Acoustic characterisation of a mobile offshore drilling unit

Guillermo Jimenez-Arranz, David Hedgeland, Stephen Cook, Nikhil Banda, Phil Johnston, and Ed Oliver

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Corresponding Author:	Guillermo Jimenez-Arranz, MSc Seiche Ltd Devon, Devon UNITED KINGDOM
Order of Authors:	Guillermo Jimenez-Arranz, MSc
	David Hedgeland
	Stephen Cook
	Nikhil Banda
	Phil Johnston
	Ed Oliver
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Acoustic characterisation of a mobile offshore drilling unit

Guillermo Jimenez-Arranz
Seiche Ltd, Bradworthy, Devon, EX22 7SF, UNITED KINGDOM; g.jimenez@seiche.com

David Hedgeland
BP, Sunbury-On-Thames, Middlesex, UNITED KINGDOM; david.hedgeland@uk.bp.com

Stephen Cook and Nikhil Banda
Seiche Ltd, Bradworthy, Devon, EX22 7SF, UNITED KINGDOM; s.cook@seiche.com; n.banda@seiche.com

Phil Johnston and Ed Oliver
Autonaut Ltd, Chichester, West Sussex, TW16 7LN, UNITED KINGDOM; phil.johnston@autonautusv.com; ed.oliver@autonautusv.com

A sound field mapping survey was carried out in December 2017, during normal operation of a 6th generation Mobile Offshore Drilling Unit (MODU) in deep waters of the North Atlantic. The study was commissioned to produce an acoustic dataset for future verification of sound propagation modelling for modern semi-submersible facilities. Four drift buoys and an Unmanned Surface Vessel were used to collect data around the MODU during dynamic positioning and intermittent periods of drilling, with focus on the platform's nearfield. The sound field mapping took place in an area with significant vessel activity and during the operation of distant, low-frequency impulsive acoustic sources. The work here presented was conducted to address the data gap that currently exists in sound measurements of large semi-submersibles. Results showed that the MODU is a primarily low-frequency source (90% of the emitted acoustic energy concentrated below 250 Hz) with tonal components in the kHz range and an average broadband sound level of 118 dB re µPa within 1 km. Noticeable sound level fluctuations with time, likely associated with changes in the operational conditions of the MODU, added significant variability to the results.

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1. INTRODUCTION

There is limited data and literature about sounds produced by large, semi-submersible offshore drilling facilities. With the intention to help address this data and knowledge gap, a sound field mapping survey was carried out to study the acoustic output of a modern, 6th generation Mobile Offshore Drilling Unit (MODU).

The acoustic survey took place during normal operations of the MODU in a deep-water area over a period of 8 days during December 2017. The semi-submersible remained at a fixed location throughout the survey, with its dynamic positioning (DP) system permanently active during intermittent periods of drilling activity. Drift buoy and an Unmanned Surface Vessel (USV) platforms were used to collect acoustic data within an area around the MODU, with receivers located at 25 m, 30 m and 60 m nominal depths. A total of 117 hours of valid continuous audio and navigation data was collected at ranges between 100 m and 5,500 m from the MODU.

The sound field mapping took place in an area with significant vessel activity, a stationary oil production platform (PP) and the MODU itself. Eight vessels operated continuously within an area of 400 km^2, including attendant/crew vessels, the acoustic survey, and other survey vessels. The presence of continuous vessel traffic and other noise[1] sources were challenging during data collection and analysis. Special attention was placed on the design of the sound mapping strategy relative to other activities and communication protocols between them, known as Simultaneous Operations (SIMOPS), to manage safe and successful field operations.

2. MATERIALS AND METHODS

A. SITE ACTIVITY

The survey area is located at the lower edge of the continental rise, in water depths of 2.5-3.5 km (see Figure 1), with a seabed consisting in a thick accumulation of semi-consolidated sediments. The MODU remained on location for the duration of the acoustic survey, continuously operating in DP mode, with 8 azimuthal thrusters located in pairs at the corners of the platform's structure at a depth of 20 m. From an acoustical perspective, the MODU is a 'distributed' source, with a number of individual sound sources spatially dispersed across the overall structure. The Production Platform (PP) was located north-east of the MODU. Crew and support vessels remained within 6 km of their respective offshore facilities. One external survey vessel operated between 3 and 6 km to the west of the MODU. Two other survey vessels remained south-east of the PP and MODU for most of the survey period. The acoustic survey vessel was the most actively mobile vessel nearest to the MODU.

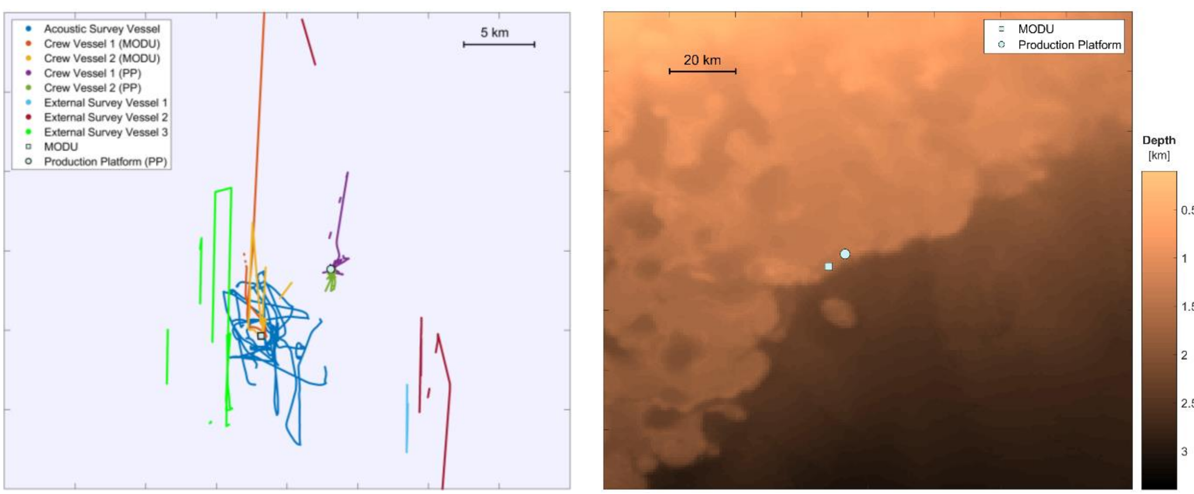

Figure 1 *Vessel tracks (left) and bathymetry of the survey area. The MODU and PP are shown as white markers.*

[1] The word "noise" refers to continuous or transient signals, of acoustic or electric nature, that are not of interest and could contaminate target sounds, in our case those produced by the MODU. The word "sound" is used with acoustic signals of interest, signals of undetermined origin, or as a generic word for a combination of acoustic signals of diverse origin or nature.

B. EQUIPMENT

Two data acquisition platforms were used for sound field mapping: the drift buoy and the USV (see Figure 2). A long 4-channel hydrophone array was installed in each drift buoy, with receivers at 30 and 60 m nominal depth. The USV was equipped with a two-channel towed hydrophone array, with the receivers nominally at 25 m depth.

The acoustic drift buoys are designed to collect audio and navigation data continuously as they drift with swell and currents. Four buoys were used for the sound study, all with the same configuration: a mast with radar reflector and strobe light; metal housing containing the battery, remote access ethernet, GPS receiver and satellite tracker; the float; Seiche *e-tube*, a water-tight metal housing containing the passive acoustic monitoring (PAM) unit, which comprised a single-board computer (SBC) with open-source software PAMGuard (64-bit, v.1.15.12) (Gillespie, 2008) and the data acquisition unit NI-9222; the *wet leg*, a protective metal pipe directly attached to the *e-tube*; and a 60 m long, 4-channel hydrophone array cable. The hydrophones were placed in pairs, at depths of 30 m and 60 m below sea surface for vertical cable orientation. The hydrophones included a preamplifier, with 34 dB and 54 dB differential gain for each coincident pair to provide usable data in the event of either clipping or low signal-to-noise ratio. The approximate nominal sensitivities for the hydrophones were -162 and -142 dB re. 1V/μPa. The audio signal was recorded for all 4 channels simultaneously at a sampling rate of 250 kHz, with 16 bit sample resolution and input voltage full-scale of 20 V (±10 V). The continuous audio data was recorded with PAMGuard and stored in WAVE (.wav) files 1.5 GB large (13 minutes, 6 seconds duration). The GPS receiver generated NMEA sentences at a rate of one per second and were stored in a SQL database. Synchronization between audio and GPS sentences was achieved through the audio file timestamp, automatically set to UTC.

The USV was equipped with: a remote control and communications system; a hull-mounted PAM unit comprising a SBC with PAMGuard, data acquisition unit NI-9222 and GPS receiver; a 25 m, lightweight hydrophone cable comprising two individually-potted ceramics and a 2.5 bar depth sensor on its tail. The two hydrophones used an identical preamplifier with 40 dB differential gain. The audio signal was recorded at a sampling rate of 300 kHz, 16 bit and input voltage full-scale of 20 V (±10 V). The continuous audio data was stored in WAVE (.wav) files of 15-minuteduration (1.0058 GB large). An additional PAM unit was installed in the acoustic survey vessel to acquire navigation information from a GPS and an AIS receiver.

The preamplifiers included a high-pass filter with a cut-off frequency of 20 Hz. The measured low-frequency sensitivity of the ceramics (10-300 Hz) and full frequency response of the preamplifiers (2 Hz – 200 kHz) were combined to obtain the sensitivity response of all hydrophones in the range of 20 Hz to 10 kHz.

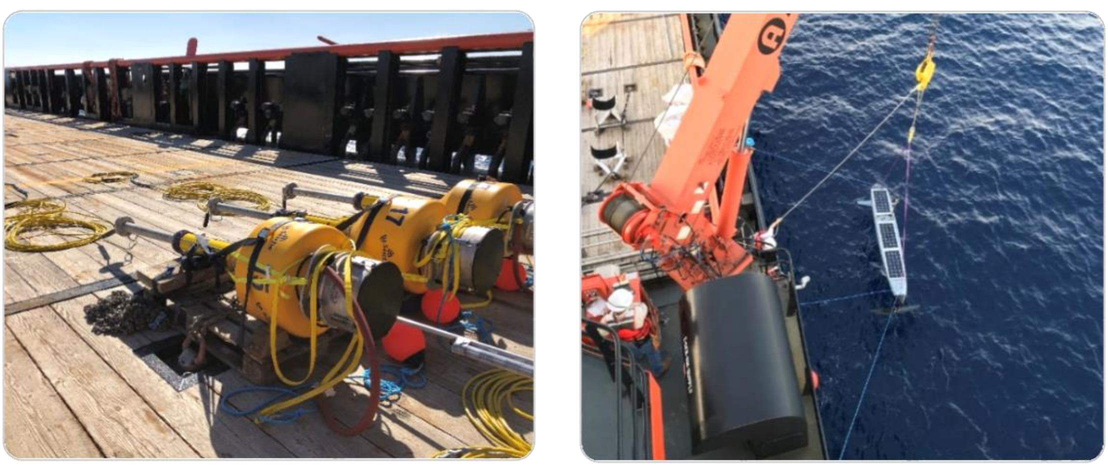

Figure 2 *Drift buoys on deck (left) and USV during deployment (right).*

C. DATA COLLECTION

Drift buoy operations started during the USV close passes, with the objective of acquiring sound field measurements at ranges of 1 km or more from the MODU. The fleet's 24-hour lookahead from the SIMOPS communication helped with a choice of deployment locations that minimised the risk of encounters with nearby vessels or platforms. The deployment of each buoy took between 15 and 25 minutes, depending on distance between drop-off points; the recovery took 30 minutes per buoy plus transit time. Due to recovery challenges and the limited duration of each deployment, the maximum number of simultaneous drift buoys in the water was three. For details on the deployment and recovery times and platforms, see **Error! Reference source not found.**.

Table 1 *Deployment and recovery UTC times for each recording platform.*

Deployment	Platform	Time In	Time Out	Total Drift [h]
1	USV	11/12/2017 19:00	14/12/2017 22:30	75.50
2	F19E9T4	13/12/2017 19:15	13/12/2017 23:00	3.75
3	F20E7T2	14/12/2017 13:00	14/12/2017 18:15	5.25
3	F15E10T5	14/12/2017 13:15	14/12/2017 18:38	5.38
3	F23E8T1	14/12/2017 13:40	14/12/2017 19:00	5.33
4	F19E9T4	14/12/2017 19:45	14/12/2017 20:15	0.50
4	F23E8T1	14/12/2017 20:00	14/12/2017 20:30	0.50
5	F19E9T4	15/12/2017 13:04	15/12/2017 15:55	2.85
5	F17E11T6	15/12/2017 13:20	15/12/2017 16:15	2.92
6	F19E9T4	16/12/2017 13:40	16/12/2017 17:10	3.50
6	F17E11T6	16/12/2017 14:00	16/12/2017 17:25	3.42
7	F19E9T4	18/12/2017 13:00	18/12/2017 17:30	4.50
7	F17E11T6	18/12/2017 13:30	18/12/2017 17:15	3.75

The USV was deployed from the acoustic survey vessel in calm weather, with 0.5 metre swell and 5-8 knots wind speed (sea state 1-2). The unmanned vessel was driven away from the deployment location through remote control to safely initialize the set waypoint track. The USV had permission to access the 500 m exclusion zone of the MODU during daylight hours. Overnight, the USV operated outside the 500 m zone, covered up to a range of 5.5 km from the MODU, with most of the transects to the east of the facility. The USV operations within the 500 m exclusion zone started the next day, in a building sea state, with winds up to 20 knots and 1-2 metre swell (sea state 4). The close tracks followed a concentric square pattern, with a closest point of approach (CPA) to the MODU of 140 m (180-190 m to its centre). The USV was recovered in calm weather on the fourth day of continuous recording.

Communications between the acoustic survey vessel and the drilling unit followed SIMOPS protocols at all times. Prior to the USV entering the 500 m exclusion zone, a vessel checklist was completed. The acoustic survey vessel stayed outside the 500 m zone, at radio-communication distance from the USV (300-400 m).

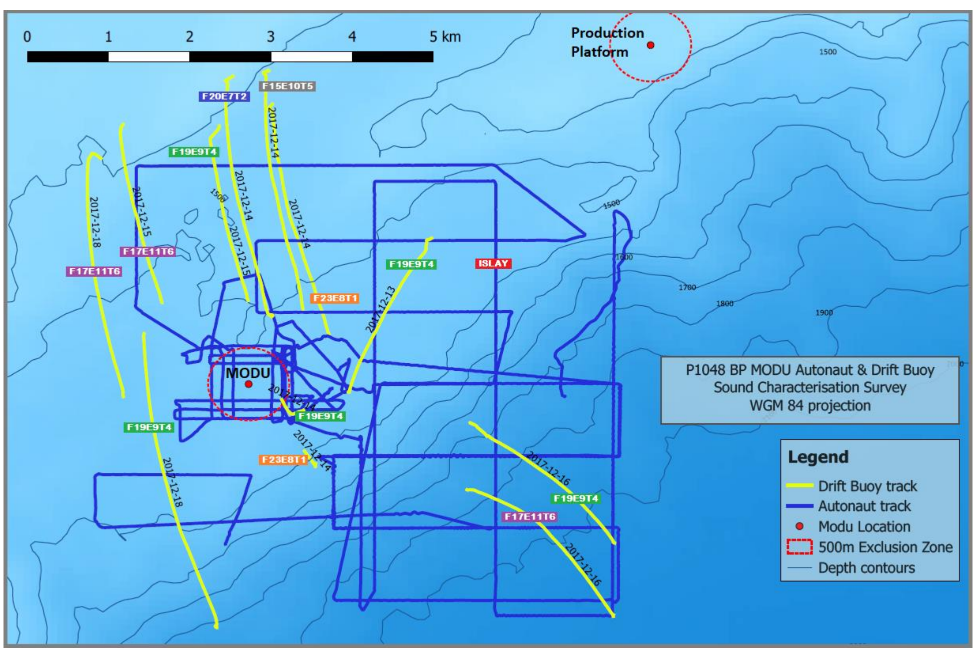

Figure 3 *Tracks followed by the USV and drift buoys during the sound source characterisation survey.*

An external vessel was present to the west of the drilling unit through most of the study duration, limiting the operational area to the east of the MODU for most of the acoustic survey. A window of opportunity opened on the last day of the survey period to the west of the MODU and two drift buoys were deployed to fill the gap in data coverage around the MODU.

Figure 3 shows the tracks followed by the drift buoys and the USV throughout the acoustic survey. A total of 4 days, 21 hours and 4 minutes of valid continuous audio and navigation recordings were collected over the survey duration. A total of 169,556 one-second audio segments containing continuous sound dominated by MODU's acoustic output were extracted from the dataset for further processing.

D. DATA QUALITY CHECK

Seven different types of signals were identified in the recordings and attributed to a likely activity: 1) Continuous, low-frequency sound with tonal components (MODU); 2) Transient, low-frequency pulses with most energy below 100 Hz; 3) Continuous, tonal low-frequency signals with broadband noise from cavitation (nearby vessels); 4) short chirp with 25 kHz central frequency (high-resolution sub-bottom profiling); 5) 38 kHz ping (echosounder); 6) 5.5 kHz continuous tone (USV power-supply self-noise); 7) low-frequency, wideband noise (USV hydrophone cable vibrations or *rubbing*). For the frequency range of interest, between 20 Hz and 5 kHz, and considering that most transitory events could be eliminated (nearby vessels, low-frequency pulses, wideband cable vibrations), the only signals capable of contributing to the recorded low-frequency sound levels, other than the MODU, were those from distant vessels and the acoustic reverberation associated with low-frequency pulses.

Figure 4 shows the average and the standard deviation of the frequency spectrum of measured MODU sound during DP, with and without low-frequency pulses being present. Six one-second audio segments were used to calculate the spectral curve of each scenario. All segments were extracted from a 15-minute period to minimise the chance of significant spectral variations with time. Between 50 Hz and 125 Hz, the reverberation from the low-frequency pulses tended to dominate over the acoustic output of the MODU. These results give an idea of the relative contribution to the processed sound levels of reverberant energy from low-frequency pulses.

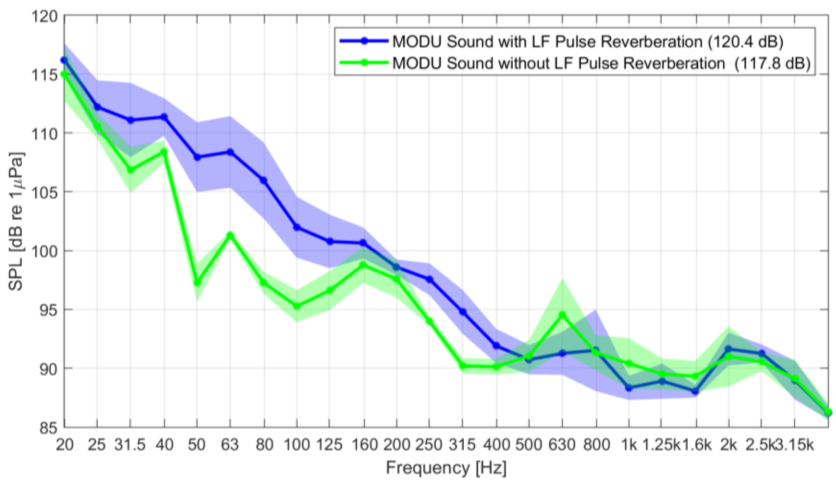

Figure 4 *Measured third-octave band spectrum averaged over six samples of MODU sound* with (*blue*) *and* without (*green*) *reverberant energy from low-frequency pulses. Measurement data was collected using the USV. The coloured area represents the std. deviation.*

E. DATA PROCESSING

The field data analysis and processing were carried out with custom software developed specifically for this project. The software imported sound recordings and geographic data (GPS and AIS), processed it, and reported statistics of the acoustic metrics. As a part of the processing, the data was resampled to 10 kHz, enabling faster data manipulation and to improve the stability of the filters used. The audio was then split into one-second clips and the peak, peak-to-peak, root-mean-square (RMS), and exposure values for the digital audio data were processed for each of those clips. The RMS and exposure values were processed in third-octave bands from 20

Hz to 4 kHz. The raw values were converted into acoustic metrics by applying the voltage resolution factor and the hydrophone's sensitivity spectrum.

The one-second clips were classified either as "valid" or "non-valid" through the software's Revision Module, a graphic user interface designed to inspect the temporal and spectral features of individual audio segments. All the low-frequency pulses and at least 75% of related reflections were successfully removed from the dataset by applying a threshold level, above which a clip is tagged as "non-valid". The threshold was individually selected for each audio file. Regardless of its simplicity, this classification method was highly effective given the difference in amplitude that existed between low-frequency pulses and the low-frequency, continuous sound from the MODU.

A portion of hydrophone self-noise events and reflections from low-frequency pulsed signals were inevitably included in the analysis dataset, due to limitations in the method used for discrimination of audio clips associated with MODU emissions. However, these masking events were estimated to have a marginal contribution to the average spectra, given their limited number and relatively low sound pressure level.

F. SOUND PROPAGATION MODELLING

An underwater sound propagation model was used to calculate the transmission loss along various azimuthal transects from the MODU's location. The transmission loss curves were used to calculate MODU's source level spectra based on far-field measurements. The predicted received levels with range were then compared to the measured data to investigate the limitations of the far field modelling assumption in the proximity of a distributed sound source like the MODU. Two range-dependent numerical models for elastic sediments were used: RAMSGeo, a parabolic equation method for low-medium frequencies; and Bellhop, a raytracing method for high-frequencies. Both algorithms are included in MATLAB software AcTUP (Duncan & Maggi, 2006).

A geoacoustic model was defined to make the propagation model account for the specific acoustic properties of the water body and seabed. The CTD information, required for the calculation of the acoustic parameters of the water column (sound speed, density and attenuation) was obtained from the NOAAWorld Ocean Database interactive map (NOAA). The speed of sound in sea water was approximated with Mackenzie's equation (Mackenzie, 1981) and the density with the formula of the specific density anomaly of sea water from Fofonoff and Millard (1983). No calculation was made on the attenuation of sound in sea water, and a null value was used (0 dB/λ, with λ being the acoustic wavelength). The acoustic properties of the seabed were calculated using the empirical equations proposed by Hamilton for different types of sediments and rocks (Hamilton, 1980), based on geological data retrieved from the Initial Reports of the Deep-Sea Drilling Project (DSDP). The bathymetry was obtained from the publicly available GEBCO database (GEBCO). The bathymetry profiles showed a ±1% slope below 7 km from the MODU. An average water depth of 2,300 m was considered for all measurement locations, which further simplified the model by reducing the number of simulated azimuthal transects to one.

3. RESULTS

A. ACOUSTIC VARIABILITY

The variability of measured sound pressure levels (SPL) with time, frequency and space was assessed with the objective of describing the sound field produced by the MODU, and to understand the contribution of sound sources and their propagation effects to the results.

I. TIME

Analysing variation of sound pressure levels with time between various data acquisition platforms operating simultaneously can help identify local, transitory noise events that may be contaminating the sounds from a given platform. It can also help identify non-local variations with potential to affect the overall sound field.

Figure 5 shows the broadband SPL RMS of one-second clips associated with MODU's acoustic emissions from two different buoys operating on the same day. The buoys, nominally spaced 1 km apart, collected data at distances of 3 – 5 km from the MODU. The strong correlation of the time-dependent sound levels measured by the two spaced buoys suggests that sound level fluctuations were not caused either by local events, or changes in the propagation path, or self-noise. A comparison of Figure 5 with the distance from the buoys to the closest vessels shows no correlation with other vessel proximity, as all vessels remained at a distance of 4 km for most of that day. The short and long-term sound level fluctuations may be caused by changes in operational conditions from weakly-directional remote sources such as the MODU, distant vessels, or low-frequency impulsive sources, which are capable of producing low-frequency, continuous sounds of varying amplitude. A statistical analysis of the entire dataset indicates a strong short-term sound level variability (< 20 dB within one-hour periods) and medium long-term variability (< 5 dB within several hours).

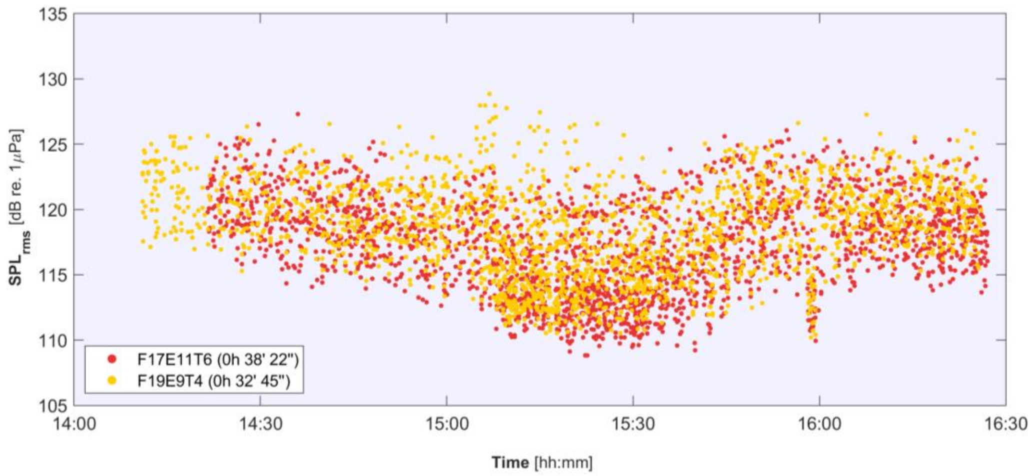

Figure 5 *Evolution with time of SPL RMS of 1 s audio samples. Measurements taken on the same day during deployment of buoys F17E11T6 and F19E9T4 with the receiver at 30 m depth. 4,267 measurements are represented.*

II. FREQUENCY

Figure 6 shows a box-and-whisker plot representation of the third-octave band spectrum generated from drift buoy measurements collected over several days at ranges of 1-2 km and a receiver depth of 30 m. The figure shows a predominantly low-frequency spectrum, with 90% of the spectral energy concentrated below 250 Hz. A tonal behaviour is also apparent, with a noticeable tonal component in the 2.5 kHz frequency band. Observations of the third-octave band and narrowband spectra at various distances from the source revealed clear tonal components near the MODU, which attenuated with distance. At the closest distances from the source, 500 Hz, 800 Hz and 2.5 kHz tones were prominent; and at distances beyond 2 km no high-energy components could be observed. The clear range-dependence of these tonal frequencies indicates that these were produced by the MODU. The tones appeared during drilling and non-drilling phases, suggesting that they may be linked to onboard machinery or the DP thrusters. The tones had a negligible contribution to the overall broadband levels.

Overlaying the box-and-whisker plot is the simulated third-octave band ambient noise spectrum. This spectrum accounts for the combined contribution from distant underwater acoustic sources that produce continuous, random-like sounds associated with natural processes (wind, rain, thermal noise, volcanic activity) or human-related activities (ship traffic). The continuous operation of the MODU prevented any measurement of ambient noise, therefore it had to be simulated to evaluate any potential masking caused by weather or distant vessels. The ambient noise spectrum was calculated for conditions of medium vessel traffic and for a wind force 4 in the Beaufort scale. The method described by Lurton (2010) was used to model the contribution from ship traffic and weather conditions, which were the dominating factors in the frequency range of interest. The selected level of vessel traffic represents the most likely scenario, as “heavy-shipping” should only be used for locations near shipping lanes (Urick, 1983). A sea state 4 corresponds to the worst weather conditions observed during the survey. For medium vessel traffic, the ambient noise is unlikely to have an impact on the measured spectral levels, but the possibility of higher ambient noise levels, however, could not dismissed. Nonetheless, ambient noise will have a minimal impact on the broadband levels associated with the MODU even in a scenario of “high” vessel traffic, as the acoustic output of the MODU would still dominate below 100 Hz, where 80% of its energy concentrates.

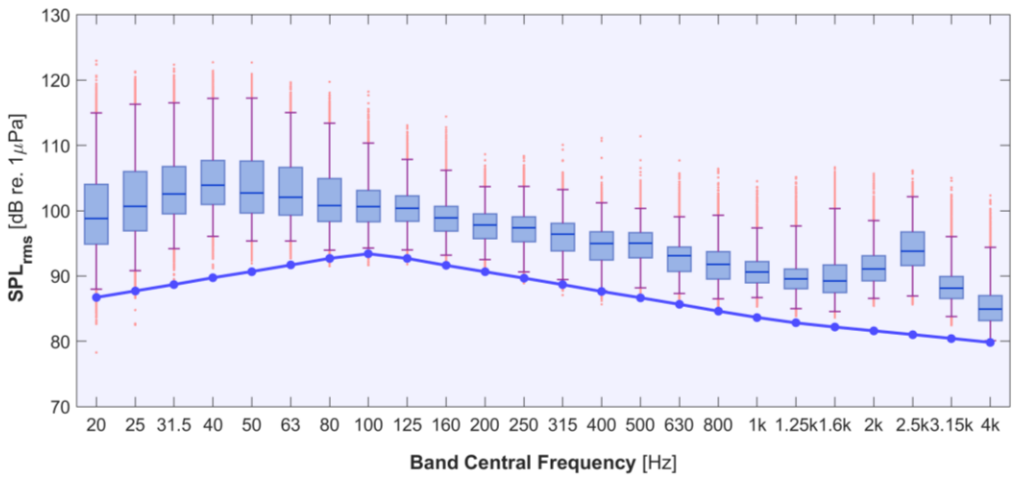

Figure 6 *Box-and-whisker plot representation of the third-octave band spectrum measured with all drift buoys at ranges of 1-2 km over the five days they were deployed (19,347 samples, receiver at 30 m depth). The simulated ambient noise spectrum is shown as a blue line.*

III. RANGE

The box-and-whisker plot of Figure 7 shows the variation in 250 m range bins of sound pressure levels measured with the USV over the deployment duration. No clear overall attenuation of sound levels with distance from the MODU can be observed. This may be caused by several factors: high-order, low-frequency reflections dominating above 2 km (see details below); the time-varying acoustic output of the MODU (refer to Section 2.I); the contribution of distant, low-frequency sources (vessel traffic and reverberation from low-frequency pulses).

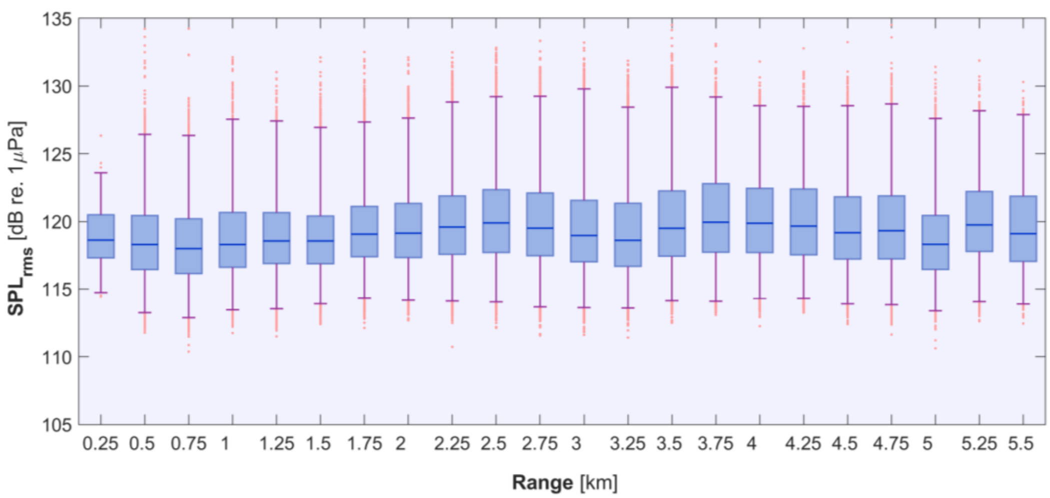

Figure 7 *Box-and-whisker plot of broadband sound pressure level in 250 m range bins. Calculated over 117,207 one-second samples. Measured by the USV at a receiver depth of 25 m over the four days it was deployed.*

The weak range dependence of sound levels attributed to the MODU can be partly explained by the presence of energy from seabed and sea surface reflections within the water column. The overall sound field becomes complex as a result, with no apparent attenuation with range. It is common to assume that in deep waters the seabed will have little impact on the measured sound levels, as the direct sound and first sea surface reflection or *ghost* will tend to dominate over second order reflections. Whilst this is generally true, the extent of the contribution of the seabed to the sound field will depend on geology, water depth and distance from the source (Urick, 1983). The Lloyd mirror effect, where a wavefield pattern occurs when the direct sound produced by a point-like source is combined with its ghost reflection, is prevalent in deep waters. This sound pressure pattern is characterised, for a given receiver depth, by a region of maxima and minima followed by a steady decay of 12 dB per doubling distance, dB/dd (Urick, 1983). Somewhere within that 12 dB/dd region, high order reflections will take over the Lloyd mirror pattern and produce a complex sound field. The range at which reflections affect the sound field can be roughly given by $r_c = K \cdot r_{LM}$, where K is a constant that depends on seabed reflectivity and water depth and $r_{LM} \approx 4\, z_r z_s/\lambda$ is the range at which the Lloyd mirror's 12 dB/dd slope starts, with z_s and z_r the depths of source and receiver. The approximate value of r_{LM} is derived from the pressure-range function of a phase-inverted acoustic dipole. A value of $K = 5$ is consistent with the sound propagation simulations of the studied area. This indicates that for frequencies below 250 Hz, where most of MODU's acoustic energy concentrates, seabed reflections will dominate at ranges higher than 2 km.

This, however, may not fully explain why sound levels do not appear to decrease with range. As discussed in the first part of this section (see Sub-Section 3.A.I. "Time"), there is a strong variability of sound levels with time. Since the data used in Figure 7 was collected on different days, changes in the operational conditions of the MODU (e.g. thruster depth and load), and the contribution from distant, low-frequency sources (low-frequency pulse reverberation, vessel traffic) could have shaped the statistical representation of sound levels with range.

IV. AZIMUTH

The spacing between outermost positioning thrusters (~100 m) is higher than the wavelength of dominant frequencies of MODU's acoustic output, therefore some level of directionality should be expected. Figure 8 represents the nearfield directivity calculated between 200 and 400 m from the centre of the MODU. The figure shows the average sound level in 45° angle bins for three third-octave frequency bands (25 , 250 and 2500 Hz) and the average of those bands (broadband signal), interpolated and normalised to the angle of maximum emission. The range interval of 200-400 m was selected to limit the difference between processed sound levels due to propagation to 6 dB, assuming a typical deep-water scenario (i.e. spherical spreading).

It can be observed that the measurements show a virtually omnidirectional pattern at 25 Hz, with the expected increased directional behaviour at higher frequencies. Sound levels appear to be higher in the north-east direction of the MODU, with the lowest acoustic energy emitted towards the north-west. Still, broadband sound levels are only 2 dB lower in the direction of lowest measured sound levels. Assuming that the data represents the sound predominantly produced by the MODU, the data analysis results suggest its broadband sound emissions are omnidirectional. However, there may be additional factors that may be contributing to create a more omnidirectional sound level distribution than MODU's own free-field, horizontal directivity. These factors are: 1) distant low-frequency sources; 2) early and high-order reflections; 3) time-dependent sound level fluctuations associated with MODU's varying operational conditions.

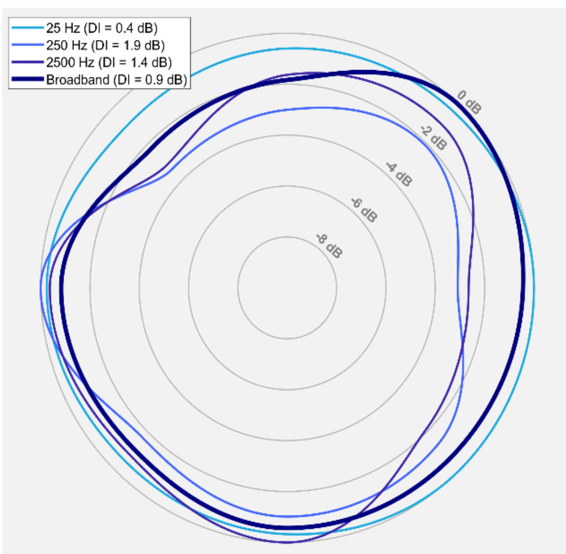

Figure 8 *Near-field directivity of the MODU at various frequencies from measurements using the USV at ranges of 200-400 m. The term DI in brackets is the directivity index.*

B. SOURCE LEVEL SPECTRA

Source level is the sound pressure level that a hypothetical, infinitesimally small emitter or *point source* would produce at a distance of one meter in a homogeneous infinite space (i.e. in free-field conditions). The source level describes the inherent, environment-independent output of an emitter at distances where its acoustic behaviour is close to that of a point source. At those distances, known as the *far field*, no interaction between integrating elements of the source occurs and, under free-field conditions, sound attenuates at a rate of 6 dB/dd. When combined with the acoustic propagation loss of the environment, the source level can be used to calculate the sound level at any point in the far field of the source. The source level may be defined for a number of frequency bands, in which case it is referred to as *source level spectrum*.

Estimating the source level spectrum of the MODU was one of the goals of this project. Six source level spectra were calculated, one for each receiver depth (25 m, 30 m, and 60 m) and different operational phase of the MODU (DP with and without drilling). This was done by fitting the simulated transmission loss curve, using least square estimates, to the measured received levels for each third-octave frequency band between 20 Hz and 4 kHz. Each transmission loss curve was calculated as the average transmission loss at three equally spaced frequencies within the band. The spectra for all receiver depths were then combined to obtain two final source level spectra, one per operational phase.

Figure 9 shows the least-square fitting process for the third-octave band centred at 250 Hz. The measurements were collected by drift buoys at a receiver depth of 30 m during MODU's drilling phase. The continuous and dotted lines represent the simulated received levels of the best fit and 95th percentile, respectively; the blue dots are the measured received levels. Note the difference in sound level between measurements and simulations below distance of 1 km. This result demonstrates the inability of the sound propagation model, which assumes an omnidirectional point source, to reproduce the near-field conditions and directional characteristics of a distributed sound source such as a MODU or other facility of similar dimensions. In this case, calculating source level assuming far field modelling assumptions, results in sound levels close to the MODU being overestimated by ~20 dB or more, depending on frequency. The transition between the near field and far field happens at an approximate distance of L^2/λ, with L the largest dimension of the source and λ the wavelength (Foote, 2014). The far-field distance increases with frequency and has a value of ~1,670 m at 250 Hz for the MODU.

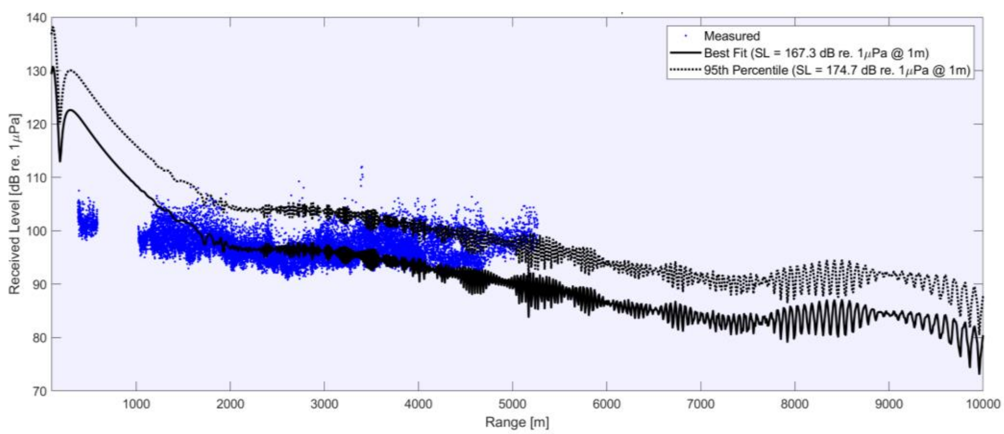

Figure 9 *Estimation of source level in the 250 Hz 1/3 octave band. Calculation made by fitting the simulated transmission loss curve (average of 232.5, 251, 271 Hz) to the measured received levels (250 Hz 1/3 oct. band). Buoy measurements at 30 m during drilling.*

The source level spectrum for the dynamic positioning phase is represented in Figure 10. The blue region indicates the root-mean square error (RMSE) of the best-fit curve. An increase of 3–8 dB in the SPL band levels during drilling operation was apparent, however the uncertainty in the fitting process (+/- 10 dB), and the observed long-term sound level fluctuations (see Sub-Section 3.A.I, "Time"), made it difficult to provide a definite conclusion about the precise source levels produced by the drilling phase.

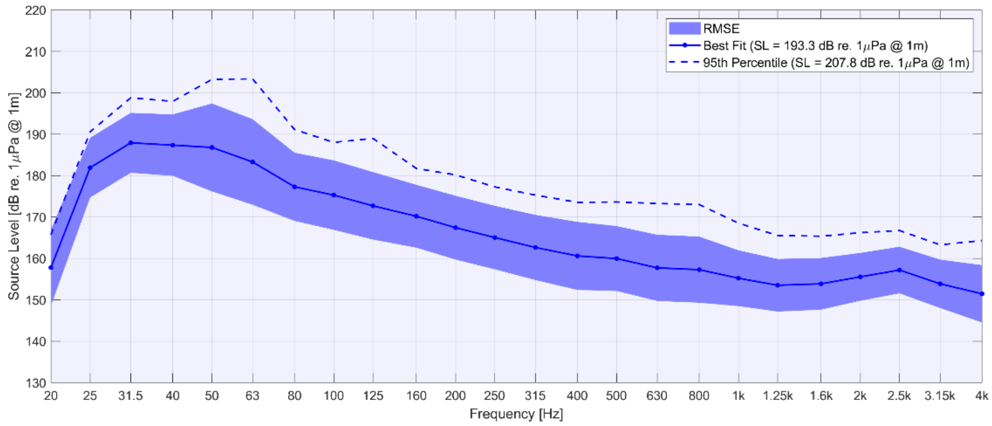

Figure 10 *Source level spectrum of MODU emissions during DP (8 thrusters active) at 30 m receiver depth.*

4. CONCLUSIONS

The study was conducted to address a data gap that currently exists in sound measurements of large semi-submersible offshore drilling facilities. A sound mapping survey was carried out during nominal operations of a mobile offshore drilling unit (MODU) to gather a dataset that could help in the understanding and future modelling of the underwater acoustic output of this type of activity. Four active drift buoys and an unmanned surface vessel collected a total of 117 hours of valid measurements at three receiver depths between 140 m (CPA) and 5.5 km from the source, during the two operational stages of the MODU (dynamic positioning and drilling), with special focus on its nearfield.

The general sound level analysis provided valuable information about the acoustic characteristics of the source, quality of the data and factors contributing to sound level variability. The frequency spectrum of the one-second audio samples indicated that 90% of the acoustic energy emitted by the MODU was below 250 Hz. Above that frequency and closest to the source, clear tonal components could be observed, which reduced in amplitude with increased distance from the MODU. An average broadband sound level of 118 dB re 1µPa was measured within 1 km from the MODU, with 90% of the values varying between 113 and 128 dB re 1µPa. Short-term (< 20 dB) and long-term (< 5 dB) variability in sound levels was identified, which were thought to be linked to the operational conditions of the MODU, and to some extent, to vessel traffic and reverberation from low-frequency pulses. Measurement data within the exclusion zone of the MODU showed a weak directional behaviour, with a broadband directivity index of 0.9 dB. Above 2 km and up to the maximum covered range of 5.5 km, sound propagation modelling confirmed that multipath reflections dominated over the direct sound for the main frequencies of the MODU, which likely contributed to the apparent lack of a clear attenuation pattern with range observed in the measurements. The accuracy of the propagation model in the proximity of the source was limited due to the point source assumption, and as a result measured sound levels were up to 20 dB lower than simulated values in the nearfield of the MODU, at distances of less than 1.6 km.

Whilst the presence of other sound sources presented challenges to isolating sounds attributable to the MODU alone, the results presented in this manuscript are representative of typical deep-water drilling operations using a modern 6th generation semi-submersible, typically supported by a number of vessels.

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