Shelburne Basin Venture Exploration Drilling Project: Sound Source Characterization

2016 Field Measurements of the Stena IceMAX

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1. Introduction

From 2015-2017, Shell Canada Limited (Shell) conducted exploratory drilling approximately 250 km off the coast of Nova Scotia, as part of the Shelburne Basin Venture Exploration Drilling Project (the Project). Shell drilled two exploration wells as part of the first drilling campaign; the Cheshire L-97A well (Cheshire), which was abandoned in September 2016, and the Monterey Jack E-43A well (Monterey Jack), which was abandoned in January 2017 (**Figure 1**). Both wells were drilled using the Mobile Offshore Drilling Unit (MODU) the Stena IceMAX (**Figure 2**) and were supported by up to four Offshore Support Vessels (OSV).

In 2014, Shell prepared a Project Environmental Impact Statement (EIS, Stantec 2014) pursuant to the *Canadian Environmental Assessment Act, 2012* (CEAA 2012). The Project's EIS included discussion on the potential interactions between Project activities and components and the potential environmental effects. Among these interactions, the EIS identified the potential biological effects from the underwater noise generated from the operations of the MODU and OSVs on the marine environment, including marine mammals and sea turtles and fish.

Drilling operations include the noise generated by the MODU as well as the noise generated by the Project OSVs. The IceMAX generates and releases three main sources of underwater noise:

i) mechanical and vibration sound associated with machinery located on the IceMAX, including engines, gears, pumps, and generators;

ii) sound associated with vibration and the creation of low pressure points and bubbles (i.e., cavitation) by the thrusters from the dynamic positioning (DP) system that run continuously to position the MODU; and

iii) sound associated with the drill string and drill bit (drilling activity).

The EIS predicted that the noise emitted from the operating MODU will likely be in the range of 130–190 dB re 1 µPa (peak frequency 10–10 000 Hz), and the sound would be non-impulsive. The range for the OSVs was predicted to be within 170–180 dB re 1 µPa.

These range values were derived from several reviews of anthropogenic sound sources. The EIS compared these predicted noise ranges to received sound levels used to assess risk of potential hearing impairment to marine mammals, sea turtles and fish found in literature. Based upon these range values, the EIS predicted that there would likely be no direct injury or permanent auditory effects on fish, marine mammals, or sea turtles from the operation of the MODU (Stantec 2014).

In accordance with Condition 3.12.3 of the Decision Statement Issued under Section 54 of the CEAA for the Project,

> *The Proponent shall monitor effects on fish and fish habitat, including marine mammals and sea turtles, to verify the accuracy of the predictions made during the environmental assessment and to evaluate the effectiveness of mitigation measures identified under conditions 3.1 to 3.11, including:*
>
> *3.12.3 verifying predicted underwater noise levels with field measurements during the first phase of the drilling program. The Proponent shall provide to the Board a plan on how this will be conducted at least 30 days in advance of drilling, and the monitoring results within 90 days after a well is suspended and/or abandoned.*

Shell contracted JASCO Applied Sciences (JASCO) to verify the underwater noise levels predicted within the Project EIS with field measurements. This report provides the results of a Sound Source Characterization (SSC) of the IceMAX. The SSC was performed to measure underwater sound levels from the Monterey Jack drilling operation, which included mechanical and vibration sound, thruster cavitation from the DP system, and direct drilling sound from the drill string and drill bit as a function of distance from the location of the source. The report also discusses the underwater sound levels generated by the Project OSVs. The Monterey Jack well was located at latitude: N 42^{o} 12.27' and longitude: W 63^{o} 37.50' in approximately 2120 m water depth. The JASCO field team deployed and retrieved all acoustic equipment from the Project standby vessel, the *Scotian Sea* (**Figure 3**) during the SSC. The measurements were performed from 31 Oct to 2 Nov, 2016.

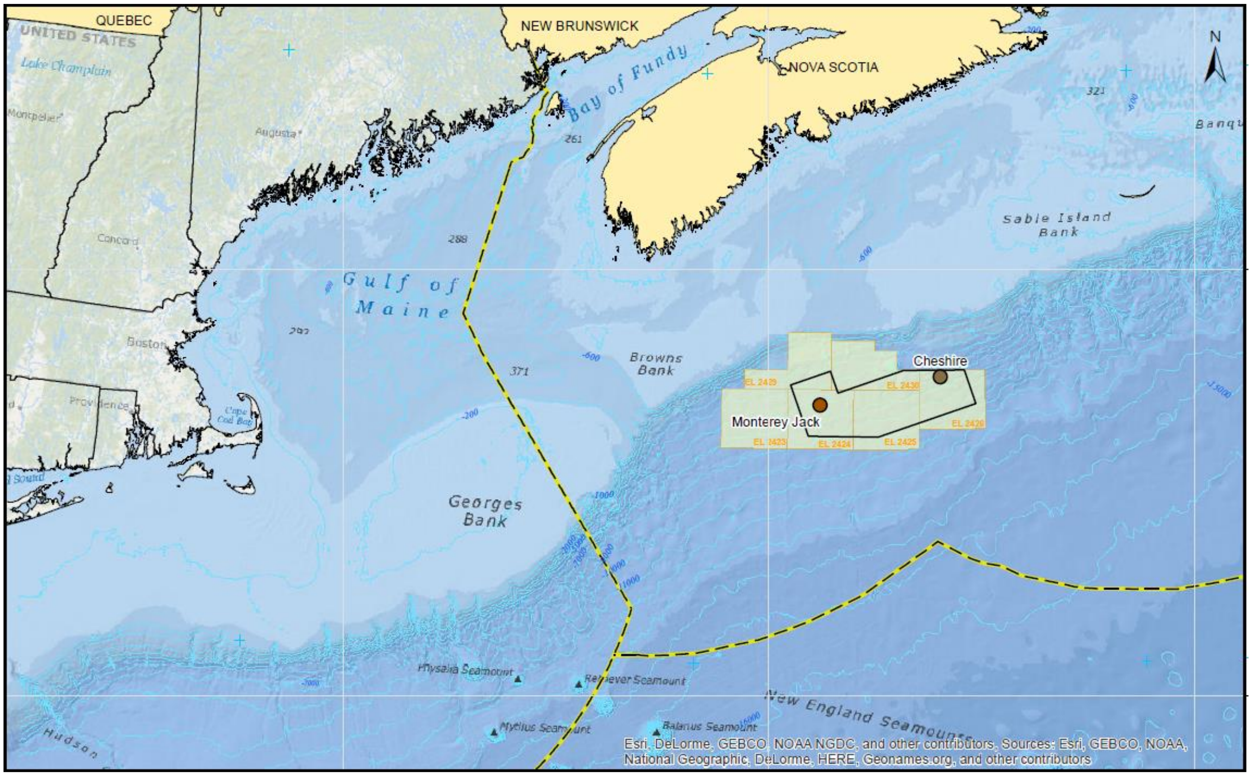


Figure 1. Location of the Cheshire and Monterey Jack well sites.

In support of the SSC, JASCO used data from the IceMAX acquired during the vertical seismic profile (VSP) program completed on 6 January 2017 for the Monterey Jack well. Measurements of the high-frequency sources are presented in Section 3.5. Furthermore, the report presents opportunistic measurements acquired in 2015 and 2016 by JASCO from the deployment of a bottom mounted recorder approximately 13 km northeast of first well of the Project drilling campaign, the Cheshire well site (see Section 4.2). These measurements provide additional data on drilling noise recorded at various distances from the IceMAX, as well as more insight into ambient noise levels.

Figure 2. Mobile Offshore Drilling Unit (MODU), the Stena IceMAX, is the source measured in the SSC.

Figure 3. Standby vessel, the *Scotian Sea*, used to deploy and retrieve acoustic equipment for the SSC.

2. Methods

2.1. Recording Equipment

A combination of static bottom-mounted recorders and a mobile ‘floating’ configuration was used to measure sound levels near the water surface and the seafloor. Three Autonomous Multichannel Acoustic Recorders (AMARs) were deployed to record underwater sound near the IceMAX: two static AMAR recorders and one mobile catenary system. Deployment locations are shown in **Figure 4** and listed in **Table 1**. This combination of recorders allowed JASCO to capture of sounds from IceMAX thrusters in DP mode, mechanical vibrations, and drilling noise from the drill string and bit during the drilling of Monterey Jack at various depths and distances from the IceMAX.

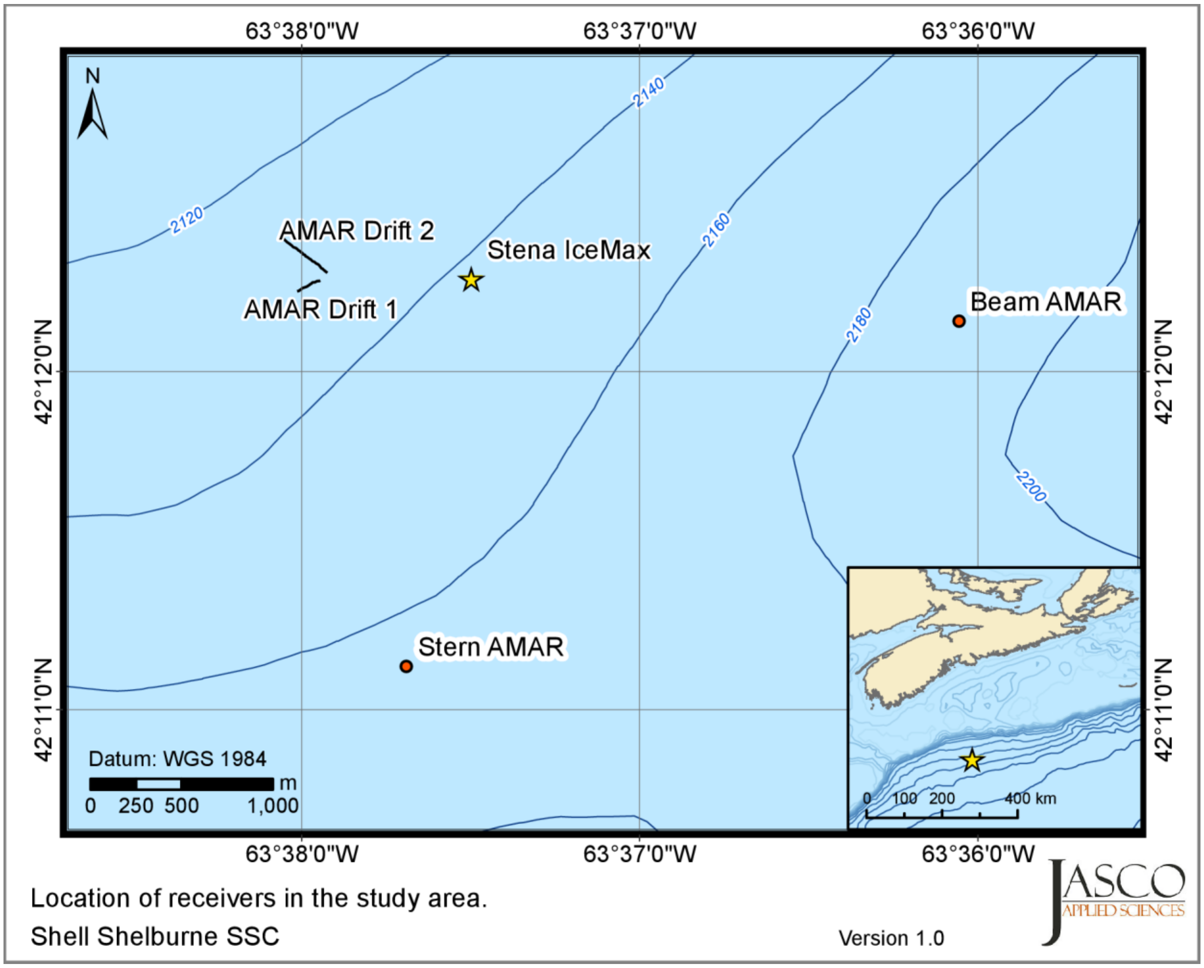
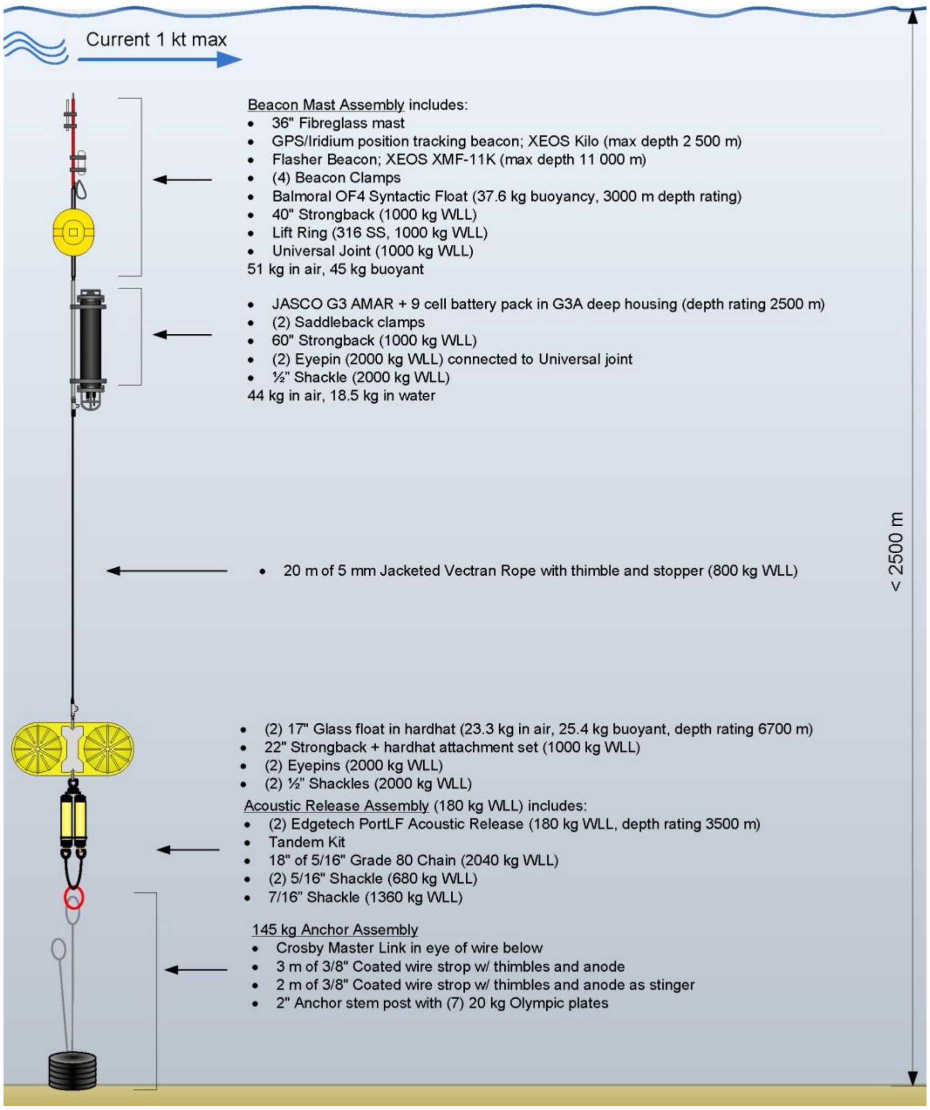


Figure 4. Map of the study area including locations of MODU and AMAR recorders. Blue lines indicate bathymetry in metres.

Table 1. Recorder locations and deployment details. The IceMAX was located at latitude 42° 12. 16.4850” N, longitude 63° 37. 29.8945” W. All times in UTC.

Position relative to MODU	Mooring type	Latitude (N)	Longitude (W)	Deployment	Retrieval	Horizontal range from source (m)	Sensor depth (m)
Stern AMAR	Static	42° 12.147’	63° 36.056’	Oct 31 14:29	Nov 2 18:15	2000	1980
Starboard Beam AMAR	Static	42° 11.127’	63° 37.689’	Oct 31 13:47	Nov 2 17:15	2140	1990
Port Beam AMAR Drift 1	Mobile	Various	Various	Oct 31 17:48	Oct 31 18:05	580 to 700	120
Port Beam AMAR Drift 2	Mobile	Various	Various	Oct 31 18:12	Oct 31 18:48	580 to 840	120
CTD Cast	N/A	42° 11.242’	63° 35.593’	Oct 31 12:30	N/A	N/A	N/A

The two static AMARs (**Figure 5**) were moored at fixed locations approximately 2 km from the MODU near the seabed in approximately 2000–2140 m of water, one off the starboard beam of the IceMAX and the other off the stern of the IceMAX (**Figure 6**), to record possible differences between sound levels in the two areas around the IceMAX. It was anticipated that the sounds from the DP system thrusters would have a directional component that could be measured with recorders oriented at 90 and 180 degrees relative to the MODU. The continuous recordings obtained from the static AMAR provide an assessment of the variability in the sound levels from the MODU over its daily operating cycle and in different sea states. The static moorings were configured to record sound levels at depths that deep diving marine mammals inhabit. With the recorders located 2 km from the IceMAX in the horizontal direction, an absolute distance, or slant range, from the surface position of the IceMAX was calculated to be approximately 2800 m. Positioning the recorders within a few water depths from the sound source ensured that the environmental effects, such as bottom/surface reflections and refraction, were minimized. The static recorder sound levels were back propagated to determine the source level of the MODU as a function of frequency.



Beacon Mast Assembly includes:
- 36" Fibreglass mast
- GPS/Iridium position tracking beacon; XEOS Kilo (max depth 2 500 m)
- Flasher Beacon; XEOS XMF-11K (max depth 11 000 m)
- (4) Beacon Clamps
- Balmoral OF4 Syntactic Float (37.6 kg buoyancy, 3000 m depth rating)
- 40" Strongback (1000 kg WLL)
- Lift Ring (316 SS, 1000 kg WLL)
- Universal Joint (1000 kg WLL)

51 kg in air, 45 kg buoyant

- JASCO G3 AMAR + 9 cell battery pack in G3A deep housing (depth rating 2500 m)
- (2) Saddleback clamps
- 60" Strongback (1000 kg WLL)
- (2) Eyepin (2000 kg WLL) connected to Universal joint
- ½" Shackle (2000 kg WLL)

44 kg in air, 18.5 kg in water

- 20 m of 5 mm Jacketed Vectran Rope with thimble and stopper (800 kg WLL)

- (2) 17" Glass float in hardhat (23.3 kg in air, 25.4 kg buoyant, depth rating 6700 m)
- 22" Strongback + hardhat attachment set (1000 kg WLL)
- (2) Eyepins (2000 kg WLL)
- (2) ½" Shackles (2000 kg WLL)

Acoustic Release Assembly (180 kg WLL) includes:
- (2) Edgetech PortLF Acoustic Release (180 kg WLL, depth rating 3500 m)
- Tandem Kit
- 18" of 5/16" Grade 80 Chain (2040 kg WLL)
- (2) 5/16" Shackle (680 kg WLL)
- 7/16" Shackle (1360 kg WLL)

145 kg Anchor Assembly
- Crosby Master Link in eye of wire below
- 3 m of 3/8" Coated wire strop w/ thimbles and anode
- 2 m of 3/8" Coated wire strop w/ thimbles and anode as stinger
- 2" Anchor stem post with (7) 20 kg Olympic plates

Figure 5. Configuration of the mooring for the static AMARs.

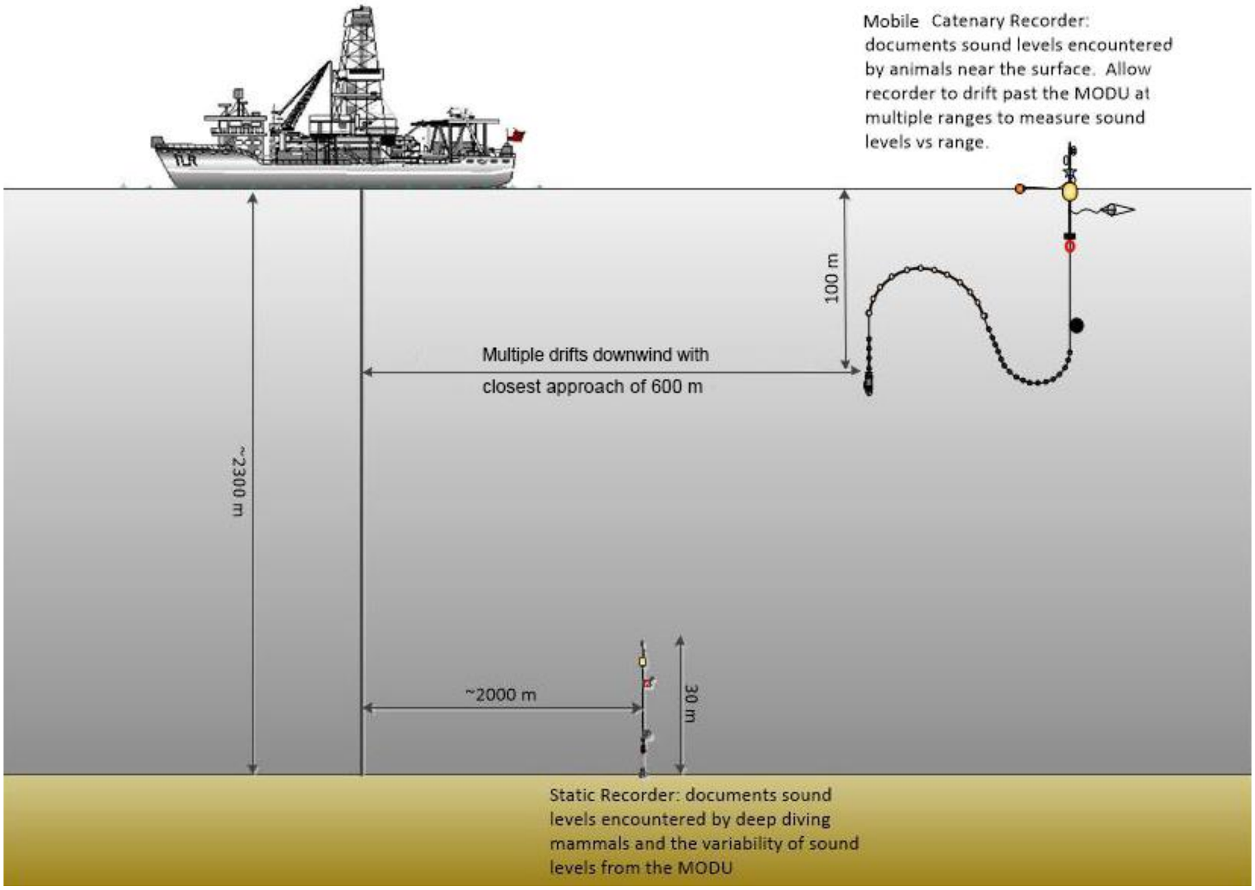


Figure 6. Diagram of measurement setup and catenary recorder.

A mobile or ‘catenary’ AMAR was deployed downwind of the MODU’s port beam (**Figure 6**). The catenary system was deployed twice at intermediate sampling locations (shown as AMAR Drift 1 and 2 in **Figure 4**). The recorder was buoyed at an operating depth of 120 m to capture sound levels near the ocean surface (**Figure 7**). The mobile mooring consisted of buoyant and non-buoyant sections, which minimized the recorder’s vertical movement. This configuration reduced flow noise and eliminated the ‘cable strum noise’ common in conventional moorings. This free-drifting system measured sound levels at different distances (or ranges) from the source to obtain a better understanding of sound levels compared with distance. It also allowed flexibility for positioning the mooring where it was safe depending on operations and weather. Using the two different systems (i.e., static and catenary) helped to determine if there were differences in the soundscape between the near-surface and the seabed.

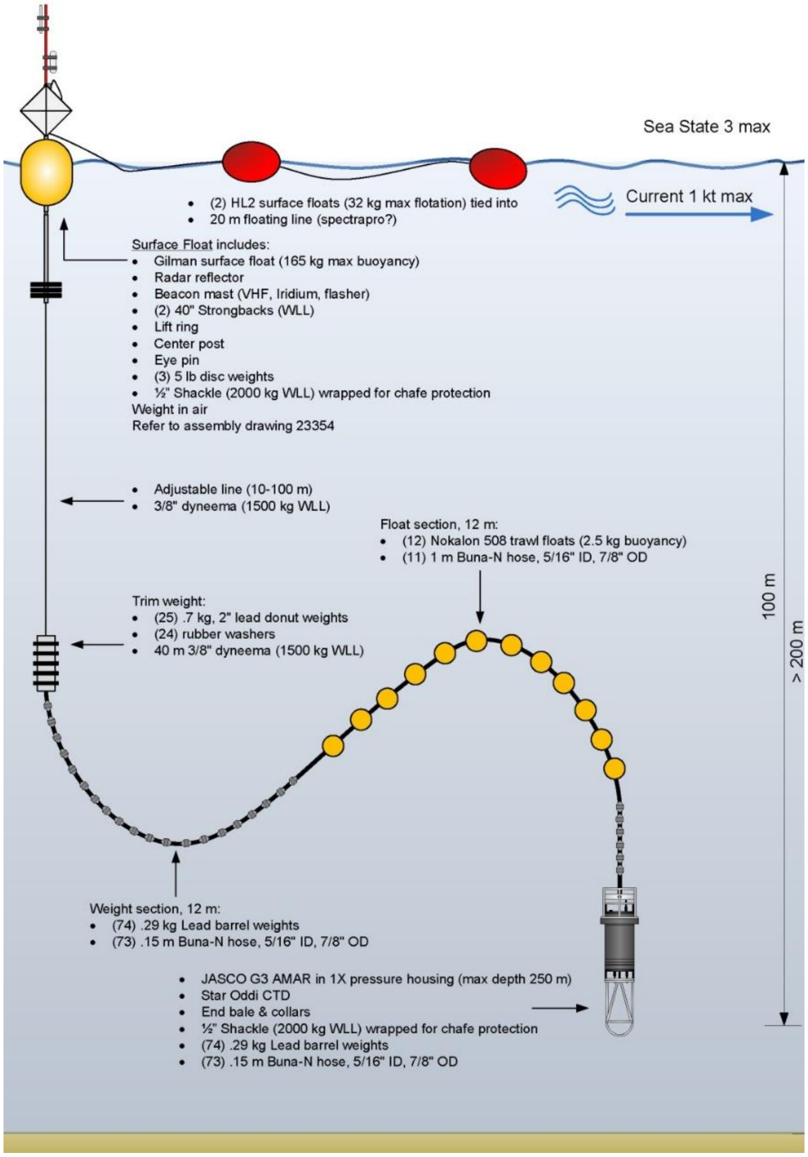


Figure 7. Configuration of the mooring for the Mobile AMAR.

Each AMAR was fitted with an M14-V35-301 hydrophone (GeoSpectrum Technologies Inc.), sampling at 64 000 samples per second (sps) giving an acoustic bandwidth of 0 to 32 kHz, with a nominal sensitivity of −165 dB re 1 V/µPa. A second channel also sampled at 375 000 sps simultaneously, giving an acoustic bandwidth of 0 to 187.5 kHz, also with a nominal sensitivity of −165 dB re 1 V/µPa. The lower sample rate captures most mechanical noise from vessels as well as vocalizations from most large marine mammals. The high sample rate captures high-frequency vessel sources such as sonars and acoustic positioning systems. It can also capture high-frequency echolocation clicks from marine mammals.

2.2. Recorder Calibrations

Each AMAR was calibrated using a 42AC pistonphone calibrator (G.R.A.S. Sound & Vibration A/S) to verify the sensitivity of the whole recording system. The pressure response of the recording system was verified by placing the pistonphone and its adapter over the hydrophone while the pistonphone produced a known pressure signal on the hydrophone element (a 250 Hz sinusoid at 152.2 dB re 1 µPa).

2.3. Acoustic Metrics

Sound levels for each AMAR, with individual metrics, are presented within this report as:

- Broadband and approximate-decade-band sound pressure level (SPL) over time for the frequency bands: 10 Hz to 32 kHz, 10–100 Hz, 100 Hz to 1 kHz, 1–10 kHz, and 10–32 kHz (**Figure 11**).
- Spectrograms: Ambient noise at each station was analyzed by Hamming-windowed fast Fourier transforms (FFTs), with 1 Hz resolution and 50% window overlap. The 120 FFTs performed with these settings are averaged to yield 1 min average spectra (**Figure 11**).
- Statistical distribution of SPL in each 1/3-octave-band: The boxes of the statistical distributions indicate the first (L_5), second (L_{50}), and third (L_{75}) quartiles. The whiskers indicate the maximum and minimum range of the data. The solid line indicates the SPL, or L_{eq}, in each 1/3-octave (**Figure 14**).
- Spectral level percentiles: Histograms of each frequency bin per 1 min of data. The L_{eq}, L_5, L_{25}, L_{50}, L_{75}, and L_{95} percentiles are plotted. The L_5 percentile curve is the frequency-dependent level exceeded by 5% of the 1 min averages. Equivalently, 95% of the 1 min spectral levels are above the 95th percentile curve (**Figure 14**).
- Daily sound exposure levels (SEL): Computed for the total received sound energy and the detected shipping energy; i.e., equivalent sound energy emitted by passing or stationary vessels. The SEL is the linear sum of the 1 min SEL. For shipping, the 1 min SEL values are the linear 1 min squared SPL values multiplied by the duration, 60 seconds (**Figure 20**). These SEL values were weighted to mimic different species-specific functional hearing groups according to the M-weighting curves for marine mammals described in the EIS (Stantec 2014).

Sound is most commonly described using the sound pressure level (SPL) metric. Underwater sound amplitude levels are commonly measured in decibels (dB) relative to a fixed reference pressure of p_0 = 1 µPa. The root-mean-square (rms) SPL was used to quantify the sounds generated by the IceMAX.

SPL (dB re 1 µPa) is the rms pressure level in a stated frequency band over a time window (T, s) containing the acoustic event:

$$\mathrm{SPL} = 10\log_{10}\left(\frac{1}{T}\int_T p^2(t)dt \Big/ p_0^2\right).$$

The SPL is a measure of the effective pressure level over the duration of an acoustic event, such as the emission of one acoustic pulse or sweep. Because the window length, T, is the divisor, events more spread out in time have a lower SPL even though they may have similar total acoustic energy density. One minute windows were used throughout the analyses.

Power spectral density (PSD) level is a description of how the acoustic power is distributed over different frequencies within a spectrum. It is expressed in dB re 1 µPa^2/Hz.

The sound exposure level (SEL, dB re 1 µPa^2·s) is a measure of the total acoustic energy contained in one or more acoustic events. The SEL for a single event is computed from the time-integral of the squared pressure over the full event duration (T_{100}):

$$\mathrm{SEL} = 10\log_{10}\left(\int_{T_{100}} p^2(t)dt \middle/ T_0 p_0^2 \right)$$

where T_0 is a reference time interval of 1 second. The SEL represents the total acoustic energy received at a location during an acoustic event. It measures the total sound energy an organism at that location would be exposed to.

Because the SPL and SEL are both computed from the integral of square pressure, these metrics are related by the following expression, which depends only on the duration of the energy time window T:

$$\mathrm{SPL} = \mathrm{SEL} - 10\log_{10}(T) \text{ .}$$

Sound level statistics, namely exceedance percentiles, were used to quantify the distribution of recorded sound levels generated by the IceMAX and OSVs. Following standard acoustical practice, the *n*th percentile level (L_n) is the level (i.e., PSD level, SPL, or SEL) exceeded by *n*% of the data. L_{max} is the maximum recorded sound level. L_{eq} is the linear arithmetic mean of the sound power, which can be significantly different from the median sound level L_{50}. SPL can also be referred to as L_{eq}, which stands for ‘equivalent level’. The two terms are used interchangeably throughout this report. The median level was used to compare the most typical sound levels between AMARs, since it is less affected by high amplitude outliers (e.g., a crustacean tapping on the hydrophone) compared to the mean sound level. L_5, the level exceeded by only 5% of the data, represents the highest typical sound levels measured. Sound levels between L_5 and L_{max} are generally from vessels passing very close to the AMAR, very intense weather events, or other infrequent conditions. L_{95} represents the quietest typical conditions.

The PSD exceedance percentiles can be directly compared to the Wenz curves (Wenz 1962), which describe the PSD levels of marine ambient sound from weather, geologic activity, and commercial shipping. **Figure 8** shows the Wenz curves along with the source levels of various types of anthropogenic sound sources. The “limits of prevailing noise” of the Wenz curves (black lines in **Figure 8**) represent the typical range of ambient sound PSD levels in the ocean and are plotted as orange dashed lines on the ambient sound PSD results in Section 3 (**Figure 14**) for comparison.

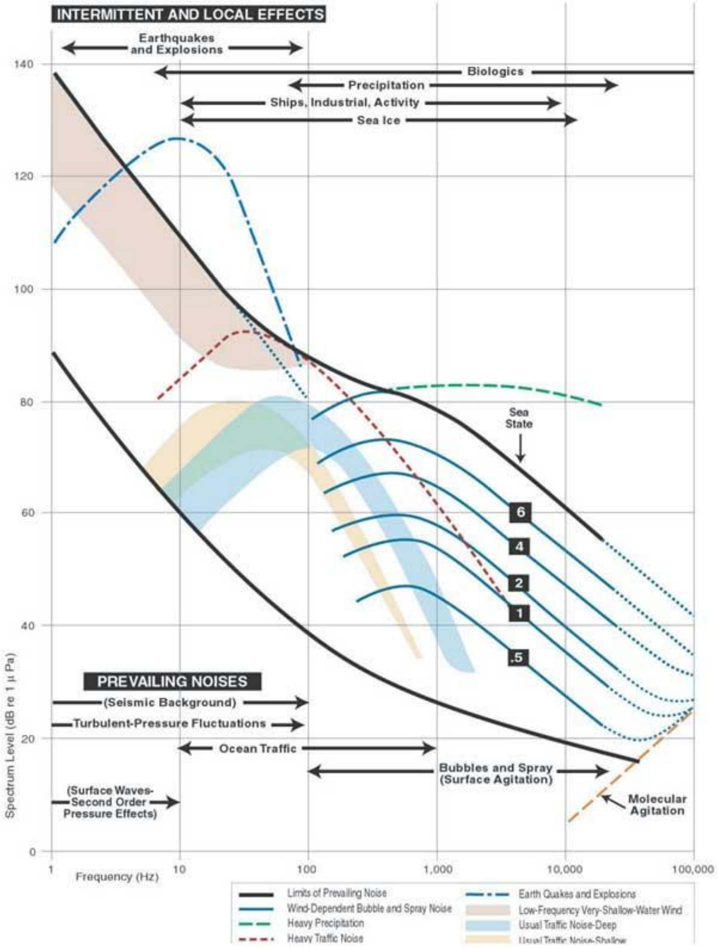


Figure 8. Wenz curves describing pressure spectral density (PSD) levels of marine ambient noise from weather, geologic activity, and commercial shipping (Wenz 1962). The limits of prevailing noise of the Wenz curves (thick black lines) are plotted as orange dashed lines on the ambient sound PSD results in Section 3 (**Figure 14**) for comparison.

2.4. Acoustic Data Analysis

Acoustic data were analyzed to determine PSD levels from the IceMAX using the following steps:

1. Extract the list of drilling events from the daily operations report provided by Shell. The reports contained a schedule of activities and approximate timings within 30 min (**Table 2**).
2. Visualize raw acoustic data with JASCO's PAMlab software. Low-frequency (<50 Hz) data were examined near activity start and end times (**Table 2**) to find the frequencies of the drilling operations. The easiest way to identify continuous sources is during onset or conclusion, due to their continuous nature.
3. Measure PSD levels for selected times during drilling.
4. Back propagate the measured PSD levels using spherical spreading (20 * $\log_{10}$ (range)) to arrive at a source level at 1 m. Spherical spreading, i.e., the weakening of the intensity of sound as it travels through deep water, was an appropriate method given all ranges between source and recorder were less than two times the water depth away. This close range minimizes environmental influence on sound propagation.

5. Plot the overall broadband levels from the AMARs as spectrograms and band level plots, PSD exceedance and boxplots, as well as daily SEL plots. These analyses show the overall contribution of drilling sound to the soundscape.
6. Overall broadband levels (L_{eq} and SEL) were back propagated and compared with levels presented in the EIS. The SEL values were filtered according to functional hearing groups called M-weightings outlined in the EIS (Southall et al. 2007). These curves (Figure 9) attempt to mimic the hearing of marine mammals within the specified group.

Table 2. Drilling Active (bit and string) times from Shell's daily operations report during acoustic data acquisition. All times in UTC.

Start date and time	End date and time	Duration (h)
Oct 31 12:00	Nov 1 03:00	15
Nov 1 05:00	Nov 1 06:30	1.5
Nov 1 07:30	Nov 1 08:30	1
Nov 1 10:00	Nov 1 11:00	1
Nov 1 12:00	Nov 2 05:30	17.5

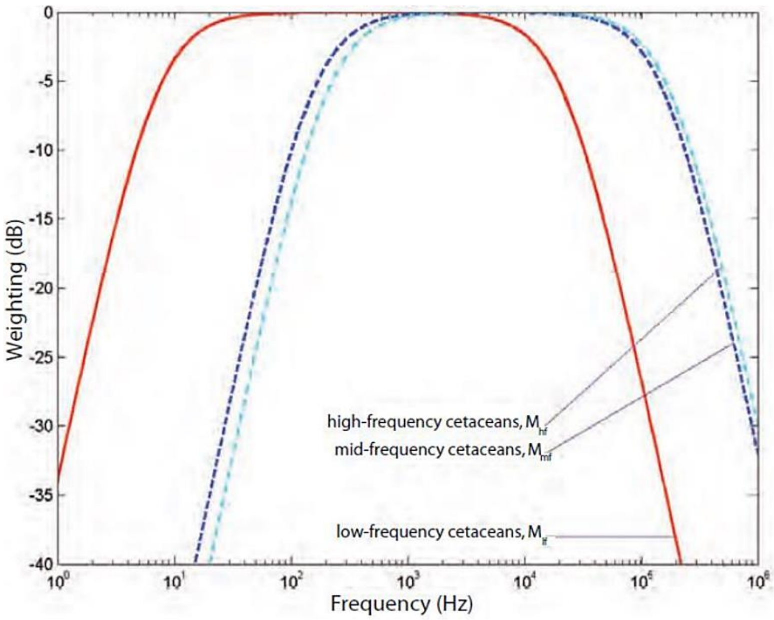


Figure 9. M-weighting curves as specified by the EIS (Southall et al. 2007).

2.5. Sound Speed Profile

A conductivity, temperature, and depth (CTD) cast was performed on 31 Oct at 12:30 UTC to determine the sound speed profile near the Stern AMAR location (42° 11.242' N, 63° 35.593' W, **Figure 10**). A sound speed profile shows the speed of sound in water at different depths. The cast was limited to 160 m deep due to the length of the lowering cable available on the *Scotian Sea*. This measurement depth was sufficient to confirm that the shape of the sound speed profile was similar to the seasonal norm derived from temperature and salinity profiles from the U.S. Naval Oceanographic Office's *Generalized Digital Environmental Model V 3.0* (GDEM; (Teague et al. 1990, Carnes 2009). The measured profile had an initial sound speed minimum at a 40 m depth, and the modelled initial minimum was at a 75 m depth. These minima result in a sound propagation channel for low frequency sounds (<1 kHz in this case) due to upward and downward refraction on either side of the minima. The seasonal profiles also show a minimum that creates a deep sound channel with its axis at 600 m. The differences between the measured and seasonal sound speed profiles are not significant enough to impact the acoustic data measurements, especially over the relatively short distances of interest and in the frequency range of drilling, mechanical and vibration, and DP energy. The overall effect of sound propagation channels is also unlikely to be significant over these distances.

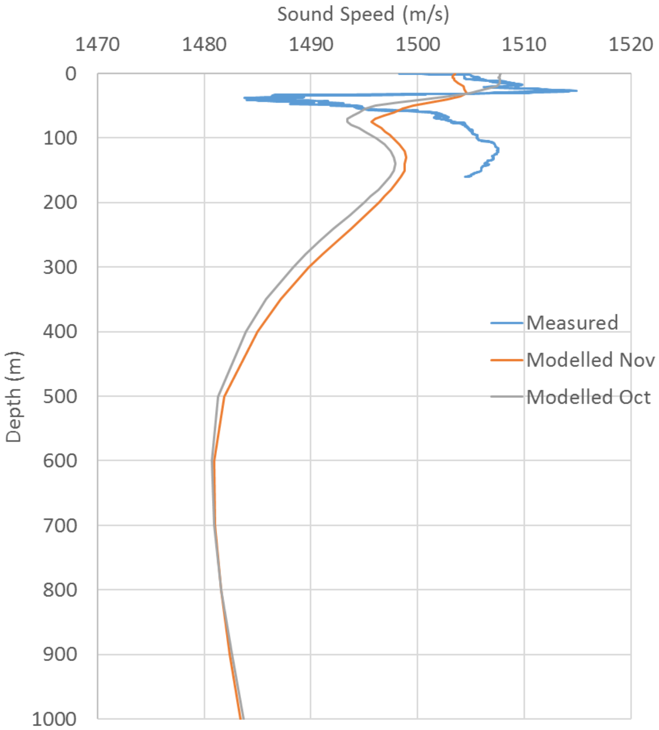


Figure 10. Sound speed profiles for the Stern AMAR measurement location. Measured data acquired on 31 Oct 2016. Modelled data derived from data obtained from *GDEM V 3.0* (Teague et al. 1990, Carnes 2009).

3. Results

3.1. Mobile AMAR Measurements

The intention of the Mobile AMAR measurements using the catenary mooring, was to acquire data at multiple ranges from the IceMAX. Unfortunately, weather conditions offshore during the study made it difficult to deploy and retrieve the mooring. These conditions only allowed for two drifts: the first drift lasted 17 minutes, and the second drift lasted 36 minutes before the mooring was retrieved. Both drifts had a closest point of approach (CPA) of 580 m to the IceMAX. Measurements over this short time period did not allow for multiple ranges to be sampled or different engineering states of the drilling operations to be recorded. The measurements obtained using the bottom moored Beam and Stern AMARs were sufficient to verify underwater noise levels predicted within the Project EIS, in accordance with Condition 3.12.3.

3.2. Static AMAR Measurements

Fifty-two hours of data were collected from each of the two static recording locations from 31 October to 2 November (**Table 1**). As per the IceMAX drilling logs, approximately 33 hours of drilling activity occurred in this period (**Table 2**). Throughout all 52 hours, the IceMAX and four OSVs were operating in dynamic positioning (DP) mode, which uses thrusters that cause cavitation noise, i.e., the noise created through vibration and creation of low pressure points and bubbles (Stantec 2014). The full period spectrograms and band-level data (**Figure 11**) do not show changes in measured sound levels at the Beam and Stern recorders that correlate with changes in the drilling state. This suggests that DP system and mechanical noise from the IceMAX and OSVs were larger contributors to the sound field than the actual sound generated from drilling activity i.e., operating drill string and bit.

Over the entire deployment period, the 100–1000 Hz band had the highest SPL on both static recorders. This band is where most sound from large vessels occurs, including the IceMAX and OSVs. The spectrograms (**Figure 11**) show lines that vary in frequency forming many ‘V’ shapes. This effect normally indicates vessels transiting past a recorder, but a vessel using dynamic positioning in changing current or wind could also generate this pattern as the level of the thruster increases and decreases, and therefore the vessel revolutions per minute (RPM) varies accordingly.

A single vessel may have come close to the recorders at the end of the deployment period, indicated by the steady tones recorded in **Figure 11**. The solid red horizontal tonal lines (**Figure 11**) are associated with machinery, such as generators, on the IceMAX and OSVs. The majority of the tonal lines are associated with 60 Hz power generation, and can likely be associated with gear ratios of the equipment. The strong 45 Hz tone is an example of this. At the end of the data acquisition, the AMAR was brought to the water surface remotely using an acoustic release. The high-frequency spikes in the 10–32 kHz band (yellow lines on in-band SPL in Figure 11) were pulses from the acoustic releases located adjacent to the AMAR. The field team had difficulty communicating with the releases due to the depth of the moorings, resulting in additional pulses being sent back and forth between the surface and the bottom. The strong tones at 20 Hz are fin whale vocalizations, which were noted during the analysis (Section 3.6).

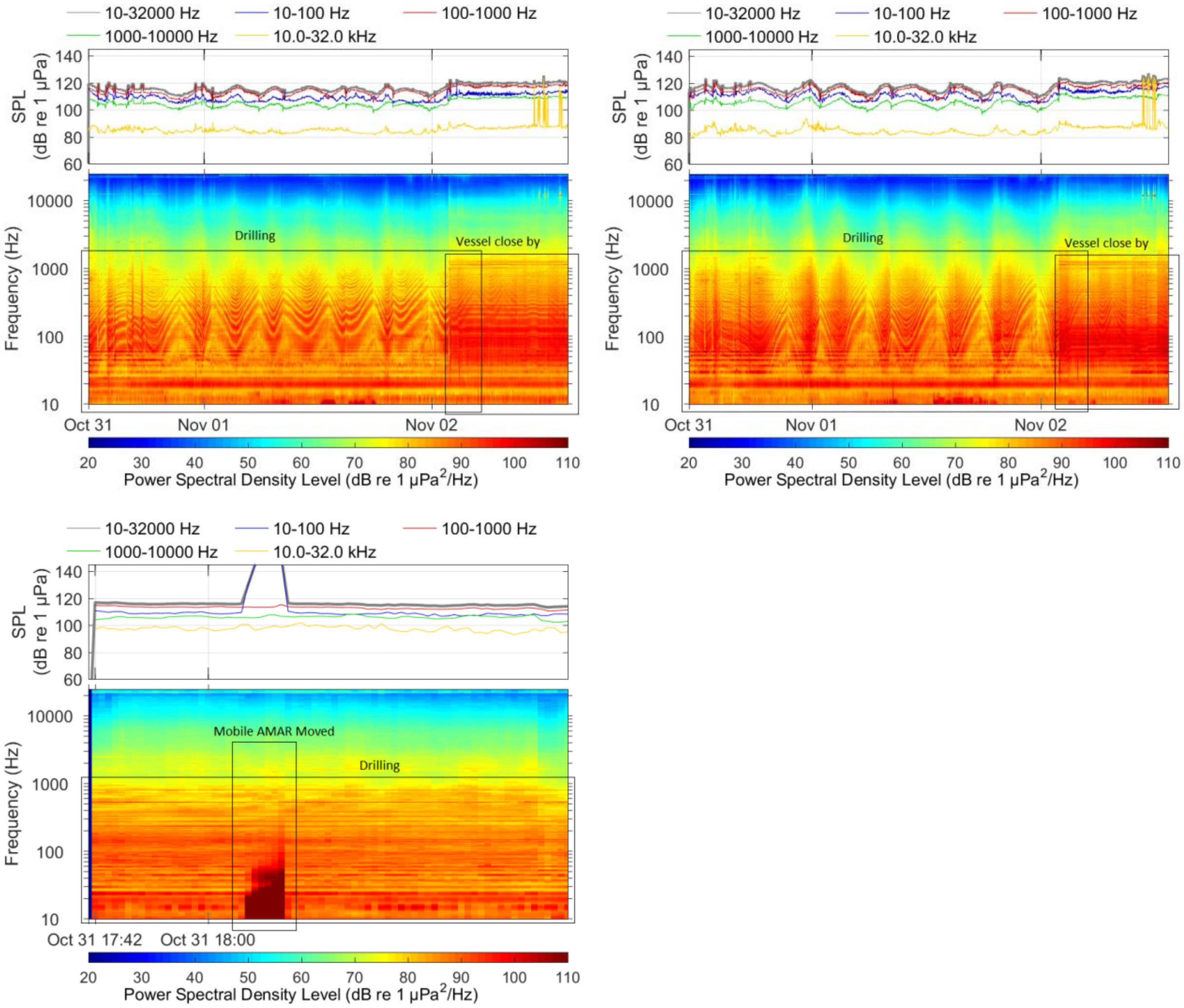


Figure 11. In-band SPL (top portion of figures) and spectrogram over time (bottom portion of figures) for Beam AMAR (top left), Stern AMAR (top right), and Mobile AMAR (bottom). The Mobile AMAR was only deployed for 53 minutes.

3.3. Narrowband Tonal Sound Levels Associated with Drilling Activity

According to the daily operations report (**Table 2**), the IceMAX was drilling at 120 RPM. That indicates that a fundamental tone of 2 Hz should have been produced. **Figure 12** shows a low-frequency spectrogram from the Beam AMAR data for the conclusion of the drilling activity. Multiple tones ceased around 05:28. The 80-second power spectral density plot (**Figure 13**) shows prominent tonal peaks at 1, 9, 12, and 14 Hz. Examining other periods for drilling start and stop times (**Table 2**) allowed a tone to be associated with drilling activity. The 1 Hz and 12 Hz tones were present throughout all the data, as was a 2 Hz harmonic from the 1 Hz tone. It was therefore determined that these tones were not directly associated with the drilling. The 9 Hz tone was only present occasionally during the period of drilling activity, so while likely associated with drilling, it was not the main tone. The 14 Hz tone was continuously present during the drilling activity period, and therefore it was designated as the drilling activity tone. The 9 and 14 Hz tones correspond to a mechanical rotation rate of 540 and 840 RPM, respectively. It appears that the rotational rate of 120 RPM for the drilling activity did not produce a measurable fundamental tone; however, the detected tones were 4.5 and 7 times the main shaft rate, likely due to gear ratios of the equipment or the number of cutting edges on the drill bit itself.

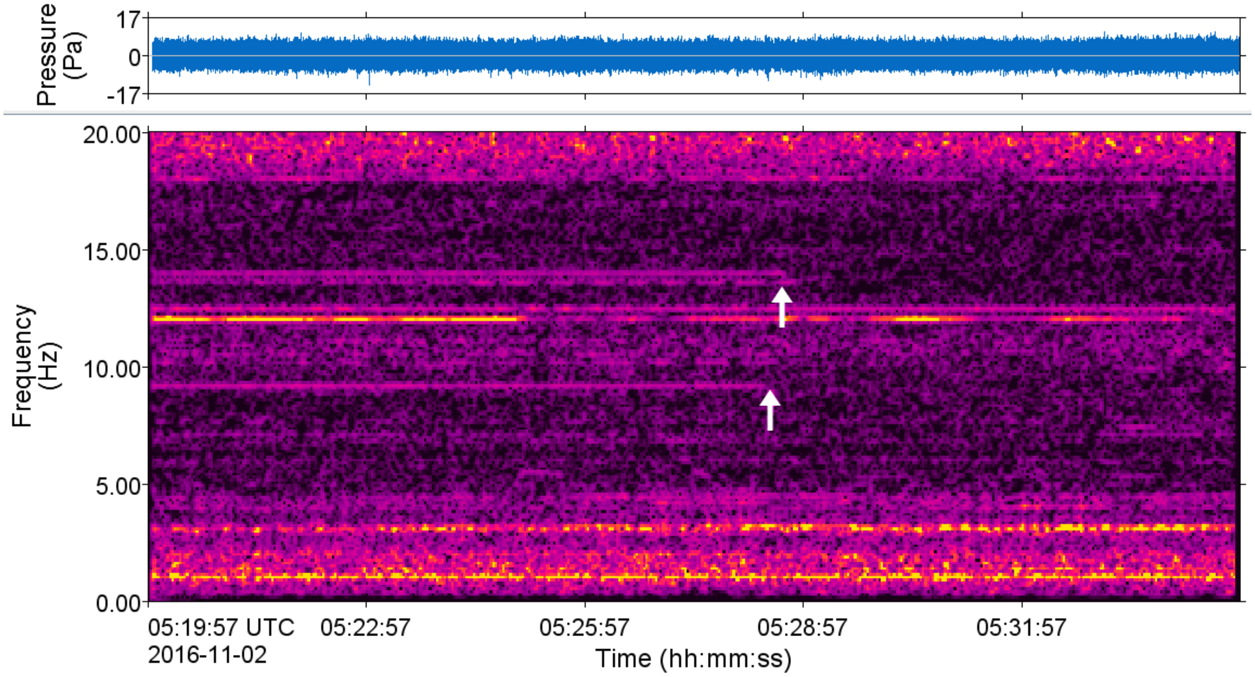


Figure 12. Spectrogram of Beam AMAR on 2 Nov showing the end points (white arrows) of the 9 and 14 Hz tones associated with drilling activity.

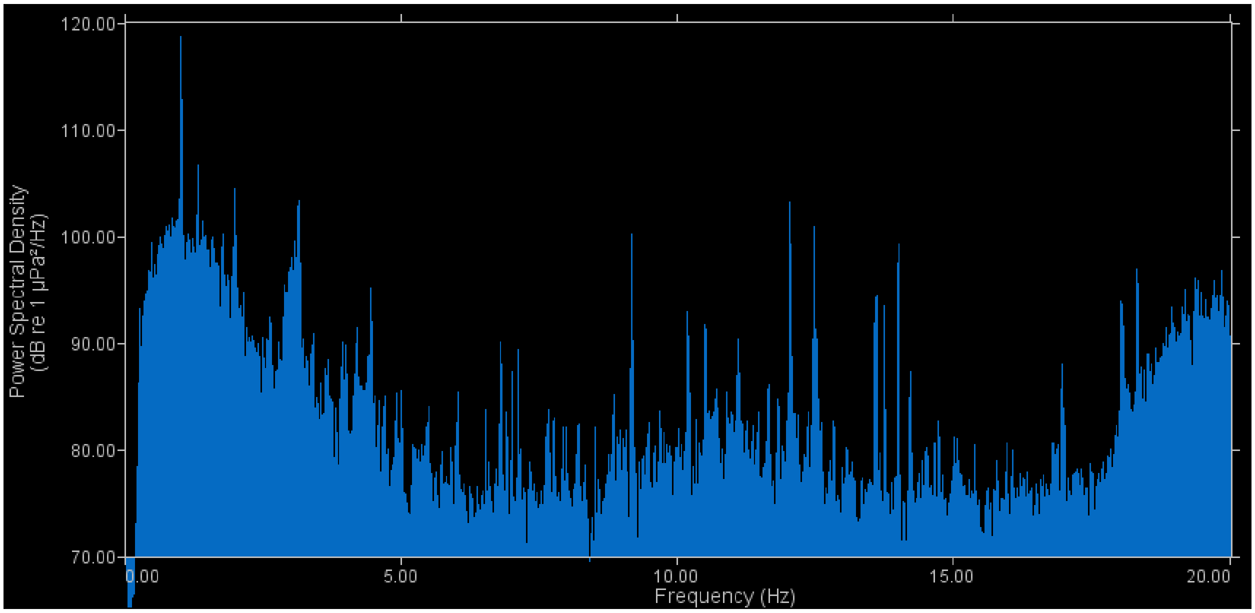


Figure 13. PSD from the Beam AMAR during drilling operations at 05:26 on 2 Nov 2016 (based on 80 seconds of data sampled at 64,000 samples per second, with 20 second advance and 10 averages).

The PSD exceedance plots (Figure 14) show the statistical distribution of sound levels over the recording period. The median (L_{50}) was above the upper limit on prevailing noise from 50–1000 Hz due to thruster sound from the IceMAX and OSVs. The increase at 20 Hz was due to fin whale vocalizations, explained in greater detail in Section 3.6. The spike at 12 kHz was caused by the acoustic release and was very prominent in the L_{eq}, but not in the other curves, due to its short duration.

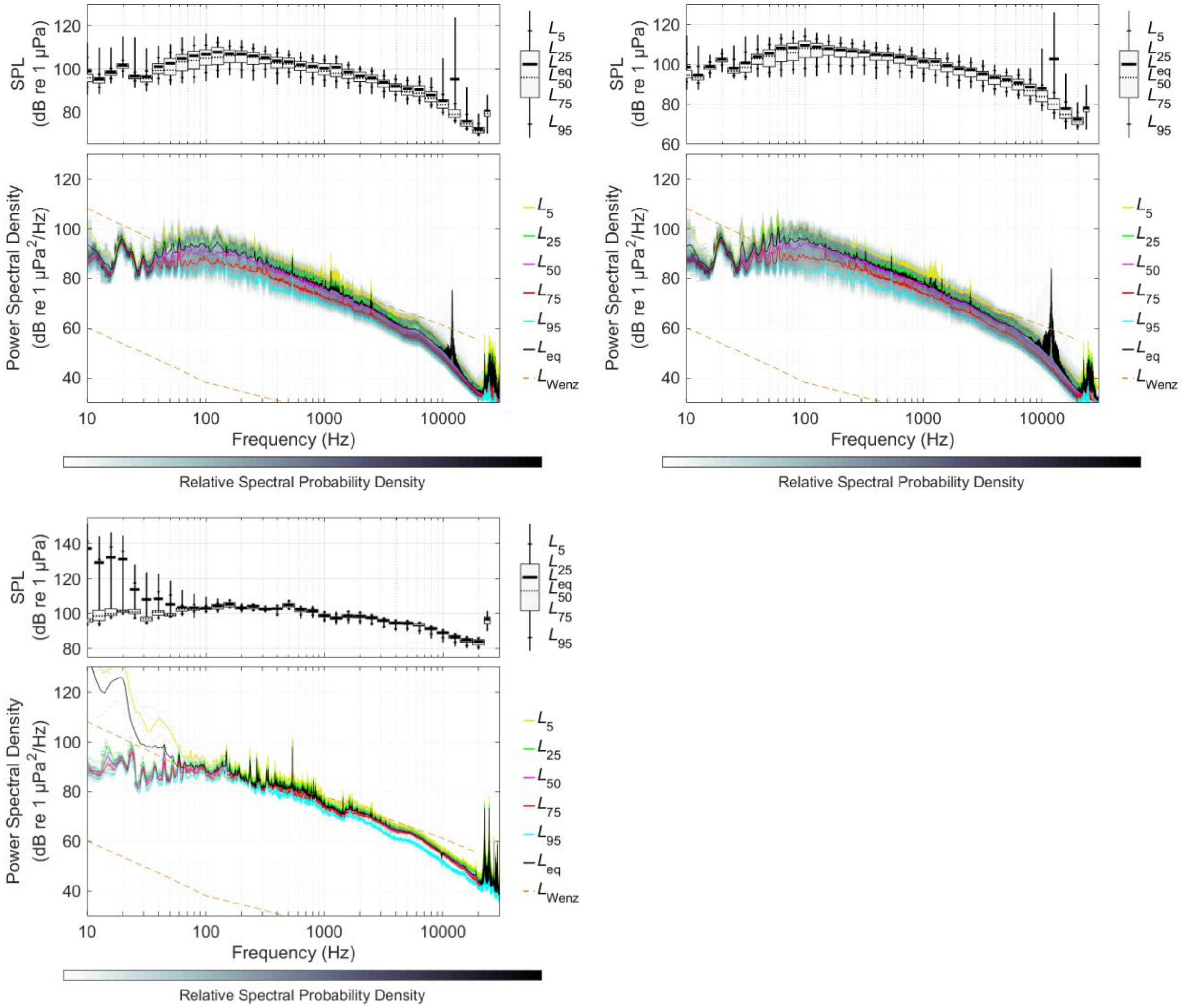


Figure 14. Exceedance percentiles and mean of 1/3-octave-band SPL (top portion of figures) and exceedance percentiles and probability density (grayscale) of 1-min PSD levels compared to the limits of prevailing noise (bottom portion of figures) (Wenz 1962). Beam AMAR (Top left), Stern AMAR (top right), and Mobile AMAR (bottom).

3.4. Broadband Sound Levels from Drilling Operation

The broadband sound levels from the MODU and OSV operations include noise emitted from thrusters, machinery and drilling activity. The broadband sound levels measured by the static recorders during the 52 hours of measurement were within 3 dB of the mean and median values for over 50% of the recordings (**Figure 15**). The measured broadband SPL were 116.8 and 118.4 dB re 1 µPa for the Beam and Stern AMARs, respectively. **Figure 15** also shows that the highest sound levels were in the 100–1000 Hz band that is associated with the DP and propulsion systems of the IceMAX and OSVs. The 10–100 Hz band contained the next highest sound levels and is also associated with mainly DP noise and with some mechanical power generation noise.

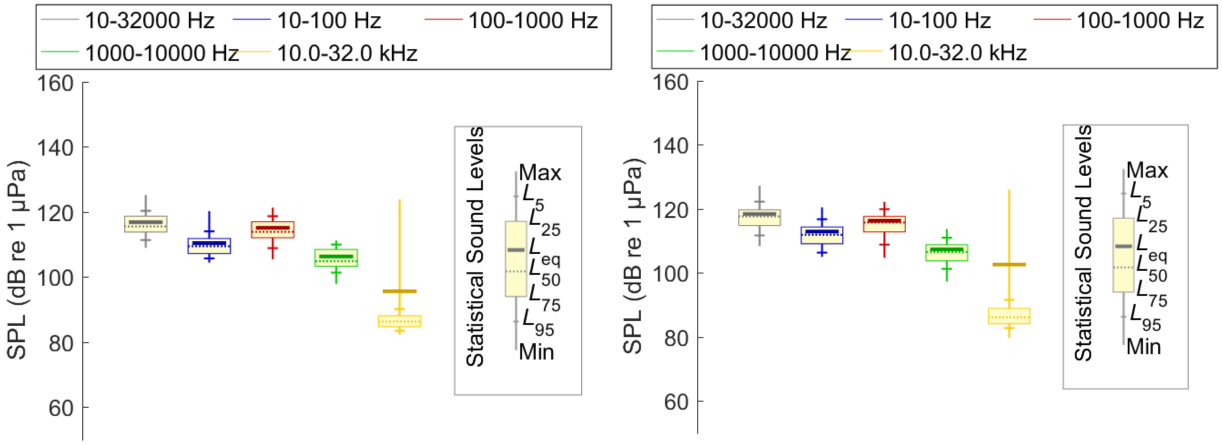


Figure 15. Statistical sound levels as a function of frequency band for the Beam AMAR (left) and Stern AMAR (right).

3.5. High-Frequency Sound Sources from the IceMAX

The PSD exceedance plots showed that exceedance levels increased above 20 kHz (Figure 14). To investigate the cause of this increase, the 375 000 sps channel was evaluated. **Figure 16** illustrates a close-up measurement acquired during Shell's vertical seismic profile (VSP) program on 6 Jan 2017. During this program, a recorder was deployed from the IceMAX moon pool and was approximately 1 m from the hull. In addition to the regular low-frequency VSP source, multiple high-frequency sources were present. The loudest high-frequency source was the pulse with tones centred around 22.5 and 24.5 kHz, at a level of 173 dB re 1 µPa. These sounds likely originated from an acoustic positioning system, the Kongsberg high precision acoustic positioning (HiPAP) ultra-short baseline (USBL) system. The lower amplitude pulses at 28, 28.5, 27, and 29 kHz were likely the returned pulses from this system. The pulse centred around 38 kHz was likely a single beam echosounder. **Figure 17** shows the high-frequency sources recorded on the AMARs. The amplitudes on the recorders were 75–95 dB re 1 µPa, depending on the source. The IceMAX uses these acoustic beacons to monitor its position as well as the echo-sounders to monitor the vessel distance to the seabed. These were therefore the sound sources recorded above 20 kHz.

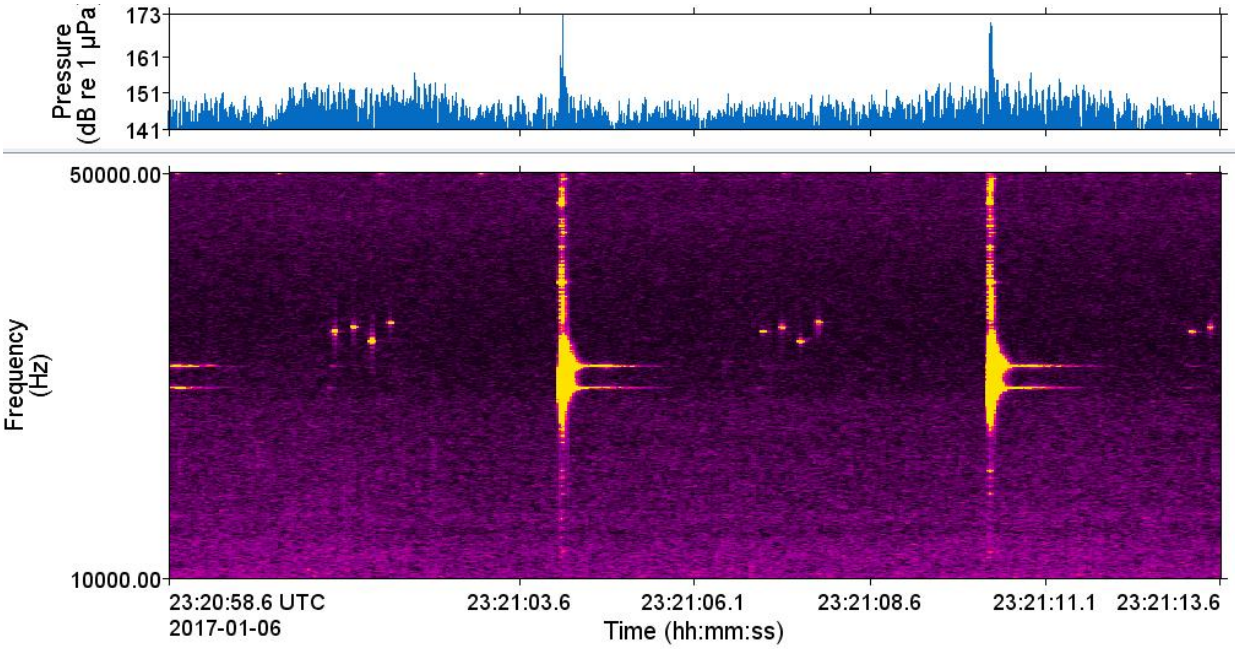


Figure 16. Spectrogram from Shell's vertical seismic profile (VSP) program measured from Stena IceMAX on 6 Jan 2017.

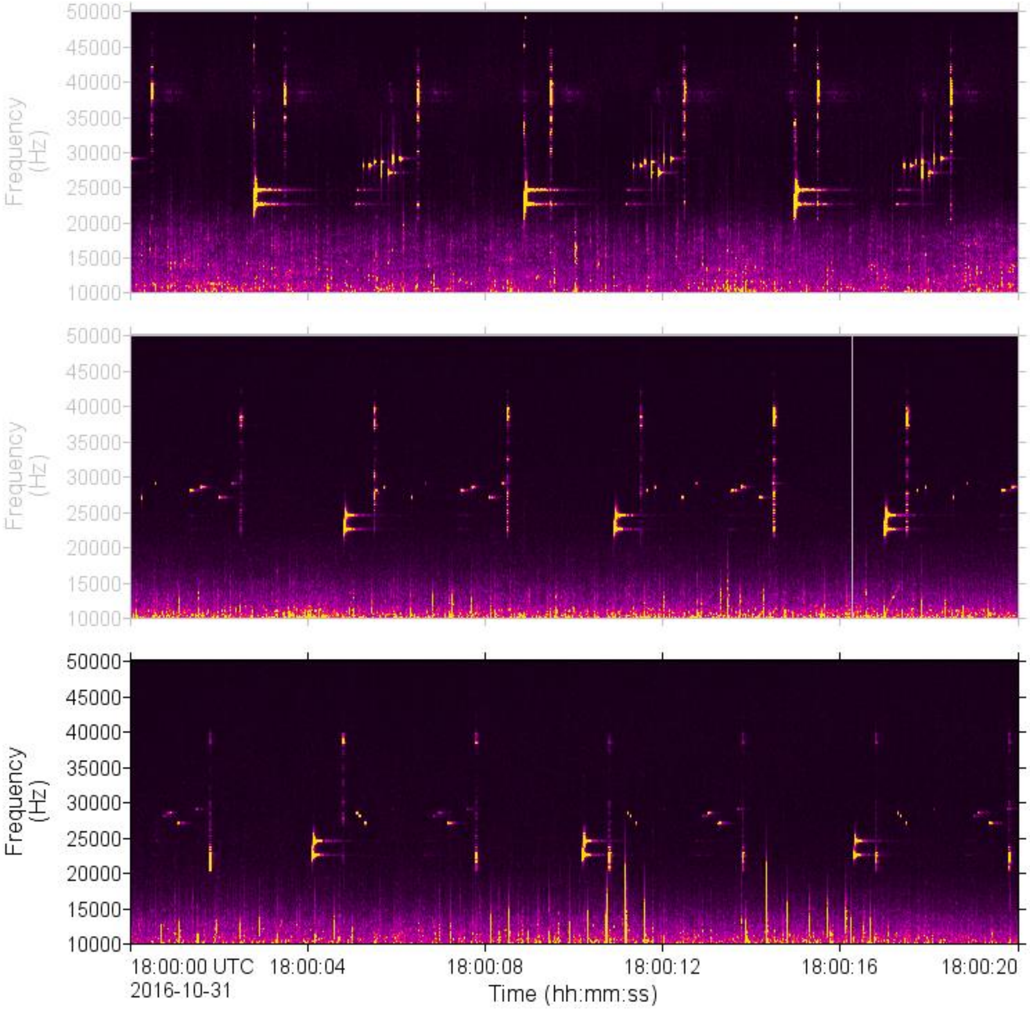


Figure 17. Spectrogram of the high-frequency sources. (Top) Mobile AMAR, (middle) Beam AMAR, and (bottom) Stern AMAR.

3.6. Mammal Vocalizations in the Data Set

Fin and sperm whales were detected during the SSC. The 20 Hz fin whale vocalizations appear as a solid line at approximately 20 Hz in the full-period spectrograms (Figure 11) and a bump in the PSD exceedance curves (Figure 14). A close-up spectrogram (**Figure 18**) shows loud 20 Hz fin whale vocalizations. There were also incoherent vocalizations above background levels, which were smeared in the spectrogram. Sperm whale clicks were detected at the same time (**Figure 19**), showing as broadband impulses with most energy between 5 and 15 kHz.

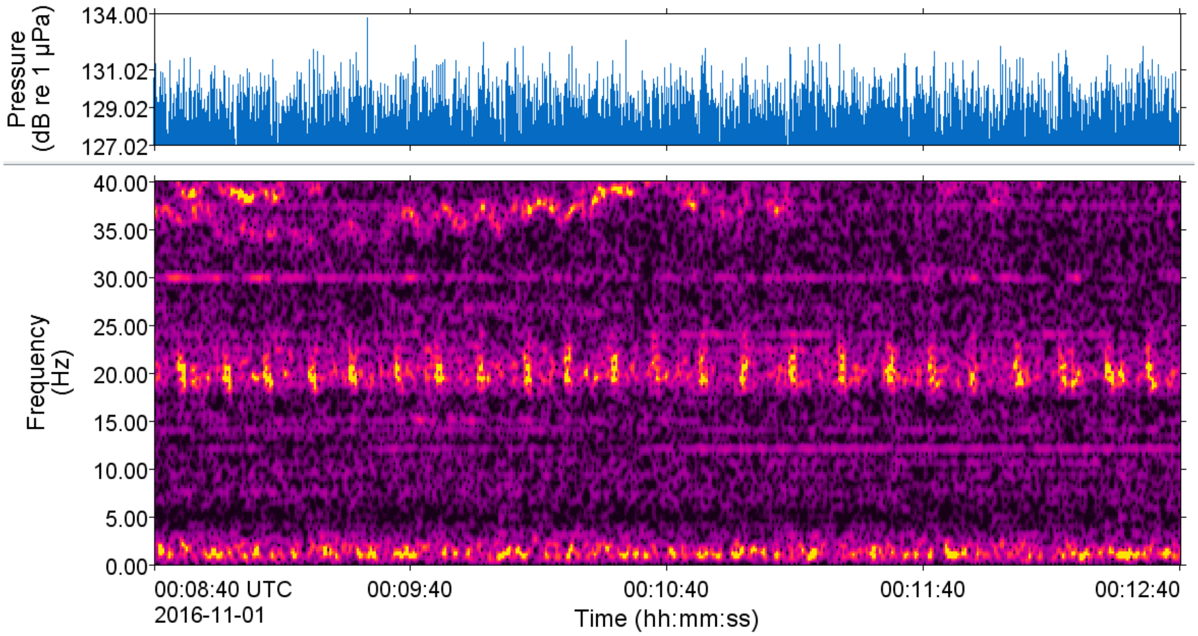


Figure 18. Spectrogram of fin whale calls recorded on the Stern AMAR on 1 Nov 2016.

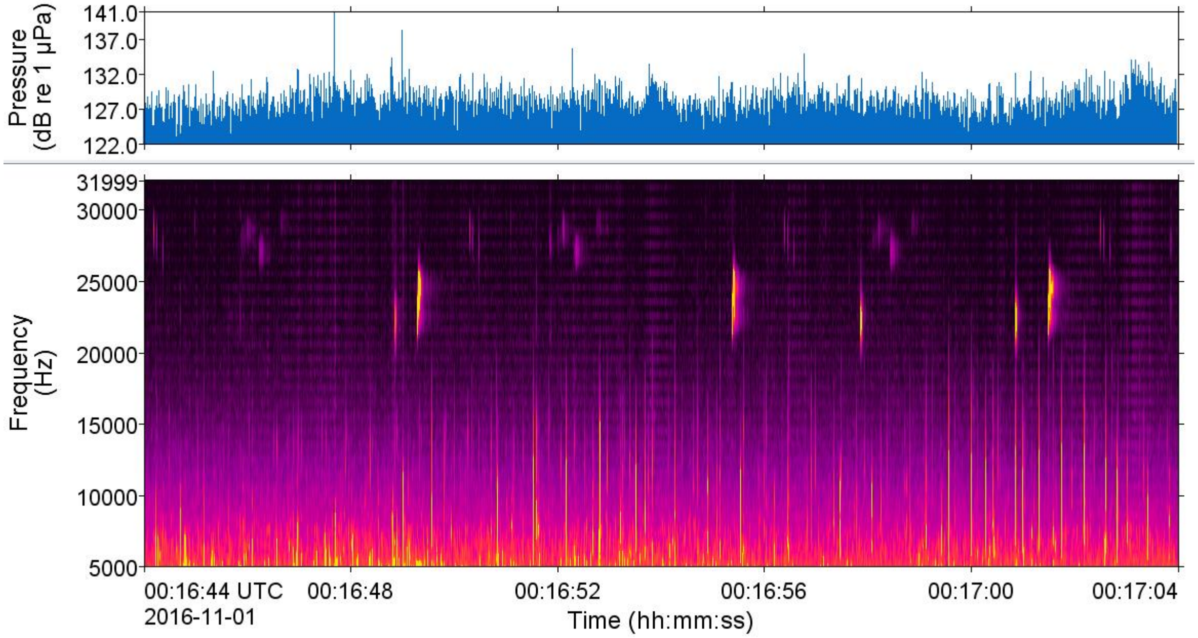


Figure 19. Spectrogram of sperm whale clicks recorded on the Stern AMAR on 1 Nov 2016.

4. Discussion

4.1. Monterey Jack Well

4.1.1. Narrowband Source Levels of Drilling Activity

The 14 Hz tone was determined to be the drilling activity tone generated by the active drill string and bit. The drilling tone was analyzed for five time periods, spread across the three days of monitoring (**Table 3**). Each 14 Hz PSD level was back propagated using 20 $\log_{10}$ (range) spreading, using the slant ranges (three dimensional ranges) in **Table 4**. It was not apparent whether the source of the tone was on the ocean surface near the MODU or on the ocean bottom near the well head; therefore, source levels were calculated for both cases. The minimum source levels were 152.2 and 154.9 dB re 1 Hz µPa^2/Hz for the surface and bottom, respectively. The maximum source levels were 168.0 dB re 1 Hz µPa^2/Hz for a source originating on the surface, and 165.5 dB re 1 Hz µPa^2/Hz for a source originating on the bottom (Tables 5 and 6). These back propagated source level values do not converge sufficiently to conclusively determine if the 14 Hz tone was coming from the surface or the bottom.

Table 3. Received PSD levels of the 14 Hz tone at selected times (5,120,000 FFT samples, 1,280,000 advance samples, 10 averages, Hamming window using the data sampled at 64,000 samples per second).

Start date and time	Beam AMAR (dB re 1 Hz µPa^2/Hz)	Stern AMAR (dB re 1 Hz µPa^2/Hz)	Mobile AMAR (dB re 1 Hz µPa^2/Hz)
Oct 31 18:00	94.5	90.7	95.3
Oct 31 18:30	97.1	88.9	99.5
Nov 1 03:00	99.0	90.9	N/A
Nov 1 06:00	96.8	93.5	N/A
Nov 2 05:00	98.3	93.9	N/A

Table 4. Horizontal and slant ranges from Stena IceMAX to each AMAR. The water depth at the IceMAX was 2000 m.

Recorder	Horizontal range (m)	Sensor depth (m)	Slant range to Stena *IceMAX* (m)	Slant range to well head (m)
Beam AMAR	2000	1980	2810	2000
Stern AMAR	2140	1990	2920	2140
Mobile AMAR	690	120	700	2000

Table 5. Back propagated source levels of the 14 Hz tone at selected times, assuming the source was at the surface. Minimum and maximum values are in bold.

Start date and time	Beam AMAR (dB re 1 Hz µPa^2/Hz)	Stern AMAR (dB re 1 Hz µPa^2/Hz)	Mobile AMAR (dB re 1 Hz µPa^2/Hz)
Oct 31 18:00	163.5	160.1	**152.2**
Oct 31 18:30	166.2	158.3	156.4
Nov 1 03:00	**168.0**	160.2	N/A
Nov 1 06:00	165.8	162.8	N/A
Nov 2 05:00	167.2	163.2	N/A

Table 6. Back propagated source levels of the 14 Hz tone at selected times, assuming the source was at the well head on the sea bottom. Minimum and maximum values are in bold.

Start date and time	Beam AMAR (dB re 1 Hz µPa^2/Hz)	Stern AMAR (dB re 1 Hz µPa^2/Hz)	Mobile AMAR (dB re 1 Hz µPa^2/Hz)
Oct 31 18:00	160.5	157.3	161.3
Oct 31 18:30	163.2	**155.5**	**165.5**
Nov 1 03:00	165.0	157.5	N/A
Nov 1 06:00	162.9	160.1	N/A
Nov 2 05:00	164.2	159.9	N/A

4.1.2. Broadband Source Levels from Operations

A key objective of this SCC was to determine the source level of the MODU operation for comparison to the levels estimated in the EIS. The *narrowban*d power spectra density levels (see Section 3.3) were required to identify sounds from active drill string and bit for this SSC, but were not directly comparable with the *broadband* SPL values from the EIS. Broadband levels were therefore, calculated and are discussed below.

The daily SEL values shown in **Figure 20** indicate total SEL and the contribution of noise from the IceMAX and OSVs. The Mobile AMAR was omitted from this analysis since it did not cover an entire 24-hour period. **Table 7** contains the total source levels and per-band source levels obtained by adding 20*log$_{10}$(range) to the mean measured sound levels (L_{eq}). The source level in the 100–1000 Hz decade band was representative of the majority of the MODU and OSV dynamic positioning noise. It was not possible to measure the source levels of the MODU and each OSV individually, since each vessel would have had to be measured in absence of all other noise to measure a source level.

The distances to SEL of 195 dB re 1 µPa^2·s (Stantec 2014) for temporary threshold shift (TTS) for the different functional hearing groups listed in the EIS are reported in **Table 8**. The daily SEL values were calculated by adding 10*log10(86400) to the broadband L_{eq} value from **Table 7** and applying M-weighting functions for the mammal functional hearing groups described in the EIS. The value of 86400 within the calculation is the number of seconds in one day.

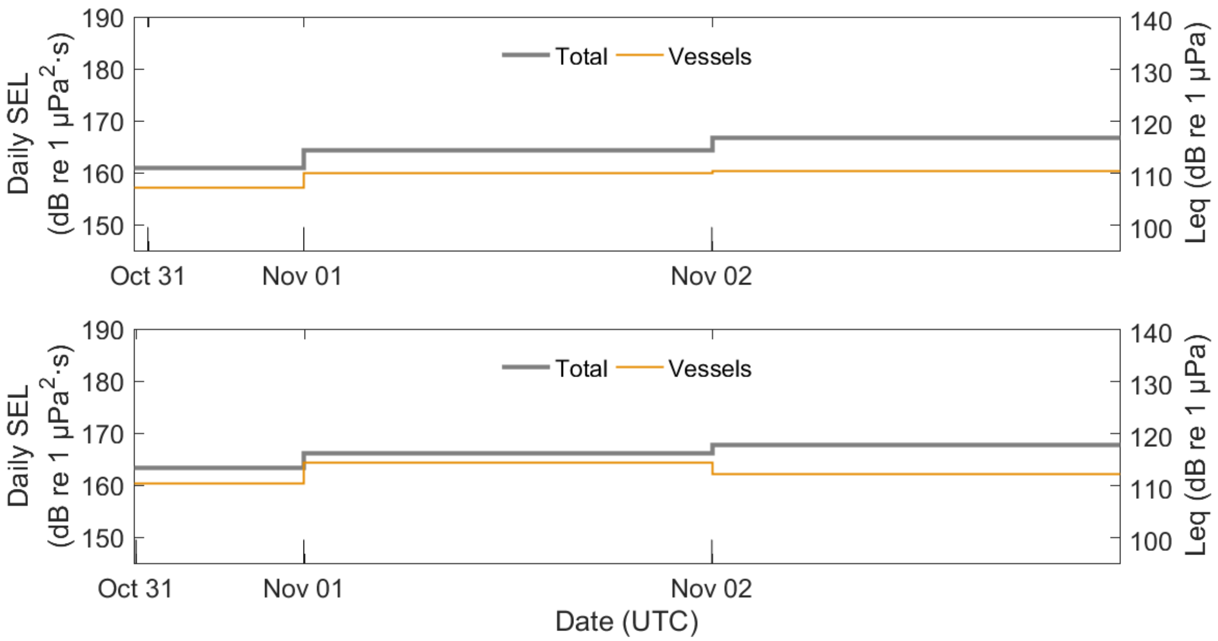


Figure 20. Total and IceMAX and OSV-associated daily sound exposure levels (SEL) and equivalent continuous noise levels (L_{eq}) at Beam AMAR (top figure) and Stern AMAR (bottom figure) in the study area.

Table 7. Broadband source levels based on the L_{eq} measured sound levels for the IceMAX and OSVs.

Band (Hz)	Source level, based on Beam AMAR (dB re 1 µPa)	Source level, based on Stern AMAR (dB re 1 µPa)
10–32,000	185.8	187.7
10–100	179.4	182.2
100–1000	184.1	185.6
1000–10000	175.3	176.7
10000–32000	164.6	171.9

The broadband source levels were 185.8 dB re 1 µPa for the Beam AMAR and 187.7 dB re 1 µPa for the Stern AMAR, which is within the 130–190 dB re 1 µPa range of source levels for the MODU. The range for the OSVs predicted in the EIS was 170–180 dB re 1 µPa. As mentioned above, it is not possible with the measurement setup to measure the individual source levels of the OSVs, but the source levels for the IceMAX and OSVs combined were less than the 190 dB re 1 µPa in the EIS for the MODU.

The hearing impairment criterion of 224 dB re 1 µPa noted for temporary threshold shift (TTS) for cetaceans (i.e., a temporary reduction in the ability to hear) within the EIS refers to peak SPL. Peak SPL can be approximated by adding 10 dB to SPL; therefore, the maximum source level would be 197.7 dB re 1 µPa peak SPL. This value is well below the 224 dB re 1 µPa defined in the EIS. Neither injury nor permanent threshold shift (PTS) of marine mammal hearing from sound levels are expected, since they require higher SPL than TTS. The EIS used the same criteria for turtles as for cetaceans, so hearing impairment is not expected in turtles.

The EIS noted that an accepted SPL threshold for potential auditory injury to fish that weighed 2 grams or heavier is 206 dB re 1uPa. This SSC found that the peak SPL of 197.7 dB re 1 µPa is below this threshold and the received SPL from the presence and operation of the MODU and OSVs are unlikely to result in injury to fish.

To assess the risk of hearing impairment effects from non-pulsed sound on cetaceans, the EIS also listed a received SEL of 195 dB re 1 µPa²·s that would result in TTS. **Table 8** lists the distances that sound from the MODU and OSV would travel before reaching an SEL of 195 dB re 1 µPa2·s for TTS. The distances are sorted by the hearing groups cited in the EIS. The daily SEL values were calculated by adding 10*log10(86400) to the broadband L_{eq} value from **Table 7** and applying M-weighting functions for the mammal functional hearing groups described in the EIS. The value of 86400 within the calculation is the number of seconds in one day. The maximum SEL of 237.0 dB re 1 µPa^2·s had a maximum range of 126.2 m from the IceMAX. Shell had protocols in place to shut down VSP operations if a marine mammal was spotted within 500 m, which is conservative based on these SEL ranges, and well within compliance with the EIS.

Table 8. Broadband SEL source levels and ranges to the M-weighted TTS criteria in the EIS (Stantec 2014).

Band (Hz)	SEL source level, based on Beam AMAR (dB re 1 µPa^2·s)	Range to 195 dB re 1 µPa^{2}s threshold (m)	SEL source level, based on Stern AMAR (dB re 1 µPa^2·s)	Range to 195 dB re 1 µPa^2·s threshold (m)
Low-frequency cetaceans	235.1	101.4	237.0	126.2
Mid-frequency cetaceans	232.6	75.8	234.3	91.8
High-frequency cetaceans	231.9	69.6	233.5	84.2
Pinnipeds in water	233.9	88.3	235.7	107.9

The one-third octave-band L_{eq} source levels (**Table 9**, **Figure 21**) were also calculated. Source levels are commonly reported in this way, and the information is a useful input for future propagation modelling.

Table 9. One-third octave-band source levels for the Beam and Stern AMARs.

One-third octave-band centre frequency (Hz)	Source level, based on Beam AMAR (dB re 1 µPa)	Source level, based on Stern AMAR (dB re 1 µPa)
10	167.6	167.7
12.5	163.9	163.6
16	167.0	167.9
20	170.5	171.6
25	165.4	167.2
31.5	165.1	169.8
40	169.9	172.9
50	171.5	174.6
63	173.6	177.3
80	174.9	177.4
100	175.5	178.6
125	176.6	177.8
160	175.7	177.0
200	175.6	176.3
250	174.9	175.8
315	174.0	175.2
400	172.5	173.9
500	172.1	173.6
630	170.7	172.7
800	170.1	171.9
1000	169.2	170.7
1250	169.5	170.5
1600	167.2	168.5
2000	165.5	166.9
2500	164.7	166.3
3150	162.5	164.3
4000	160.7	162.5
5000	159.5	161.4
6300	159.0	159.9
8000	156.5	157.6
10000	154.0	156.9
12500	164.0	171.7
16000	144.4	146.8
20000	140.6	141.5
25000	148.9	147.1

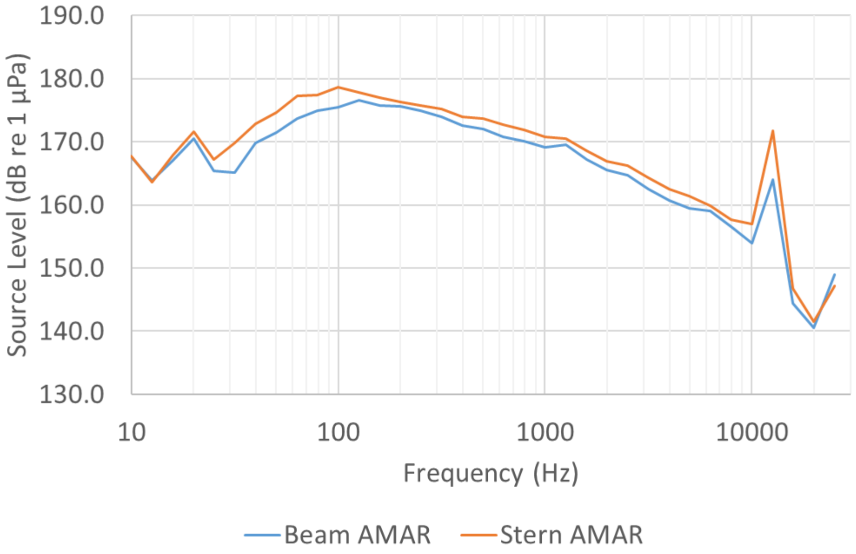


Figure 21. One-third-octave-band source levels for the Beam and Stern AMARs.

4.2. Cheshire Well

As part of an unrelated project to study sounds on Canada's East Coast (Environmental Sciences Research Fund (ESRF); Delarue et al. 2017), JASCO was contracted to deploy an AMAR 13 km northeast (42° 32.856' N, 62° 10.574' W) of the Cheshire L-97A well site from late August 2015 to mid-July 2016 (Station 5, **Figure 22**).

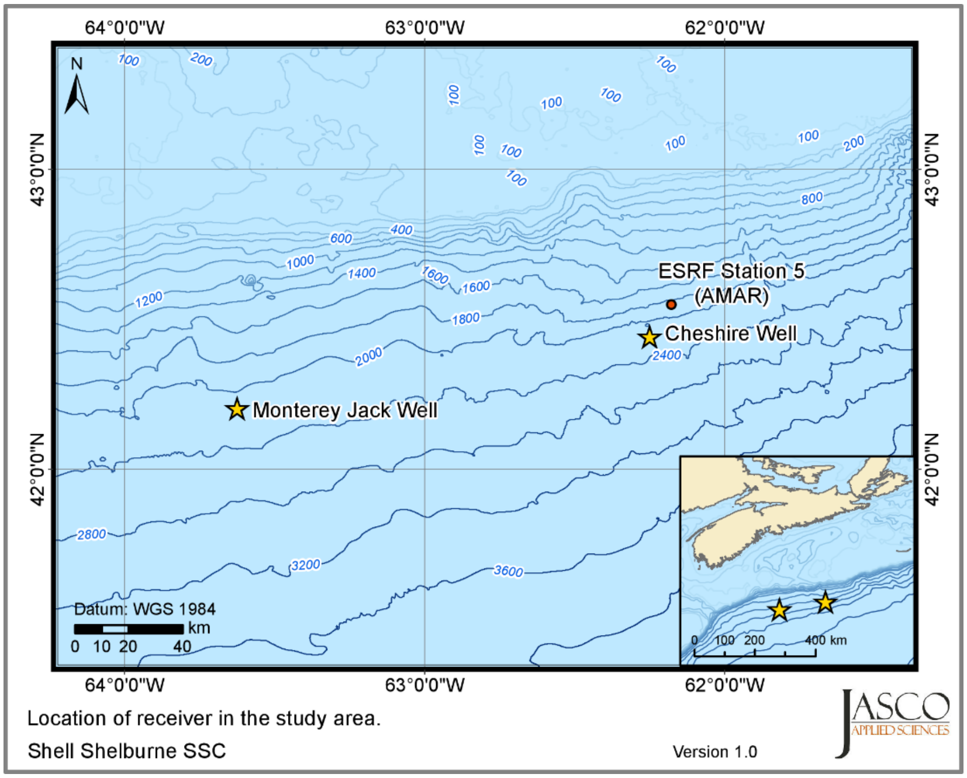


Figure 22. Map of Shell Project well sites and the ESRF AMAR. Blue lines indicate bathymetry in metres.

The sounds from the IceMAX and OSVs, while on station at the Cheshire well site, were visible in the data captured by the ESRF AMAR. The increase from 50–1000 Hz is visible in the spectrogram (**Figure 23**) and the PSD plot (**Figure 24**). The band at 20 Hz from mid-September to April is due to the fin whale mating chorus, a feature observed throughout the deep waters off eastern Canada. The sudden drop in sound levels in early March 2016 is likely associated with the cessation of drilling activity and departure of the IceMAX from the Cheshire location until it returned to the Cheshire well site late May 2016. The average broadband SPL from April, representing ambient levels in absence of the IceMAX and OSV operations and fin whale sounds, is 104.0 dB re 1 µPa. The broadband SPL from June, representing levels during drilling operations, with IceMAX and OSVs present, without the presence of fin whale 20 Hz notes, is 107.8 dB re 1 µPa. This indicates the mechanical sound and thrusters from the DP system from the IceMAX and OSVs contributed to an increase of 3.8 dB over ambient levels at a distance of 13 km from the drilling operations.

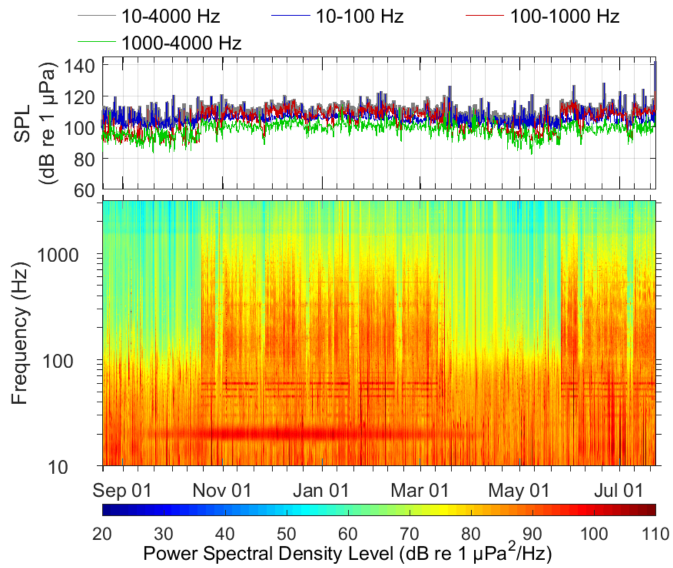


Figure 23. ESRF Station 5, 13 km from the Cheshire well site in 2015-2016: In-band SPL (top) and spectrogram over time (bottom).

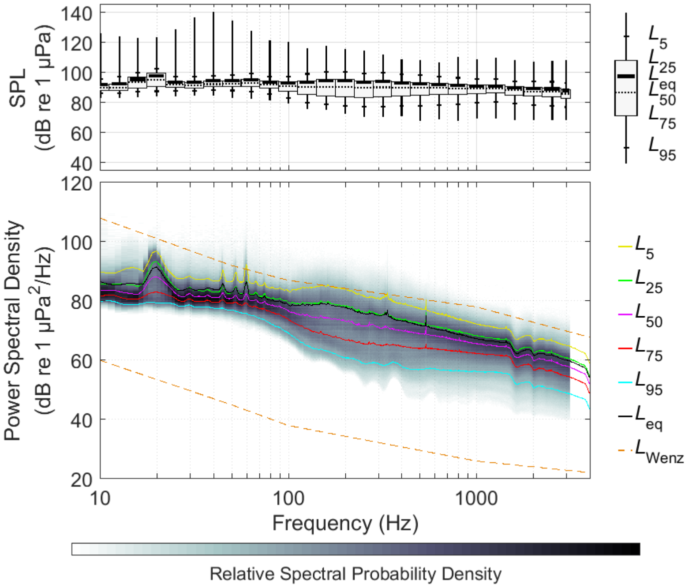


Figure 24. Sound level distribution at ESRF Station 5, 13 km from the Cheshire well site: (Top) Exceedance percentiles and mean of 1/3-octave-band SPL and (bottom) Exceedance percentiles and probability density (grayscale) of 1-min PSD levels compared to the limits of prevailing noise (Wenz 1962).

5. Conclusions

In accordance with CEAA Condition 3.12.3, a Sound Source Characterization (SSC) was performed to verify predicted underwater noise levels within the Project EIS with field measurements. The SCC measured the underwater sound levels from the drilling operation, which included mechanical and vibration sound, thruster cavitation from the DP systems generated by the IceMAX (MODU) and the OSVs, as well as drilling activity sound from the drill string and drill bit generated by the IceMAX.

The SSC verifies that the noise emitted by the Project drilling operations, inclusive of OSV traffic, falls within the range of 130–190 dB re 1 µPa predicted within the EIS. The noise emitted from drilling operations is therefore not likely to result in auditory injury to fish, marine mammals, or sea turtles.

As per the SCC, broadband source levels based on the L_{eq} measured sound levels for the static Beam and Stern AMAR recorders, which included OSV noise, were 185.8 and 187.7 dB re 1 µPa, respectively. These source levels are within the 130–190 dB re 1 µPa range of the source levels predicted for the MODU in the EIS (Table 7). The range of source levels for the OSVs predicted in the EIS is 170–180 dB re 1 µPa. Although it was not possible with the SCC measurement setup to measure the individual source levels of the OSVs, the source levels for the IceMAX and OSVs combined were less than the 190 dB re 1 µPa predicted in the EIS for the MODU. The frequency band that contributed most to the broadband level was 100–1000 Hz, which is associated with thruster noise from DP operation. The next largest contributor was the 10–100 Hz band where DP noise dominated and some mechanical noise from with power generation occurred.

The SSC determined that the noise generated by the MODU during drilling activity was negligible compared to the noise generated by the DP thrusters and machinery from of the IceMAX and the OSVs. The sound pressure levels (SPL) measured during drilling activity were very low compared to sound measured from thrusters used in DP systems and mechanical noise from generating power on the IceMAX and OSVs. Sound emitted from drilling activity was low enough that it could often not be detected. Additionally, the full period spectrograms and band-level data (**Figure 11**) did not show changes in measured sound levels at the Beam and Stern AMARs that correlate with changes in the drilling state (as per the IceMAX daily operations report, **Table 2**). This suggests again that DP system noise from the IceMAX and OSVs were larger contributors to the sound field than that generated from drilling activity.

Peak sound level was used for marine mammal hearing impairment criterion. The hearing impairment criterion for temporary threshold shift (TTS) for cetaceans within the EIS was 224 dB re 1 µPa. Peak SPLs were approximated by adding 10 dB to the measured 187.7 dB re 1 µPa (i.e. the maximum source level value). The peak source level of 197.7 dB re 1 µPa was well below the 224 dB 1 µPa criterion for TTS within the EIS. The criteria for permanent threshold shift (PTS) was higher than for TTS, so these effects are not likely to occur. This finding supports the prediction within the EIS that there would likely be no direct injury or permanent auditory effects on marine mammals because of Project drilling operations. The EIS also noted that peak levels of noise above 206 dB re 1 µPa are needed to elicit damage to fish 2 grams or heavier. The resulting peak SPL of 197.7 dB re 1 verifies that it is unlikely that direct injury to fish will occur due to the presence and operation of the MODU and OSVs.

Temporary threshold shift (TTS) was also examined based on the SEL that a mammal would be exposed to over an entire day. The EIS outlined that the onset of TTS on cetaceans from non-impulsive noise (e.g., vessel sound) can occur from an SEL of 195 dB re 1 $\mu Pa^2 \cdot s$. The mammal hearing group weighting functions were applied to the broadband SEL and distances to the 195 dB re 1 $\mu Pa^2 \cdot s$ threshold were calculated (**8**). None of the ranges exceeded the 500 m radius safety zone defined in the EIS and monitored for marine mammals during VSP activities. The EIS used the same criteria for turtles as for cetaceans, so no hearing impairment is expected.

6. Acknowledgements

We would like to thank the captain and crew of the M/V *Scotian Sea* as well as Eric Lumsden and Carmen Lawrence from JASCO for performing the fieldwork.

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