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JASA ARTICLE

Proximate underwater soundscape of a North Sea offshore petroleum exploration jack-up drilling rig in the Dogger Bank

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ABSTRACT:
Little is known about localized, near-field soundscapes during offshore hydrocarbon drilling campaigns. In the Dogger Bank, North Sea, underwater noise recordings were made 41–60 m from the drill stem of the *Noble Kolskaya* jack-up exploration drilling rig. The aims were to document noise received levels (RLs) and frequency characteristics of rig-associated near-field noise. The rig produced sound pressure levels (SPLs) of 120 dB re 1 μPa in the frequency range of 2–1400 Hz. Over transient periods, RLs varied by 15–20 dB between softest (holding) and noisiest (drilling) operations. Tonal components at different frequencies varied with depth. Support vessel noise was significantly louder than the jack-up rig at frequencies <1 kHz, even in its noisiest "boulder-drilling" phase, though radiated noise levels were higher above 2 kHz. Rig SPLs fell rapidly above 8 kHz. Marine mammals, such as harbor porpoise (*Phocoena phocoena*) forage regularly near offshore oil and gas rigs and platforms, and it is predicted that animals experience different noise regimes while traversing the water column and can potentially detect the higher-frequency components of drilling noise to a distance of 70 m from the source; however, while levels were unlikely to cause auditory injury, effects on echolocation behavior are still unknown.
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I. INTRODUCTION

Underwater noise measurements of exploratory drilling are carried out regularly in environmentally sensitive areas, such as Special Areas of Conservation (SACs) as part of environmental impact assessment (EIA), comparative assessment (CA) (Bagstad *et al.*, 2013), and/or net environmental benefit analysis (NEBA) [e.g., Efroymson *et al.* (2003)] processes; however, time windows with which to conduct noise campaigns are short and constrained to operator schedules, as opposed to ideal measurement conditions, and data remain confidential and confined to commercially sensitive internal reports. Consequently, peer-reviewed studies are scarce, and to our knowledge, none to date have been published from a North Sea operational offshore oil and gas (O&G) three-legged jack-up hydrocarbon exploration drilling rig.

Marine mammals are recorded visually and acoustically in the vicinity of North Sea offshore O&G exploration drilling rigs and production platforms on a regular basis (Todd *et al.*, 2009; Todd *et al.*, 2016; Delefosse *et al.*, 2018; Todd *et al.*, 2020); however, information on rig-associated soundscapes is lacking.

Sound pressure level (SPL) measured in the near field of a large distributed source such as a jack-up exploration drilling rig varies considerably and is generally lower than would be measured from an equivalent point source, e.g., a single air gun. Aside from logistical reasons (e.g., difficult or unsafe access), measurements are rarely made 1 m from the drill stem, and as a consequence, source level (SL) cannot be used as a reliable level for prediction with distance, necessitating back calculation using known or expected change in level (propagation loss) from source to receiver. Far-field measurements are also challenging because all access to offshore installations is via costly helicopter, i.e., personnel are not allowed to transfer from a rig/platform to the vessel required to perform measurements at distance. Consequently, measurements are either made from the sides of the installation, close to the source, or only at distance from a vessel, which means that both near-field and far-field measurements are rarely possible. Moreover, most offshore installations are distanced from shore, which means access is both financially costly and logistically challenging.

Underwater noise data vary substantially with offshore installation type and location, and only a handful of studies have carried out drilling noise measurements from offshore hydrocarbon installations in a range of water depths and geographic locations (Table I). Reported received levels and frequencies of drilling noise from various offshore installations range from 120 to 145 dB re 1 μPa root mean square (rms) (measured 10–1000 m from the source) at frequencies of 1.4 Hz to 4 kHz (Table I). Consequently, there is a clear need for more data on noise around different types of offshore installations in varying water depths and conditions.

Here we describe underwater noise made during initial stages of jack-up rig positioning and various phases of

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TABLE I. Details of sound produced by various offshore hydrocarbon exploration installations excepting geotechnical drilling (*), which is performed as part of a construction process, e.g., for foundations.

Installation type	Operation	Received level	Frequency (Hz)	Measurement distance from source (m)	Water depth (m)	Location	Reference
Jack-up rig	*Geotechnical drilling	142–145 dB re 1 μPa rms	30–2000	10–50	7–13	Australia	Erbe and McPherson (2017)
Semi-submersible	Exploration drilling	125 dB re 1 μPa	29 and 70	13–15	60–150	USA	Gales (1982); Richardson *et al.* (1995)
Semi-submersible	Exploration drilling	120 dB re 1 μPa rms	30–1000	500 and 1000	46	Chukchi Sea	Quijano *et al.* (2018b)
Multi-leg drilling rig and production platform	Exploration drilling and production	119–127 dB re 1 μPa	5; 4.5 and 38	30 and 9–61	27–58 and 40–60	USA	Gales (1982); Richardson *et al.* (1995)
Caisson-retained island	Exploration drilling	130 dB re 1 μPa	5300	220	—	Canadian Beaufort Sea	Greene (1987)
Concrete island drilling structure	Exploration drilling	88–89 dB re 1 μPa and 124 dB re 1 μPa	1.375 and 1.5	1370 and 259	—	Alaskan Beaufort Sea and under ice	Hall and Francine (1991)
Northstar Island, on ice	Exploration drilling and production	124 dB re 1 μPa	10–10,000	1000	—	Alaskan Beaufort Sea	Blackwell *et al.* (2004)
Northstar Island, on ice	No drilling or production	98 dB re 1 μPa	—	500	—	Alaskan Beaufort Sea	Blackwell *et al.* (2004)

operation. The specific objective of this work was to measure and document received level (RL) and frequency characteristics of near-field sounds produced by jack-up rig-related industrial activities, such as drilling and associated support vessel activities, and to place them into the context of harbor porpoise (*Phocoena phocoena*) hearing.

The location is inhabited year-round by harbor porpoises (Camphuysen, 2001; Todd *et al.*, 2009). As part of a complementary study, porpoises have been shown to forage actively around the jack-up installation at this location (and at other offshore installations in the Dogger Bank), predominantly at night and mostly independently of routine activities such as drilling, cementing/casing, and support vessel operations (Todd *et al.*, 2009; Todd *et al.*, 2016). Consequently, the noise regime reported here can be considered to be typical of that experienced by porpoises in the local vicinity of the rig at time of measurement, although comparison of porpoise acoustic behavior in relation to drilling-related activities forms part of another study and is not reported here.

The study approach involved making near-field recordings of underwater sounds from the sides of an operational jack-up drilling rig in a bid to improve understanding of drilling noise in general and of the acoustic environment experienced by harbor porpoises when foraging near and between the legs of jack-up rigs undergoing routine drilling campaigns in the North Sea.

II. MATERIALS AND METHODS

A. Timing and location

Measurements were made during a winter 2004 exploratory drilling campaign in the Entenschnabel block B4–05 German sector of the central North Sea. The environmental impact statement (EIS) stipulated that, because exploratory drilling occurred close to the Dogger Bank SAC under the European Union (EU) Habitats Directive (92/43/EEC, 1992), real-time acoustic measurements during installation and initial operation of the drilling process were required. Data were collected over seven days (30–31 October, 1–3 November, and 6–7 November 2004). Near-field measurements were taken from the three-legged jack-up gas exploration drilling rig *Noble Kolskaya*, situated at 55° 41.570′ N 004° 05.396′ E in a water depth of 40 m. A full description of study area, sediment type, and the *Noble Kolskaya*'s technical specifications is given in Todd *et al.* (2009).

The *Noble Kolskaya* was located to the west of a constellation of several offshore installations. The nearest production platform was the A6-A, located 13.89 km away, also frequented by porpoises (Todd *et al.*, 2009). There were also two gas pipelines running 4.63 km to the east of the site. Applying a most conservative case of cylindrical noise spreading and neglecting absorption losses (these would be minimal at low frequencies discussed in the Introduction), SPLs from the A6-A platform would be reduced by over 40 dB, and those from the other O&G fields located at a distance of ca. 37 km away would be reduced by more

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than 46 dB. If generated levels were similar to those measured from the *Noble Kolskaya*, this would reduce levels to background noise. Whilst not ideal, radiated noise from these other acoustic sources was likely distanced sufficiently to not prejudice measurements made during this study. This situation was unavoidable, as permission was granted only to obtain measurements from around the *Noble Kolskaya*; other installations belonged to different operators, with no permission to enter their 500-m shipping exclusion zones.

B. Equipment

Acoustic measurements were made using two simultaneously deployed non-directional, spherical Sonar Research and Development (SRD) Ltd. hydrophones (HS70 and HS150), with resonant primary frequencies of 70 and 150 kHz, respectively. Both transducers had good low-frequency (<10 kHz) sensitivities: around –205 to –211 dB re 1 V/μPa. Equipment used was calibrated pre- and post-measurement, at Loughborough University, using specialized electronic and tank-testing facilities, to determine transfer functions of individual system components. Hydrophones were positioned in various orientations relative to the calibrated sound source and output calibration charts were compared with originals and values used during data analysis and modelling. Calibration was traceable to the UK national standards maintained by the National Physical Laboratory (NPL) and validated by comparison with those of other national metrology institutes in the Key Comparison exercise organized under the auspices of the Consultative Committee on Acoustics Ultrasound and Vibration, CCAUV (Robinson and Lepper, 2006). Amplifiers and filters were sourced from the hydrophone manufacturer to ensure system compatibility, which is an integral aspect to calibration. During field work, sensitivity of each hydrophone was monitored continuously, to convert voltage into pascal and to ensure there were no noticeable deviations that might indicate loss of calibration.

The recording setup is provided in supplemental Fig. S1.[1] All data were saved in uncompressed format and Universal Time Coordinated (UTC) time stamped. Data acquisition was made directly to a personal computer (PC) hard disk for low frequencies, "audio band" (<24 kHz), using a Roland UA30 digital interface to a 16-bit resolution 48 kHz sampling, and for high-frequency (HF) "ultrasonic" (10 Hz to 200 kHz) data, a 6062E National Instruments PCMCIA interface to a 12-bit resolution 320–400 kHz sampling. Additional digital recordings were made in the audio bandwidth (24 kHz) on digital magnetic tape using a Sony TDS-D7 digital audio tape (DAT) recorder to 16-bit resolution. Various conditioning preamplifiers were used to maximize recording use of dynamic range and improve the signal to noise ratio. The audio-band recordings were alternating current (AC) coupled using 1 Hz high-pass filters, whilst the HF recordings were made with a band-passed preamplifier set from 2 to 150 kHz. Real-time spectral analysis was displayed for both channels on screen, and a loudspeaker (Quad 11 L, UK) played output from the LF channel. At the time of the study, these were the latest technologies available, and data have just been released from a non-disclosure agreement (NDA) for publication, thus representing a rare opportunity to publish commercially sensitive data.

C. Field procedures

On 30 October 2004, the *Noble Kolskaya* was sited at Block B4–05, where tugs released the rig and jacking-down commenced to facilitate vertical drilling of a new well. Prior to each noise measurement, a conductivity temperature depth (CTD) profile was undertaken using a SeaBird SBE-19 SeaCat probe at a sample rate of 2 Hz. Semi-diurnal tidal heights and current speed around the rig were predicted using POLTIPS-3 (Proudman Oceanographic Laboratory Tidal Information and Prediction Software); as such, estimated bending angles of the faired hydrophone cable did not exceed 5°, and measurement position drifts were considered negligible. Measurement technique involved a subsurface buoy and bottom mooring, ensuring the faired hydrophone was almost completely immune to effects of surface motion. Recordings were made in Beaufort Sea state $\leq$3. While the 2004 noise measurements predated de Jong *et al*. (2011) and NPL (2014) and any of the current standards [ANSI/ASA (2009); ISO (2016)], the measurement procedure effectively followed these guidelines. Far-field noise measurements from the rig's support vessel (*Northern Seeker*) were attempted during the campaign but were unsuccessful due to, *inter alia*, severe weather conditions and logistical and time constraints; consequently, estimations of SL from the drilling rig were not possible.

To investigate acoustic fields generated by standing waves and to monitor time variance in acoustic transmissions, real time, *in situ* suspended hydrophone profiles were collected 41, 52, 59, and 60 m from the drill-stem location (Fig. 1). Data were quality controlled in the field by two acoustic technicians, and data analysis and modelling were conducted ashore after field trials. Only ½ and ¾ water-column depth comparisons were made. For brevity, only data collected from the starboard explosives platform are presented visually.

D. Operations

A detailed record of rig operations was obtained from personnel, which was cross-referenced to acoustic measurements. Operational categories were divided into rig "installation" (when tugs were present), "tank discharge," "preloading," "drill preparation," "drilling" the 30 or 24 inch hole, and other operations, such as arrival/departure of helicopters and support vessels. Acoustic sequences were recorded over various frequency bands, during multiple phases of the *Noble Kolskaya*'s drilling operation. Details of diesel engines and AC generators were obtained for both the rig and its support vessel, *Northern Seeker*, and are presented in Table II. An attempt was made to correlate acoustic transmissions with various rig-generated noise sources and to attribute tonal signals to physical sources on board

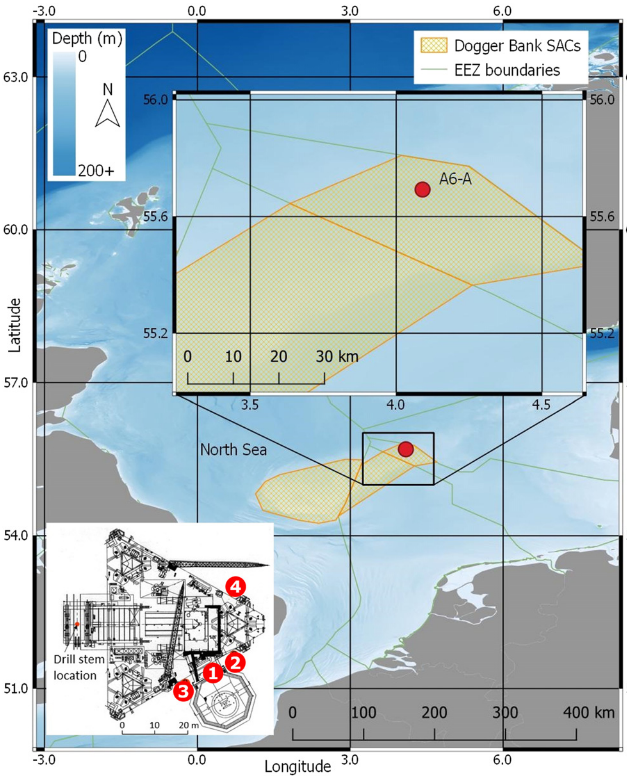

FIG. 1. (Color online) Location of the *Noble Kolskaya* exploration jack-up rig (red dot) in the German sector of the Dogger Bank and plan view of rig showing noise-measurement locations 1 (starboard rail), 2 (starboard explosives platform), 3 (container), and 4 (port forward anchor). Only data from the starboard explosives platform (60 m from drill stem) are presented. Black arrow points to the drill-stem location.

the rig and support vessel. Details of the top-drive system were also obtained for the *Noble Kolskaya*. The rotation rate of this drive is continuously variable between 0 and 240 rpm, and no records were kept of the actual rate used at any one time.

E. Data analysis

CTD values were converted to sound-speed profiles as per Roquet *et al.* (2015). Fugro Ltd. collected and assessed seabed type, and descriptions were provided internally. Acoustic data were processed in the time and frequency domain using custom-written MATLAB version 2.0 software scripts. Assessment of broadband and tonal components concomitant with the *Noble Kolskaya*'s operations were assessed. Measurement values were also compared to prevailing limits of noise taken from generalized ambient noise spectra (Wenz, 1962). Allowing for hydrophone systems' transfer functions, data were converted to received SPL (dB re 1 μPa) or power spectral density (PSD) (μPa/$\sqrt{}$Hz), via methods similar to Alessio (2016). A 0.091 Hz analysis bandwidth was used for frequencies 1–110 Hz. A broader, 2.93 Hz bandwidth was used for analysis of frequencies from 90 Hz to 24 kHz. High-resolution, fast Fourier transforms (FFTs) were executed for spectral analysis (Welch, 1967). For 43.7–87.4 s time windows, Welch (1967) averaging techniques were also used to reduce indistinct noise variance and to assess tonal-component time stability. At frequencies between 25 Hz and 13 kHz, 1/3 octave band analysis was performed. Displayed data yield examples of typical time-variant characteristics of rig operations.

F. Harbor porpoise hearing thresholds

Frequency components of drilling noise are generally <10 Hz (Greene, 1987), but no experimental data of hearing thresholds for harbor porpoises at this frequency exist. Lowest testing frequency for this species is 125 Hz from narrow-band sweeps. HF components of drilling noise measured in this study were used to calculate distance at which harbor porpoise could potentially detect noise based on measurements of porpoise hearing threshold exposed to narrow-band frequency modulated (FM) signals between 250 Hz and 180 kHz (Kastelein *et al.*, 2010). Unmasked hearing thresholds were 116 dB re 1 μPa at 250 Hz, 94 dB re 1 μPa at 500 Hz, and 82 dB re 1 μPa at 1 kHz. Consequently, these thresholds were used to extrapolate porpoise hearing thresholds at frequencies measured in this study (Table III) to estimate ranges at which harbor porpoise could potentially detect drilling noise, but behavioral reactions of animals were not assessed.

TABLE II. Noise-generation sources aboard *Noble Kolskaya* (top) and engine details for *Northern Seeker* (bottom). Blank cells represent missing information.

Noble Kolskaya	No.	Make and model	Power	Maximum rpm[a]/Hz	CFR (Hz)
Top drive	1	Maritime Hydraulics DDM650L	807 kW	240/4.0	
Diesel engine	4	Wärtsilä 8R22 (8 cylinder)	1070 kW	1000/16.7	133
Diesel engine	1	Wärtsilä 12V200 (V12)	1800 kW	1500/25.0	300
AC generator	4	Stromberg HSPTL	1450 kVA	1000/16.7	
AC generator	1	Leroy Somer LSA 54LP/4P	3200 kVA	1500/25.0	
Northern Seeker	No.	Make and model	Power	Maximum rpm[a]/Hz	CFR (Hz)
Main engine #1	1	Wickman Ax7	2100	380/6.3	44.3
Main engine #2	1	Bush			
Aux engine #1	1	Detroit Diesel	100	1852/31.0	123
Aux engine #2	1	Volvo Panther	300		

[a]Rotations per minute (rpm).

TABLE III. Estimates of distance at which harbour porpoise can detect the sound of drilling. Hearing thresholds for harbour porpoise were extrapolated from Kastelein *et al.* (2010).

Frequency (Hz)	Measured sound level (dB re 1 μPa rms)	Harbor porpoise hearing threshold (dB)	Potential detection range (m)
2.8	140.6	NA[a]	NA
250	121	116	NA
880	117	85	69
1263	114	80	66

[a]Not available (NA).

Sound speed profiles obtained from CTD measurement data were used to calculate transmission loss (TL) at several frequencies using Bellhop ray tracing (Jensen *et al.*, 2011).

III. RESULTS

CTD data revealed that the water column was well-mixed vertically, with a mean ± standard deviation (SD) temperature of 11.8 ± 0.00 °C and salinity of 35.1 ± 0.03 practical salinity units (PSU). Due to the rig's proximity to an amphidromic point in the German bight, maximum current speed was minimal, at 0.26 ms^{-1}. The Fugro Ltd. report revealed that the bottom boundary comprised sand and clay, with an estimated speed of sound of 1800 ms^{-1} (Hamilton and Bachman, 1982). There was a harmonic median sound speed, c_{hm}, of 1498.35 ms^{-1}. Sound speed near the sea surface was 1496.28 ms^{-1}, and at the seafloor it was 1496.92 ms^{-1}, with a subsurface isovelocity layer 1496.28–1496.30 ms^{-1} between 0 and 1.27 m depth.

A. Signal analysis

Over 140 acoustic sequences were recorded over various frequency bands (see supplemental Fig. S2).[1] A total of 3 h 13 min of acoustic recordings were collected during multiple phases of the *Noble Kolskaya*'s drilling operations. Audio-band analysis during the drilling phase in mid-water, for an 87 s window at 18 m depth is shown in supplemental Fig. S3.[1] To estimate levels and stability of both tonal and broadband noise components, comparisons were made between recordings at different and similar depths during different industrial operations. Analysis of HF signals determined that the sharp decline in levels around 8 kHz continued, attaining a "floor" of ca. 60 dB re 1 μPa/$\sqrt{}$Hz for frequencies up to the maximum recorded (150 kHz), >40 dB (100×) the LF power density.

Figure 2(a) presents RLs during various operational phases from the starboard explosives platform. Pre-drill, holding, and tank discharge recordings exhibit similar median spectral levels between 98 and 101 dB re 1 μPa/$\sqrt{}$Hz in the 1–3 kHz frequency band. At frequencies <3 kHz, levels increase gradually above the holding-period recording. During tank discharge, a sound-density level increase of ca. 10 dB re 1 μPa/$\sqrt{}$Hz was recorded for frequencies between 5 and 20 Hz and a further increase of

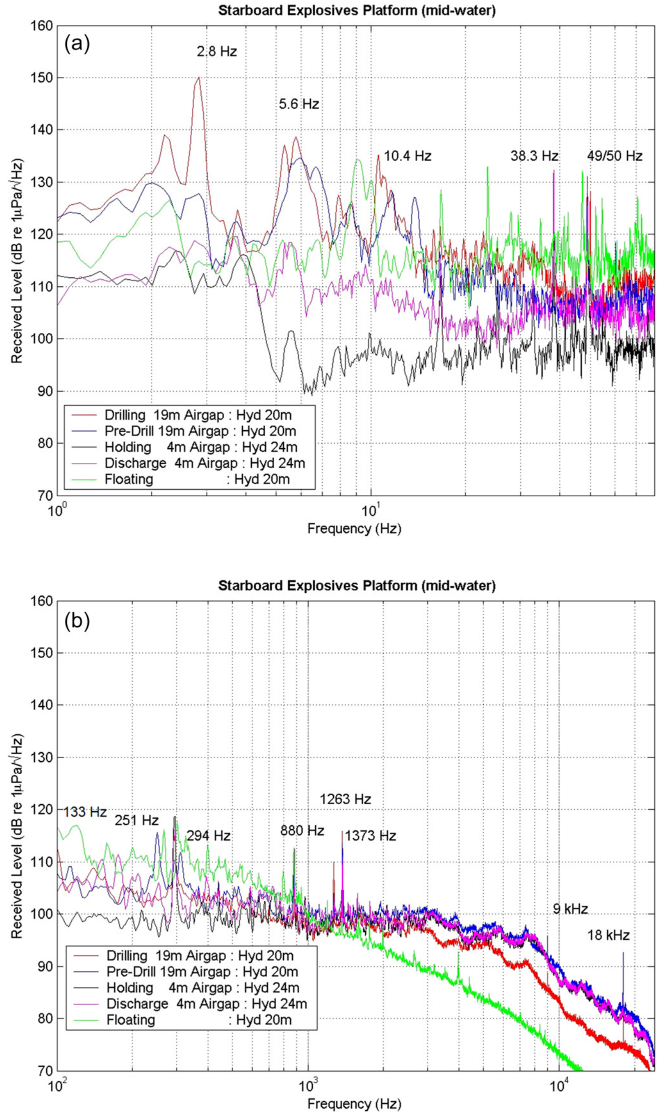

FIG. 2. (Color online) PSDs in low-frequency band (a) (analysis bandwidth 0.091 Hz) and mid-frequency band (b) (analysis bandwidth 2.93 Hz) of received signals measured 60 m from the source at the starboard explosives platform for various operations. Air gap refers to distance from bottom of the hull (barge) to water's surface. Hyd, hydrophone depth.

around 10 dB re 1 μPa/$\sqrt{}$Hz during pre-drill and drilling phases. Figure 2(a) also shows that, during drilling, 2.8, 5.6, and 10.4 Hz strong tonal components were recorded, details for which are presented in Table IV. Further tonal components are clear at 10.4, 251, 294, 880, 1263, and 1372 Hz. Observed equivalent-peak received levels in dB re 1 μPa were 124 at 10.4 Hz, 121 at 251 Hz, 124 at 294 Hz, 117 at 880 Hz, 114 at 1263 Hz, and 120 at 1373 Hz.

Figure 2(b) shows that 251 Hz signal was observed only during pre-drill phase, whilst many of the others were relatively stable during all recordings. During measurements prior to lowering the rig legs (i.e., barge floating), 294 and 880 Hz tonals were present, but components at 1263 and 1373 Hz were not observed. Additional tonal components at 9 and 18 kHz were observed above the background level in all recordings. Levels while the barge was floating with tugs

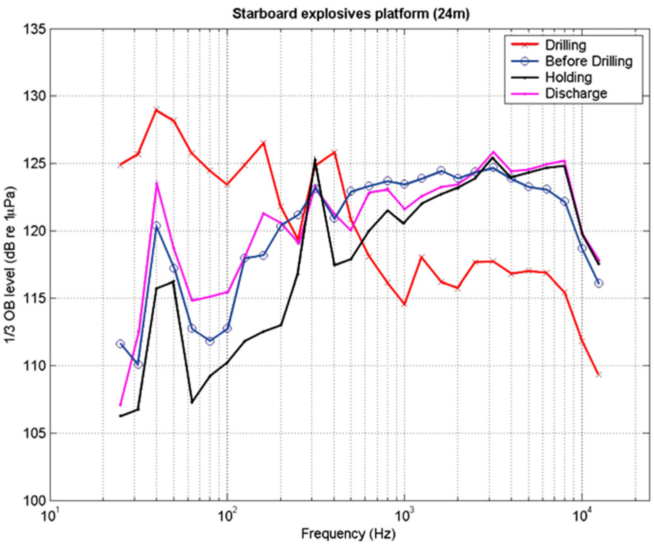

FIG. 3. (Color online) 1/3 octave spectral analysis, mid-water starboard explosive platform.

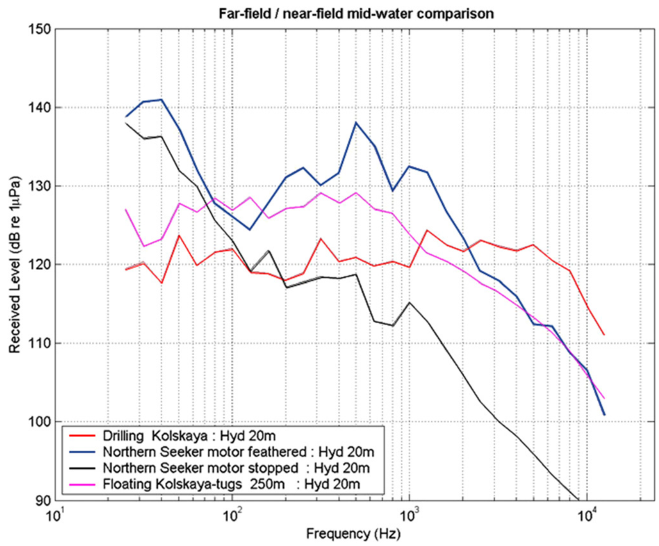

FIG. 4. (Color online) 1/3 octave plots of the *Northern Seeker* support vessel measurements, compared to drilling phase levels and levels measured when the tugs were present at the beginning of rig installation.

in attendance (prior to jacking up, with legs lowered) were higher than any rig operations in the 25 Hz to 1 kHz band, though drilling and pre-drilling levels were higher at low frequency. All rig operations were also noisier than floating at frequencies above 1 kHz.

Figure 3 1/3 octave band levels demonstrate increases in median broadband (non-tonal) sound pressure density for the drilling phase for frequencies <300 Hz, whereas above this frequency, pre-drill, tank discharge, and holding spectral levels are very similar. Again, the slightly quieter (>300 Hz) signal levels for the drilling phase can be seen. All phases show rapid reduction in median sound level above 8 kHz.

Following measurements from the rig, additional recordings were performed aboard the support vessel *Northern Seeker*. The aim was to obtain far-field levels; however, worsening weather meant these recordings were unusable for far-field measurements. Noise produced by the support vessel was measured (Figs. 4 and 5). At frequencies <1 kHz, sound levels emitted by the vessel are far in excess of those generated by the rig, even in its noisiest "boulder-drilling" phase. With the vessel's main engines turned off, it was quieter >400 Hz; with engines running, this cross-over frequency rose to 2 kHz. Transmission loss is shown in supplemental Fig. S4.[1]

TABLE IV. Measurements of drilling and associated sound.

Activity	Spectral density level (dB re 1 μPa/$\sqrt{}$Hz)	Frequency	Harmonics (all had 9 kHz and 18 kHz)
Floating: pre-installation (tugs present)	115	10–100 Hz	294 and 880 Hz
Tank discharge	110	5–20 Hz	
	98	1–3 kHz	
Pre-drilling preparation	120	5–20 Hz	251 Hz
	101	1–3 kHz	
Drilling	150.6 (drilling rocks)	2.8 Hz	5.6 and 10.4 Hz
	138.5	5.6 Hz (harmonic)	
Holding	112	1–3 Hz	
	98	5 Hz to 3 kHz	

B. Audibility to harbor porpoise

SPLs shown in Fig. 6 were calculated using a selection of measured sound levels (Table III) at 10 m below the water surface. These figures show SPL against horizontal distance to the source.

Using linear interpolation on experimental data presented by Kastelein *et al.* (2010), estimated detection thresholds for harbor porpoises at these frequencies were calculated (Table III). There are no data available for 2.8 Hz, so this was removed from the simulation. For 250 Hz, the detection threshold is larger than SPL at all distances; therefore, it is unlikely that noise can be detected by harbor porpoises. For 880 and 1263 Hz, detection distances are estimated to be 69 and 66 m, respectively, which means it is unlikely that noise at these frequencies can be detected beyond these distances by harbor porpoises at a level 10 m below the water surface.

IV. DISCUSSION

This research investigated routine underwater noise produced by a jack-up exploration drilling rig within 60 m of the drill stem and levels that harbor porpoise could potentially be exposed to in the immediate vicinity of the rig. RL and frequency values are comparable to those measured at other drilling platforms but are the first to be recorded for a three-legged jack-up drilling rig engaged actively in O&G exploration. We were also able to predict the range at which harbor porpoise could potentially detect rig noise.

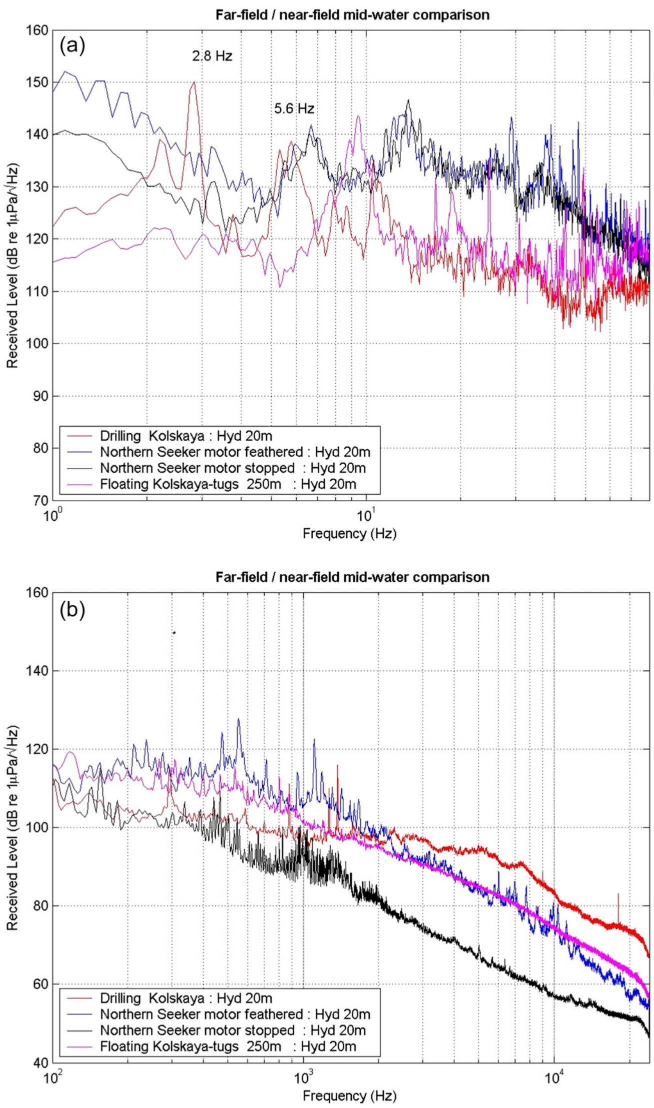

FIG. 5. (Color online) HF (a) and LF (b) plots of *Northern Seeker* measurements compared to the drilling phase levels and levels recorded prior to rig installation, with three tugs present.

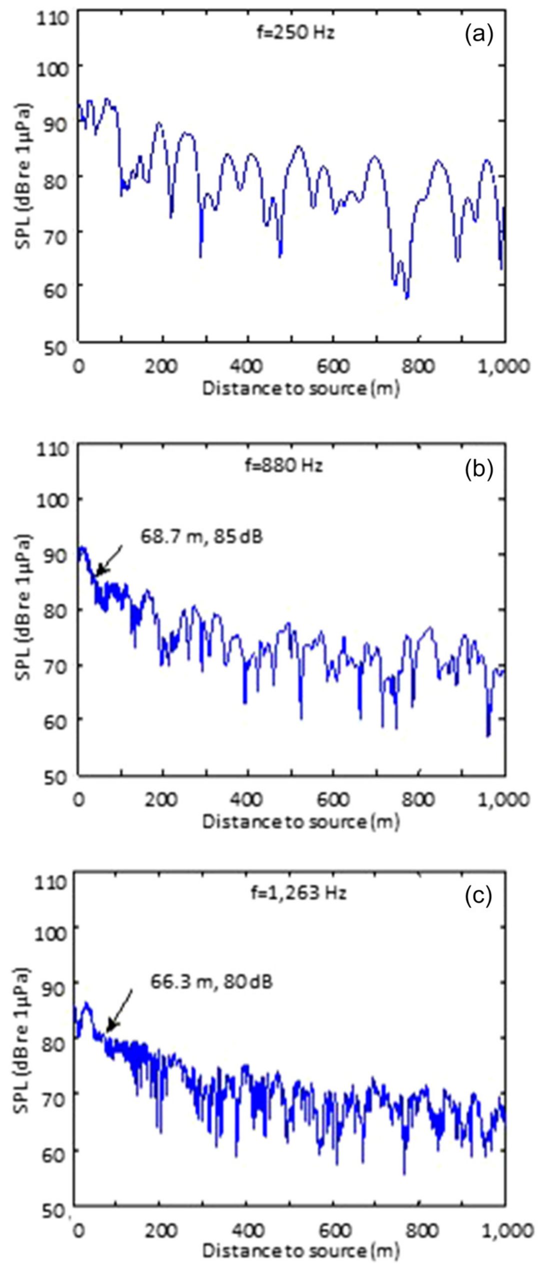

FIG. 6. (Color online) SPL at 10 m from the water surface, changing with distance to the source, with source level of 121 dB at 250 Hz (a), 117 dB at 880 Hz (b), and 114 dB at 1263 Hz (c).

A. Generated noise levels

The LF components—seen both as an increase in median sound-density level within certain frequency bands and as development of tonal components—were the highest recorded received levels observed during measurements. The 2.8 Hz tonal was recorded at a received level of 141 dB re 1 μPa $\pm$ 1 dB at ca. 60 m from the drill-stem location. For an equivalent sound spectral density level of 150 dB re 1 μPa/$\sqrt{}$Hz, this is ca. 25 dB above the upper limit of the prevailing limits of noise taken from the generalized ambient noise spectra (Wenz, 1962) for the same frequency. The 2.8 Hz component is around 22 dB above the equivalent sound spectral density level for the pre-drill period.

Numerous other lower-level components were observed both during preparation and drilling phases. These were seen as both clearly defined tonals and elevated broadband sound level densities. Strong variations in these levels were observed over relatively short time periods, which, according to the drill-stem operator, are due to changes in drilled substrate material. The loud and strong 2.8 Hz tonal was present only when hard rock/boulder formations were encountered in otherwise soft substrate and was evident as a strong increase in noise levels on the rig itself. Strongest median sound level densities were observed below 4 Hz. "Quiet"—i.e., non-boulder-drilling—periods in both pre- and during-drilling phases were around 125 dB re 1 μPa/$\sqrt{}$Hz and were approximately 15–20 dB above the equivalent levels measured during the tank discharge and holding phases. A reduction to $<$90 dB re 1 μPa/$\sqrt{}$Hz sound level density was observed in frequencies above 10 kHz and $<$80 dB re 1 μPa/$\sqrt{}$Hz for frequencies above 80 kHz.

Received levels were similar when compared to values of exploration drilling from semi-submersible platforms and other metal-legged drilling rigs 119–127 dB re 1 μPa (Gales, 1982; Richardson *et al.*, 1995; Quijano *et al.*, 2018a) at near-field locations, *c.f.*, 125 dB re 1 μPa in this study. RL reported by Erbe and McPherson (2017) for geotechnical drilling had higher received levels of 142–154 dB re 1 μPa, likely due to the different type of drilling machinery used—e.g., the drill in that study used a rotational speed of 1500–1600 rpm, while in this study it was substantially lower, continuously variable between 0 and 240 rpm. Primary operating frequencies reported here (2–1400 Hz) are very similar to other exploration drilling campaigns, which were recorded between 4.5 Hz and 2 kHz (Gales, 1982; Richardson *et al.*, 1995; Quijano *et al.*, 2018b).

When the general form of measured spectra (quiet rig noise of 98 dB) is compared against published ambient noise levels (Wenz, 1962; Andrew *et al.*, 2002), rig noise lies approximately 10 dB above ambient up to 300 Hz and approximately 20 dB until 8 kHz is reached, and levels drop to close to background levels from there on. Vessel noise is considerably higher, lying generally 20 dB above the output from the rig itself.

B. Tonal sources

Strong variations in sound-density level during the drilling phase were observed. All recordings show a broadband LF level of between 110 and 125 dB re 1 μPa/$\sqrt{}$Hz. Strong components at both 49 and 50 Hz were also observed but are almost certainly related to mains power interference, and consequently analysis of acoustic data in the vicinity of these frequencies is not attempted. The 251 Hz signal observed only during the pre-drilling phase (whilst other signals were relatively stable during all the recordings) is close to, and thus likely a harmonic of, the mains frequency. During measurements prior to lowering of the rig legs (i.e., barge afloat), the 294 and 880 Hz tonals were present, but the components at 1263 and 1373 Hz were not detected. Additional tonal components at 9 and 18 kHz were observed above the background level in all recordings. This could be electrical noise. It is too high-frequency to be mains but is possibly related to the analogue-to-digital converter.

There are several frequencies that have clear signals in the acoustic record. The 2.8 Hz tonal recorded in the drilling record can be attributed to the rotation of the drill stem itself, since this frequency converts to 168 rpm, a typical figure used during the drilling phase. Tonal frequencies were limited to similar frequencies recorded on other platforms: 1.2 kHz (Gales, 1982) versus 1.4 kHz (*Noble Kolskaya*). The strongest tones from all metal-legged platforms measured by Gales (1982) were at very low frequencies, near 5 Hz, reflecting the generally low rotation rates of the drill stem and its apparently dominant influence in noise generation, at least when drilling through relatively hard formations.

Barge "floating" records revealed clear tonal spikes at the eight-cylinder and 12-cylinder diesel engine shaft rates (16.7 and 25 Hz; Table II). Since these were evident at a lower level during other measurement periods, they were likely due to improved coupling of engines' vibrations when the barge (rig's "hull") was in the water. The eight-cylinder engines' shaft rate was particularly evident in supplemental Fig. S3a,[1] during and immediately prior to drilling. Clear acoustic signatures from the cylinder firing rates (CFRs) revealed tonals at 133 Hz [in the floating record; Fig. 2(b)] and a very clear tonal at 394 Hz in all other recordings (Fig. 2 and supplemental Fig. S3a).[1]

Similar signatures can be seen in the *Northern Seeker* support vessel records. The main engine CFR revealed a peak at ca. 40 Hz, which was not detectable when the engine was stopped. Similarly, the auxiliary engine generated a tonal at its shaft rate of ca. 30 Hz). LF components, e.g., at 6.6 and 13 Hz, were more challenging to attribute, although the 6.6 Hz component was close to the main engine shaft rate (Table II), but it was still present when this engine was stopped.

C. Audibility to harbor porpoise

There are no available hearing detection thresholds for harbor porpoise at the low frequencies produced by drilling, purely because it requires a 1500 m deep acoustic holding tank to play a 1 Hz signal to a porpoise, which is not practicable. For higher frequencies, at 10 m below the water surface, harbor porpoises could potentially detect drilling noise of 880 Hz within 69 m and 1263 Hz within 66 m from the source horizontally, and it is clear that they would experience changes with water depth.

Harbor porpoises produce dominant narrow-band high-frequency (NBHF) click components within 110–150 kHz (Møhl and Andersen, 1973; Verboom and Kastelein, 1995, 1997; Au *et al.*, 1999; Teilmann *et al.*, 2002; Villadsgaard *et al.*, 2007; Kastelein *et al.*, 2017), 5 orders of magnitude higher than dominant tonal frequencies produced by drilling (Fig. 2). Whilst results show that harbor porpoises can potentially detect HF components of drilling noise out to a distance of 69 m from the source, noise is unlikely to interfere with or mask echolocation clicks. No inference is made as to short- or long-term behavioral effects, as this is beyond the scope of this study.

V. CONCLUSIONS

Noise produced from an O&G jack-up exploratory drilling rig is similar to that measured at other types of drilling rigs with most sound emitted below 100 Hz but with some HF components up to 8 kHz. Noise measured between the legs of the jack-up drilling platform is expected to be audible to harbor porpoise up to 69 m at these frequencies but is not expected to interfere with their acoustic communication or foraging.

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[1]See supplementary material at https://www.scitation.org/doi/suppl/10.1121/10.0002958 for additional figures and results.

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