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SOUND SOURCE LIST

A description of sounds commonly produced during ocean exploration and industrial activity

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Center for Marine Acoustics

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List of Abbreviations and Acronyms

Short Form	Long Form
2D	two-dimensional
3D	three-dimensional
ADCP	Acoustic Doppler Current Profiler
AUV	autonomous underwater vehicle
BIWF	Block Island Wind Farm
BOEM	Bureau of Ocean Energy Management
BSEE	Bureau of Safety and Environmental Enforcement
CHIRP	compressed high intensity radar pulse
COST	Continental Offshore Stratigraphic Test
CPT	cone penetrometer test
CTD	conductivity, temperature, and depth
dB	decibel(s)
dB re 1 µPa	decibel(s) referenced to 1 micropascal
dB re 1 µPa·m	decibel(s) referenced to 1 micropascal meter
DP	dynamic positioning
DST	deep stratigraphic test
DTH	down-the-hole
FPSO	Floating, Production, Storage, and Offloading
in^3	cubic inch(es)
hr	hour(s)
HRG	high-resolution geophysical
Hz	hertz (cycles per second)
kHz	kilohertz (thousands of cycles per second)
km	kilometer(s)
kt	knot(s)
J	Joule(s)
LNG	liquified natural gas
LPSL	lowest practicable source levels
µPa	micropascal
m	meter(s)
MBES	multi-beam echo sounders
MODU	mobile offshore drilling unit
NMFS	National Marine Fisheries Service
OCS	Outer Continental Shelf
PDBS	phase differencing bathymetric sonars
PIES	pressure inverted echo sounder
psi	pound(s) per square inch

Short Form	Long Form
ROV	remotely operated vehicle
s	second(s)
SAS	synthetic aperture sonar
SBES	split-beam echosounder
SBP	sub-bottom profiler
SEL	sound exposure level
SL	source level
SPL	sound pressure level
TNT	trinitrotoluene
UWC	underwater calculator

1 Introduction

The primary purpose of this document is to describe activities and equipment that may introduce sound into the marine environment.

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

This sound source list is not meant to be a comprehensive list but has been developed to highlight key sources relevant to activities managed by the Bureau of Ocean Energy Management (BOEM). As such, we focus on acoustic sources used by the marine energy and extraction industries, as well as the scientific research community. Acoustic sources used for military applications are not included here.

We provide a brief description and representative information for each source type—such as example brands and models, source levels, frequency ranges—where available. Source levels are included where reliable data exist, but these measurements are not available for many sources. For most, received levels at various distances have been used to infer source levels, meaning that estimations of transmission loss have been made. efer to the references for further detail about the measurements and calculations.

We note that a report from the Joint Industry Programme (Jiménez-Arranz et al. 2020) describes many of these sources in great detail and may serve as a more comprehensive resource for sound level information.

Generally, source levels are given in decibels referenced to 1 µPa·m. It is important to understand that this value is calculated rather than measured. For most sources, measurements at 1 m are either impossible to take or would not be informative for predicting received levels in the far field. Measurements are usually made in the far field, where the source starts to behave as a single radiating element, or "point source." However, for in-water pile driving for bridge and vessel terminal/dock construction, measurements are often made at 10 m from the pile and may be referred to as "source levels" in some references. So far, this practice has not continued in source level reporting for the pile driving of large wind turbine monopiles, likely because treating a pile as a point source 10 m away is nearly as impractical as a measurement at 1 m. Most source levels in this document are referenced to 1 m, and special note is made if the reference is anything else.

Different acoustic metrics have been used in reporting and describing sound sources, e.g., sound exposure level (SEL or L_E), cumulative sound exposure level (SEL_{cum}) over a given period of time, peak sound pressure level (Lpk or $L_{p,pk}$), and root-mean-square sound pressure level (SPL or $L_{p,rms}$). To simplify the discussion, this document only includes metrics that are most relevant for the sources in question. For example, for most of the HRG sources, we report SEL for a single pulse of sound, as reported by Crocker and Fratantonio (2016); for impact pile driving, we include SEL over a single pile driving strike, denoted by SEL_{ss}.

Unless otherwise noted, "beamwidth" corresponds to Crocker and Fratantonio's (2016) measurement of "beamwidth – 3dB," defined in that document. The term "broadband" is not defined well in the literature, but generally refers to a source that covers a wide range of frequencies, rather than something producing sound in a discrete frequency range. For definitions of acoustic metrics, please refer to ISO 18405 *Underwater Acoustics – Terminology* (ISO 2017).

This document contains the best information currently available. We acknowledge that new sources may be in development and become widely used in future years. The authors will make a good faith effort to periodically update this document with new information. If readers recognize an omission, please reach out, and we will do our best to incorporate.

2 Airguns

Seismic airguns are used to locate resources under the ocean floor and create an impulsive signal by injecting a bubble of highly compressed air into the water. They are essentially steel cylinders, typically a meter or less in length, containing internal air chambers and are towed behind the source vessel at a depth of several meters. Airguns are connected by electronic cables and high-pressure air hoses to shipboard air compressors and triggering electronics. The chamber is filled with compressed air (usually 2,000 psi for commercial purposes); when the trigger signal is received, a port opens, and the compressed air is rapidly released. The airgun signal includes a component called the "bubble pulse," which consists of the source bubble oscillating before dispersing into the water column or venting into the atmosphere at the ocean's surface. The time between the primary pulse and the bubble pulse is dependent on the volume of the air chamber, which can vary from less than 10 cubic inches (in^3) to as large as 2,000 in^3. Airguns can be deployed as single elements or as part of an airgun array comprising dozens of individual elements.

2.1 Single Airguns

Sounds from a single airgun are impulsive, intermittent with dominant frequencies below 500 Hz. A major factor influencing source level is the volume of the airgun chamber. Sounds from single airguns are considered omnidirectional. See Jiménez-Arranz et al. (2020) for further detail.

Surveys that use single airguns (or small arrays of four or fewer airguns) are typically intended to image the uppermost kilometer or less of the seafloor with source frequencies primarily between 10–200 Hz (Jiménez-Arranz et al. 2020). The time interval between single airgun “shots” is usually less than 6 s, and the reflected signals are received by a single hydrophone streamer of several hundred meters in length to create 2D reflection profiles. High-resolution 3D surveys utilizing multiple hydrophone streamers are becoming more common, and, though rarer, ocean bottom receivers (e.g., ocean bottom nodes) can also be used for high-resolution airgun surveys. Imaging targets include shallow geohazards, earthquake faults, and shallow resources such as gas hydrates or sand deposits. Typical industry surveys that use single airguns are likely to cover only one Outer Continental Shelf (OCS) lease block, which is usually 4.8 km on a side (this differs from deep-penetration surveys). Including vessel turns at the end of lines, the time required to survey one OCS lease block is approximately 36 hr. High-resolution academic research surveys vary in duration depending upon research goals, ranging anywhere from approximately 1 to 30 operational days, but the most common duration is 8 to 12 operational days.

The “bubble pulse” of a single airgun can degrade the imaging resolution of the seismic reflection data, so dual-chamber airguns have been developed to minimize this problem. Dual-chamber airguns, also referred to as generator-injector airguns, have a generator chamber that discharges first, then the injector chamber fires several milliseconds later to prevent the collapsing bubble from oscillating, reducing the interference from the bubble pulse.

Example brands and models include the Sercel 30/30 in^3 Mini-Generator-Injector Airgun; the Sercel 105/105 in^3 Generator-Injector Airgun; sleeve airguns (which uses an external sleeve as the port mechanism); and single chamber airguns (e.g., Bolt, Sercel G-guns).

2.2 Airgun Arrays

Deep-penetration 2D and 3D seismic reflection surveys use large arrays of as many as several dozen airguns distributed in a rectangular-spaced configuration towed behind the vessel. Total airgun volumes can vary depending upon desired objectives, ranging upwards to thousands of cubic inches. The airguns are discharged at regular time intervals, typically every 10 s (International Association of Oil & Gas Producers 2011), to produce sub-bottom images to depths greater than 10 km. Most of the energy produced by airgun arrays are below 250 Hz (with 90% of the energy between 70–140 Hz), but there may be additional energy up to 20 kHz (Jiménez-Arranz et al. 2020; Madsen et al. 2006). The reflected signals from the airgun array are received by either towed hydrophone streamers, which can be more than 12-km long (including multiple streamers for 3D surveys or a single streamer for a 2D survey), or extensive seafloor arrays of ocean bottom cables, nodes, or seismometers.

Airgun arrays have important advantages as a seismic source compared to single airguns. Large "tuned" arrays use airguns of varying chamber volumes to reduce the bubble pulse of the array source signature and increase the resolution of the source signal. A horizontally distributed array of airguns produce a downward-focused source signal. The signals from the individual airguns are in-phase in the vertical direction but out-of-phase horizontally. Therefore, the vertically propagating signal has a higher peak amplitude than the horizontal component. In addition, the number of airguns in an array is a much more important factor in determining the peak output level of the source than total airgun volume. Peak-to-peak amplitude of an airgun array increases linearly with the number of airguns but only increases by the cube root of total air volume (Caldwell and Dragoset 2000); Jiménez-Arranz et al. (2020) plotted this relationship (**Figure 1**).

Most deep-penetration surveys are conducted by the hydrocarbon exploration industry, typically covering areas off existing leases or covering multiple lease areas. Academic and government surveys are also conducted every year for geologic research. As of 2020, the U.S. academic research fleet includes one dedicated seismic vessel with a 36-gun array with total airgun volume up to 6,600 in^3. Academic research surveys vary in duration depending upon research goals, ranging anywhere from approximately 10 to 35 operational days.

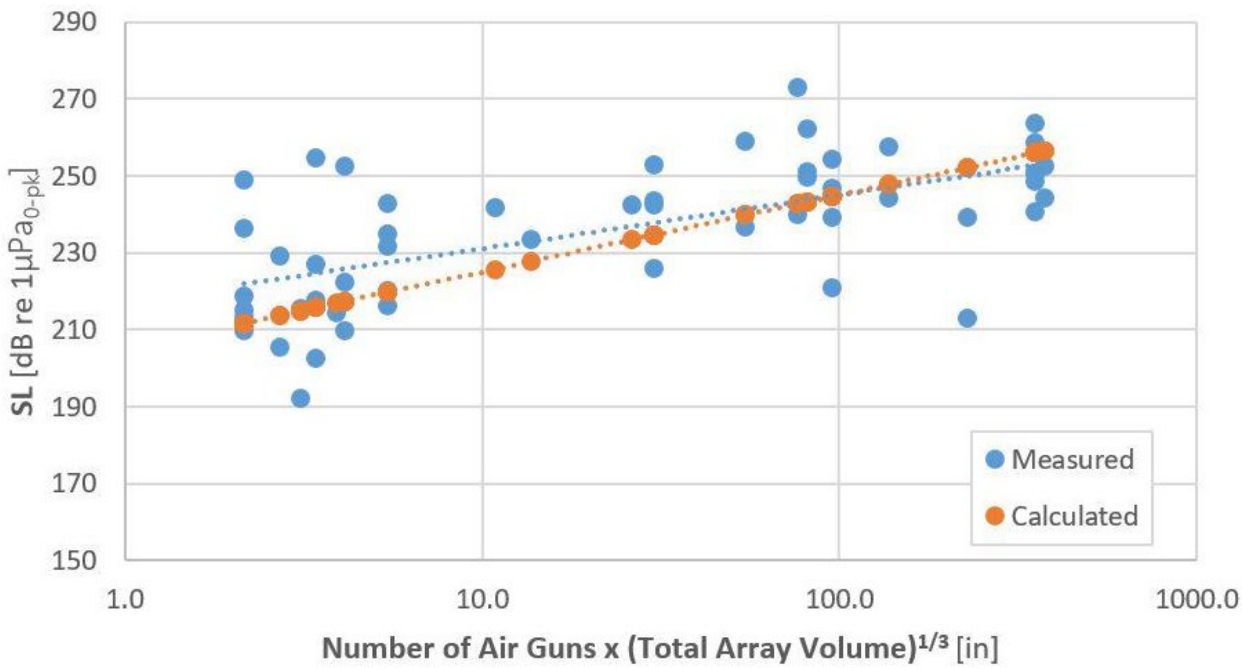

Figure 1. Peak source level of an air gun array as a function of the number of airguns and cube root of its total volume

Comparison between measurements (blue) and approximate equation by (Caldwell and Dragoset 2000). Adapted from Jiménez-Arranz et al. (2020).

Table 1 provides source levels of some airguns and airgun arrays from reports compiled in Jiménez-Arranz et al. (2020); for more detailed information, see the references directly.

Table 1. Airgun sound level examples

Airgun Type and Number	Airgun Volume (in^3)	Water Depth (m)	Source Depth Below Surface (m)	Lpk Source Level (dB re 1 µPa·m)	SPL Source Level (dB re 1 µPa·m)	Reference
Single	10	35	1.5	–	201	Ireland et al. (2009)
Single	10	35	1.5	–	240	Ireland et al. (2009)
Single	10	22	2.25	–	210	Funk et al. (2010)
Single	10	40	2	–	206	Ireland et al. (2009)
Single	10	45	2	–	204	Reiser et al. (2010)
Single	10	45	2	–	227	Reiser et al. (2010)
Single	20	10	2	–	241	Hauser et al. (2008)
Single	20	10	2	–	245	Hauser et al. (2008)
Single	30	20	6	–	206	Ireland et al. (2009)
Single	30	40	6	–	253	Ireland et al. (2009)
Single	30	30	6	–	183	Funk et al. (2010)
Single	30	50	6	–	188	Funk et al. (2010)
Single	40	15	1	222	–	Greene Jr. and Richardson (1988)

Airgun Type and Number	Airgun Volume (in^3)	Water Depth (m)	Source Depth Below Surface (m)	Lpk Source Level (dB re 1 µPa·m)	SPL Source Level (dB re 1 µPa·m)	Reference
Single	40	15	2	–	209	McPherson and Warner (2013)
Single	40	< 20	NA	–	191–194	Nedwell and Edwards (2004)
Single	60	38	6	–	206	Blees et al. (2010)
Single	70	< 8	1.1	–	201 & 243	Aerts et al. (2008)
Single	70	55	8.5	–	214	Beland et al. (2013)
Single	70	550	8.5	–	231	Beland et al. (2013)
Cluster (2)	20	22	2.25	–	234	Funk et al. (2010)
Cluster (2)	20	30–40	2.25	–	223	Funk et al. (2010)
Cluster (2)	20	35	1.5	–	207	Ireland et al. (2009)
Cluster (2)	20	35	1.5	–	226	Ireland et al. (2009)
Cluster (2)	20	40	2	–	211	Ireland et al. (2009)
Array (3)	330	34	3, 9, 18	–	193	Greene Jr. and Richardson (1988)
Array (4)	40	40	2	–	225	Ireland et al. (2009)
Array (4)	40	40	2	–	218	Reiser et al. (2010)
Array (4)	40	45	2	–	231	Reiser et al. (2010)
Array (4)	280	30	2.5	242	–	Patterson et al. (2007)
Array (8)	320	15	2	–	228, 250	McPherson and Warner (2013)
Array (8)	440	< 8	1.8	–	233, 235	Aerts et al. (2008)
Array (8)	440	< 8	1.1	–	217, 244	Aerts et al. (2008)
Array (8)	440	< 8	1.8	–	231, 264	Aerts et al. (2008)
Array (10)	880	10	2	–	237	Hauser et al. (2008)
Array (12)	2,868	20, 44	NA	–	202	Greene Jr. and Richardson (1988)
Array (16)	640	15	2	–	235, 249	McPherson and Warner (2013)
Array (24)	3,147	30	6	–	232, 255	Funk et al. (2008)
Array (24)	3,147	50	6	–	232, 248	Funk et al. (2008)
Array (26)	3,000	40	6	–	232, 255	Blees et al. (2010)
Array (36)	3,320	40	8.5	–	263	Ireland et al. (2007)

Notes: Lpk = peak sound pressure level; SPL = root-mean-square sound pressure level

Further reading

- International Association of Geophysical Contractors. 2014. Lowest practicable source levels (LPSL): the implications of adjusting seismic source array parameters. https://iagc.org/wp-content/uploads/2020/07/IAGC-Working-Paper-Lowest-Practicable-Source-Level-Dec-2014.pdf
- International Association of Geophysical Contractors. 2002. Airgun arrays and marine mammals. http://www.geophysicalservice.com/Uploads/Old_Site/Reports/airgun_arrays.pdf.

3 Marine Vibrators

Alternative names: Marine vibroseis

Marine vibrators use hydraulic or electromagnetic methods to produce a non-impulsive signal that is several seconds long. They can be “tuned” to cover a specific frequency range (e.g., 5–20 Hz or 5–100 Hz). The duration and duty cycle of the signal can also be specified, depending on the needs of the survey. In general, marine vibrators are more tunable than airguns, allowing them to have lower peak pressures and to better suppress extraneous frequencies above ~150 Hz (Feltham et al. 2017; Laws et al. 2018; Teyssandier and Sallas 2019), thereby reducing the leakage of sound into frequencies that are not necessary. These and other features of vibrators may reduce their impact on marine species relative to airguns (Matthews et al. 2020).

Since vibrators do not require compressors, they are also more portable than airguns, and they can be more readily deployed on smaller vessels. Marine vibroseis sometimes is discussed as a potential replacement for airguns for particular purposes, especially in shallow water or environmentally sensitive areas (Feltham et al. 2017; Laws et al. 2018; Teyssandier and Sallas 2019). Despite ongoing testing (Feltham et al. 2017), marine vibrators still remain experimental and are not yet commercially produced. As there is no typical commercial vibrator source at this moment, we do not report source levels here.

4 High-Resolution Geophysical Sources

High-resolution geophysical (HRG) sources constitute a broad category of acoustic sources used to image below the seafloor or detect characteristics (e.g., bathymetry, roughness) of the seafloor itself. HRG sources can be towed behind ships, mounted on a ship's hull, or deployed on remotely operated vehicles (ROVs), autonomous underwater vehicles (AUVs), autonomous surface vessels, and seafloor landers. HRG sources usually operate at lower power than airguns, resulting in shallower subseafloor imaging capability. HRG sources also are operated at higher frequencies than airguns, leading to better resolution of sub-bottom features. Applications of HRG sources include imaging stratigraphy or geologic structures beneath the seafloor and mapping seafloor bathymetry, texture, and reflectivity characteristics (Ruppel et al. 2022).

HRG sources are widely used for scientific research, site characterization for renewable energy projects, evaluation of seafloor conditions for oil and gas operations, identification of sand and gravel resources, characterization of marine habitats, location of archaeological sites, mapping marine unexploded ordnances, detection of seafloor mineral resources, and detection and avoidance of marine hazards. Operators select HRG sources that have sufficient power and appropriate frequencies to detect and/or image the geologic target with acceptable resolution. Multiple sources may be deployed simultaneously to achieve survey goals or to provide complementary and coincident datasets (e.g., swath bathymetry data and sub-bottom imaging). The spacing and orientation of HRG survey lines are designed to provide appropriate coverage of the target while taking into account factors—such as ocean currents and natural features (e.g., shelf-break, underwater sand ridge)—that could affect the quality of acquired data.

4.1 Sparkers

Alternative names: Archer

A sparker is a seismic source that uses an electrical discharge from a ship-based power supply (100s to 10,000 J) to vaporize saltwater, rapidly creating a bubble that produces an omnidirectional pulse of sound, typically up to 3 ms in duration and with most energy between 50 Hz and 4 kHz. A single hydrophone or multichannel hydrophone streamer typically is towed to detect sound reflected from sub-bottom features. Sparkers usually are towed at a depth of a few meters; they can be mounted on sleds and are sometimes simply bare electrodes at the end of a high-voltage power cable. Sparker signals can penetrate tens of meters to several hundred meters below the seafloor, depending on the power level of the sparker and the nature of the sediments. Sparkers can operate at frequencies higher than airguns, which leads to better vertical resolution in the resulting data. Sparkers do not have an integral receiver and therefore are not classified as sub-bottom profilers.

Different types of sparkers have various settings. For example, the depth of the SIG ELC820 is adjustable. In comparing sources at 1-m depth to sources at 5-m depth, Crocker and Fratantonio (2016) found substantial differences in the sound pressure time series, including differences in secondary bubble oscillations and overall waveform duration. At 5 m, pulse widths and bandwidths were more consistent with manufacturer's stated specifications, so two energy levels for that depth are covered in **Table 2**. The Applied Acoustics Delta Sparker was also tested at both 1-m and 5-m depths. A 5-m example was chosen as the lower extreme for **Table 2** because the Delta Sparker had lower source levels when deployed at 5 m.

Dura-Spark operates at a fixed depth but can be deployed with a different number of electrodes, or "tips." Although total energy is important, the sound levels seem to correlate best with the joules (J) per tip, with a recommended maximum of 5 J/tip.

All sparkers are omnidirectional, impulsive, and intermittent sources.

Table 2. Sparker sound level examples

Sparker Configuration (examples)	Lpk Source Level (dB re 1 µPa·m)	SPL Source Level (dB re 1 µPa·m)	SEL Source Level (dB re 1 µPa²s·m²)	Approximate Frequency Range (kHz)
Applied Acoustics Delta Sparker at 500 J and 5-m tow depth (7.5-ms pulse)	203	185*	163	0–1.3
SIG ELC820 sparker at 300 J and 5-m tow depth (4.1-ms pulse)	207	196	171	0–3.7
SIG ELC820 sparker at 300 J and 1-m tow depth (4.1-ms pulse)	207	198	174	0–1.7
SIG ELC820 sparker at 700 J and 5-m tow depth (6.4-ms pulse)	214	201	179	0–1.0
Applied Acoustics Delta Sparker at 2,400 J and 1-m tow depth (9.5-ms pulse)	–	205	185	0–0.5
Applied Acoustics Dura Sparker at 2,000 J, 400 tips (5.0 J/tip) (2.4-ms pulse)	224	214	188	0–2.8

Notes: Lpk = peak sound pressure level; SPL = root-mean-square sound pressure level; SEL = sound exposure level
* Recordings of the Applied Acoustics Delta Sparker showed two distinct pulses whose separation in arrival time varied with energy input. Because SPL depends greatly on pulse duration, it is a less meaningful measurement than SEL and L_{Pk} for this device.
Source: Crocker and Fratantonio (2016)
Other example brands and models: Geomarine GeoSource Sparkers (400–800 J)

4.2 Boomers

Alternative names: thumper (an obsolete name that was used in early development of boomers)

Modern boomers are towed seismic sources that use an electrical pulse to force a circular plate away from another component of the system to generate a pulse focused in a cone of up to 90° with typical pulse durations of 0.6–0.8 ms (Ruppel et al. 2022). Although boomers can produce sounds up to several kilohertz in frequency, the dominant frequency is typically between 1.5–3 kHz (Jiménez-Arranz et al. 2020). The cone geometry depends on the number of boomer plates, which can range from one to three. Boomers do not have an integral receiver and are therefore not classified as sub-bottom profilers. Seismic reflections are detected and recorded by a separately towed streamer with one or more hydrophones. Depending on sediment characteristics and the energy supplied to the boomer, boomers can produce sub-bottom images to depths of more than 100 m below the seafloor.

All boomers are broadband, directional, impulsive, intermittent sources.

Table 3. Boomer sound level examples

Boomer Configuration (examples)	Lpk Source Level (dB re 1µPa·m)	SPL Source Level (dB re 1 µPa·m)	SEL Source Level (dB re 1µPa^{2}s·m^2)	Approximate Frequency Range (kHz)	Beam Width
Applied Acoustics AA200 (single plate, 0.8-ms pulse operated at 50 J)	203	191	160	0–8.1	47°
Applied Acoustics AA200 (single plate, 0.8-ms pulse operated at 250 J)	209	200	169	0–4.3	90°
Applied Acoustics AA251 (single plate, 0.7-ms pulse operated at 300 J)	216	207	176	0–4.3	72°
Applied Acoustics S-Boom (three plates, 0.6-ms pulse operated at 700 J)	211	205	172	0–6.2	61°

Notes: Lpk = peak sound pressure level; SPL = root-mean-square sound pressure level; SEL = sound exposure level
Source: Crocker and Fratantonio (2016)

4.3 Bubble Guns

Alternative names: Bubble pulser

Bubble guns are towed seismic sources that generate a low-frequency, narrowband impulse by rapidly compressing a fixed volume of air within a flexible plate or pair of plates (Falmouth Scientific Inc. 2018; 2020). The system is designed to produce a repeatable, directed impulse for improved bottom imaging and penetration. Bubble guns do not have an integral receiver and are therefore not classified as sub-bottom profilers. Seismic reflections are detected and recorded by a separately towed streamer with one or more hydrophones. Depending on sediment characteristics and the source's configuration, bubble guns can produce sub-bottom images to depths of more than 100 m below the seafloor. Bubble guns are typically used for imaging of sediments that are difficult to penetrate with other sources (e.g., coarse sand, gravel tills). Bubble gun sources are not as commonly used as other seismic sources (e.g., airguns, boomers, or sparkers) or sub-bottom profilers. The precise beamwidth of bubble gun sources has not been measured, meaning that their directionality cannot be fully assessed at this time.

Bubble guns are directional, impulsive, intermittent sources.

Table 4. Bubble gun sound level examples

Model	Plates and Volume	Source Depth (cm)	Lpk Source Level (dB re 1 µPa·m)	SPL Source Level (dB re 1 µPa·m)	SEL Source Level (dB re 1µPa^{2}s·m^2)	Approximate Frequency Range (kHz)	Pulse Duration (ms)	Reference
Falmouth Scientific Inc. HMS-620D	Single plate, 15 in^{3}§ (246 cm^3)	86	201	194	167	0–1.6	2.0	Crocker and Fratantonio (2016)
Falmouth Scientific Inc. HMS-620D	Dual* 15 in^3 + 15 in^{3}§ (491 cm^3)	86	204	198	173	0–1.1	3.3	Crocker and Fratantonio (2016)

Model	Plates and Volume	Source Depth (cm)	Lpk Source Level (dB re 1 µPa·m)	SPL Source Level (dB re 1 µPa·m)	SEL Source Level (dB re 1µPa^{2}s·m^2)	Approximate Frequency Range (kHz)	Pulse Duration (ms)	Reference
Falmouth Scientific Inc. HMS-620XL LF	Single, 120 in^3 (2.0x10^3 cm^3)	~150	220	-	-	0–1.7	-	Falmouth Scientific Inc. (2018)

Notes: Lpk = peak sound pressure level; SPL = root-mean-square sound pressure level; SEL = sound exposure level
Source: All data based on measurements by Crocker and Fratantonio (2016) on a Falmouth Scientific Inc. HMS-620D and the user's manual for the HMS-620XL LF. The low end of the dominant source frequency bandwidths was at about 20 Hz.
§15 in^3 for single plate volume from Falmouth Scientific Inc. (2014)
* Both channels did not trigger simultaneously for dual-plate mode, but Crocker points out that the results still "are consistent with the manufacturer's specification of 200 and 204 dB re µPa·1m for single- and dual-plate modes, respectively."

4.4 Sub-Bottom Profilers (SBPs)

Alternative names: Compressed High Intensity Radar Pulse (CHIRP) sonar, CHIRP fish, or CHIRPs; dual-frequency SBP (for parametric SBP)

SBPs are complete systems containing both source and receiver. These systems can either be mounted on a ship's hull or towed behind the ship at depths ranging from the water surface to near the ocean bottom. Here, we focus on two common types of SBPs: CHIRP sonars and parametric SBPs.

Instead of operating at a single frequency, CHIRP systems are generally single-channel systems that emit a user-defined signal (usually less than 40 ms in duration) that sweeps across a band of frequencies ranging between 400 and 24,000 Hz, depending on imaging goals. The received signal is compressed by correlating with the output pulse to produce a high-resolution sub-bottom profile. Because the energy of the source is spread over the sweep duration in a controlled manner, CHIRPs sources are not considered impulsive like boomers, sparkers, and airguns. Additionally, the transducer configuration of CHIRP sonars produces a beampattern, with the main lobe pointing directly downward.

The parametric SBP is a dual-frequency sub-bottom profiler. They can be mounted over the side of a vessel or at the vessel's hull, towed, or used on ROV/AUV systems. The instrument can simultaneously transmit two signals of slightly different high frequencies (called primary frequencies) (Westervelt 1963), and the interaction generates two new signals: a difference and a sum frequency (e.g., primary frequencies of 100 and 110 kHz yield a difference frequency of 10 kHz and a sum frequency of 210 kHz). The difference and sum frequencies typically have levels reduced from the original primary frequencies by 30–40 dB and 6–12 dB, respectively (Wunderlich 2021), and the summed frequency and harmonics rapidly attenuate due to absorption of high frequencies.

Penetration depth of the generated difference frequency depends highly on the bottom sediments. For soft, muddy sediments, penetration can be up to 50 m. The systems generate short signal lengths (often ~0.07 ms) and very restricted beamwidths (e.g., ± 1.8° at 4–15 kHz), enabling high horizontal and very high vertical resolution (< 10 cm) (Wunderlich and Müller 2003).

Table 5. SBP sound level examples

Model	Power	Pulse Duration setting (ms)	Bandwidth setting (kHz)	Lpk Source Level (dB re 1 µPa·m)	SPL Source Level (dB re 1 µPa·m)	SEL Source Level (dB re 1µPa^{2}s·m^2)	Pulse Duration (measured) (ms)	Bandwidth (measured) (kHz)
EdgeTech 424	100%	10	4–24	173	167	142	3.5	9.2–13.1
EdgeTech 424	50%	10	4–24	177	171	146	3.3	9.1–13.7
EdgeTech 424	100%	5	4–24	182	177	149	1.6	8.6–14.1
EdgeTech 424	100%	10	4–24	182	176	152	3.4	9.0–13.7
EdgeTech 424	100%	10	4–16	186	180	156	3.7	8.0–11.1
EdgeTech 512i	50%	30	0.5–7.2	176	171	151	11.6	3.3–4.8
EdgeTech 512i	100%	5	1.0–10.0	182	178	151	2.0	4.0–7.7
EdgeTech 512i	100%	20	0.5–7.0	186	178	159	14.6	1.8–6.0
EdgeTech 512i	100%	20	0.7–12.0	183	179	158	9.0	5.2–8.6
EdgeTech 512i	100%	100	0.5–2.2	181	175	160	35.7	1.4–1.8
Knudsen 3202 (single transducer)	1	8	—	204	199	177	5.8	3.3–5.6
Knudsen 3202 (single transducer)	4	1	—	212	208	177	0.8	0.0–8.7
Knudsen 3202 (single transducer)	4	8	—	211	207	184	5.4	3.4–5.7
Knudsen 3202 (single transducer)	4	32	—	211	207	190	22.2	3.5–5.5
Knudsen 3260	—	64	3.5, 12	—	199–232	—	—	—

Notes: Lpk = peak sound pressure level; SPL = root-mean-square sound pressure level; SEL = sound exposure level
Specifications for towed and hull-mounted SBPs. All data from acoustic test facility experiments by Crocker and Fratantonio (2016) except EdgeTech SB-216S. SB-216S measurements from field tests by Chorney et al. (2011) with minimum slant range measurements of 46 m. Knudsen 3260 specifications reported in Ruppel et al. (2022).
Other example brands and models: EdgeTech 216 sub-bottom profiler, EdgeTech 3200 sub-bottom profiler, EdgeTech 3100 SB-216S sub-bottom profiler, EdgeTech SB-216S sub-bottom profiler

Table 6. Parametric SBP sound level examples

Parametric SBP Model	SPL Source Level (dB re 1 µPa·m)	Intended Deployment	Pulse Duration (ms)	Ping Rate (pings/s)	Transmit Beam Width	Primary Frequency (kHz)	Secondary Frequency (kHz)
TOPAS PS 18	208	Vessel hull, near surface	20	1	Approx. 4.5° x 4.5°	15–21	0.5–6.0
Innomar SES-2000	> 240	ROV, ~2,000 m depth	0.07–1.5	40	Approx. ± 2°	85–115	4–22

Notes: SPL = root-mean-square sound pressure level
Sources: Data for TOPAS PS 18 are from Kongsberg Geoacoustics Ltd (2019); data for Innomar SES-2000 (first generation of the Innomar “standard-rov” SBP) are from Innomar Technologie GmbH (2022).

4.5 Acoustic Corers

An acoustic corer is a stationary acoustic source deployed on a tripod on the seafloor; it has an arm (12-m diameter) that rotates to cover a full circle. An acoustic corer unit has two sonar heads (one low and one high frequency), as well as a parametric sub-bottom profiling system. Acoustic corers are used to detect shallow (15–40 m) subsea hazards such as boulders, cavities, and abandoned infrastructure by generating a 3D “acoustic core” to full penetration depth. Because the sources are so close to the seabed (typically within 5 m) and the sounds are directed downward, little lateral propagation is expected. Essentially, this is a specialized type of CHIRP sonar; see descriptions of CHIRP sonars for further details.

Sounds from acoustic corers are considered narrowband, directional, and non-impulsive.

Table 7. Acoustic corer sound level examples

Model	SPL Source Level (dB re 1 µPa·m)	Beamwidth (degrees)	Pulse Duration (ms)	Operating Frequency (kHz)
PanGeo Subsea Acoustic Corer Low Frequency CHIRP Neptune 4108 A/B Transducer	177.5	73	4.5	2–6.5
PanGeo Subsea Acoustic Corer High Frequency CHIRP Neptune 4108 C/D Transducer	177.5	73	4.5	4.5–12.5
PanGeo Subsea Acoustic Corer Parametric Sonar	239	3.5	0.25	90–115

Notes: SPL = root-mean-square sound pressure level
Source: 84 Federal Register 66156

4.6 Multi-beam Echo Sounders (MBESs)

Alternative name: swath bathymetry

Echo-sounding equipment is used to calculate water depth or to distinguish marine biota beneath the transducer. Echo sounders work by emitting a short pulse of sound into the water column and then receiving, processing, and returning sound pulses reflected from the seafloor and objects in the water column. If the speed of sound in sea water is known, the device can calculate water depth by multiplying the speed of sound by half the time from transmit of a pulse to receipt of an echo. Many echo sounders also utilize data from sensors that detect salinity, temperature, and conductivity—measurements that are used to calculate the speed of sound throughout the water column and can allow survey personnel to determine more accurately water depths from the acoustic returns. Modern echo sounders emit either a continuous-wave or swept frequency (frequency-modulated or chirp) pulse.

MBES systems transmit a sound pulse at a particular frequency in a fan shape that is narrow along the track of the vessel and wide orthogonal to the vessel track. Modern lower-frequency MBES systems (< 100 kHz) may use multiple transmit pulses (up to 16 per ping) across the swath to minimize the influence of the vessel movements on the results. MBES systems electronically form multiple received beams across the swath to detect returns from this transmit fan pulse and calculate a single travel time (and thus depth) to the seafloor within each receive beam. Depending on the system, up to 1,024 receive beams can be electronically formed for each transmit pulse, from which potentially 1,024 soundings can be calculated. Therefore, one pass of the survey vessel ensonifies multiple swaths of the seafloor along the vessel track, from which water depths can be determined. Thus, subsequent and contiguous swaths ensonified by a moving vessel can survey a larger area in a shorter time and with fewer track lines than is possible using a single-beam echosounder system. The width of the swath depends on the angular extent of the outgoing sound pulse, multi-beam operating frequency, and water depth. MBES systems that operate at low frequencies (e.g., 12 kHz) are used to survey at depths up to 10,000 m, while others operating at high frequencies (e.g., > 300 kHz) are used to survey at depths as shallow as 10 m or less.

These systems can be either pole mounted or permanently mounted in the hull of a ship. Generally, systems < 100 kHz are permanent installations due to the size of the transmit and receive elements, while higher frequency (> 100 kHz) systems are small enough to be mounted on a pole for ease of installation on multiple vessels.

Table 8. Multi-beam echo sounder sound level examples

Model	Power Setting/ Source Level	Pulse Duration Setting (ms)	Transmission Frequency (kHz)	Along-track Beam Width	Across-track Beamwidth (down 3 dB)	Lpk Source Level (dB re 1 µPa·m)	SPL Source Level (dB re 1 µPa·m)	SEL Source Level (dB re 1 µPa²s·m²)	Pulse Duration (measured) (ms)
Reson Seabat 7111	230 dB	0.17	100	1.5°	~160°	228	224	185	0.15
Reson Seabat 7111	230 dB	0.17	100	6.0°	~160°	215	211	173	0.15
Reson Seabat 7111	230 dB	3.0	100	1.5°	~160°	227	223	179	2.68
Reson Seabat 7111	200 dB	0.17	100	1.5°	~160°	200	196	158	0.16
Konigsberg EM 122	210 dB	2–15	12	0.5°–2°	140°	–	–	–	–

Notes: Lpk = peak sound pressure level; SPL = root-mean-square sound pressure level; SEL = sound exposure level
Source: Crocker and Fratantonio (2016), Kongsberg Maritime AS (2011)
Other example brands and models: Reson Seabat 7160, Reson Seabat T20-P, R2Sonic 2024, Kongsberg EM 2040, Kongsberg EM 302, Kongsberg EM 304, Kongsberg EM 122/124, Kongsberg EM 712, Kongsberg EM 2040

4.7 Side-scan Sonars

Alternative name: backscatter

Side-scan sonar technology generates an image of seabed morphology, submerged objects, and other features present on the seafloor or in the water column. Due to their high operating frequencies, they do not penetrate far into the bottom and so are used to examine the surface of the seabed. Side-scan sonars transmit sound pulses in a beam that is narrow in the direction along the ships track and wide orthogonal to the ships track. Each fan-shaped pulse ensonifies the seafloor in a swath across the survey vessel trackline. The sound pulses are reflected off the seafloor and by objects lying on the seafloor. Changes in backscatter intensity generally result from changes in sediment composition and texture, presence of hardbottom/ledges, archaeological resources/shipwrecks, debris, etc. As the vessel moves forward, an image of the seafloor and the relative size and location of objects on the seafloor either side of the vessel is viewed on a graphical display.

Because these types of sonars are used to detect relatively small objects, they operate at higher frequencies (100–1,500 kHz). As the name suggests, the geometry of side-scan sonar is set up to best sample the sides, so measurements directly under the systems tend to have low resolution, and data from that portion of the swath sometimes is not used. Those areas are captured by overlapping adjacent tracks. Additionally, the height above the ocean floor is critical to how the fan ensonifies the bottom. Often, in deeper waters, towed sonar "fish" are used to lower the system into the water column to the desired height off the bottom. Side-scan sonars often are used in conjunction with other equipment (e.g., split-beam echosounder) to locate objects away from the vessel track requiring further identification.

Table 9. Side-scan sonar sound level examples

Model	Power Setting (%)	Transmission Frequency Setting (kHz)	Pulse Duration Setting (ms)	Range (m)	Lpk Source Level (dB re 1 µPa-m)	SPL Source Level (dB re 1 µPa·m)	SEL Source Level (dB re 1 µPa2s·m^2)	Pulse Duration (measured) (ms)	Beamwidth
EdgeTech 4200	100	400	–	400	210	205	176	1.3	2.6°
EdgeTech 4200	100	400	–	50	210	205	176	1.1	1.9°
EdgeTech 4200	100	100	–	50	206	201	171	1.1	1.6°
EdgeTech 4200	50	100	–	50	200	195	1,665	1.1	1.9°
Klein 3000	–	445	0.1	100	227	223	182	0.088	1.2°
Klein 3000	–	132	0.4	600	224	219	184	0.343	1.8°
Klein 3000	–	132	0.1	100	224	220	179	0.081	2.1°
Klein 3000	–	132	0.05	100	224	220	176	0.042	2.2°

Notes: Lpk = peak sound pressure level; SPL = root-mean-square sound pressure level; SEL = sound exposure level
Source: Crocker and Fratantonio (2016)
Other example brands and models: Klein 3900

5 Oceanographic Acoustic Instruments

Oceanographic acoustic instrumentation refers to devices designed specifically to sense features of the water column.

5.1 Split-beam and Single-beam Echosounders

Alternative names: scientific echo sounders, fish finders, fathometers (simple single-beam systems used primarily for ship safety)

The acronym SBES may be used for either single-beam or split-beam echosounders. Although the return signal is processed differently, these two types of echosounders are functionally similar in terms of the sound emitted into the water column (Ruppel et al. 2022).

Single-beam echosounders transmit a sound pulse aimed vertically below the vessel to calculate the distance to the seafloor directly beneath the ship. They provide information on just one dimension (depth), so they cannot be used to precisely locate a target within the water column. Typically, higher operating frequencies are used for shallow depths, and lower frequencies are used for greater depths. For example, an echosounder operating at 200 kHz would be used in shallow (< 100 m) water, and an echosounder operating at 12 kHz would be used in very deep water (> 6,000 m). If a high level of detail about seafloor depths is needed, a survey vessel must complete many closely spaced track lines because depth is only calculated directly beneath the ship.

Split-beam echosounders can locate a target in three dimensions and are used to measure backscatter intensities returned from objects in the water column, such as differing water density layers, fish schools, or other flora and fauna. These instruments transmit sound energy in a cone-shaped beam, but because they use separate receivers (hence the name "split-beam"), the difference in phase of the return signal on each receiver can be used to calculate the location of the target. They are usually mounted on or within a ship's hull. The Simrad EK80 can emit many frequencies simultaneously. Typical shipboard installations utilize transducers operating at 18, 38, 70, 120, or 200 kHz.

Table 10. Split-beam and single-beam echosounder sound level examples

Model	Power Setting	Transmission Frequency (kHz)	Lpk Source Level (dB re 1 μPa·m)	SPL Source Level (dB re 1 μPa·m)	SEL Source Level (dB re 1 $\mu Pa^2 s \cdot m^2$)	Pulse Duration (ms)	Beamwidth (degrees)
Simrad EK80	100%	10–500 kHz	–	212	–	8	~7–16
Simrad EK80	100%	–	–	229	–	–	~7–16
Generalized SBES	–	12–200	–	223-231	–	0.06–16	–
Teledyne Odom Echotrac CV100	12	200	195	192	149	0.045	7
Echotrac CV100	12	200	196	193	156	0.181	7
Echotrac CV100	12	200	180	175	145	1.133	7
Echotrac CV100	8	200	191	187	153	0.356	7
Echotrac CV100	4	200	179	176	133	0.046	7

Notes: SPL = root-mean-square sound pressure level
Source: Crocker and Fratantonio (2016), Jiménez-Arranz et al. (2020), Kongsberg Maritime AS (2022)
Other example brands and models: Simrad EK60, Teledyne Odom Echotrac MK III, Garmin ECHOMAP UHD 63cv Fish Finder/Chartplotter Combo, Furano FCV587 Fish Finder

Further reading

- Kongsberg. Scientific echo sounders and current profilers (ADCP). https://www.kongsberg.com/maritime/products/mapping-systems/fishery-research/scientific-echo-sounders/

5.2 Acoustic Doppler Current Profilers (ADCPs)

An ADCP is a hydroacoustic current meter, similar to a sonar, for measuring water current velocities over a depth range using the Doppler effect of sound waves scattered back from particles within the water column. These systems can be statically mounted anywhere throughout the water column or deployed on research vessels. The working frequencies of static ADCPs range from 38 kHz to several megahertz. The Teledyne Marine Ocean Surveyor works at 38, 75, or 150 kHz. Research vessels may run one or more ADCP, commonly at frequencies of 38, 75, and/or 150 kHz. These systems are highly directional and are generally configured to project their beams downward (for hull-mounted configurations) to monitor the water column. They operate by observing the backscatter from particles suspended throughout the water column. ADCPs are sometimes mounted on conductivity, temperature, and depth (CTD) carousels; moorings; and ROVs, AUVs, or human-operated vehicles.

Table 11. ADCP sound level examples

SPL Source Level (dB re 1 µPa·m)	Max Pulse Duration	Dominant Frequency (kHz)	Broad or Narrowband	Omnidirectional or Directional	System
211–227	37 ms	38–300	Narrowband	Directional	Teledyne, various models*

Notes: SPL = root-mean-square sound pressure level
*Range of source levels given to represent several models from Teledyne instruments.
Source: Teledyne Marine (2020)
Other example brands and models: RDI OS-38, RDI OS-75, RDI OS-150, RDI WM-300, RDI WM-600, RDI WM-1200

5.3 Acoustic Doppler Velocimeters

Alternative names: Doppler velocity log

Similar to an ADCP, an acoustic Doppler velocimeter measures the instantaneous velocity of a moving object, like a ship or an AUV, by using the Doppler effect (Zhang et al. 2001). It sends out a short acoustic pulse that travels through the focus point for the receiver beams, and the echo is recorded in each of the acoustic receivers. To obtain the velocity vector, the echo is processed to find the Doppler shift, and the scaling is adjusted with the measured speed of sound in the liquid. In addition to continuous sampling, the velocimeter also supports burst sampling, where data are sampled rapidly for a short period of time before the system "sleeps" to preserve battery power and recorder memory.

Table 12. Acoustic Doppler velocimeter sound level example

SPL Source Level (dB re 1 µPa·m)	Dominant Frequency (kHz)	Broad or Narrowband	Omnidirectional or Directional	Impulsive or Non-impulsive	Continuous or Intermittent
182–187	250–350	Narrow	Directional	Non-impulsive	Intermittent; 2/second

Notes: SPL = root-mean-square sound pressure level
Source: Chorney et al. (2011) for the Kongsberg HUGIN 1000 AUV Doppler Velocity Log
Other example brands and models: Nortek Vector, SonTek 1997

5.4 Phase Differencing Bathymetric Sonars (PDBSs)

Alternative names: interferometric swath bathymetry systems, interferometers

PDBSs utilize two transducers mounted athwartship on an outward-facing frame facing down towards the seafloor to transmit and receive acoustic pulses. The process of interferometric bathymetry can be applied to data from both MBES and side-scan sonar, but this section focuses on PDBS-specific systems. These systems ensonify a swath of the seafloor, which is narrow along the vessel track, and wide orthogonal to the vessel trackline in a manner similar to a side-scan sonar and MBESs. In contrast with MBESs, PDBS systems measure the depth and angle of a target based on the phase difference of acoustic returns received on two outward-facing transducers. Because they are not limited in beam observation angle, PDBSs can cover wider swaths in shallow water than MBESs (Sewada et al. 2018). Effectively, these systems use the phase discrimination method to measure depths across a swath, whereas MBESs electronically form received beams to measure depths. Acoustic backscatter from these sonars is used as a substitute for side-scan sonar data. Transmission frequencies of PDBSs in use today are generally greater than 100 kHz.

Table 13. Phase differencing bathymetric sonar systems sound level examples

Model	Power Setting (%)	Pulse Duration Setting (ms)	Lpk Source Level (dB re 1 µPa·m)	SPL Source Level (dB re 1 µPa·m)	SEL Source Level (dB re 1 $\mu Pa^2 \cdot s \cdot m^2$)	Pulse Duration Measured (ms)	Beamwidth
Bathyswath SWATHplus-M	100	0.09	216	207	163	0.032	1.2 ± 0.2°
Bathyswath SWATHplus-M	100	0.215	223	218	180	0.183	1.2 ± 0.2°
Bathyswath SWATHplus-M	100	2.15	207	202	175	1.845	1.2 ± 0.2°
Bathyswath SWATHplus-M	30	0.215	215	209	172	0.192	1.2 ± 0.2°

Notes: Lpk = peak sound pressure level; SPL = root-mean-square sound pressure level; SEL = sound exposure level
Source: Crocker and Fratantonio (2016)
Other example brands and models: Bathyswath-2, Kongsberg Geoswath 4, Edgetech 6205 PDBS

5.5 Synthetic Aperture Sonars (SASs)

SAS is essentially a way of processing a series of side-scan sonar, MBES, and/or interferometric data as if they were coming from a long array of sensors instead of the same device at different times. The resolution of a standard sonar array is based on the ratio of the wavelength of the source pulse to the length of the array. For example, a ratio of 1:60 (i.e., the array is 60 wavelengths long) means that 1-m resolution on the seabed is discernable at 60-m distance. Increasing the array length also increases the achievable resolution. With SAS, resolution parallel to the direction of track becomes range independent, because the farther a target is, the more pings sample it, lengthening its measuring synthetic “array.” This method can have a huge advantage over standard side-scan sonar near maximum ranges.

These systems emit multiple transmit pulses for each ping and processes the acoustic returning signal to "synthetically" increase the array length and bandwidth, thus increasing the swath coverage and resolution. Frequencies can range from 50–400 kHz. Although these instruments can and have been mounted on hulls, most modern applications are built for deployment on autonomous vehicles or towed bodies, which provide stability and depth control.

Table 14. Synthetic aperture sonar sound level examples

System	SPL Source Level (dB re 1 µPa·m)	Dominant Frequency (kHz)	Pulse Duration (ms)	Maximum Operation Depth (m)	Reference
Kraken AquaPix MINAS	210	337	Adjustable 1–10	6,000	Kraken Sonar Systems Inc (2022)
SL Hydrospheric SLH ProSAS-60	220	52.5–67.5	Selectable 5–50	6,000	SL Hydrospheric LLC (2013)

Notes: SPL = root-mean-square sound pressure level
Other example brands and models: AST ProSAS60, Kongsberg HISAS 1030

Further reading

- Hansen RE. 2023. *Synthetic Aperture Sonar Technology Review*. Marine Technology Society Journal. 47(5): 117–127

5.6 Sector Scan Sonars

Alternative names: 3D sonars, rotary side-scan sonars

Sector scan sonars utilize side-scan sonar technology to image up to a 360-degree field of view. They may be used for ROV obstacle avoidance, target detection and recognition, navigation, site inspection, search and recovery, and surveillance. They typically are very high frequency and able to achieve very high-resolution imagery of areas and objects in their immediate vicinity.

For example, 3D sonars typically use frequencies of 400–800 kHz or higher and can operate in water depth to ranges of 91–183 m. Their beams can be very narrow (1.5–3.0 degrees), and their projection fan is similar to an MBES or a side-scan sonar. They may be deployed from ROVs or mounted above the seafloor.

A rotary side-scan sonar provides a continuous record of the evolution of the seabed field through time. It is effectively a scientific sonar used to observe phenomena like the movement of sediment ripples over time (Traykovski 2007). They are deployed on fixed-position mounts with a rotating arm several meters above the seabed, providing a circular image of the seafloor. These systems typically are mounted very close to the seafloor (1–10 m), and source levels are much lower than their towed relatives (Jones and Traykovski 2018).

Table 15. Sector scan sonar sound level example

System	Operating Frequency (kHz)	Pulse Duration (ms)	Beamwidth	Reference
Furuno CH37BB	60, 113, 162	Adjustable 0.2–10.6	6° increments up to 225°	Furuno (2022)

Other example brands and models: Kongsberg Marine 1071 and 1171 High Resolution and Domed Sonar Heads, Teledyne Marine 3D BlueView

5.7 Pressure Inverted Echo Sounders (PIESs)

Alternative names: inverted echo sounders, current- and pressure-recording inverted echo sounder (CPIES)

PIESs are oceanographic instruments that are utilized for subsidence monitoring or to measure the speed of sound in the water column. They transmit an acoustic pulse (typically once or twice an hour) that is reflected off the sea surface and detect the pulse on the seabed to measure two-way travel time through the water column. They simultaneously measure pressure at the seabed. Pressure measurements are converted to depth to find the acoustic distance traveled from the seabed to the surface and back again. By combining depth and travel time, the average sound speed in the water column can be calculated.

Some PIESs are designed to be free-fall deployed, but ROV deployments are also feasible. PIESs log data at programable intervals for a period of time and can be deployed for months or even several years, depending on battery life. They operate in water depths up to 6,000 m and are recovered via an ROV or acoustic release for retrieval at the sea surface.

PIESs are narrowband, intermittent sources.

Table 16. Pressure inverted echo sounder sound level examples

System	SPL Source Level (dB re 1 µPa·m)	Receiver Sensitivity (dB re 1 µPa)	Dominant Frequency (kHz)	Pulse Duration (ms)	Pings/Hour	Maximum Functionality Depth (m)	Reference
URI IES Model 6.2C	170–197	–	12	6	24	6,700	University of Rhode Island (2022)
Sonardyne PIES	190–202	80–120	14–20	–	Adjustable < 1–60	5,000	Sonardyne (2022)

Notes: SPL = root-mean-square sound pressure level

Further reading

- University of Rhode Island. Inverted echo sounders (IES/PIES/CPIES). http://www.po.gso.uri.edu/dynamics/IES/index.html

5.8 Expendable Sound Velocimeters (XSVs)

These systems are used to determine the speed of sound in the water column. A probe is dropped into the water; as it descends, it records the velocity of sound in the water with very high precision (within 0.25 m/s). XSVs typically allow a water sample to pass through them as they descend. Water continuously passes between a source and receiver plate at a known distance, and the sound speed is measured directly by timing the transit times (Lockheed Martin 2013).

Example brands and models include the Lockheed Martin XBT/XSV.

6 Communication/Tracking Acoustic Sources

6.1 Acoustic Locators

Alternative name: pingers (differs from "pinger" under the acoustic deterrent section)

This section focuses only on acoustic locators, not deterrence devices. Pingers can be attached to a range of objects used for ocean research or for industrial applications. They transmit a short signal that is received on the ship's transceiver and is used to locate the item with the pinger. For example, they may be used to find gear that was deployed on the seafloor, or to determine the depth of an instrument that was deployed on a wireline in the water column. Pingers are often relatively low powered (SPL source levels typically < 190 dB re 1 μPa·m) and typically operate at frequencies from 10–50 kHz (Ruppel et al. 2022).

Table 17. Acoustic locator sound level example

System	Transmission Frequency (kHz)	SPL Source Level (dB re 1 μPa·m)	Pulse Duration (ms)	Reference
Edgetech CAT	9.3–10.7	192	22	EdgeTech (2022)

Notes: SPL = root-mean-square sound pressure level
Other example brands and models: Benthos UAT-376

6.2 Acoustic Transponders

Acoustic transponders are widely used in oceanographic research and commercial applications to verify the health (e.g., battery life) of an instrument, release equipment from the seafloor, or navigate in three dimensions below the ocean's surface.

Acoustic releases are used to recover instrumentation from the seafloor (e.g., seafloor moorings, landers, ocean bottom seismometers, ocean bottom nodes). An acoustic release is usually a passive listening device, but it can be probed from the command unit to respond, providing information on elevation angle, range, and whether the release has been triggered. These signals are only generated when requested by the command unit operator, usually right after deployment and to initiate retrieval. Signals are generally short in duration and are typically in the 5–15 kHz frequency range. They are non-impulsive, intermittent signals.

Table 18. Acoustic transponder sound level example

Vessel	Transmission Frequency (kHz)	Pulse Frequency (s)	SPL Source Level (dB re 1 μPa·m)	Reference
AUV (Kongsberg HUGIN 1000)	21.5 and 22.5	30	199.9	Chorney et al. (2011)

Notes: SPL = root-mean-square sound pressure level
Other example brands and models: Edgetech 8242XS Acoustic Release, Sonardyne 7410

6.3 Underwater Navigational Signals

Several types of low-power instruments can be used for short-range communication to assist in underwater navigation and communication between instruments. These instruments can be integrated into other equipment types (such as AUVs) and can help transmit information to other underwater instruments.

A transceiver produces the initial signal, and the responder replies with its own acoustic pulse. Ultra-Short-BaseLine (USBL) acoustic positioning systems have several transducers separated by a fixed distance called the “baseline;” phase differencing between these transducers is used to calculate the direction to the subsea transponder. These signals are non-impulsive and intermittent.

Table 19. Underwater navigational signal sound level examples

Model	Frequency Range (kHz)	SPL Source Level (dB re 1 µPa·m)	Beam Pattern	Omnidirectional or Directional	Reference
Applied Acoustics Fatboy Beacons 1160 Series	21–31	206	± 15°	Directional	Applied Acoustics Inc. (2022)
Blue Robotics Water Linked M64 Acoustic Modem	100–200	Not provided, but maximum range is 200 m	–	Omnidirectional	Blue Robotics Inc. (2022)
Edgetech 4380	21–28	187–192	± 90°	Omnidirectional	EdgeTech (2014)
Edgetech 4380	21–28	192–197	± 30°	Directional	EdgeTech (2014)
Sonardyne Compatt 6 8300-3111 (USBL)	19–34 kHz	187–196	–	Omnidirectional	Jiménez-Arranz et al. (2020)

Notes: SPL = root-mean-square sound pressure level
Other example brands and models: Easytrak M-USBL 2671

7 Geotechnical Survey Methods

Geotechnical surveys are conducted to determine the physical and mechanical properties of sediments and the stratigraphy or structure of the sediment layers. These surveys typically rely on either on-site measurements of these physical properties (e.g., via cone penetrometer tests [CPTs] or similar tests) or the acquisitions of actual specimens (e.g., via bottom grabs, coring, or drilling), which can then be tested in the laboratory. There are some systems that generate and use acoustic signals to acquire this data (e.g., acoustic corers); however, with many of these methods, noise is produced as an unintended by-product of the mechanical process of acquiring the sample. Generally, the noise produced is low level and low frequency (< 2,000 Hz).

The spatial scale of geotechnical surveys varies by program. For example, a typical vibracore survey for the Marine Minerals Program would obtain 10–15 cores per day in an area measuring 1 square mile. For site characterization of offshore wind farms, one geotechnical (vibracore, CPT, and/or deep boring) sample may be taken at each potential turbine location, usually at the rate of one sample per day. In addition, geotechnical samples would be taken intermittently along the potential cable route to shore. For oil and gas purposes, geophysical surveys may identify shallow anomalies worthy of geotechnical sampling to identify pipeline routes or the location of other types of bottom-founded infrastructure.

7.1 Vibracores

Alternative name: vibracoring

Vibracores obtain shallow samples of unconsolidated sediment and may, in some cases, also be used to gather information to inform the archaeological interpretation of features identified through a high-resolution geophysical (HRG) survey. They typically are not used in waters greater than a few hundred meters. Vibracore samplers typically consist of a core barrel and an oscillating driving mechanism that forces the core barrel into the sediment; the bottom end contains a cutting bit. To penetrate seafloor sediments, the core barrel is vibrated by a pneumatic or electric vibrahead, causing local liquefaction of sediment along the core barrel surface. For pneumatic vibracore units, an air compressor on the deck of the vessel delivers compressed air that is necessary to drive the vibrahead.

After the core barrel has been driven to its full length, it is retracted from the sediment and returned to the deck of the vessel with a sample in the tube. Each core typically takes approximately 5–10 minutes to complete; then, the vessel relocates and deploys the equipment again. Although the sounds produced may be considered “continuous” while vibracore operations are underway, the total operation introduces sound to the water intermittently.

For BOEM’s Marine Minerals and Renewable Energy Programs, cores up to 6 m long with 8-cm diameters are typically obtained, although some devices have been modified to obtain samples up to 12 m long. Sediment samples of 1.5 to 6 m are also acquired to determine sediment characteristics and sand resource thickness (BOEM 2019). For BOEM’s Oil and Gas Leasing Program, cores up to 15 m long can be obtained (BOEM 2017). For research, various systems are used.

Chorney et al. (2011) measured underwater sounds from a pneumatic vibracore deployed off the *R/V Ocean Pioneer* and back-calculated the SPL source level to be 187.4 dB re 1 µPa·m. Though there were some narrow peaks between 80–400 Hz, spectral levels were fairly constant up to 3 kHz, where they began to drop off. Vessels may be dynamically positioned during vibracoring, which also adds underwater noise to the marine environment from thruster use. Other times, vessels are live-boated during operations.

Table 20. Vibracore sound level example

SPL Source Level (dB re 1 µPa·m)	Dominant Frequency (Hz)	Broad or Narrowband	Omnidirectional or Directional	Impulsive or Non-impulsive	Continuous or Intermittent
187.4	80–3,000	Broad	Omnidirectional	Non-impulsive	Intermittent; 20 pulses per second

Notes: SPL = root-mean-square sound pressure level
Source: Chorney et al. (2011)
Other example brands and models: NAVCO AVS80PV bin hopper pneumatic piston vibrator, NAVCO BH-8 pneumatic vibrator, 271B Alpine pneumatic vibracore, SEAS VC-700 vibracore system

7.2 Jet Probes

Jet probes usually are used to support other data collection methods, such as vibracoring or sub-bottom profiling, but are limited to shallow waters (typically < 30m) (BOEM 2017). They acquire indirect physical information on subsurface lithology by surveying the thickness and composition of the sediment layer. A jet probe is a rigid stainless-steel tube connected to a high-pressure cylinder, which pushes water through the tube to penetrate the loose bottom sediments. There are no known measurements of underwater sounds produced by jet probes, but sound levels are predicted to be low, because there is no cutterhead or bit and because they are powered by a water pump.

Example brands and modes include the AquaSurvey EM-Tipped jet probe.

7.3 Bottom Grab Samplers

Bottom grab samplers typically use clamshell-like scoops to collect samples of sediments and benthic biota from the topmost layers of the seabed. The grab is lowered to the seabed and is activated automatically when it hits the substrate or is activated by remote control. The shells swivel together in a cutting action to remove a section of the seabed. In soft-bottom areas, an Ekman or Van Veen bottom grab sampler is ideal. For hardbottom areas, a heavier Ponar grab sampler is required because the tapered edges can cut a deeper bite from the sediment, and a box corer may be required in very hard sediments. When more delicate benthic biota need to be sampled, a slurp hose may be used to gently suction the organisms off the seafloor into a clear plastic container to bring back to the ship. One grab sample takes about 5–15 minutes to obtain, but the time depends on the depth of the water at the sample site (BOEM 2019).

To our knowledge, sound levels from bottom grab samplers have not been measured. However, considering their relatively small size, we expect them to produce low-level mechanical noise (likely < 2 kHz) for very short periods of time during use. Short-duration sounds may also be produced when the sampler makes contact with the seabed and when the springs close.

Example brands and models include the following: Wildco Ponar bottom grab sampler, Rickly Ekman bottom grab sampler, VanVeen bottom grab sampler, and slurp samplers (or slurp hose/suction sampler).

7.4 Deep Borings

Alternative names: deep core samples, geologic borings

Deep borings are used to sample and characterize the geological properties of sediments at the maximum expected depths of the structure foundations. This work is usually conducted after geophysical data has been analyzed. For offshore wind site characterization, deep borings usually are collected in conjunction with CPTs; CPTs are best in clay, silt, sand, and consolidated sediment, while deep borings can be used with any sediment type including harder bedrock. A drill rig is used to obtain deep borings. The drill rig is typically mounted on a jack-up barge supported by four “spuds” that are lowered to the seafloor (for information about typical sound levels associated with different drilling platforms, see drilling and production section). Deep borings can generally reach depths of 30–61 m and can range from 3–20 cm in diameter. There are no known acoustic measurements of deep borings.

A variety of drilling platforms and equipment are used to obtain deep borings. They vary from ship to ship, so no “example models” are given here.

7.5 Cone Penetrometer Tests (CPTs)

Alternative names: cone penetration test, core penetration testing

CPTs are used to supplement or replace deep borings (BOEM 2017). They provide a precise stratigraphy of the sampled core but do not allow for a capture of an undisturbed soil sample, as deep borings can do. A CPT is a pointed steel pipe that is forced into the seafloor to determine near-seafloor stratigraphic profile. The top of a CPT drill probe is typically up to 8 cm in diameter, with connecting rods less than 15 cm in diameter. Penetration is achieved through a hydraulic jacking mechanism that pushes the cone into the seafloor, with maximum penetration of about 100 m. In waters less than 30 m, floating or jack-up barges typically are used; in deeper water (> 30m), the CPT can be placed on seafloor. These rigs sometimes can be remotely controlled. To examine sediment properties, a CPT may have variety of additional instruments, such as a geophone to measure shear and compressional waves, soil conductivity meter, pH meter, etc.

Sound levels from a Mini-CPT were measured from the *R/V Ocean Pioneer* while dynamic positioning (DP) thrusters were also operational (Chorney et al. 2011). The measured 1/3 octave band levels while the Mini-CPT was operational were virtually identical to periods when only the DP thrusters were in use. Therefore, the use of CPTs did not significantly increase underwater sound levels beyond contributions from the DP thrusters.

A similar finding was reported by Tetra Tech Inc. (2014); several 20-minute measurements of sound levels (in the 100–4,000 Hz range) measured approximately 0.5 mile from the source during a 5-m deep CPT showed that the CPT increased underwater sound levels very little; there was no difference in sound levels when the CPT was in the water versus on the deck, indicating that the vessel itself was the primary source of noise during operations.

Example brands and models include Fugro CPT, GeoMil CPT, and Mini-CPT.

7.6 Geotechnical Drilling

Alternative names: shallow test drilling, standard penetration testing

Shallow test wells are used to evaluate subsurface properties for potential hazards or physical structures. They are actively drilled, often using an engine, from a drilling barge, jack-up rig, or semi-submersible. “Shallow test drilling” refers to drilling into the seabed at depths less than those in a deep stratigraphic test, i.e., less than 500 feet.

Standard penetration testing is a method in which a sample tube is driven into the seabed at the bottom of a borehole; the number of blows required to penetrate the seabed provides an indication of the density of the substrate and is termed the “standard penetration resistance.”

Another type of geotechnical drilling is called standard rotary coring. Two or three tubes (core liner, holder, and drill bit) are used in conjunction to obtain cores longer than 30 m and up to several hundred meters into seafloor. They are typically powered by diesel or gas engines, using air or muds for cooling the drill bits. This method is not used very commonly.

Erbe et al. (2017) measured sounds from a jack-up rig geotechnical drilling in shallow water (7–13 m). In one location, using an 8.3 cm drill bit to penetrate 4–20 m into the seafloor (including sand, mudstone, and limestone), they back-calculated the SPL source level to be 145 dB re 1 µPa·m, with most of the energy in the 30–400 Hz range. At another site, penetrating 17 m into the seafloor (mostly sand), SPL source levels were 142 dB re 1 µPa·m.

Erbe et al. (2017) also measured sounds from a jack-up rig during standard penetration testing. They back-calculated SPL source level to be 160 dB re 1 µPa·m, with most of the energy below 3 kHz. In another instance, working in 12-m water depths, SPL source levels during standard penetration testing were estimated to be 151 dB re 1 µPa·m. In the first case, the seabed comprised sand, mud, and limestone, and in the second case, the seabed consisted of only sand and therefore produced lower source levels.

One study used a small jack-up barge in a shallow bay in the UK to collect hard rock samples via a 20-cm diameter rotary corer, as well as soft sediments using a percussion-operated corer (Willis et al. 2010). The cores ranged from 9–23 m depth. The authors use an unusual notation of acoustic units, so we do not report received levels here. Both core types had dominant energy below 100 Hz, with most energy centered around 10 Hz. Received levels measured at 7.5-m distance from hard rock coring were roughly equivalent to levels measured at 23 m from soft sediment coring (Willis et al. 2010).

A different report from Tetra Tech reports sound levels measured at 150-m distance while drilling 4.5-inch diameter bores into clay and mud (Tetra Tech Inc. 2014). The depth of the bore was not reported. SPLs varied from 95–108 dB re 1 µPa while drilling was taking place, but this is comparable to ambient noise measurements taken before drilling commenced (Tetra Tech Inc. 2014).

7.7 Other Geologic Coring

Alternative name: shallow core sampling

There are several types of mechanically operated and weighted corers used in shallow core sampling:

- *Gravity corer*: A weighted tube (like PVC) is lowered from the vessel to the seafloor using a cable/winch. This method may be used in both shallow and deep water, and maximum penetration into the mud is typically 1–3 m.
- *Piston corer*: A core barrel is lowered to the seafloor with a large weight-stand and piston setup. The piston is triggered near the seafloor, driving the core barrel, with its internal acrylic liner, into the sediment. Typical piston cores are usually 5–30 m.
- *Long corer:* This specialized piston corer is designed to obtain deeper sediment samples. The corer is typically released at a predetermined height above the seafloor to initiate a free-fall to penetrate the sediment. The long corer on the *R/V Knorr* (part of the U.S. Academic System Fleet) can obtain cores up to 45 m in length in water depths up to 4,000 m (Curry et al. 2008).
- *Multicorer*: Using a frame lowered to the seafloor, four or more short push cores are taken at the same time in separate acrylic tubes. These corers obtain high-resolution samples of near-seafloor sediments and are generally less than 1.5 m each.

These systems are gravity- or mechanically operated, and do not use active drilling technology. There are no known acoustic measurements of these geologic coring methods. However, given the shallow penetration of the cores and the overall size of these systems, sound levels are expected to be low.

A variety of equipment configurations may be used to obtain these shallow-depth samples. They vary from ship to ship and research team to research team, so no example models are provided here.

7.8 Geotechnical Drillships

Special geotechnical drillships are required when conducting geotechnical surveys in water that is too deep for jack-up rigs or semi-submersibles. These vessels may be used by the oil and gas industry or for scientific purposes to better understand climate change, geology, and the Earth’s history through the collection and study of core samples. Modern drillships use DP systems to hold them in place, compensating for surge, sway, and yaw while operating in depths up to 6,000 m. An acoustic referencing device (beacon or pinger) deployed on the seafloor and a combination of thrusters keep the ship over a specific location. The drilling, propulsion, and positioning systems can be diesel-electric powered. Occasionally, limited scope single-channel seismic surveys can confirm existing site characterization geophysical data and drill site conditions. Checkshot surveys performed during academic drilling expeditions can calibrate surface seismic surveys or develop zero offset vertical seismic profiles; these profiles are used to derive formation velocities and identify certain features, such as faults and overpressure zones.

The *JOIDES Resolution* (formerly SEDCO/BP 471) is a scientific drillship used by the International Ocean Discovery Program. Stephen et al. (2006) deployed accelerometers in and on the seafloor to obtain measurements during various *JOIDES* operations. Most of the energy from drilling was below 9 Hz. We are not aware of in-water measurements from drillships, but it is likely that near the water’s surface, sounds would be dominated by the DP thrusters, while the sound of the drillbit and rotating machinery would dominate closer to the seafloor. See **Section 8** (Drilling and Production) for sound levels related to drilling and **Section 15** (Dynamic Positioning Systems) for more information on expected sound levels from thrusters.

7.9 Continental Offshore Stratigraphic Test (COST) Wells

Alternative name: deep stratigraphic test (DST) wells

COST wells are drilled not to encounter hydrocarbons but to provide information about regional stratigraphy, ground truth interpretation of geophysical data by providing samples of rock, estimate age of sediments from collected microfossils, and evaluate potential quality of source rocks (BOEM 2017). A DST is defined in 30 CFR 251 as "drilling that involves the penetration into the sea bottom of more than 500 feet (152 meters)." Drilling is done by conventional rotary drilling equipment from a drillship or jack-up barge, depending on the water depth and sea state. See **Section 8** (Drilling and Production) for predicted sound levels.

7.10 ROV Push Corers

Push corers are used to obtain sediment cores from an ROV platform at any water depth. Typically, a T-bar on an ROV arm gently pushes acrylic tubes into the substrate. The cores collected are typically up to 1.5 m long. There are no known recordings of ROV push corers, but it is unlikely that the sounds from coring would exceed the sounds generated by the ROV.

These systems are usually custom made to fit the configuration of the ROV being deployed, so example models are not provided here.

8 Drilling and Production

A range of facilities may be used for offshore drilling and production, depending on water depth, duration of the planned activity, environmental conditions (e.g., ice cover), and other factors. In some cases, drilling is required for installment of offshore wind turbines; further information about offshore wind can be found in **Section 10** (Pile Driving).

Several components of drilling platforms may introduce sounds into the ocean, such as pumps, compressors, drill bits penetrating the seabed, DP systems, and other machinery. During production, generators, engines, exhausts, and other elements may also introduce some noise into the water, and the levels of noise produced generally depend on the platform type and degree of coupling between these mechanical sources and the structure.

This section describes the type of platforms used for drilling and production, and examples of measurements that have been made. Additional acoustic measurements and descriptions can be found in Jiménez-Arranz et al. (2020).

8.1 Fixed Platforms

Fixed platforms typically are limited to relatively shallow waters (up to 500 m) because the concrete or steel legs are anchored to the sea bottom. The platform deck contains production facilities, the drilling rig, and accommodations for the crew. They are designed for long-term use, and although the drilling rig is not a permanent part of the structure, it may be left on the platform for economic reasons. Compared to other platforms, there is little data on sounds emitted from fixed platforms. Gales (1982) measured sounds from a range of drilling platforms and found that fixed platforms produced relatively low levels of noise during both drilling and production, likely because the machinery is located well above the water line, and there is a relatively small contact area between the legs of structure and the water. For example, at 30-ft distance from one fixed platform, SPLs in the frequency range of 50–500 Hz were around 130 dB re 1 µPa (Gales 1982). Nedwell et al. (2003b) reported SPLs of 135 dB re 1 µPa at 500 m from a platform during production (while support vessels were operating nearby), and Blackwell and Greene Jr. (2003) reported SPLs of 107 dB re 1 µPa at 340 m from a different platform.

8.2 Drillships

A drillship is a type of mobile offshore drilling unit (MODU). It is a dynamically positioned floating vessel that is used to drill wells in deep water. Drilling from a drillship typically produces more noise than from an island or platform, as the machinery is contained within the hull, which is coupled to the water. Noise from drillships is also highly variable, depending on the type of equipment used, type of hole that is being drilled, and substrate composition (Richardson et al. 1995). Greene Jr. (1987) measured noise from several drillships and found that the dominant energy was typically below 600 Hz, with the prominent tones coming from the diesel-electric generators. Estimated SPL source levels (back-calculated from measurements) from an ice-strengthened "conical drilling unit" in the Arctic ranged from 175 to 191 dB re 1 µPa·1 m (Hall et al. 1994). Nedwell and Edwards (2004) measured underwater noise from a 250 m-long drillship and found dominant energy in the 100–400 Hz range, with SPL source levels estimated to be 195 dB re 1 µPa·m. There are no known measurements of production noise from drillships.

8.3 Semi-submersibles

Semi-submersibles, another type of MODU, are floating platforms that use pontoons acting as submerged floats. They may be anchored or dynamically positioned. They are accompanied by support vessels and typically operate in waters up to 10,000 ft. The machinery is mounted on decks above the surface and noise propagates through the floatation or the risers (rather than the hull, as in drillships). Greene Jr. (1986) measured sounds from a semi-submersible in the Bering Sea and found that, at 1-km distance, noise from the semi-submersible did not exceed natural levels of ambient noise. Low-frequency (10–500 Hz) SPL source levels were back-calculated to be 154 dB re 1 µPa·m. Nedwell and Edwards (2004) measured sound 100 m below a semi-submersible (at 40-m horizontal distance from the drill shaft) and found an increase (compared to background noise) of 10–20 dB in the 20–500 Hz range. They did not report SPL source levels, but spectral peaks between 100–1,000 Hz ranged from 95–125 dB re 1 μPa^2/Hz. When only the DP system was operating (no drilling), noise levels increased at frequencies 2–30 Hz. Jiménez-Arranz et al. (2019) used drifting buoys to record a variety of sounds while a semi-submersible was operating in 2,300 m of water. Closest to the MODU, there were tones at 500 Hz, 800 Hz, and 2.5 kHz; these tones were present whether or not drilling was taking place, suggesting they were produced by the DP thrusters. During drilling, the majority of acoustic energy was below 250 Hz; SPLs measured at 1 km in 1/3 octave band centered at 250 Hz were around 100 dB re 1 µPa (Jiménez-Arranz et al. 2019). There are no known measurements of production noise from semi-submersibles.

8.4 Floating, Production, Storage, and Offloading (FPSO) Facilities

When not used for drilling, FPSOs are ship-shaped vessels that are moored in place to assist with processing and storage of hydrocarbons. They can be deployed over deep-water areas and typically gather oil and gas from multiple wells through flow lines. They typically are used for smaller fields when it is not practical or cost-effective to lay pipelines. Since the processing equipment is mostly on the deck (above the waterline), most noise from processing machinery dissipates into the air. The highest sound levels are produced by the DP thrusters and during the process of docking or undocking with tankers. Erbe et al. (2013) measured noise from a range of FPSOs (238–340 m length) and found that mean SPL source levels ranged from 174 to 183 dB re 1 µPa·m.

8.5 Jack-Up Rigs

Jack-up rigs, another type of MODU, are the most common platform used for drilling. They are used in shallower waters (up to 500 ft) and have a buoyant hull and movable legs, allowing the hull to be raised or lowered to the desired water level. Independent or mat-supported legs make contact with the seabed (on large footings) or may penetrate the seabed. Gales (1982) found that noise generated by drilling from bottom-standing steel platforms was very low frequency, typically < 40 Hz. Marine Acoustics Inc. (2011) measured sounds from a jack-up rig in Cook Inlet, Alaska. They found that sounds were generated by the diesel engines, mud pumps, ventilation fans, and generators. Most of the energy for these sources was below 1,000 Hz. The highest SPLs were estimated to be 137 dB re 1 µPa·m for the 141–178 Hz frequency band.

8.6 Man-made Gravel Islands

Drilling sometimes occurs from man-made islands, especially in the Alaska region. Construction of the islands may involve a number of noise-producing activities; several of these were measured by Moulton et al. (2003) in Alaska. Noise from ice road construction, trucks driving along ice roads, ice cutting, and trenching had SPLs (in the 10–10,000 Hz frequency range) around 120 dB re 1 µPa at 100 m from the source (Moulton et al. 2003).

Early studies of underwater noise from gravel islands showed that drilling noise is low frequency (most energy below 350 Hz) and generally faded into ambient noise within about 1.5–2 km from the island (Malme and Mlawski 1979; Richardson et al. 1995). More recent work showed a peak in energy at higher frequencies (1,000 Hz); Blackwell et al. (2004) recorded airborne (microphone), waterborne (hydrophone), and iceborne (geophone) sounds near a gravel island in Alaska in winter of 2001 and 2002 of a Varco brand top-drive drill (250 rpm, 1,000 hp) powered by diesel generators. Source levels were not explicitly reported, but during drilling (not production), SPLs at 200–250 m from the source were measured to be 105–116 dB re 1 µPa. The highest overall SPLs were measured at 1,000 m (124 dB re 1 µPa), also during drilling, but not production. In general, during drilling, sound levels increased vin the 60–250 Hz and 650–1,400 Hz frequency bands, with a clear spectral peak around 1 kHz. There were also some lower-frequency tones (20–60 Hz) presumed to be associated with power generation on the island. Gallagher et al. (1992) measure SPLs (in the 20 Hz–1 kHz band) during drilling under full ice cover at 117 dB re 1 µPa at 215 m. Production noise from artificial islands is very low; Blackwell et al. (2004) measured SPLs at 97 dB dB re 1 µPa at 500 m distance.

8.7 Caissons

Boreholes called caissons (or drilled piers) are drilled into the ground or ballasted onto the bottom and then filled with concrete, sand, or gravel. Hall and Francine (1991) measured waterborne sounds under ice during drilling from a caisson and found that sound levels in the 20–1,000 Hz frequency range were 90 dB re 1 µPa (rms) at 1,370 m from the source; source levels were not calculated. Caisson drilling operations require many support vessels, particularly in the Arctic, which may contribute more acoustic energy into the environment than drilling alone.

8.8 Sounds from Drilling and Production

Table 21. Drilling sound level examples

Platform Type	SPL Source Level (dB re 1 µPa·m)	SPL Received Level (dB re 1 µPa)	Distance to Source (km)	Frequency Range of Measurements (Hz)	Dominant Frequency (Hz)	Reference
Drillship	–	137.7	0.5	20–40,000	Main energy 40–1,000	Nedwell and Edwards (2004)
Semi-submersible	155	–	–	80–4,000	–	Greene Jr. (1986)
Semi-submersible	193.3	113–128	1 km	20–4,000	Main energy < 250	Jiménez-Arranz et al. (2019)
Jack-up rig	137	–	–	–	Main energy 141–178 Hz	Marine Acoustics Inc. (2011)

Platform Type	SPL Source Level (dB re 1 µPa·m)	SPL Received Level (dB re 1 µPa)	Distance to Source (km)	Frequency Range of Measurements (Hz)	Dominant Frequency (Hz)	Reference
Ice island	–	116	0.250	–	Spectral peaks at 60–250 & 650–1,400	Blackwell et al. (2004)
Ice island	–	92	1.0	–	Spectral peaks at 60–250 & 650–1,400	Blackwell et al. (2004)
Ice island	–	124	1.0	–	Spectral peaks at 60–250 & 650–1,400	Blackwell et al. (2004)
Conical drilling unit	–	150	0.3	10–10,000	–	Hall et al. (1994)
Caisson	–	90	1.37	20–1,000	Main energy < 1,000	Hall and Francine (1991)

Notes: SPL and $L_{p,rms}$ = root-mean-square sound pressure level
See Jiménez-Arranz et al. (2020) for additional examples.

Table 22. Production sound level examples

Platform Type	SPL Source Level (dB re 1 µPa·m)	SPL Received Level (dB re 1 µPa)	Distance to Source (km)	Frequency Range of Measurements (Hz)	Dominant Frequency (Hz)	Reference
Fixed platform	195.6	129.1	0.34	10–20,000	Main energy at 80 Hz 1/3 octave band	Blackwell and Greene Jr. (2003)
FPSO	174–183	–	–	20–2,500	Main energy < 70	Erbe et al. (2013)

Notes: SPL and $L_{p,rms}$ = root-mean-square sound pressure level
See Jiménez-Arranz et al. (2020) for additional examples.

9 Dredging

Dredging is a process in which sediments are removed from the seafloor and transported to be deposited or are moved from the seafloor to a ship. This activity can take place several purposes, including increasing shipping lanes, opening new areas for construction, extracting valuable metals, remediating contaminated sediments, or renourishing beaches. BOEM’s Marine Minerals Program issues leases for the dredging of sand from Federal waters to be deposited on eroding beaches. Instead of providing example brands and models, a general description of the dredge types is provided below, followed by a brief synopsis covering what is known of dredging sounds. Additional detail on dredging and its associated sounds can be found in Jiménez-Arranz et al. (2020), McQueen et al. (2018), and Central Dredging Association (2011).

9.1 Hydraulic Dredges

Hydraulic dredges extract dredged material and water from the sea bottom onto a barge or hopper. The two most common types are cutterhead pipeline dredges and trailing suction hopper dredges.

Cutterhead pipeline dredges (also called cutter suction dredges) rarely are self-propelled and typically must be transported to and from the dredge site, where they are secured in place by special anchor pilings, called spuds. Pipeline dredge size is based on the inside diameter of the discharge pipe, which commonly ranges from 6 to 36 inches. Cutterhead pipeline dredges are capable of dredging in waters up to 30 m deep and have accurate bottom and side slope cutting capability. They require an extensive array of support equipment including pipeline (floating, shore, and submerged), boats (crew, work, survey), barges, and pipe handling equipment. Cutterhead pipeline dredges have a mechanical device (i.e., cutterhead), which is at the end of the "ladder" and has rotating blades or teeth to break up or loosen the bottom material so that it can be sucked through the dredge pipeline.

Trailing suction hopper dredges are self-propelled, ocean-going vessels with a section of their hull compartmented into one or more hoppers. Fitted with powerful pumps, the dredges suck sediment from seafloor through long intake pipes, called drag arms, and store it in the hoppers. The end of the drag arm has an opening called a draghead, which makes contact with the seafloor. A slurry of water and sediment is generated from plowing the draghead “teeth” and using high-pressure water jets and pump suction velocity. The dredged slurry is distributed within the vessel’s hopper; the solids settle out, and the water portion of the slurry is discharged from the vessel through its overflow system. When the hopper attains a full load, dredging stops, and the ship travels to a pumpout location, where the dredge hooks up to an in-water pipeline and conveys the material to a shore placement site (e.g., beach nourishment).

9.2 Mechanical Dredges

Mechanical dredges mechanically dig or gather sediment from the bottom using a bucket. They may also be called backhoe dredges, grab dredges, bucket dredges, bucket ladder dredges, or clamshells. These dredges are usually fixed via anchoring or DP systems. Material is scraped off the bottom and lifted up to the ship using a winch. Mechanical dredging is widely used in the research community to sample hard materials from the seafloor for studies of volcanic areas (e.g., mid-ocean ridges) and deep-sea minerals. These dredges may be used in offshore wind projects to reach cable-burying depths in problematic areas where simple jetting cannot be used.

An "agitation dredge" refers to a dragged device used to smooth sediment bottom irregularities left by a dredge, often referred to as a "mechanical leveling device or drag bar." Sediment-smoothing devices typically are used for dredging of navigation channels, but they can be used in association with offshore borrow areas to smooth the surface of the dredging environment and promote dredge efficiencies.

9.3 Sounds from Dredging

Dredging produces distinct sounds during each specific phase of operation: excavation, transport, and placement of dredged material (Central Dredging Association 2011; Jiménez-Arranz et al. 2020). Engines, pumps, and support vessels used throughout all phases may introduce low-level, continuous noise into the marine environment. The sounds produced during excavation vary depending on the sediment type—the denser and more consolidated the sediment is, the more force the dredger needs to impart, and the higher sound levels that are produced (Robinson et al. 2011). Hydraulic dredges (with cutterheads or drag arms in continuous contact with the seabed) produce nearly continuous sounds during the excavation process. On the other hand, sounds from mechanical dredges occur in intervals as the dredge lowers a bucket, digs, and raises the bucket with a winch. During the sediment transport phase, many factors—including the load capacity, draft, and speed of the vessel—influence the sound levels that are produced (Reine et al. 2014b). Sounds are also produced during pumpout operations when dredge plant pumps are operated (Central Dredging Association 2011). Dredging activities as a whole generally produces low-frequency sounds; most energy is below 1,000 Hz, with peaks typically occurring between 150–300 Hz (McQueen et al. 2018).

McQueen et al. (2018) summarized results from several studies that measured sounds during dredging operations. For cutterhead suction dredges, SPL source levels were 168–175 dB re 1 µPa·m (Greene Jr. 1987; Reine et al. 2012b; 2014a). Trailing suction hopper dredges were slightly louder, with SPL source levels ranging from 172–190 dB re 1 µPa·m (McQueen et al. 2018). Dickerson et al. (2001) recorded a maximum SPL of 124 dB re 1 µPa at 154 m during the moment when the grab hit the seabed; during other phases of operation (e.g., raising and lowering of grab dredge, dumping sediment on barge), the received SPL was closer to ~110–115 dB re 1 µPa at 154 m. Finally, SPL source levels during backhoe dredge operations ranged from 163–179 dB re 1 µPa·m (Nedwell et al. 2008; Reine et al. 2012a). Hydraulic dredges are generally louder than mechanical dredges, and dredging of coarser sediments usually produces more noise than softer sediments (Jiménez-Arranz et al. 2020). Additional detail and measurements of dredging sounds can be found in Jiménez-Arranz et al. (2020), McQueen et al. (2018), and Robinson et al. (2011).

Dredging noise can be either continuous or intermittent, and is typically non-impulsive and omnidirectional.

Table 23. Dredging sound level examples

Activity	SPL Source Level (dB re 1 µPa·m)	References
Cutterhead suction dredge	168–175	Greene Jr. (1987), Reine et al. (2012b), Reine et al. (2014a)
Trailing suction hopper dredge	172–190	Nedwell et al. (2008), de Jong et al. (2010)
Grab dredge	–	Dickerson et al. (2001)
Backhoe dredge	163–179	Nedwell et al. (2008), Reine et al. (2012a)

Notes: SPL = root-mean-square sound pressure level

10 Pile Driving

10.1 Impact Pile Driving

Alternative name: impact pile installation

In-water impact pile driving is used to drive piles into the substrate for offshore wind turbine and meteorological tower installation and for coastal construction. Impact pile driving employs either a diesel or hydraulic hammer to strike the pile head and force the pile into the sediment. The typical hammer strike rate is approximately 0.6 to 1.5 strikes per second. The energy output of the hammer can vary from tens to thousands of kilojoules (kJ).

Underwater noise levels generated from impact pile driving depend on many factors, including pile material (steel, concrete, timber, etc.) and size, substrate, hammer energy, and water depth. In general, impact pile driving noise has most of its acoustic energy below 2 kHz. Impact pile driving noises are characterized as impulsive, with nominal pulse duration (defined as the time window that contains 90% of pulse energy) (Madsen 2005) of about 30–50 ms (Hildebrand 2009).

Several acoustic metrics are used to characterize impact pile driving sound levels: single strike sound exposure level (SEL_{ss} or $L_{E,ss}$), peak sound pressure level (Lpk or $L_{p,pk}$), and root-mean-square sound pressure level (SPL or $L_{p,rms}$). **Table 24** shows nominal 10-m sound levels of several common pile types and sizes used in coastal construction based on a comprehensive review of several large datasets, including Caltrans 2015 summary report (Buehler et al. 2015), pile driving measurements from Navy installations (Illingworth & Rodkin Inc. 2012; 2017; Reyff et al. 2013; Tierra Data Inc. 2020), and data from the Alaska Department of Transportation (Austin et al. 2016; Denes et al. 2016) and Washington State Department of Transportation (Laughlin 2005a; 2005b; 2007; 2010; Soderberg and Laughlin 2016).

Table 24. Impact pile driving sound level examples from coastal construction projects

Pile Material	Pile Size (in)	Pile Size (m)	SEL_{ss} (dB re 1 µPa^2-s)	SPL (dB re 1 µPa)	Lpk (dB re 1 µPa)
Timber pile	12–14	0.3–0.36	156	166	176
Concrete pile	16–16.5	0.4	159	169	180
Concrete pile	24	0.61	162	173	185
Steel H pile	14	0.36	178	188	206
Steel pipe pile	24	0.61	176	187	204
Steel pipe pile	30	0.76	179	191	205
Steel pipe pile	36	0.91	181	193	208
Steel pipe pile	48	1.2	182	196	210
Steel pipe pile	96	2.4	198	209	222

Notes: SEL_{ss} = single strike sound exposure level; SPL = root-mean-square sound pressure level; Lpk = peak sound pressure level
These levels are not true "source levels," because measurements at 10 m are typical for pile driving applications.

It should be noted that in certain cases, piles could be installed at a slant angle instead of vertical (e.g., raked piles), which would influence sound levels measured in different azimuthal directions.

Offshore wind projects typically use large monopiles or jacket foundations. It is neither practical, safe, nor particularly informative to conduct measurements at a 10-m distance when driving such large piles, so there are no direct measurements comparable to those provided above for smaller construction projects. To date, many more windfarms have been constructed in Europe than in the U.S., so the U.S. has had to rely on data from European windfarms to assess pile driving sound source characteristics and noise abatement techniques. These data require extrapolation and have proved challenging to analyze, as they were not designed for assessing source levels but rather for meeting environmental compliance requirements. In most European waters, developers are required to record received levels at 750 m from the foundations; therefore, acoustic data collection has been focused at that range.

However, there are a few measurements from construction of offshore wind turbines in U.S. waters. At the Block Island Wind Farm, Amaral et al. (2018) measured sound levels at various distances during pile driving of jacket foundations (50-in pile diameter, 30-m water depth). It should be noted that the slant range of the jacket piles influenced the measurements, so caution is encouraged with interpretation. Nonetheless, the authors reported SPL received levels between 150–160 dB re 1 µPa at approximately 750 m from the piles. Two monopiles (7.8-m diameter) were installed off the coast of Virginia (27-m water depth) in 2020. Dominion Energy (2020) recorded sounds during this process; without noise mitigation, Lpk source levels were back-calculated to be 221 dB re 1 µPa·m, but with a double bubble curtain, Lpk source levels were around 212 dB re 1 µPa·m because a good portion of energy > 200 Hz was attenuated by the bubble curtain. The unmitigated SPL source level was 213 dB re 1 µPa·m; the mitigated SPL source level was 204 dB re 1 µPa·m.

In addition, BOEM commissioned a team to identify the best propagation model to use when predicting transmission loss out to the isopleths currently required by the National Marine Fisheries Service (NMFS) for marine mammals and endangered species. The team utilized the Compile II Workshop data (a compilation of numerous European pile driving measurements used to test and compare predictive pile driving propagation models) and damped cylindrical spreading algorithm (Ainslie et al. 2020). The resulting report by Heaney et al. (2020) describes the Mach cone—a conical wave produced during impact pile driving—and explains how it is handled in the analysis. Several SEL received levels measured at various ranges are available for several diameter piles included in the Compile II data, as well as corrections for sediment type, pile diameter, penetration depth, etc. The tool created by the team is titled “Damped Cylindrical Spreading Model for Offshore Steel Piles,” and is referred to as “DCSiE” for Dampened Cylindrical Spreading in Excel. It presents the range to the isopleths, as required by current NMFS guidance, after the user provides five input parameters, including an SEL and the range at which that level was measured. Both the report and the associated tool or script are available through the BOEM Office of Renewable Energy website or the BOEM ESPIS website.

Bellmann et al. (2020) provides the best comparison of sound mitigation techniques for pile driving scenarios currently available. Figure 31 on page 105 of that report plots resulting noise reduction from big bubble curtains for various air supply rates as a function of frequency. Additionally, Figure 32 on page 109 provides the noise reduction for various types and combinations of mitigation techniques and noise abatement technologies. Different designs and combinations of noise mitigating skirts and bubble curtains achieved reductions in SEL of 13–22 dB re 1 µPa^{2}s. Finally, the report also provides a detailed description and analysis of the physics of the noise generating and propagation modes for impact pile driving.

Further reading

- Martin SB, Barclay DR. 2019. Determining the dependence of marine pile driving sound levels on strike energy, pile penetration, and propagation effects using a linear mixed model based on damped cylindrical spreading. Journal of the Acoustical Society of America. 146:109–121.

10.2 Vibratory Pile Driving (Installation or Removal)

Alternative names: vibratory pile installation or extraction

Similar to impact pile driving, vibratory pile driving is a conventional method used to drive piles into the substrate for offshore and coastal construction. Instead of using an impact hammer to pound the pile into the sediment, vibratory pile driving employs a vibratory hammer that sits on the top of the pile with a series of oscillating weights that continuously exert vertical vibrations on the pile. These vibrations cause the sediment surrounding the pile to liquefy, allowing the pile to penetrate the substrate. The vibratory hammer typically oscillates at a frequency of 20–40 Hz (Matuschek and Betke 2009). Vibratory hammers may also be used to extract and remove piles by loosening them from the sediment.

Vibratory hammers operate continuously while they are in use, but the time it takes to install or remove a pile varies. For example, it could take a few minutes to install a sheet pile, while a larger steel pile could take up to 2.5 hours (Illingworth & Rodkin Inc. 2017). In general, in-water vibratory pile driving noise has most of its acoustic energy below 2 kHz. Although vibratory pile driving has been used for installation of piles as large as 22 m in diameter for bridge construction (Wang et al. 2014), there have been no cases to date where vibratory hammers were solely used to install piles for offshore wind farm construction (Tsouvalas 2020); instead, a combination of vibratory piling and impact methods typically is required to install piles to their full penetration depth (Tsouvalas 2015).

Similar to impact pile driving, underwater noise levels generated from vibratory pile driving and removal depend on pile material (steel, concrete, timber, etc.) and size, as well as substrate, hammer energy, and water depth. The California Department of Transportation (Buehler et al. 2015) provided a summary of nominal measurements of 10 m sound levels of several common types and sizes used in coastal construction (**Table 25**).

Table 25. Vibratory pile driving sound level examples

Pile Material	Pile Size (in)	Pile Size (m)	Water Depth (m)	SPL (dB re 1 μPa)
Steel H pile	12	0.3	< 5	150
AZ steel sheet pile (typical)	24	0.6	~ 15	160
AZ steel sheet pile (loudest)	24	0.6	~ 15	165
Steel pipe pile	12	0.3	< 5	155
Steel pipe pile (typical)	36	0.9	~ 5	170
Steel pipe pile (loudest)	36	0.9	~ 5	175
Steel pipe pile (loudest)	72	1.8	~ 5	180

Notes: SPL = root-mean-square sound pressure level; Lpk = peak sound pressure level
These levels are not true "source levels," because measurements at 10 m are typical for pile driving applications.
Source: Buehler et al. (2015)

10.3 Down-the-Hole (DTH) Pile Installation

Alternative names: DTH pile driving, DTH pile drilling, rock socket drilling, rock anchor drilling, DTH hammering

The use of DTH pile installation has been increasing, especially in areas with hard bedrock or where the soil overlying rock is too shallow to allow piles to terminate with sufficient resistance to lateral or tensile loads (i.e., horizontal or rotational forces acting on the piles). DTH pile installation uses a combination of percussive and drilling mechanisms, with a hammer acting directly on the rock to create a hole to settle the pile. Drill cuttings and debris from the drilling are removed by an air-lift exhaust up the inside of the pile. It is considered one of the fastest ways to drill through hard rock for pile installation and is, therefore, finding increased application in marine construction.

Noise characteristics for DTH pile driving include both impulsive and non-impulsive components. The impulsive component of the DTH pile driving is the result of a percussive hammer striking the bedrock, while the non-impulsive component is from drilling and air-lifting of cuttings and debris from the pile. Only a limited number of studies have been conducted on DTH pile driving noise, but its characteristics strongly resemble those of impact pile driving, though with a higher hammer striking rate (approximately 10–15 Hz). The dominant frequencies from DTH pile driving are below 2 kHz, similar to conventional impact and vibratory pile driving (Guan et al. 2022; Guan and Miner 2020).

Studies have also shown that there are two different mechanisms in DTH pile installation: DTH pile driving and DTH pile drilling. For DTH pile driving, the hammer strikes both the drill bits and the metal pile shoe at the base of the pile; for DTH pile drilling, there is no physical contact between the hammer and the pile, and the entire pile installation process is done by advancing the pile into the drilled hole (Guan et al. 2022). Therefore, sounds generated from DTH pile driving are more impulsive, and the sounds levels are expected to be higher than those from DTH pile drilling for comparably sized piles (Guan et al. 2022).

As with impact and vibratory pile driving, noise levels from DTH pile driving vary with pile size. Measurements of DTH pile driving to date show that single strike SELs at 10 m from the pile were 145–147 and 163–164 dB re 1 µPa^{2}s for 18- and 42-inch piles, respectively (Denes et al. 2019; Guan and Miner 2020; Reyff 2020; Reyff and Heyvaert 2019). The SPLs for the 18- and 42-inch piles were measured to be 161–162 and 178–180 dB re 1 µPa, respectively (Denes et al. 2019; Guan and Miner 2020; Reyff 2020; Reyff and Heyvaert 2019). A summary of measured sound levels from various DTH pile driving at 10 m (the distance that is often customary for pile driving) are provided in **Table 26**.

Table 26. DTH pile installation sound level examples

Pile Size (in)	SEL_{ss} (dB re 1 µPa^2-s)	SPL (dB re 1 µPa)	Lpk (dB re 1 µPa)	SEL (dB re 1 µPa^2-s)	Reference
8	144	NA	170	156	Reyff (2020); Reyff and Heyvaert (2019)
18	146	162	172	157	Guan and Miner (2020)
24	155	170	183	165	Hayvaert and Reyff (2021)
42	164	179	194	174	Denes et al. (2019); Reyff (2020); Reyff and Heyvaert (2019)

Notes: Lpk = peak sound pressure level; SPL = root-mean-square sound pressure level; SEL = sound exposure level
These levels are not true "source levels," because measurements at 10 m are typical for pile driving applications.

11 Platform Decommissioning

Decommissioning offshore platforms requires severing conductors—steel pipe-like structures of various diameters and wall thicknesses—that connect the platforms. This process generally occurs 15–25 ft below the seabed because all material above that level must be removed as part of the decommissioning process according to the regulations. Two types of conductor severance are explosive and mechanical cutting.

11.1 Explosive Conductor Severance

Explosive severance is a special subset of confined underwater explosions and a common technique for the removal of conductors as part of the decommissioning of oil platforms. The process can either involve a "bulk charge," which is a single mass of explosive material detonated at a single point, or the more effective "shaped charge." Using a shaped charge involves lining explosives around the interior wall of the conductor and directing the explosion outward, severing the conductor with less explosive material than would be required when using a bulk charge (BSEE and BOEM 2017; Twachtman Snyder & Byrd Inc. 2000).

The Bureau of Safety and Environmental Enforcement (BSEE) created an underwater calculator (UWC version 3), built on the original work in explosive removal by Dzwilewksi and Fenton (2003), and, which includes additional measured data and the latest regulatory isopleth for marine animals (mammal, sea turtles, and fish) based on NMFS acoustic guidance thresholds. Version 2 of the UWC was reviewed by an external Center for Independent Expertise (Ainslie 2016). BSEE has yet to release this tool to the public. Until then, Ainslie (2016) and Dzwilewksi and Fenton (2003) provide a fair explanation of how the UWC works.

11.2 Removal by Underwater Cutting

Parts of underwater platforms, such as well conductors or vertical pipes, are sometimes removed via mechanical cutting. This process utilizes a hydraulically activated, specialized cutter that penetrates into the conductor before it can begin cutting. Completing the cutting of all conductors on a platform often requires more than one trip in and out of the well, sometimes with different types of knives, before the entire section can be removed from the platform. BOEM supported a study to measure sound levels during conductor cutting of a platform located 12 km off the coast of Southern California, in water depths of 170–200 m (Fowler et al. 2022). The majority of the acoustic energy from cutting was in the frequency range 125–2,000 Hz, and received SPLs measured at 106–117 m from the platform ranged 120–130 dB re 1 µPa. In total, 40 individual cutting events occurred. Reported cutting times were 4–27 hours for conductors with multiple casing strings and 0.7–8 hours for those without casing strings (Fowler et al. 2022).

12 Other In-Water Industrial Activities

A range of other industrial activities, not captured in the other parts of this document, may introduce noise in the marine environment. For example, there are numerous techniques for laying cables and pipelines on the ocean floor. Several of the most common are presented here, but which technique is used in any location depends on the type of cable or pipe being deployed, water depth, available vessels and equipment, and many other factors. In the Gulf of Mexico, pipeline burial is required only in water depths less than 200 ft. In many cases, there are no recordings of these activities in the field and no reporting of source levels. For the limited data that exists, we report received levels at the distances that were measured.

12.1 Operational Noise from Offshore Wind

While windfarms are operating, each wind turbine generator generates low-level continuous sounds, but sound levels are much lower than during construction. Nearly all energy associated with operations is below 1 kHz and may contain strong tonal elements (Tougaard et al. 2020). This type of noise is considered to be continuous, omnidirectional, and non-impulsive.

At Block Island Wind Farm (BIWF), Elliott et al. (2019) measured operational sounds underwater over several months of operation in 2016 and 2017. Overall, recordings from Block Island indicate that there is a correlation between underwater sound levels and increasing wind speed, but this is not clearly influenced by turbine machinery; rather, it may be explained by the natural effects that wind and sea state have on underwater sound levels (Elliott et al. 2019; Urick 1983).

A recent compilation of operational noise from several wind farms with turbines up to 6.15 MW in size showed that operational noise generally attenuates rapidly with distance from the turbines (falling below normal ocean ambient noise within ~1 km from the source), and the combined noise levels from multiple turbines is lower or comparable to that generated by a small cargo ship (Tougaard et al. 2020). Larger turbines do produce higher levels of operational noise, and the least squares fit of that dataset would predict that an SPL measured 100 m from a hypothetical 15 MW turbine in operation in 10 m/s (19 kt or 22 mph) wind would be 125 dB re 1 µPa. All turbines in that dataset except for BIWF were operated with gear boxes of various designs rather than the newer direct drive technology. Stöber and Thomsen (2021) noted that operational noise from BIWF, using direct drive, was expected to be approximately 10 dB lower than other equivalently sized jacket pile turbines. There is also reason to believe, based on the Tougaard et al. (2020) dataset, that operational noise from jacket piles could be louder than that of monopiles due to the larger surface area for the foundation to interact with the water; however, the report does point out that received level differences among different pile types could be confounded by differences in water depth and turbine size. Additional data is needed to fully understand the effects of size, foundation type, and drive type on the amount of sound produced during turbine operation.

Table 27. Offshore wind operational noise sound level examples

Wind Farm Name	Foundation	Nominal Power (MW)	Water Depth (m)	Wind Speed (m/s)	Distance from Turbine (m)	Received SPL	Dominant 1/3 Octave Band Center (Hz)	SPL in Dominant Frequency Band
Middlegrunden[1]	Concrete	2	5	6	20	109	25	106
Bockstigen-Valar[1]	Monopile	0.5	5	8	20	113	160	110
Vindeby[1]	Concrete	0.45	4	13	14	127	25	126
Alpha Ventus[1]	Tripod	5	30	12	92	110	90	157[2]
Sheringham Shoal[3]	Monopile	3.6	19	9	50	127	160	122
C-power[4]	Jacket	6.15	25	11	60	128	50	Not reported
Block Island[5]	Jacket	6	30	2	50	112.2	–	Not reported
Block Island[5]	jacket	6	30	12	50	119.5	–	Not reported

Notes: SPL = root-mean-square sound pressure level
Operational noise from wind turbines taken at different distances.
[1] Tougaard et al. (2009)
[2] Normalized to 1m distance, Stöber and Thomsen (2021)
[3] Pangerc et al. (2016)
[4] Thomsen et al. (2015)
[5] Elliott et al. (2019)

12.2 Jetting/Trenching

Trenching sleds dig the trenches for laying pipeline or cable. A trenching sled displaces the sediment with a water jet and may be operated by a diver or an ROV. Depending on the technique used, the cable may be laid directly into the trench as the trench is being cut, allowing the sediment to settle back into the trench and cover the cable, or a separate burying pass may be made after the cable is laid.

Nedwell and Edwards (2004) measured sounds from a 130 m-long trenching vessel and found that sound levels were similar to those produced during pipeline-laying in the same area (see below), with the exception of a 20 kHz tonal sound, which they attributed to the vessel's DP thrusters. Source levels for trenching were not reported. Nedwell et al. (2003b) recorded underwater sound 160 m from trenching activity with the hydrophone 2 m below the surface (and water depth 7–11m) and back-calculated the SPL source level of trenching to be 178 dB re 1 µPa·m (assuming propagation loss of 22logR). They describe the sound as generally spanning a wide range of frequencies, variable over time, and accompanied by some tonal machinery noise and transients associated with rock breakage.

12.3 S-lay, J-lay, Reeling, Pull-tow, and Other Cable-laying Methods

All oil and gas pipelines in the U.S. are required to be tested offshore after installation, and the S-lay and J-lay methods are most common. In S-lay pipeline installation, the pipe is eased off the stern of the vessel as the boat moves forward. It curves downward and forms an "S" when it reaches the seabed. Maintaining proper tension is critical during the S-lay method, so the support vessel must exert appropriate forward thrust. S-lays can be performed in waters up to 6,500 ft. In the J-lay method, the pipeline is inserted in an almost vertical position; it is lifted high off the stern of the boat, so there is less curvature and less strain on the pipe, which makes it a viable option in deeper waters. Once offshore, certain joints must be welded into place, so specialized vessels equipped with welding stations are required. In reeling, smaller diameter or more flexible pipe is used. The pipes are assembled and welded onshore and then wrapped around a reel and placed on the reel barge. The pipe is simply rolled out as installation is performed. Several miles of pipeline can be installed at once.

The process of laying pipeline may introduce noise, but noise is also introduced into the water from the DP systems, the movement of supply ships and tugs, and anchoring. Up to 10 ships may be operating in the same area during this time. Nedwell and Edwards (2004) measured noise from a pipeline-laying ship working in both shallow (< 50 m) and deeper (50–100 m) waters near the Shetland Islands. In shallower areas, they found increased sound levels at distances up to 2.3 km at frequencies < 1 kHz; by 7.4 km from the source, sounds from pipeline-laying had faded into ambient noise. Johansson and Andersson (2012) measured sounds during pipe laying operations in 40 m water depth; at 1.5 km distance, the SPL was 130.5 dB re 1 µPa. DP thruster were active when the measurements were taken, so it is difficult to know sound levels from pipeline-laying alone.

12.4 Cable Laying for Offshore Wind

Current plans for proposed offshore wind farms call for a jet plow to be used in the deployment of cables. Here, the plow is towed on the seabed behind a cableship. Water is jetted through the plow and displaces the sediment so that the cable can be laid, then the sediment is allowed to settle back in place. This process results in a small amount of sediment disturbance in a very narrow corridor. Burial speeds are typically 0.2 km/hour. Sometimes a pre-lay grapnel run must be carried out, which is a seabed clearance exercise that removes any unexpected debris (e.g., fishing wires) from the cable route. Nedwell et al. (2003a) measured sounds during cable laying for an offshore wind site and estimated SPL source levels to be 178 dB re 1 µPa·m, though the exact conditions and equipment used were not described.

Table 28. Offshore wind cable laying sound level example

SPL Source Level (dB re 1 µPa·m)	Dominant Frequency	Broad or Narrowband	Omnidirectional or Directional	Impulsive or Non-impulsive	Continuous or Intermittent	Other Notes
178 dB	80 Hz–2 kHz	Broad	Omnidirectional	Non-impulsive	Continuous	2-m water depth

Notes: SPL = root-mean-square sound pressure level
Source: Nedwell et al. (2003a)

12.5 Installation of Scour Protection Systems

Offshore wind turbines may require scour protection systems to help withstand increased seabed drag created by the presence of the foundation. Installation of scour protection involves the deliberate removal of sediment from around the foundation by hydrodynamic forces (such as waterjets) and either replacing or supplementing those sediments by surrounding the structure with stone or rock. Usually, the material is sent down a tube to the bottom. After these systems are in place, there is no significant noise associated with them; noise occurs only during their construction.

Nedwell and Edwards (2004) measured sounds produced during rock placement (associated with pipeline-laying described above). They found no measurable difference between sounds recorded while rock placement was occurring and when it was not. The sounds from the DP thrusters dominated the recordings.

12.6 Anchoring Systems

Floating windfarms require anchoring systems to hold the wind turbines in place. There are several types of anchoring systems being considered, but the most common are suction piles or gravity-based foundations. Sounds produced during construction of these systems are expected to be lower than for impact pile driving, but there are no known measurements (Koschinski and Lüdemann 2013). For gravity-based foundations, noise would be created by the DP system of the vessel and suction hopper dredge (**Section 9**). For suction piles, underwater suction pumps would be required and would generate some low-level continuous noise, but installation is relatively fast (4–5 hours). There are no known measurements of installations using these various anchoring systems.

12.7 Liquified Natural Gas (LNG) Compressors

LNG facilities generally come in two forms based on whether they are providing LNG to vessels or receiving LNG from them. If they are providing LNG, then they typically need compressors and heat exchangers to remove the thermal energy from compressing gas into a liquid. The reverse is true for receiving facilities; they require thermal energy to expand and gasify the LNG. The mechanical components needed include heat exchangers, pumps, and piping and control systems; this equipment generates continuous noise after the facility is operational. To minimize in-air noise, mitigation measures—such as enclosures around compressors, silenced exhaust systems, and insulation of pipes—may be implemented.

Additionally, siting and construction of these facilities requires many of the same sources found throughout this document. Some of the many sources include HRG surveys for planning the construction of the site, vessels to transport construction equipment, pile drivers, and DPs for construction vessels and the onload/offload of LNG. Sound levels from these sources are not discussed further in this section.

Another complicating factor is the placement of the liquification/gasification plant. It can be onshore, on the ocean, on the terminal, or even on the vessel itself. All these factors need to be considered when considering acoustic impacts from these facilities.

Table 29 provides the measurements of airborne noise in several noise sensitive areas (e.g., residential areas) near two LNG compressor stations during operations.

Table 29. Liquid natural gas compressor sound level examples

Compressor Station	Noise Sensitive Area	Distance and Direction from Proposed Compressor Stations (ft)	Calculated Ambient Sound (dBA L_{dn})	Estimated Sound Levels of Station at Full Load (dBA L_{dn})	Station Noise and Ambient Sound Levels (dBA L_{dn})	Potential Increase Over Ambient Sound Level (dBA)
Centerville	NSA 1 (residences)	1,050 east	48.4	51.3	53.1	4.7
Centerville	NSA 2 (residences)	3,000 southeast	58.9	39.1	58.9	0
Centerville	NSA 3 (jail)	2,600 north	48.4	40.6	49	0.6
Golden Meadow	NSA 1 (residence)	3,300 north	46.7	43.8	48.5	1.8

Notes: NSA = noise sensitive area (referring to homes, schools, churches, or any location where people reside and gather)
Data from airborne noise measured near the East Lateral Express Project (Columbia Gulf Transmission LLC 2021). When considering impacts to human ears, A-weighting is typically used, and in-air sound levels are reported in dB relative to 20 µPa. L_{eq} is an A-weighted sound level containing the same energy as the instantaneous sound levels measured over a specific time period, while L_{dn} takes into account the duration and time of day the noise is encountered. Specifically, the L_{dn} is the L_{eq} plus a 10 dBA penalty added to account for people's greater sensitivity to nighttime sound levels.

13 Explosives

Underwater explosions are used for both military and civilian applications. The discussion here focuses on non-military use of underwater detonations, which may include confined explosions (e.g., for removal of offshore structures, ice management) or open-water explosions (e.g., removal of unexploded ordnances).

13.1 Open-Water Explosives

In open water (free field, in the water column), the explosion of "high" explosives like trinitrotoluene (TNT) creates a high-pressure shock wave, which propagates in all directions at a speed of 5,000–10,000 m/s (Urick 1983). In deep water, the shock wave is followed by a series of bubble pulses that are caused by successive oscillations of the gaseous materials from the explosion. Most of the energy from these pulses is concentrated in the lowest frequencies, but the level of energy depends on water depth and charge size. For conventional high explosives, the peak sound pressure in micropascals is given by Richardson et al. (1995):

$$p_{pk} = 5.24 \times 10^{13} \left(\frac{w^{1/3}}{r}\right)^{1.13} \quad (1)$$

where *w* is the charge weight in kg of TNT, and *r* is the distance in m.

The time constant t_0, which is used to describe the duration (in microseconds) for the pressure to decay to $\frac{1}{e}$ of its initial pressure value, is expressed by Richardson et al. (1995) as

$$t_0 = 92.5 w^{1/3} \left(\frac{w^{1/3}}{r}\right)^{-0.22} \quad (2)$$

Using $r = 1$ m and taking the logarithm of Equation (1), shows that the Lpk source level of the initial shock wave is given by

$$Lpk\ source\ level = 274 + 7.53 \log_{10} w \text{ (in dB re 1 µPa·m)} \quad (3)$$

When the explosion is in relatively shallow water, the reflected impulse is phase-reversed and would tend to reduce the subsequent pulse oscillation. If the explosion is near the surface, no bubble pulses would occur, and the gas globe from the explosion would break the sea surface. Under these conditions, the source levels would be significantly reduced.

In one study, von Benda-Beckmann et al. (2015) measured received levels of explosions in shallow waters at distances of 100–2,000 m from the source. In water depths of 6–22 m, measured SEL from a 263 kg charge was 216 dB re 1 $\mu Pa^2 s$ at 100 m from the source and 196 dB re 1 $\mu Pa^2 s$ at 2,000 m. They found that SELs were lower near the surface than near the seafloor or in the middle of the water column, and most of the acoustic energy was below 1,000 Hz.

Further reading

- Arons AB, Yennie DR, Cotter TP. 1949. Long range shock propagation in underwater explosion phenomena I. U.S. Navy Department Bureau of Ordnance. NAVORD Report 478.

13.2 Confined Underwater Explosives

Besides free-field (open-water) explosions, there are additional applications for explosives in the ocean in the sediment or bedrock. This method typically is used for structure removal and shipping channel maintenance or expansion. The confined detonation maximizes the ability to break the structure/bedrock and minimizes environmental impacts. Due to the placement of the charges below the ocean floor (often identified as "below the mudline"), the physics of the noise generation and propagation is unique. Effectively, the sediment not only attenuates the noise before it can enter the water column, but the shock wave propagation distance is reduced, and the formation of the oscillating gas bubble is reduced or even eliminated. This effect changes the peak sound pressure level, duration, and frequency content of the signal. Additionally, the charges may be significantly less omnidirectional if shape charges are employed.

For the purposes of ship channel deepening, there is limited data regarding sound propagation from explosives. One study by Hempen et al. (2007) showed that a conservative estimate of peak pressure p_{pk} can be taken to be proportional to a calculation using explosive charge weight w and range r.

$$p_{pk} \propto \left(\frac{w^{\frac{1}{3}}}{r}\right)^{1.23} \qquad (4)$$

13.3 Low-order Deflagration

As an alternative to high-order detonations, a newer method called deflagration allows for the controlled burning of underwater explosives. Typically, an ROV uses a small, targeted charge (e.g., 20–250 g) to initiate rapid burning of the ordnance; when this process is complete, the remaining debris can be cleared away. Recent work has demonstrated that both Lpk and SEL measured from deflagration events may be up to 20 dB lower than equivalent-sized, high-order detonations (Robinson et al. 2020).

14 Vessel Noise

For convenience, all vessel noise has been combined into a single section in this document. The instruments described in the rest of this document may be deployed from a range of vessel types varying in size, shape, propulsion type, configuration, age, and state of upkeep and repair, as well as with varying degrees of noise quieting technology built into the vessel or applied post-construction. Rather than delve into the myriad variations of these factors, we simply provide several descriptions of typical vessel configurations. Jiménez-Arranz et al. (2020) provides a more comprehensive summary of vessel noise, as well as measurements of radiated noise from various-sized vessels.

For geophysical surveys, survey equipment is typically deployed from a single vessel ranging from approximately 30 to 275 ft (9 to 84 m) in length, depending on the survey activity to be conducted and the equipment needs. However, in some cases, such as in wide-azimuth surveys, two source vessels could be involved. Sometimes, an additional ship or ships are used to record sound signals at greater distances from the acoustic sources to protect a long streamer, tender ocean bottom nodes, or conduct other complex operations. For drilling activities, vessels may remain offshore for weeks or months and travel periodically to an onshore support base for fuel, supplies, equipment repairs, and crew changes. Smaller vessels may be deployed for day-long operations (e.g., windfarm operation) as necessary. During transit to and from shore bases, survey vessels typically travel at speeds that optimize efficiency, except in areas where transit speed is restricted. ROVs are expected to be significantly quieter than typical ocean vessels because they move relatively slowly and are much smaller in size. New types of ROVs may rely on different types of propulsion; for example, ocean-based gliders typically use ocean currents to move and thus are expected to be very quiet, and sail drones rely on wind and may only produce flow noise from the vessel moving through water.

Noise from vessel transit is a combination of tonal and broadband sound (Richardson et al. 1995; Ross 1976), with dominant frequencies typically between 5 Hz and 1 kHz. Transiting vessels generate continuous noise from propeller cavitation, onboard machinery, and hydrodynamics of water flow (Ross 1976). The actual radiated sound depends on several factors, including the type of machinery on the ship, material conditions of the hull, how recently the hull has been cleaned, interactions with the sea surface, and shielding from the hull (which reduces levels in the front of the ship). American National Standard Institute (2009) provides procedures for measuring and describing underwater sound from ships.

Source levels for many vessels are in the range of 150–170 dB re 1 µPa·m (Richardson et al. 1995), but sounds are less intense during some operational activities, such as seismic surveying, when vessel speeds are lower (approximately 5 kt) (Zykov and Carr 2012). Both vessel speed and vessel size can affect the amount of cavitation noise produced (Ross 1976).

Table 30. Vessel noise sound level examples

Vessel Type (Vessel Name)	Length (m)	Speed (kt)	SPL Source Level (dB re 1 µPa·m)	Aspect
Open Skiff (*Ursa*)	4.3	6.8	166.1	–
Open Skiff (*Ursa*)	4.3	13	167.0	–
Open Skiff (*Ursa*)	4.3	16.3	169.1	–
Bow Picker (*Canvasback*)	9.8	1.9	129.2	Bow

Vessel Type (Vessel Name)	Length (m)	Speed (kt)	SPL Source Level (dB re 1 µPa·m)	Aspect
Bow Picker (*Canvasback*)	9.8	1.9	131.8	Stern
Bow Picker (*Canvasback*)	9.8	6.0	145.3	Bow
Bow Picker (*Canvasback*)	9.8	6.0	143.2	Stern
Crew Vessel (*Qayaq Spirit*)	12.2	7.3	151.0	Bow
Crew Vessel (*Qayaq Spirit*)	12.2	7.3	148.8	Stern
Crew Vessel (*Qayaq Spirit*)	12.2	20.7	184.7	Bow
Crew Vessel (*Qayaq Spirit*)	12.2	20.7	184.3	Stern
Military Boat (*Nunatak*)	19.8	6.7	163.8	–
Military Boat (*Nunatak*)	19.8	8.5	169.6	–

Notes: SPL = root-mean-square sound pressure level
Source: Jiménez-Arranz et al. (2020)

Table 31. Vessel noise sound level examples

Vessel Type	Length (m)	Speed (kt)	SPL Source Level (dB re 1 µPa·m)
Chemical product tanker	149	13.8	183.1
Open hatch cargo	199	13.0	181.8
Bulk carrier	173	8.0	178.2
Bulk carrier	173	16.0	192.1
Bulk carrier	219	0 (moored)	156.6
Bulk carrier	225	14.2	185.9
Cruise ship	230	10.0	176.0
Cruise ship	230	19.2	195.0
Crude oil tanker	241	12.6	179.4
Container ship	294	21.1	185.0

Notes: SPL = root-mean-square sound pressure level
Source: Jiménez-Arranz et al. (2020)

Table 4.5 in Jiménez-Arranz et al. (2020) summarizes the general acoustic characteristics of three different size-classes of vessels; this summary is provided below in **Table 32**. In the scope of their document, they define small, medium, and large vessels as < 25 m, < 100 m, and > 100 m in length, respectively.

Table 32. Summary of general acoustic characteristics for vessels

Large Vessels	Medium Vessels	Small Vessels
• Main energy content is below 100 Hz, due to slow turning engines and propellers, great power, large hulls, and drafts. • Low-frequency spectrum is dominated by blade rate. • Propeller cavitation contributes to frequencies up to 10 kHz. • Slow speed diesel engines (< 250 rpm) are relatively quiet compared to those used in smaller vessels. • Large oil tankers and cargo carriers are the loudest, with source levels typically in the range of 175–185 dB.	• The low-frequency spectrum is dominated by tones related to blade rate, and in second place is the engine firing rate. • Broadband components are associated to propeller cavitation and flow noise, which peak at 50–150 Hz and may extend up to 100 kHz. • Pumps and compressors can also contribute with high-frequency tones. • Source levels from medium–small vessels are typically in the range of 165–175 dB. • Icebreakers produce higher frequency content and broadband sound levels than vessels of comparable size, due to their greater power and increased propeller cavitation.	• The spectra in small vessels is dominated by high frequencies. • These vessels are equipped with small propellers that operate at high speeds. • Blade rate tones are produced at relatively high frequencies, and propeller cavitation dominates in the 0.5–10 kHz region. • The medium- and high-speed diesel engines typically installed in small vessels are very noisy. The radiated levels can mask propeller cavitation. • Source levels of small vessels are generally < 165 dB.

Source: Table 4.5 of Jiménez-Arranz et al. (2020)

15 Dynamic Positioning (DP) Systems

Alternative name: acoustic positioning

DP systems are used to control a vessel's position with propellers and thrusters for station-keeping, docking, or maneuvering. The computer-controlled system uses input from gyrocompasses, motion sensors, global positioning systems, active acoustic positioning systems, and wind sensors to determine relative movement and environmental forces at work. A variety of research and work vessels use DP systems, including mobile offshore drilling, coring and pile driving units, oceanographic research vessels, and cable-laying ships. DP systems produce both high-frequency and low-frequency sounds.

The active acoustic positioning systems used in DP, which are functionally similar to echosounders, can be sources of high-frequency sound. These systems are generally quieter than other components of the sound from DP vessels for various reasons: their pulses are narrowband in frequency; the transponders have narrowly directed beams; each individual pulse is very short; and their high frequency leads to faster attenuation.

Table 33. DP vessel active acoustic positioning system sound level examples

Devices	Potential Mode Settings	SPL Source Level (dB re 1 µPa·m)	Dominant Frequency (kHz)	Reference
Kongsberg HiPAP hull-mounted transducers	Low power (max 1.5 km), High power (max 2–3 km)	188–206	20–32	Kongsberg Maritime AS (2013)
Kongsberg HiPAP stationary seabed-based transponders	Beam widths (15–90°)	178–206	10–32	Jiménez-Arranz et al. (2020)
Sonardyne Compatt transponders	Beam widths (directional vs. omni)	184–202	19–50	Jiménez-Arranz et al. (2020)

Notes: SPL = root-mean-square sound pressure level

The lower frequency and higher amplitude components of noise generated by DP systems comes from the vessel thrusters. As with propulsion, source levels during the use of DP vary greatly based on size and type of vessel, type of thruster, and operational conditions. Generally, a wider variety of thruster types are used in DP than in standard propulsion. Some drive types include transverse tunnel thrusters, z-drives, L-drives, azipull thrusters, and retractable thrusters (Warner and McCrodan 2011). Transverse tunnel thrusters can be located on the ship's bow or stern, or in both locations. Because the impeller is usually closer to one side or the other, the thrusters produce sound that is both directionally variable and differing depending on which direction they are pushing. The design also makes them more prone to cavitation at relatively low operational speeds, leading to much higher source levels relative to their thrust (Fischer 2000).

DP is often used for the purposes of some industrial activity. Many studies have found that the measured acoustic levels of DP alone are higher than those of DP combined with the intended activities such as drilling (Jiménez-Arranz et al. 2020; Kyhn et al. 2011; Nedwell and Edwards 2004) and coring (Warner and McCrodan 2011). Nedwell and Edwards (2004) reported that DP thrusters of semi-submersible drill rig *Jack Bates* produced periodic noise (corresponding to the rate of the thruster blades), with most energy between 3–30 Hz. Warner and McCrodan (2011) found that most DP-related sounds from the self-propelled drill ship, R/V *Fugro Synergy* were in the 110–140 Hz range. Sounds in this range varied by 12 dB during DP, while the broadband levels, which also included diesel generators and other equipment sounds, varied by only 5 dB over the same time period. In general, similar to propulsion, sounds from DP are generally below 1 kHz, with tones related to engine and propeller size and type. All above sources report high variability in levels with time, due in part to the intermittent usage and relatively slow rotation rates of thrusters used in DP.

Rutenko and Ushchipovskii (2015) compared ice breaking tugs *Pacific Endurance* and *Smit Sakhalin* while both were in transit and using DP. *Pacific Endurance* is a battery diesel tug, meaning that it has diesel generators that charge batteries and electric engines that turn its propellers. The slightly smaller *Smit Sakhalin* is powered by diesel engines. In measurements taken at a distance of 600 m, *Smit Sakhalin* produced less sound while it was traveling at 10 kt than at the same distance while stationary using DP. In contrast, *Pacific Endurance*, generally quieter than *Smit Sakhalin*, was even quieter in DP, with measurements below 160 Hz not exceeding background levels recorded in the absence of operating vessels.

Some example measurements are included in **Table 34**, but care should be taken when considering noise levels from DP thrusters due to the high directionality of the source. Most reports do not identify the direction in which noise was measured, nor do they provide multiple measurements based on bearing.

Table 34. Dynamic position system vessel sound level examples

Vessel Type	Vessel Length (m)	SPL Source Level (dB re 1 µPa·m)	Received SPL (dB re 1 µPa) at Measured Distance	Approximate Distance of Measurements (m)	Dominant Frequency (Hz)	Reference
Coring vessel	104	168.9	115–155	60–1,000	110–140	Warner and McCrodan (2011)
Drill ship	62	175.9	140–149	74–207	100–1,000	Chorney et al. (2011)
Dive support	107	178.2	–	–	–	Wyatt (2008)
Semi-submersible drilling rig	113 x 78	–	188.4	~100	2–30	Nedwell and Edwards (2004)
Drill ship	228	190.0	117–132	500–38,000	100–200	Kyhn et al. (2011)

Notes: SPL = root-mean-square sound pressure level

16 Acoustic Deterrent Devices

Alternative names: pinger (differs from "pinger" in the acoustic locator section), acoustic harassment device

Acoustic deterrent devices are used worldwide by commercial fisheries to prevent interactions with marine mammals (Jefferson and Curry 1996; Mate et al. 1986; Reeves et al. 1996). Additionally, acoustic deterrent devices are used to protect aquaculture assets from pinnipeds. Source levels often reflect whether the goal is to alert an animal or to keep it away from an area. Much of the relevant research on the effects of acoustic deterrents has been conducted in the context of marine aquaculture (Coram et al. 2014; Lepper et al. 2014). These devices are typically non-impulsive (e.g., predator sounds, in-air noisemakers), but some are impulsive (e.g., seal bombs, banging pipes). Some acoustic deterrent devices are controlled by the user in terms of how often they are deployed and/or how close they are deployed to an animal (e.g., seal bombs) or have variable, programmable settings.

Table 35. Acoustic deterrent device sound level examples

Device	SPL Source Level (dB re 1 µPa·m)	Dominant Frequency (kHz)	Impulsive or Non-impulsive	Continuous or Intermittent
Acoustic alarms (transducers/pingers)	Variable: 120 to > 200 dB	Variable: 1 to 160	Non-impulsive	Intermittent with varying duty cycles (typically below 50%)
Seal bomb	226 dB (estimated)	< 0.4	Impulsive	Intermittent (duty cycle controlled by person deploying device)

Notes: SPL = root-mean-square sound pressure level
Source: Wiggins et al. (2021)

17 Ice Breaking and Ice Management

Ice breaking is a process conducted by special-purpose vessels (icebreakers) to navigate through ice-covered waters and provide safe passage for other vessels. Ice management is a maneuver performed by special-purpose vessels to push ice floes out of the way and provide a safe zone for nearby ships or structures.

Some icebreaker ships ram forward into the ice, back away, and then make another run into the ice. Other icebreakers have bows that slide over the ice and push it downwards until it cracks. Sounds from icebreakers are primarily produced via propellor cavitation associated with backing and ramming maneuvers, when levels can increase up to 15 dB at frequencies below 100 Hz and fluctuate with operation (Richardson et al. 1995; Roth et al. 2013). Physical crushing of ice does not appear to contribute to significant amount of noise during icebreaking (Thiele 1988). Icebreakers generate more intense sounds than similar size vessels (Richardson et al. 1995). Icebreakers can also rely upon the use of DPs, and some use bubbler systems to help push ice out of the way for ice management (Roth et al. 2013). Icebreakers are classified by their brake horsepower based on their ability to break through various thicknesses of ice (e.g., heavy and medium) and typically operate at full, half, or quarter power (NMFS 2020). Icebreakers often have vessel escorts following behind.

Although they may generally be assumed to be roughly omnidirectional sources, the presence of the vessel, multiple layers of ice, and air-water interface all affect propagation and directionality.

Table 36. Ice breaker sound level examples

Vessel Name	SPL Source Level (dB re 1 µPa·m)	Dominant Frequency (Hz)	Note	Reference
Coast Guard Cutter *Healy*	190–200	10, 50, 100	Backing and ramming maneuvers	Roth et al. (2013)
MS *Voima* (max. 10.2 MW)	190	–	Icebreaking full astern	Richardson et al. (1995)
MS *Voima* (max. 10.2 MW)	180–185	–	Icebreaking full ahead	Richardson et al. (1995)
MV *Arctic* (max. 11.0 MW)	184	10–1,000	Icebreaking ahead	Richardson et al. (1995)
MV *Arctic* (max. 11.0 MW)	191	10–1,000	Icebreaking astern	Richardson et al. (1995)

Notes: SPL = root-mean-square sound pressure level

18 Aircraft

Aircraft are used to transport crew to offshore platforms or for surveys of marine mammals, and include both manned aircraft (e.g., propeller and jet engine aircraft, fixed-wing craft, and helicopters) and unmanned systems.

For jet engine aircraft, the engine is the primary source of sound. For propeller-driven aircraft and helicopters, the propellors and rotors also produce noise. Aircraft generally produce low-frequency sound below 500 Hz (Richardson et al. 1995).

Sound from aircraft enters the water column at the air-water interface via a critical incident angle or cone. After the sound has entered the water column, it propagates outwardly as an omnidirectional point source. Beyond this cone, sound is not transmitted into the water and instead is reflected off the sea surface. With an idealized flat sea surface, the maximum critical incident angle is ~13 degrees (Urick 1972). When the sea surface is not flat, there may be some additional penetration into the water column in areas outside of this 13-degree cone.

Erbe et al. (2017) demonstrated that some radiated noise from unmanned aircraft (drones) flying above the water does penetrate into the water column, but received SPLs were generally < 108 dB re 1 µPa even when the drone was flying as low as 5 m above the water's surface; a similar finding was demonstrated by Christiansen et al. (2016).

Table 37. Aircraft sound level examples

Aircraft	SPL Source Level (dB re 1 µPa·m)	Measured SPL (dB re 1 µPa)	Aircraft Altitude (m)	Dominant Frequency (Hz)	Broad- or Narrowband
Maritime patrol aircraft	162	124	76	56–80	Broadband with distinct tones
Medium utility helicopter	149	109	152	< 22	Broadband with distinct tones
Turbo prop	147	107	457	82	Tonal

Notes: SPL = root-mean-square sound pressure level
Source: Jiménez-Arranz et al. (2020)

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