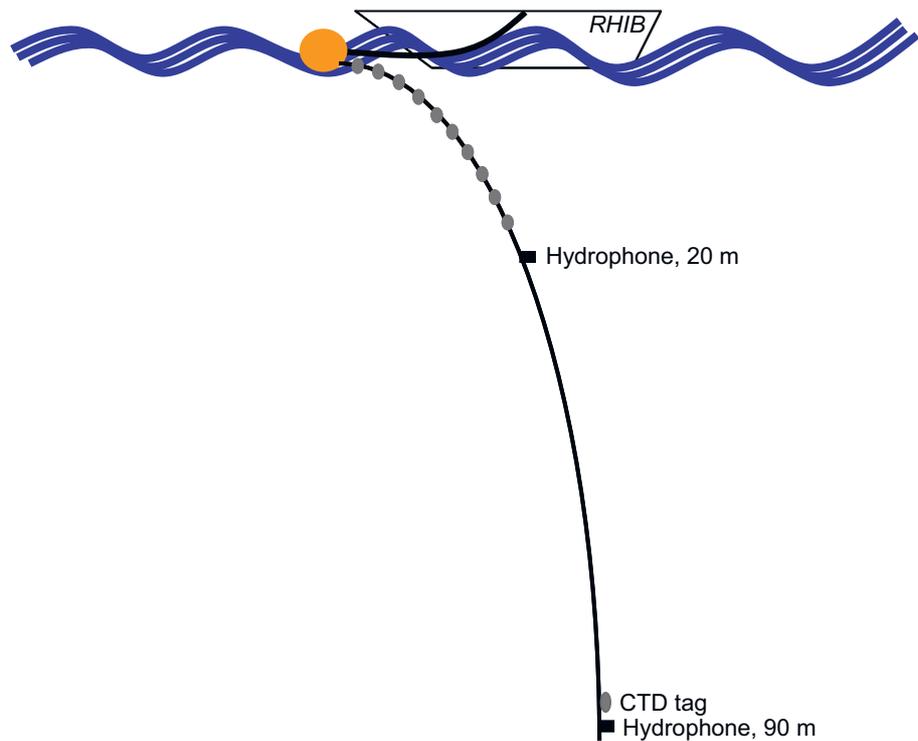
Recordings were made with a Reson TC 4032 hydrophone (Reson A/S, Slangerup, Denmark) (Serial number 4309034) with 100 m cable and a measured sensitivity of -174 dB re $1\text{V}/\mu\text{Pa}$ ($-/+ 2.5$ dB) between 10 Hz and 80 kHz. The signal was amplified and filtered through a custom-made amplifier box (20 or 40 dB gain, 10 Hz - 50 kHz band pass filter) and recorded on a linear PCM Recorder (Olympus LS-10). Recordings were made with a sample rate of 96 ksamples/s, 16 bit resolution. The recorded sound was monitored simultaneously by headphones during recordings. Notes were taken regarding various variations in the incoming sound. The hydrophone was calibrated and the recording chain tested before and after field recordings in Greenland. The calibration was made with a pistonphone standard sound source at 250 Hz (Brüel & Kjær 4223).

2.3 Recording procedure and setup

Recordings were made from a small rigid hull inflatable boat (RHIB), operated from a larger mother vessel (Esvagt Preventer). The hydrophone was suspended below the RHIB from a large buoy (Figure 2.2) with the hydrophone at either approx. 90-95 m or 20-25 m depth and weighted down by weights mounted below the hydrophone. Ten small trawl floats attached along the upper part of the cable acted as a spring to dampen motion caused by waves and swell. During recording the RHIB drifted with wind and current.

Recordings were made at approximate distances of 500 m, 1 km, 2 km, 4 km, 8 km, 16 km and 32 km distance from Stena Forth. The position of the RHIB was logged continuously by GPS and the distance to Stena Forth could be calculated afterwards. The position of the mother craft, Esvagt Preventer, and other ships in the area was also logged continuously by means of an AIS receiver connected on the bridge of Esvagt Preventer to a computer with *shipplotter* software (www.coaa.co.uk).

Figure 2.2. Recording set-up. Sound was recorded at 20-25m and 90-95 m depth. The hydrophone was suspended below a large and ten small boyos to prevent drag on the cables. A CTD tag was placed just above the hydrophone to record conductivity, temperature and depth. Weights kept the cables straight in the water. The squares mark the two hydrophone depths.



Support vessels are ubiquitous at drilling sites and therefore part of the general noise associated with drilling or oil production. Sound received at ranges of more than one km from the rig will therefore be composite sounds rather than sounds from the drilling operation per se (Greene, 1987), nevertheless we kept an effort to minimise the impact from other vessels on the recordings from Stena Forth. At least one support vessel was always standby near Stena Forth, the vessel *Esvagt Connector*. By agreement with the crew on *Esvagt Connector* the ship moved to the position furthest allowable from the Stena Forth in a direction to the far side of the recording RHIB, before recordings and remained stationed there during recordings. In the same fashion the mother craft *Esvagt Preventer* positioned itself as far from the recording RHIB as the Cairn safety personnel would allow and was always at least as far from the recording RHIB, as the RHIB were from the Stena Forth (up to eight km distance from Stena Forth and hereafter *Esvagt Preventer* remained at min eight km distance). The *Esvagt Preventer* is a normal standby vessel. During each recording session *Esvagt Preventer* stopped all engines for a few minutes in order to establish the possible impact of noise from *Esvagt Preventer* on the recordings from Stena Forth. During recordings all engines were stopped on the recording RHIB and echo sounders were not used.

Recordings were made at sea state 2 or below. Due to Cairn safety regulations recordings were only obtained during daylight hours.

2.4 Sound speed profile

Conductivity, temperature and depth were measured by means of a CTD tag (Star Oddi, DST-CTD tag, ID 5443) placed on the hydrophone cable a little above the hydrophone. The logger sampled once every second and a profile was made whenever the hydrophone cable was lowered

down/up. Sound velocity was calculated by the Leroy equation (Leroy 1969, in Urick 1983 p. 113).

2.5 Analysis

Individual recordings were analysed and a number of parameters extracted from each wav-file, as described below. All analysis was done in Matlab (Mathworks, inc. 2010R).

2.5.1 Received level

Expressed as rms (root mean square) pressure calculated over the entire duration of the file (up to 10 minutes).

2.5.2 M-weighted levels

Calculated based on directions in Southall et al (2007), appendix 1. Mean power density spectra (see below) were weighted with the curves provided by Southall et al. (2007) and total signal power found by summing the power of the weighted spectrum across the entire frequency range.

2.5.3 Power density spectra

Average power density spectra were estimated over 1 minute segments of each file. Averaging was by the Welch method (MatLab function `pwelch`), with FFT-size of 8192 and 50% overlapping Hann-windows.

2.5.4 Third-Octave band levels

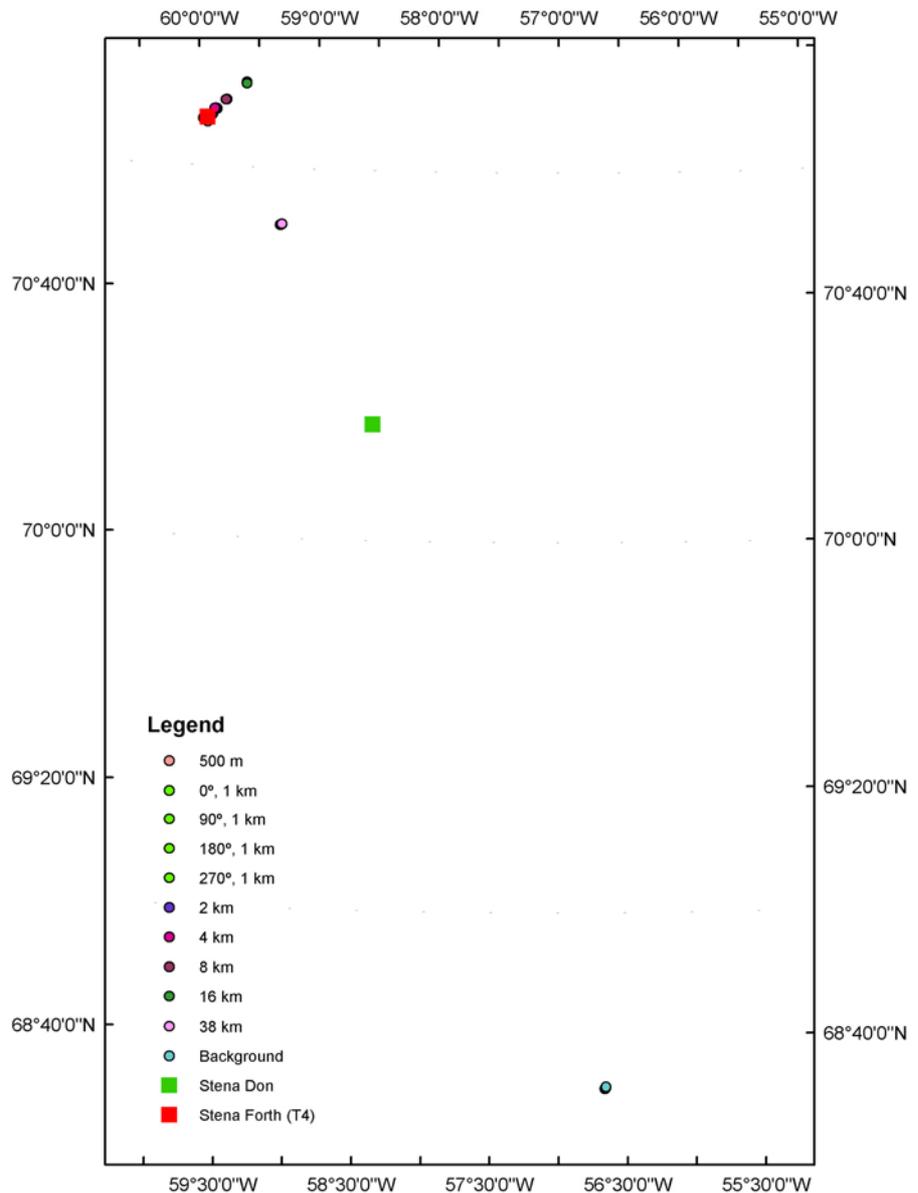
Third-octave band levels (TOLs) were calculated by the Matlab function `filtbank` (Christophe Couvreur, Faculte Polytechnique de Mons, Belgium), according to the ANSI S1.1-1986 standard. TOLs were calculated for non-overlapping segments each of 10 s duration.

3 Results

3.1 Recordings

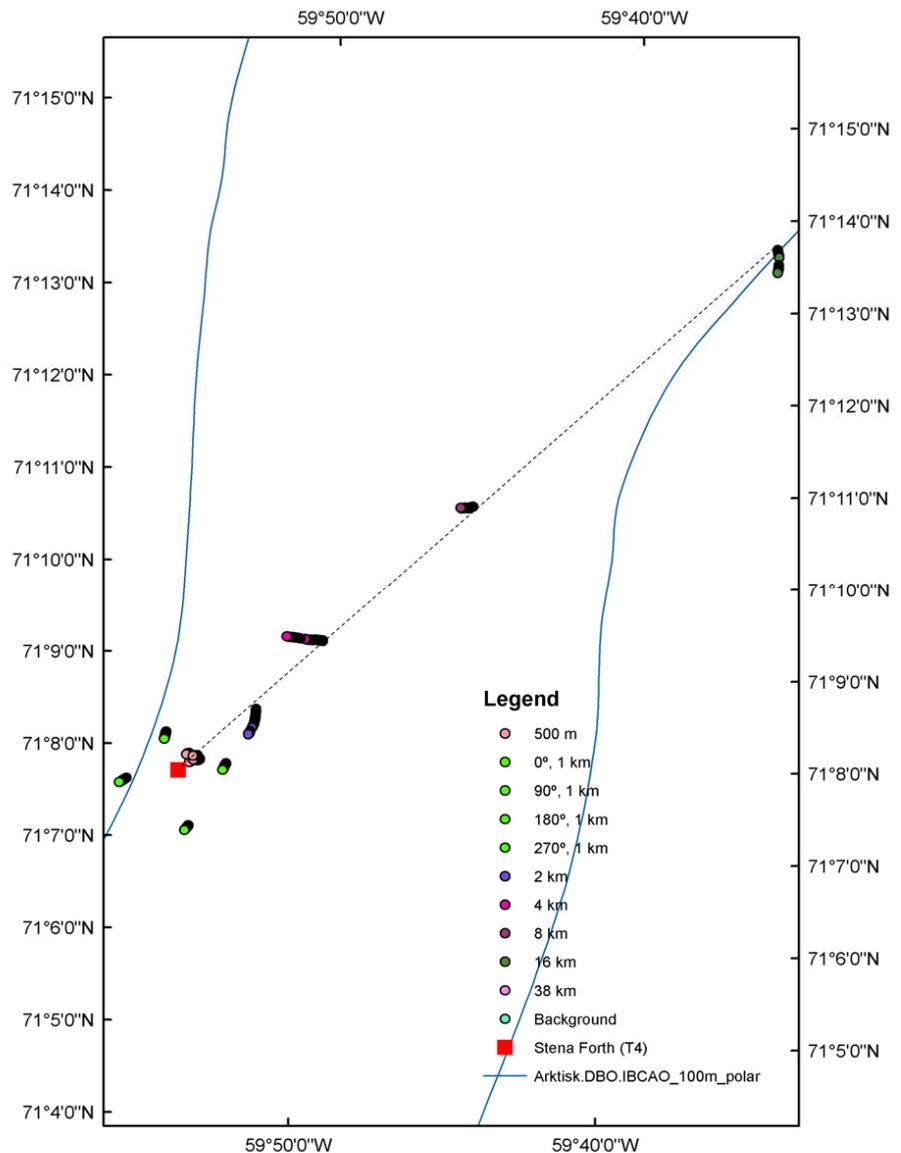
Nine days were available at the drilling sites (19-26th September), and of these, two days had sea state at or below 2, thus allowing for noise recordings. We recorded noise from Stena Forth on both days: On 19th September when the ship was drilling and on 24th September where various maintenance activities were conducted on board the ship. On 27th September we made background noise recordings at a site south of both Stena Forth and Stena Don (see Figure 3.1). Sea state was too high at all times when we were at the Stena Don site. Thus only recordings from Stena Forth were obtained.

Figure 3.1. Background noise recordings. Map of recording positions, Stena Forth and Stena Don.



We obtained between 10 and 50 min of recordings at each of the approximate distances 500 m, 1 km, 2 km, 4 km, 8 km, 16 km and 38 km distance from Stena Forth. For the shorter distances recordings were made along a line approximately perpendicular to the longitudinal axis of Stena Forth (abeam on port side). At the approximate distance of 1 km, noise was recorded around the drillship at four angles: 85°, 167°, 254°, 342° bearing from Stena Forth, relative to the midline of the ship (see Figure 3.2).

Figure 3.2. Map of recording positions and Stena Forth. The broken line indicates the original transect in the bearing 225° from the heading of Stena Forth (heading 165°). The dots mark GPS positions of the recording RHIB every 1 minute and show the drift of the RHIB. The depth to seabed at the location of Stena Forth is 484 m.



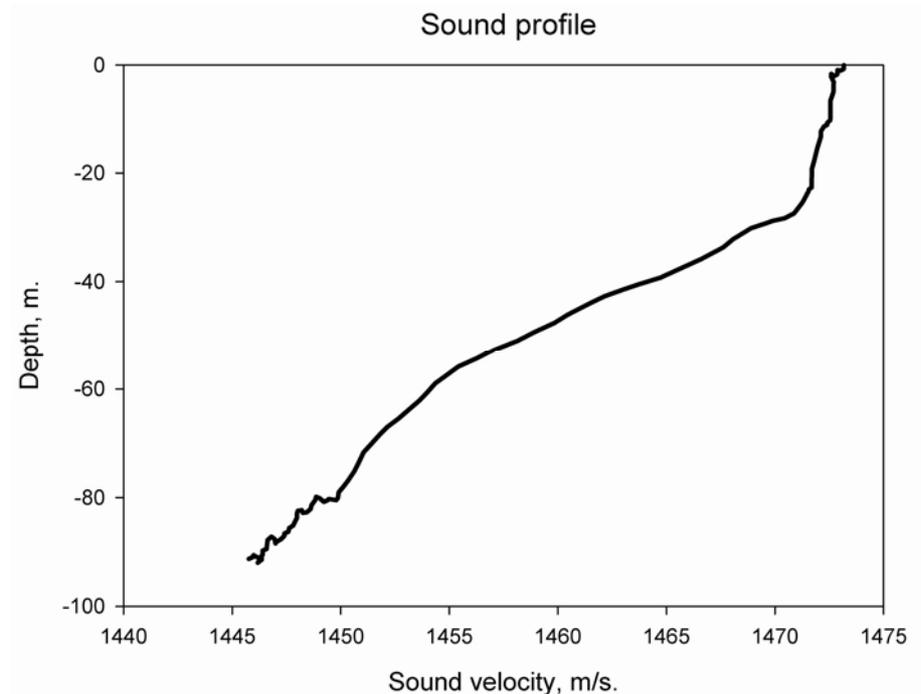
Recordings at each site were divided up into shorter files of up to 10 minutes duration in order to ease processing of the files afterwards and reduce the risk of loss of data due to failure of the recorder.

Recordings where more than 0.2% of samples were clipped were discarded. A number of recordings at the far distances were polluted by nearby ships and were also not included in analysis.

3.2 Sound profile

The sound profile was calculated from the CTD data obtained 16 km from Stena Forth. The Leroy equation was used (Leroy 1969, given in Urick 1983). The sound velocity profile closely matches the temperature gradient of the water column. In the top layer the water is mixed by wave actions and the water temperature is therefore constant with depth until app. 30 m where after the temperature drops steadily with depth (Figure 3.3).

Figure 3.3. Typical sound profile obtained from CTD data at 16 km distance from Stena Forth.



3.3 Received levels

Figure 3.4 shows received levels of noise as a function of distance from the drillship, recorded on two days with different activities (drilling and maintenance) and calculated using different frequency weighting functions. In general the received levels for maintenance activities were higher (taking distance into account) than noises associated with drilling and levels in general decreased with increasing distance from drillship, although with the recordings at 38 km as a pronounced exception. Source levels were estimated assuming spherical spreading using the mean received levels recorded at 500 m and 1 km for maintenance and drilling, respectively. During maintenance the estimates source level was 190 dB re 1 μ Pa rms and during drilling it was 184 dB re 1 μ Pa rms.

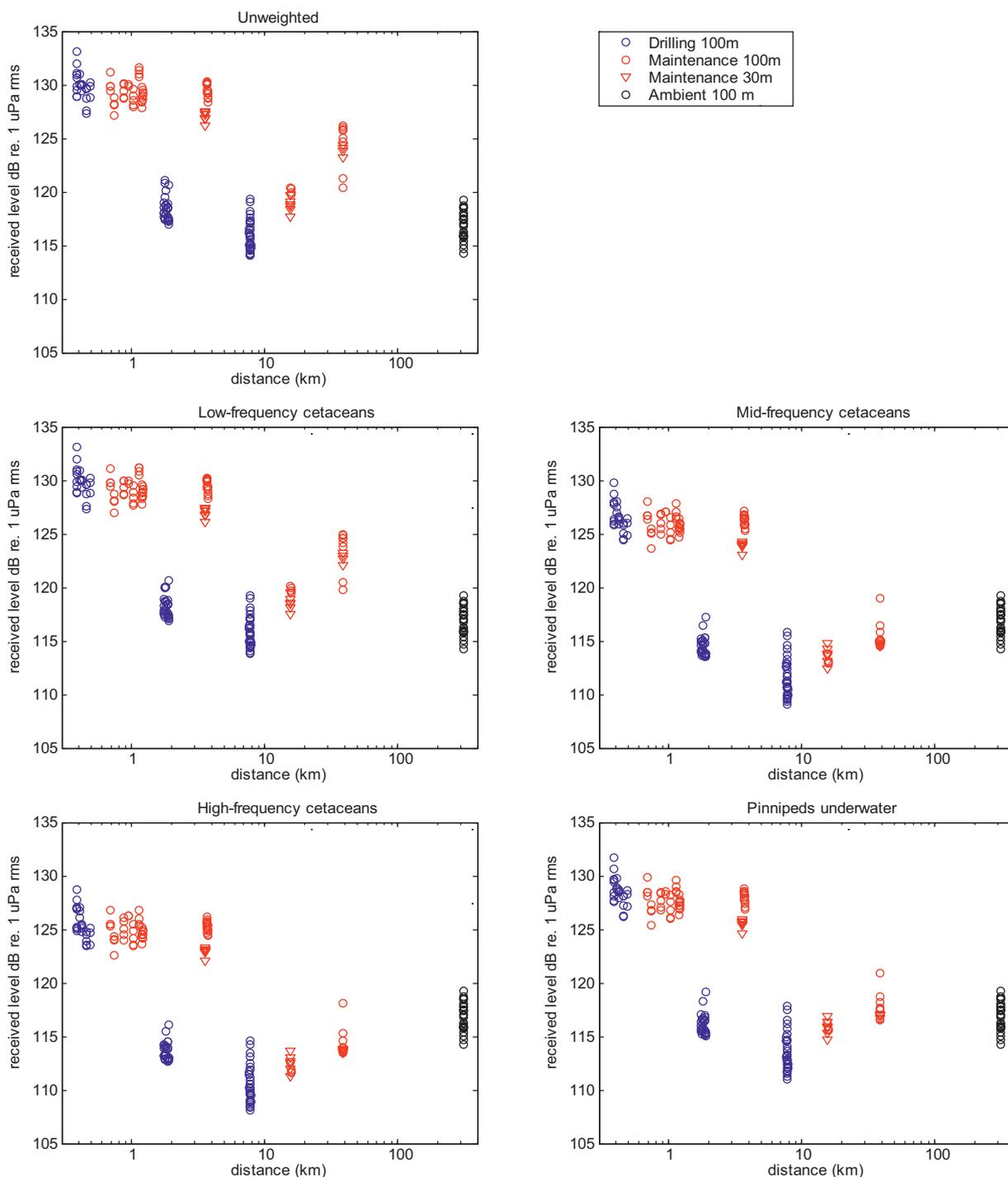


Figure 3.4. Received levels at different distances from the Stena Forth drillship during two different activities: active drilling and maintenance, September 2010. Each data point represents an average over a 1-minute recording period. Top left shows wide-band levels (10 Hz – 40 kHz), other figures show M-weighted levels, sensu Southall et al. (2007).

3.3.1 Spectral characteristics

Figure 3.5 shows one-third-octave band levels and power spectrum density levels from all recording distances and conditions. Elevated and range dependent levels were detectable across almost the entire frequency spectrum. During drilling elevated noise levels were detectable in the range from 100 Hz to well beyond 10 kHz at close range (0.5 km), decreasing to about 4 kHz at distances 2 km and 8 km. During maintenance levels were elevated from 20 Hz to well above 10 kHz at all distances up to and including 38 km from Stena Forth. There were different

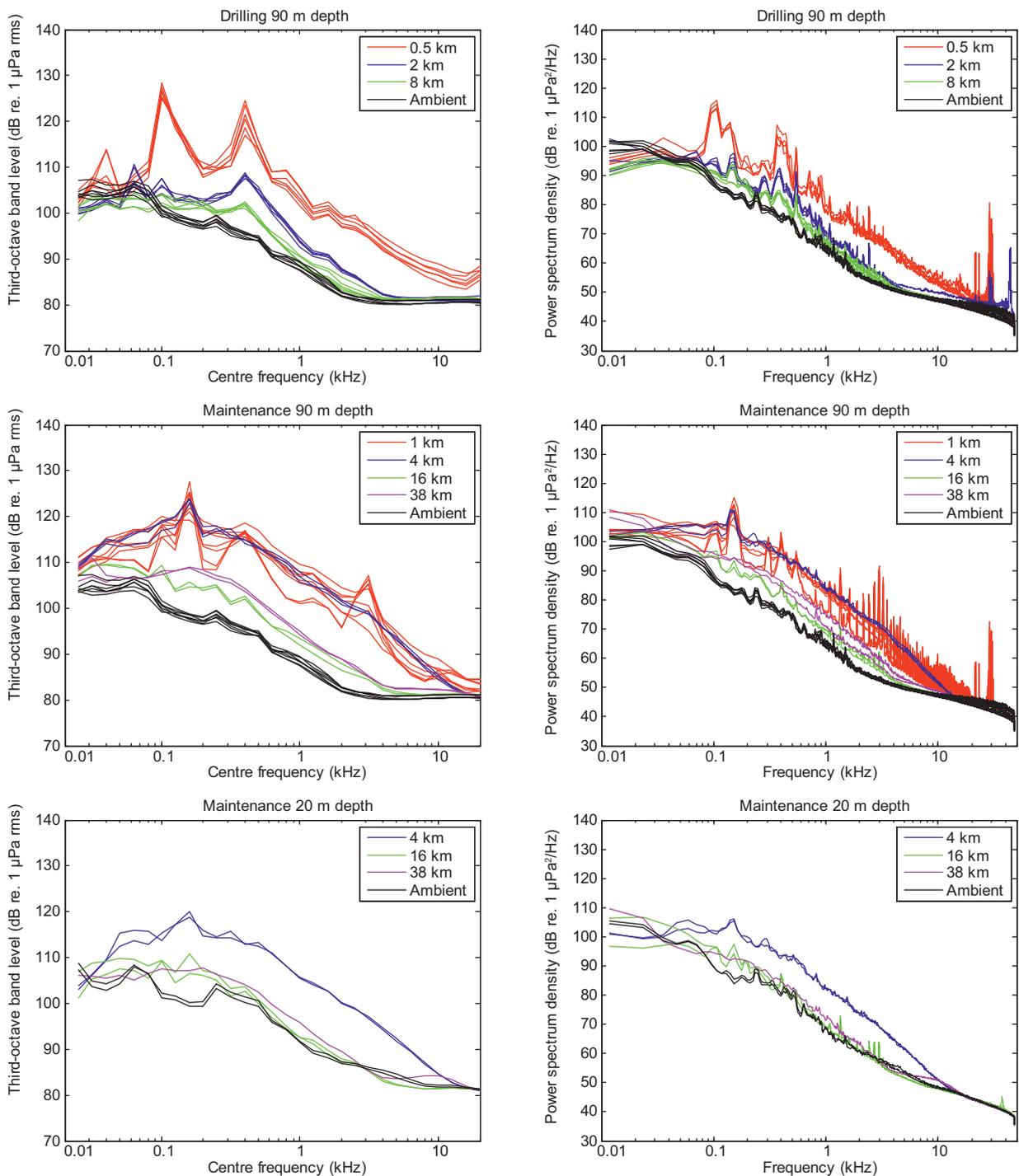
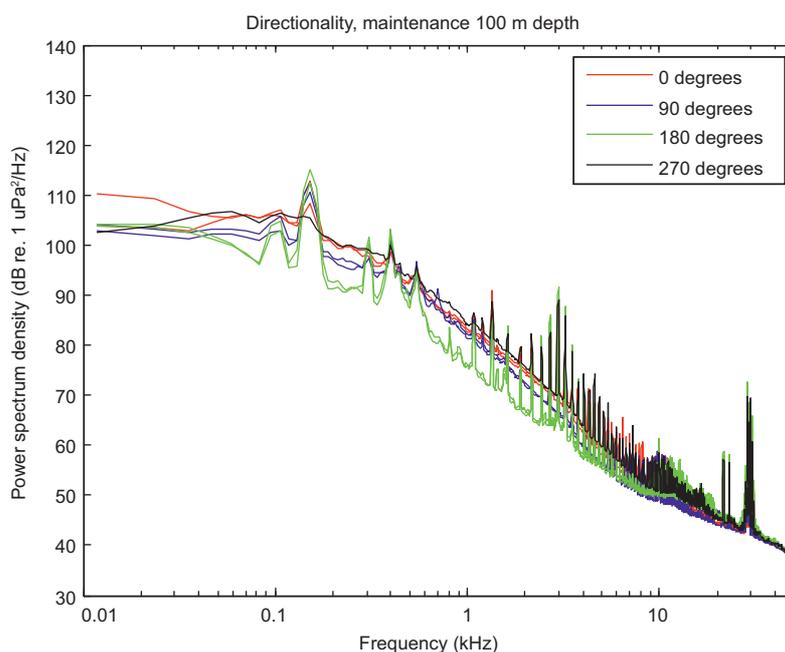


Figure 3.5. Noise spectra at different distances from the drillship and during two different activities (drilling, top; maintenance, middle and bottom). Left panels show third-octave band levels. Each line represents the median spectrum calculated from one recording, between 4 and 10 minutes of duration. Right panel shows power spectrum densities for the same recordings.

prominent frequency peaks (tones) depending on both range and activity of Stena Forth. The most consistent peak is at 400 Hz, clearly detectable at all distances out to and including 8 km, both during drilling and maintenance and thus a consistent noise source from the drillship. Other peaks were at 100 Hz, only prominent out to 1 km from the drillship and a peak at about 3 kHz, only present during maintenance at some distances (1 km and 16 km, but not 4 km). An additional set of peaks were present in the range 20-35 kHz, clearly detectable out to at least 2 km during both drilling and maintenance.

Recordings were made around Stena Forth at four angles, expressed in relation to the stern of Stena Forth ($= 0^\circ$) at 85° , 167° , 254° and 342° and at a distance of app. 1 km. The one-third-octave band peaks measured varied little with angle to Stena Forth (Figure 3.6) and were pronounced at 100 Hz, 160 Hz and several in the range 200-600 Hz. These peaks were detectable in all four directions. A large number of peaks with a harmonic structure were present from around 1 kHz to beyond 10 kHz, except in the recordings made in the direction of the starboard side of the drill-ship. Noise levels were comparable across directions, except behind the ship (180°), where levels were consistently about 5 dB lower than the other directions in the range up to about 10 kHz. These measurements were made during maintenance activity at Stena Forth. During recordings at 180° a supply ship approached Stena Forth. After arrival the Olympic remained at a distance of app. 9 km at an angle of app. 270° from the heading of Stena Forth during the remaining recordings at the angles 0° , 90° and 270° . The supply vessel kept the distance and stayed there until all measurements were taken. The ship was at a distance of app. 4-4.8 km during the measurements taken at 180° . Due to the supply ship laying standby during recordings, we were asked to reduce recording time to 15 min at each angle. Therefore only recordings at 90 m depths were taken. On the same day sound measurements were made at 4, 16 and 38 km distances. The spectra peaks are levelled out somewhat with distance, however the Stena Forth spectral signature with peaks at 100 and 160 Hz are still elevated at a range of 38 km from Stena Forth.

Figure 3.6. Average power spectra of signals recorded at approximately 1 km distance from Stena Forth in September 2010 at four different directions around the ship. Zero degrees correspond to forward direction along the length axis of the ship.



Background noise measurements were made 316 km from Stena Forth and at 211 km distance from Stena Don on 27th September. The third-octave-band levels are included in figure 3.5. There are elevated peaks at 63, 250 and 500 Hz. These peaks may arrive from either Stena Forth, Stena Don, the passing supply ship *Troms Vision* (MMSI 235708598) that passed the RHIB during recordings at a closest distance of 8.2 km, or a combination of the three. The third-octave-band background noise levels are higher than previously stated for Greenland for bands below 500 Hz (Simon, 2010).

3.4 Temporal variation

The noise was not stationary, but varied substantially over time. Figure 3.7 shows examples of variation in rms- and peak-peak sound pressure level over 1 minute periods at various distances. In several recordings a substantial number of short peaks with amplitudes 5-15 dB above overall mean are present. Figure 3.8 shows how the third-octave band levels calculated in 10 second windows varied in time and again substantial variation were observed. Largest variation was seen during drilling.

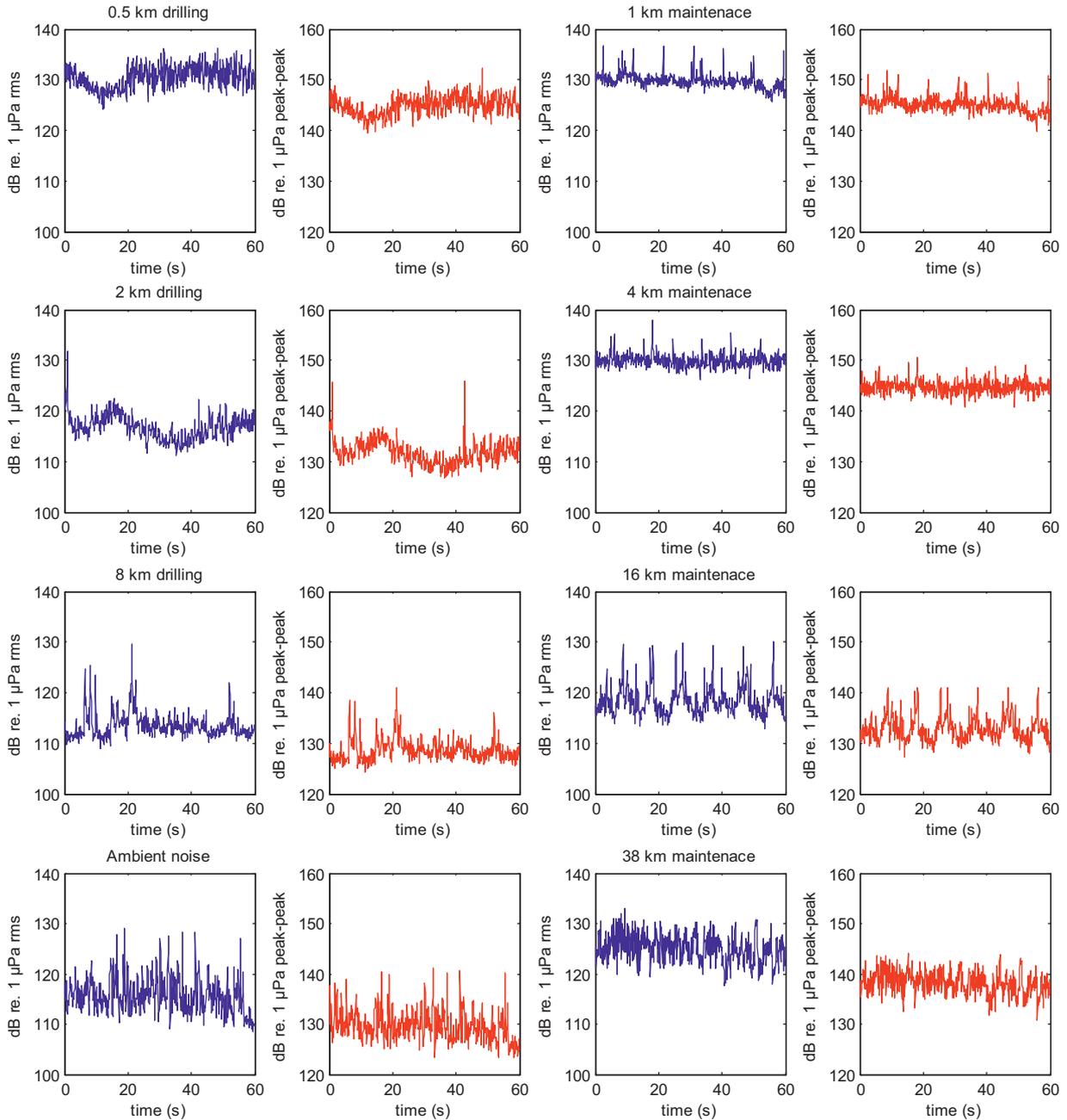


Figure 3.7. Examples of temporal variation in recordings from Stena Forth. Each figure shows rms (blue) and peak-peak (red) values calculated by a running 100 ms (non-overlapping) window. Notice the two different scales in the Y-axis between rms and peak-peak. Please note that the ambient noise has not been removed to make these graphs.

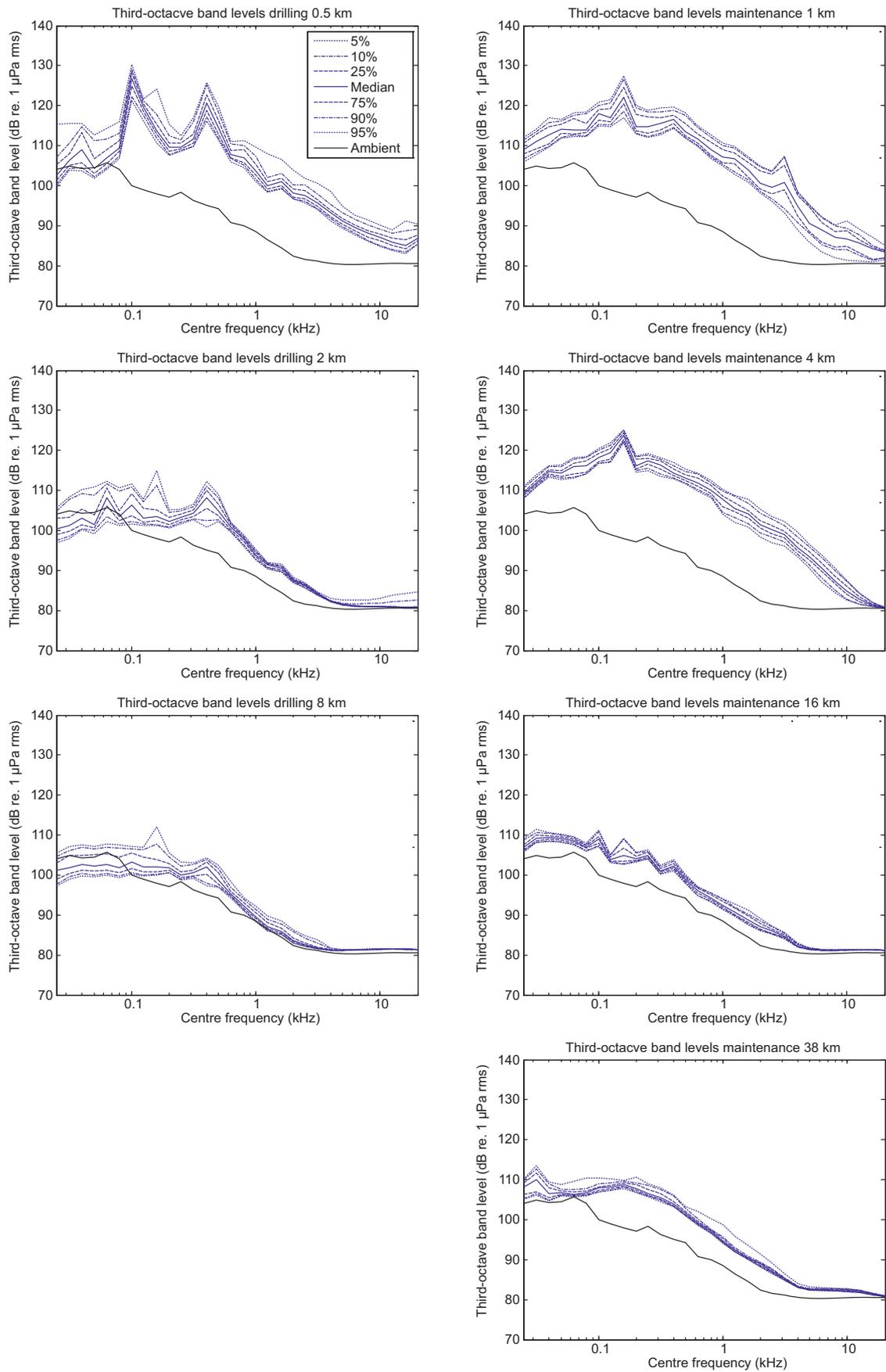
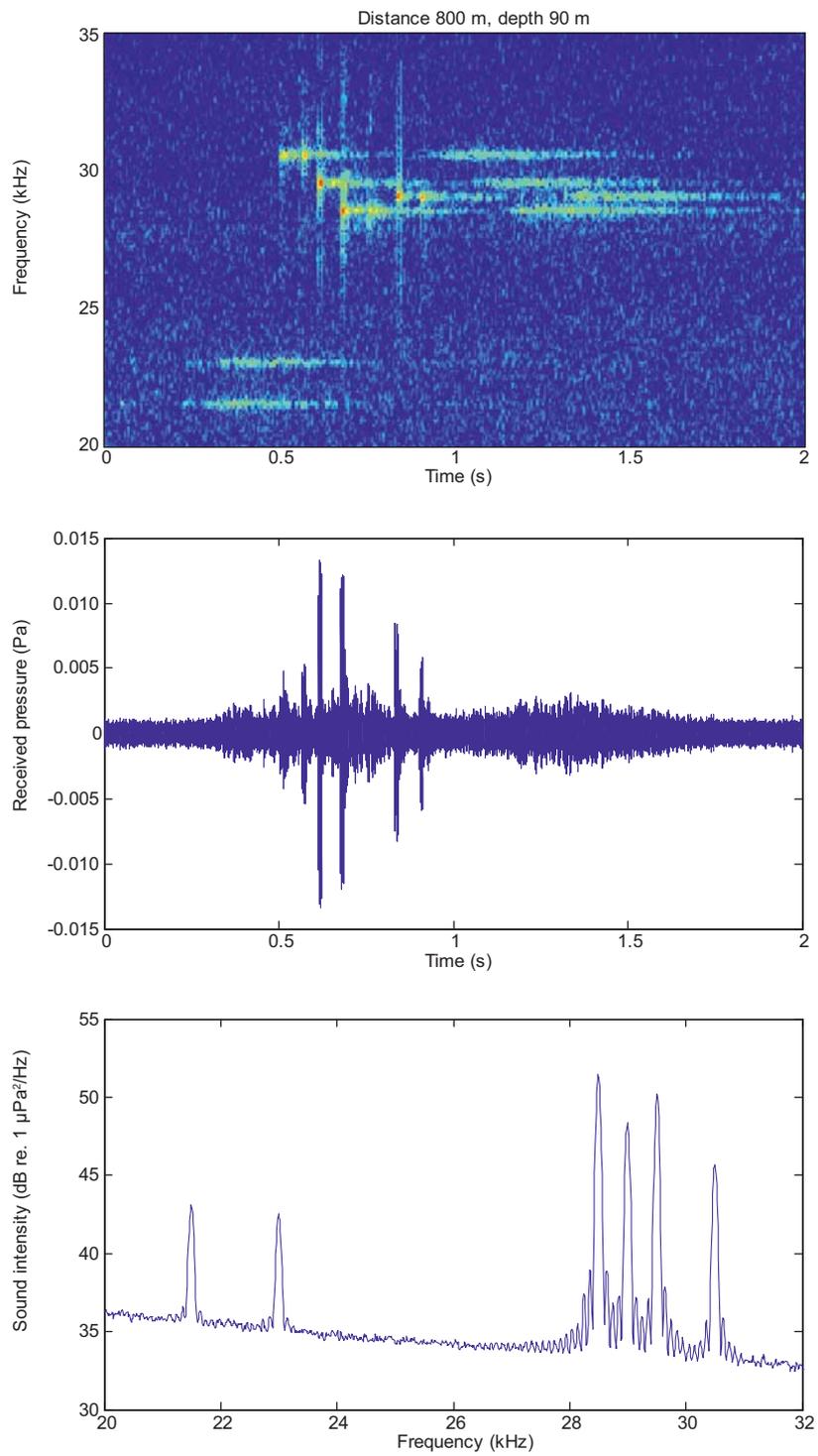


Figure 3.8. Third-octave band levels at 7 different distances from the drillship, during drilling (left panel) and maintenance (right panel). Curves shown are median levels, as well as 5%, 10%, 25%, 75%, 90% and 95% percentiles of levels, based on time intervals of 10 seconds. Median third octave band level for ambient noise is shown in all figures in black. Recording depth 90 m. Only recording directions perpendicular to the length axis of the ship included at 1 km distance.

3.5 Sounds related to the dynamic position system

Figure 3.9 shows signals clearly detectable between 20 kHz and 35 kHz at close range to the drillship. These sounds were generated as part of the dynamic positioning of Stena Forth. Dynamic positioning is the means to keep Stena Forth in place, since the area is too deep for normal anchoring. In dynamic positioning one to several transponders are placed on the seabed below the ship. One or more transducers, placed in the hull of the ship, emit a signal to which the transponders reply with individual signals. The received transponder signals in combination with automatically measured sound velocity, as well as data from wind, current and motion sensors are used to automatically control the propellers and thrusters of the ship to exactly counter-act the effects of current and wind, thus keeping the ship at an exact position and heading. The transponders are normally not retrieved after drilling has ceased. From the spectrum peaks it appears that Stena Forth uses two signals transmitted every 2.44 s and four transponders for the dynamic positioning.

Figure 3.9. Control signals for the dynamic positioning system. Two master signals are transmitted at 21.5 and 23.0 kHz and four slave signals transmitted at 28.5, 29.0, 29.5 and 30.5 kHz. Recorded at app. 800 m range at a depth of 90 m. Spectrogram calculated with 1024 point windows, 50% overlap, Hann-weighted. Pressure signal bandpass filtered 20-32 kHz. Power spectrum 1 minute average (Welch method, 8192 points, Hann weighted windows, 50% overlap).



4 Discussion

The present report presents the noise profiles of the drillship Stena Forth, as recorded on two days in September 2010. Only few other accounts of drillship noise exist (Greene 1987 and Richardson et al. 1995 summarises results from four different drillships based on grey literature and industry reports). Drillships are known to make more noise than other drill rigs (semi-submersible, artificial islands/caissons, jack-ups) because the hull containing the drilling machinery is well connected to water. Not surprisingly it has been found that source levels and spectral content of the noise changes with performance and when machinery is replaced (Richardson et al. 1995). The presented data are thus restricted to the machinery of Stena Forth and the conditions applying to the drilling season of 2010 in West Greenland only.

4.1 Source levels

Both drilling and maintenance noise were readily discernable underwater, and resulted in marked increases in sound pressure levels throughout the entire frequency spectrum 20 Hz to well above 10 kHz and with clearly discernible peaks in the range below 500 Hz. The received level generally decreased with range (Figure 3.4) for both drilling and maintenance work, however with the 38 km recording range as a marked exception. At 38 km distance the noise level was higher than at 16 km range the same day. As the recordings were not obtained concurrently, the higher levels recorded at 38 km could be due to higher levels of noise emitted from Stena Forth at the time of recording. Another possibility is that refraction of sound in the deeper layers of the ocean (approximate depth 400 m) caused a convergence of sound at the 38 km range. The presence of a supply ship (the Canadian tug *Jim Kilabuk* MMSI 316232000) during recordings may also have influenced recordings at 38 km, even though the supply ship was at a distance of 22 km from the recording site at closest point, steaming 8.6 kt.

The broadband source levels of Stena Forth correspond to the highest published broadband source levels of icebreakers, but are higher than typical from tankers and tugs, other common noise sources around Arctic drilling sites (Thiele 1981; Richardson et al. 1995). Richardson et al. 1995 summarises on recordings of various man-made noise from vessels and airplanes and reports broadband source levels up to 177-193 dB re μPa (rms) from icebreakers and broadband source levels up to 186 dB re μPa from tankers that has the most energy below 430 Hz. Arveson and Vendittis (2000) report wideband source levels of a merchant cargo ship up 178-193 dB re 1 μPa (rms) at speeds from 8 to 16 kt, respectively. Thile and Ødegaard (1983) measured third-octave band source levels up to 198 dB re 1 μPa from the container ship M/S Jutlandia. The Stena Forth is thus a substantial noise source in Baffin Bay, during maintenance work (SL = 190 dB re 1 μPa rms) in relation to typical vessel types found in the Arctic, and during drilling where the source level (SL = 184 dB re 1 μPa rms) corresponds to that of a large tanker.

4.1.1 M-weighting

Received levels were also calculated using different frequency weighting functions corresponding to that of typical marine mammal groups, namely low frequency cetaceans, mid frequency cetaceans, high frequency cetaceans and pinnipids in water. These weighting functions were suggested by Southall et al. (2007) as a standard measure when analysing noise to evaluate possible effects on marine mammals. Although they are based on many assumptions and in some cases very little or even no experimental support, they are included for comparison with other studies.

Figure 3.4 shows the four differently weighted received levels along with the un-weighted received levels. The interpretation of the data is that the noise from Stena Forth is more audible and hence with greater potential for impact for the groups with good low frequency hearing: the large mysticete whales and the pinnipeds, whereas the sound is less audible to the odontocetes (toothed whales, dolphins and porpoises), although the difference among groups is at most 5 dB.

4.1.2 Spectral content

The spectral peaks or tones observed depend on the work load on the different engines, generators etc. a board, and since the 400 Hz tone was visible both during drilling and maintenance work, it likely arose from a continuously operating source, such as the generators. Such changes in spectral content are also observable in figure 3.7 as the temporal variation and as the differences in spectral content between the recording distances (figure 3.5). The spectral analyses showed that the tonal signatures were still visible as peaks in the spectrum at distances of 38 and 16 km, respectively. Such peaks have also been observed for other recorded drill platforms (Greene 1987; Blackwell et al. 2004) and as with ordinary ships, each platform has its own frequency signature. The only other published recordings of drillships were made in shallow water of the *Canmar Explorer I* and *II* and the drilling barge *Kulluk* in the Beaufort Sea, Canada (Greene, 1987). These drillships showed different tones depending on activity, where drilling caused fewer tones than well-logging. During drilling the sound spectrum of Explorer I had tonal peaks up to 1850 Hz and the received level of the 20-1000 Hz band was 122-125 dB re 1 μ Pa measured at a distance of 170 m, water depth of 17 m and with the hydrophone at 9 m. The sister ship Explorer II had received levels in the 20-1000 Hz band of 134 dB re 1 μ Pa measured at 200 m distance, water depth of 17 m and hydrophone depth of 9 m. Explorer II had pronounced peaks at 254 and 277 Hz that were discernable in subsequent autonomous sonobuoy recordings measured at several km ranges. The Kulluk drilling barge on the other hand had no significant tones above 90 Hz, but had a much higher general sound level of 143 dB re 1 μ Pa in the 20-1000 Hz band at a range of 980 m. The Kulluk was drilling in 31 m deep water during recordings and there were several supply boats nearby contributing to the recordings. At a range of 10 km the noise level had not fallen to below the median ambient background noise levels for any of the three drillships, and the Kulluk was still more than 20 dB above (Greene 1987).

For Explorer I during well-logging the third-octave-band levels were highest at the centre frequencies 80, 160 and 200 Hz and reached mean

received levels of 116-118 dB re 1 μ Pa measured at a distance of 900 m and a water depth of 17 m. For Explorer II the third-octave-band levels were highest at the centre frequencies 50, 125, 160 and 250 Hz during drilling with mean received levels of 122-131 dB re 1 μ Pa, recorded at a range of 200 m and a water depth of 17 m. The third-octave-band levels of Kulluk were highest at the centre frequencies of 50, 160, 200, 400 and 500 Hz with levels from 126- 129 dB re 1 μ Pa measured at 900 m distance. The corresponding third octave band levels of Stena Forth are similar, but centred at 100 and 400 Hz with received levels measured at 500 m distance with mean maximum (\pm standard deviation) levels of 129 ± 1 and 123 ± 2 dB re 1 μ Pa, respectively measured at 90 m during drilling operation. During maintenance the mean received maximum third-octave-band levels centred at 100, 160 and 400 Hz was 119 ± 1 , 126 ± 3 , 118 ± 1 dB re 1 μ Pa at app. 1 km distance and hydrophone depth of 90 m (figure 3.5 and 3.6).

The spectral properties of Stena Forth may serve as a signature in sonobuoy recordings as have been tried for the Explorer I and II drillships (Greene 1987). Such signature spectrums in combination with passive acoustic monitoring of marine mammals may be used to examine whether the noise of the drilling actions displaces marine mammals from the drilling sites and whether habituation occurs.

4.1.3 Conclusion

The noise levels of Stena Forth correspond to those measured from other drillships and are above those reported from semi-submersibles and drill rigs. The wideband source levels are among the highest published for icebreakers and tankers, and correspond to fast moving merchant ships with source levels up to 184-190 dB re 1 μ Pa during drilling and maintenance work, respectively. Both drilling and maintenance work results in tones that are higher than the background noise levels at ranges of 16-38 km from the ship. This spectral signature of Stena Forth may for example be utilised for monitoring the drill noise in connection with passive acoustic monitoring of marine mammals in the area.

4.2 Future monitoring

The present results are only representative for the drillship Stena Forth and only for the activities conducted during the two days of recording. For the season 2011 Cairn has contracted the "Leiv Eiriksson" (a semi-submersible drilling rig) and the "Ocean Rig Corcovado" (a drillship) to drill at two new sites in West Greenland. Since each rig/ship produce a different noise levels and spectra, the exposure from the two new rigs should be assessed, as well as the noise from Stena Don, if it continues to be in use. Since the present results were limited by weather, we suggest a new approach for future noise assessments in offshore Greenland, and that is to deploy dataloggers that automatically records noise throughout the drilling season. The use of several autonomous recorders not only increases the amount of data that can be recorded but also provides time synchronised recordings at several distances simultaneously, removing the need to assume a constant sound emission from the drill ship when assessing transmission loss.

With such dataloggers in place before the drilling season begins background noise recordings will be obtained automatically as well. In the same fashion the entire noise picture of the drill operation will be obtained since the coming and going of supply and standby vessels will be recorded as well. We suggest that a number of dataloggers are deployed along a line from each rig, for example in the direction of the main shipping lane to and from the drill operation. The same set-up can be used in combination with monitoring of presence of marine mammals in the area and may help assess if the animals are displaced from the area during drilling actions.

After the recordings were made, we became aware that vertical seismic testing was being performed regularly to test the drilled wells. Despite that these sounds are of transient nature they are part of the entire noise contribution from the drilling activity and may well be of much higher source levels than the drilling noise. Source levels of the well testing should thus be measured as well to accurately evaluate possible effects on marine life.

4.3 Abbreviations and technical terms

CTD-tag	Measures conductivity temperature and depth.
M-weighting	Generalized frequency weightings for various groups of marine mammals, allowing for their functional bandwidths and is appropriate for characterizing auditory effects of strong sounds. Specifications see appendix 1 in Southall et al., 2007.
pp	Peak-to-Peak.
PSD	Power Spectrum Density.
PSU	Practical Salinity Unit, o/oo.
RHIB	Rigged Hulled Inflatable Boat
rms	Root Mean Square.
SL	Source Level referenced to 1 m from sound source.
TOL	Third-Octave-Band Level.

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NERI National Environmental Research Institute

DMU Danmarks Miljøundersøgelser

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Denmark
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Department of Policy Analysis

National Environmental Research Institute
Vejlsovej 25
PO Box 314
DK-8600 Silkeborg
Denmark
Tel: +45 8920 1400
Fax: +45 8920 1414

Department of Freshwater Ecology
Department of Terrestrial Ecology

National Environmental Research Institute
Grenåvej 14, Kalø
DK-8410 Rønde
Denmark
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ISBN: 978-87-7073-248-2
ISSN: 1600-0048