# DRAFT ADEON Hardware Specification
# Version 1.1

# Atlantic Deepwater Ecosystem Observatory Network (ADEON): An Integrated System

## Contract: M16PC00003


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**20 October 2017**

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# ADEON Hardware Specification

Submitted to:

ADEON
*Contract:* M16PC00003

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20 October 2017

P001339
Document 01412
Version 1.1 DRAFT

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Suggested citation:

Martin B, C.A. Hillis, J. Miksis-Olds, M. Ainslie, and J. Warren. 2017. *ADEON Hardware Specification*. Document 01412, Version 1.1 DRAFT. Technical report by JASCO Applied Sciences for ADEON.

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# 1. Introduction

## 1.1. ADEON Project

The Atlantic Deepwater Ecosystem Observatory Network (ADEON) is a five-year study of the US Mid- and South Atlantic Outer Continental Shelf (OCS) that includes three-years of data collection. The lead P.I. for this project is Dr. Jennifer Miksis-Olds, University of New Hampshire (UNH). Dr. Miksis-Olds leads a collaborative research team consisting of individuals from UNH, OASIS, TNO, JASCO, Stony Brook University, and NOAA.

This observatory network will generate long-term measurements of the natural and human factors that describe the ecology and soundscape of the OCS. Ocean processes, marine life dynamics, and human ocean use are each inherently three-dimensional and time-dependent, and each occur at many spatial and temporal scales. No single measurement system (*in situ* or remote) is sufficient for describing any of the ocean state variables, and a “multi-platform, multi-variable” observational approach integrated with models is required (Seim et al. 2009). ADEON combines acoustic information with contextual data from space-based remote sensing, hydrographic sensors, and mobile platforms to fully comprehend how human and natural (biotic and abiotic) components create the soundscape and influence ecosystem dynamics of the OCS. Measurements made within this research program serve as a baseline for pattern and trend analyzes of ambient sound and the ecosystem components contributing to the OCS soundscapes.

The outputs of this study will be standardized tools for comparing soundscapes across regions and predictive models for the soundscape and overall ecology of the southeast OCS in water depths between 100–1000 m. The data and models will allow the public to estimate short-term and cumulative effects on the soundscape from changes in human activity as well as ecosystem changes driven by climate change or other environmental factors. The project’s public data management interface will be used by interested parties to create value-added products so that the information is used as widely as possible.

## 1.2. Objectives

### 1.2.1. ADEON Project Objectives

The ADEON project objectives are:

- Establish an ecosystem observation network that provides baseline monitoring and supports predictive modeling of the soundscape and its relationship to marine life and the environment of the Mid- and South Atlantic Planning Areas.
- Develop standardized measurement and processing methods as well as visualization metrics for comparing ADEON observations with data from other monitoring networks.
- Assess baseline soundscape and ecosystem conditions in support of predictive environmental modeling and trend analyzes in the planning areas.
    - How do soundscape and ecosystem components vary with water depth across the OCS?
    - How do the soundscape and ecosystem components vary with latitude along the OCS?
    - Where are the hot spots of human activity that impact ecosystem/habitat health impacts?
- Assess the spatial and temporal distribution of the soundscape and biological scatterers, including their expected variation and correlation with distance from the bottom lander locations.
    - What are the environmental factors that define and constrain the horizontal range of appropriate extrapolation of observations measured at the stationary bottom lander sites?

- Develop and apply new methods to effectively visualize five-dimensional (5D–time, latitude, longitude, frequency, and depth) soundscape data with interactive visual analysis tools that enable users to explore, analyze, and integrate ancillary ecosystem data streams with the 5D soundscape.
- Develop a robust data management system that archives and provides public access to multiple data streams to encourage future development of ecological models targeted at questions beyond the scope of this study.

### 1.2.2. ADEON Standardization Objectives

The ADEON standardization objectives are:

- Ensure compatibility within ADEON between soundscapes based on measurements and those based on models.
- Ensure compatibility between measurement data from different researchers or institutes within ADEON.
- Facilitate compatibility between ADEON soundscapes, whether based on measured or modeled prediction, and soundscapes produced by a hypothetical future or parallel project within the US EEZ.
- Facilitate compatibility between metrics used to quantify ADEON soundscapes and those used to monitor ambient sound in the context of the EU's Marine Strategy Framework Directive (MSFD).

This report, the draft *Hardware Specification*, is the second of five Standardization reports, which together meet the above four objectives. The ADEON project has implemented an autonomous ocean observatory that includes multiple hardware components. This report describes the selected hardware and the characteristics of bottom landers and equipment required to meet the project objectives.

## 1.3. Report Structure and Terminology

This document describes the ADEON hardware and how it's performance is measured. The Calibration, Deployment and Good Practice Guide contains details of how the equipment was configured for ADEON data collection. In this document, Section 2 provides an overview of the hardware selected. Section 3 describes the generic structure of autonomous acoustic recorders along with performance issues associated with trade-offs in selecting different types of components. Quantitative and qualitative metrics for assessing the performance of recorders are described in Section 3.4. Section 4 describes active acoustic echo sounders for biologic measurements. The main report is followed by:

- Appendix A. Calculating Sound Levels from Acoustic Recordings.
- Appendix B. Sample Specification Sheet for Autonomous Recorders.
- Appendix C. Specification Sheets for Equipment
- Appendix D. Terms and Definitions

# 2. ADEON Hardware

## 2.1. Overview

The ADEON program selected a range of hardware components to generate a time-series of acoustic and supporting data that address the project objectives (Section 1.2.1). Conceptually, the ADEON network consists of stationary bottom landers, towed array missions using sailboats, and vessel-based measurements supplemented with space-based remote sensing (Figure 1). It also leverages data from established ocean observation systems and databases (Figure 1, Table 1).

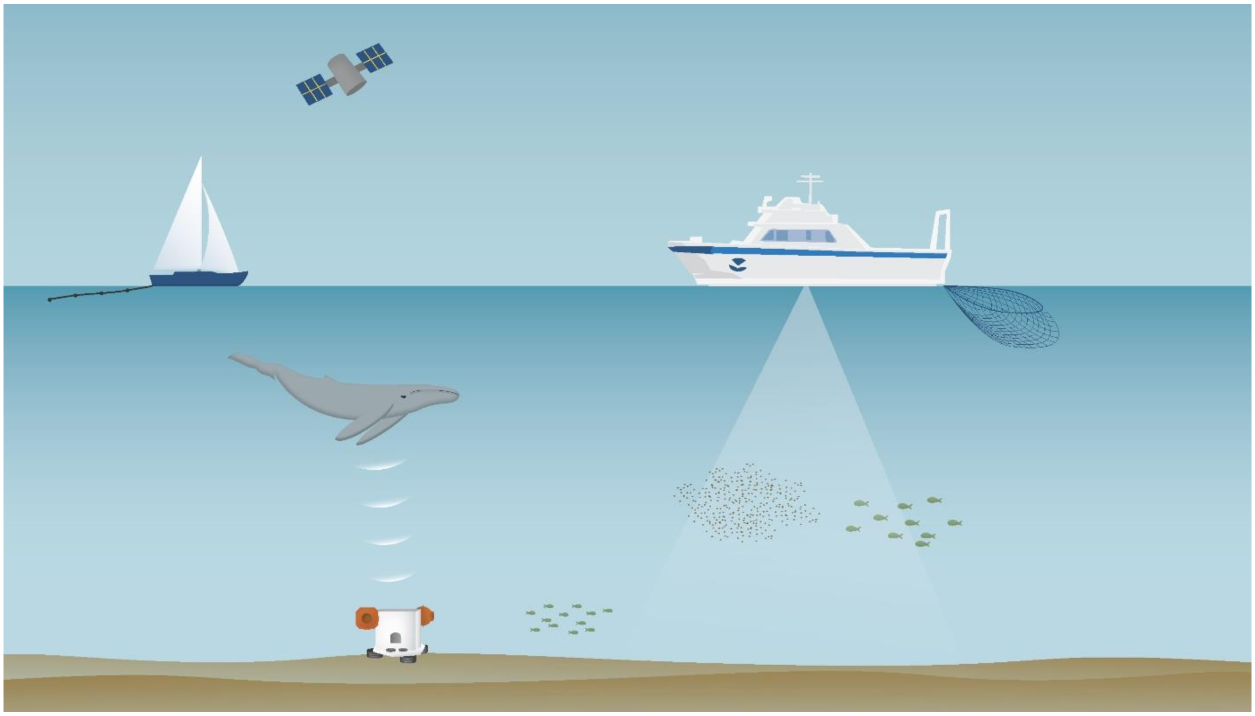


Figure 1. ADEON design including stationary bottom landers, mobile platforms, and remote sensing satellites for data collection.

The seven stationary bottom landers provided a continuous time-series of passive acoustic data, active acoustic backscatter measurements of the prey field, hydrographic measurements of the local physical environment, and detections of passing tagged fish. Two types of bottom landers were deployed—four bottom landers without active acoustic backscatter measurements and three bottom landers with active acoustics and fish tag loggers. The passive acoustic data from the ADEON bottom landers complement measurements performed by the Duke / USN Living Marine Resources Program being conducted until mid-2020, NOAA's AMAPPS program through summer 2019, and the long-term Noise Reference Station program.

The time-series measurements from the bottom landers were supplemented with targeted measurements from a towed array support vessel, the bottom lander service vessel, and remote sensing (Table 1). During the bottom lander service cruise, the service vessel:

- Made detailed water column measurements with conductivity, temperature and depth (CTD) loggers and active sonar transects,
- Conducted net tows to sample the zooplankton community structure, and

- Had visual observers document the presence of marine life including sunfish, turtles, sharks, birds, and marine mammals.

Separate towed array cruises deployed a horizontal line array (HLA) with 32 hydrophones channels spaced for effective beamforming at 800 Hz, which provided bearing-time-response (BTR) curves of the ambient sound field. The arrays estimated ambient noise directionality from 50 Hz to 1 kHz, albeit with poor bearing resolution at the lower frequencies. The tow vessel also regularly collected CTD measurements.

Table 1. ADEON sensor platforms, types, and sampling periods.

| Platform | Sampling protocol | Omni acoustics | Directional acoustics | Horizontal line array | Active acoustics | CTD/SST | Chlorophyll a | Dissolved oxygen | Fish tracking | Visual observations | Vessel tracking | Wind, wave, and surface features |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Standard bottom landers (4) | Continuous on duty cycle | ✓ | ✓ | | | ✓ | | ✓ | | | | |
| Active acoustic bottom landers (3) | Continuous on duty cycle | ✓ | ✓ | | ✓ | ✓ | | ✓ | ✓ | | | |
| Towed array | During cruises | ✓ | ✓ | ✓ | | ✓ | | | | | | |
| Vessel measurements | Continuous: Active acoustics, SST, and Chl a<br>Station sample: CTD, net tow<br>Day hours: Visual observations | | | | ✓ | ✓ | ✓ | ✓ | | ✓ | | |
| Remote sensing | As available | | | | | ✓ | ✓ | | | | ✓ | ✓ |
| Accessible databases | As available | | | | | ✓ | | | | | ✓ | ✓ |

Space-based remote sensing is an excellent resource that provided a continuous data set of chlorophyll-a concentration; net primary productivity (NPP); sea surface temperature (SST); wind and wave fields; large vessel traffic (S-AIS); and fishing traffic (VMS). The data sources and resolutions of the satellite data are shown in Table 2. These data were supplemented with accessible databases such as the Argo program (which measures oxygen, carbon dioxide, and pH), Global Real-Time Ocean Forecast system (RTOFS) program, and the Pioneer Coastal Ocean Observatory north of the project area. The satellite data were also supplemented by data from oceanographic buoys within the project area, specifically buoys NDBC41010, NDBC41002, NDBC41004, NDBC41025, and NDBC44014 (see Figure 2).

Table 2. Temporal and spatial resolutions of the selected ADEON remote sensing data

| Parameter | Data Source | Spatial Resolution | Temporal Resolution |
|---|---|---|---|
| Chlorophyll-A (CHL-a) | NASA VIIRS | 4 km | 8-day composite |
| Sea Surface Temperature (SST) | NASA Modis-Aqua | 4 km | 8-day composite |
| Net Primary Productivity (NPP) | Oregon State (VGPM model). | 12 km | 8-day |
| Mixed Layer Depth (MLD) | Oregon State (Hycom model). | 12 km | 8-day |
| Wind speed and direction | IFREMER (France) | ¼ degree | Daily |

| Parameter | Data Source | Spatial Resolution | Temporal Resolution |
|---|---|---|---|
| Oceancurrents (includes geostrophic components) | GlobCurrent (France) | ¼ degree | Daily |
| Oceancurrents (including wind driven component) | GlobCurrent (France) | ¼ degree | 6-hour |

## 2.2. Selected Hardware Components

### 2.2.1. Bottom lander sensors

#### *2.2.1.1. Omni-directional and Directional Passive Acoustics*

The passive acoustic recordings were made by Autonomous Multichannel Acoustic Recorders (AMARs; JASCO Applied Sciences). The AMAR is a well-tested, high-performance recorder that exceeds the minimum recorder specifications described in Section 3 and Appendix B. The AMAR was equipped with M36-V35-100 omnidirectional hydrophones and M20-601 directional hydrophones from GeoSpectrum Technologies. Our team has a long and successful history using the AMAR and Geospectrum hydrophones. The equipment was extensively trialed on the ADEON bottom lander prior to the ADEON deployment.

#### *2.2.1.2. Active Acoustics – Acoustic Zooplankton and Fish Profiler (AZFP)*

The AZFP from ASL Environmental Sciences collected the active acoustic data for ADEON on the bottom landers. These recorders are described in Section 4. They were selected because they are well-known within the scientific community (and our team) to be reliable for remote data collection and calibrations.

#### *2.2.1.3. Conductivity-Temperature-Dissolved Oxygen*

The Sea-Bird MicroCAT SBE-37 CT-DO logger was chosen to measure conductivity, temperature and dissolved oxygen because of its accuracy, reliability and ease of integration. The MicroCAT family is a world standard for CT logger instruments, with very well-established accuracy and precision. Sea-Bird has produced more than 10,000 instruments in this family, so the reliability is also well-proven. A dissolved oxygen sensor is a standard option, allowing us to record several important parameters with one instrument and no extra engineering effort at the bottom lander design phase.

There are two types of dissolved oxygen sensors: electrode and optical designs. The conventional sensor is the electrode design, in which oxygen diffuses through a membrane into an electrolyte and reacts with an electrode. The measured current is proportional to the oxygen concentration. This type of sensor is sensitive to both biological and non-biological fouling, particularly in moored applications. In contrast, the optical sensor design is more resistant to fouling, as it does not depend on the sensitive membrane and electrolyte.

The selected MicroCAT logger has an integrated optical DO sensor, with the additional benefit of the pumped CT path helping to further minimize the risk of sensor fouling. Details of the SBE-37 are provided in Appendix C.1.

#### 2.2.1.4. Fish-tag Loggers

The VEMCO VR-2W fish-tag loggers were deployed on the bottom lander. They were selected due to their low cost and the large number of fish tagged with the VEMCO 69 kHz tags. Specifications of the loggers are provided in Appendix C.2.

### 2.2.2. Towed Array

*ADEON team members have made use of towed arrays owned by the USN in previous projects, and have requested access to the hardware for ADEON. We are still discussing which array and tow vessel will be employed for ADEON, if any. This section will be completed once the choice of array is resolved.*

### 2.2.3. Service Vessel Sensors

#### 2.2.3.1. EK-60 and EK-80 Active Acoustics

The EK-60 or EK-80 multibeam echo sounders provided by the UNOLS fleet of vessels gathered the active acoustic data for the ADEON program. Details of these sonars is provided in Section 4.

#### 2.2.3.2. Conductivity-Temperature-Depth

The standard oceanographic CTD available on the UNOLS vessel used for the bottom lander service trips provided local full-water-depth CTD data for ADEON.

#### 2.2.3.3. Net-tows

The ADEON project used complementary set of nets to sample zooplankton and nekton in the water column. The fish and zooplankton collected with the nets served as truth data that validated our analysis of the echo sounder data. Ring nets (net diameter between 30–75 cm) with fine mesh (~300–500 micron) were deployed vertically to capture small zooplankton.  A mid-water trawl (either a Methot (Methot 1986), Neuston (David 1965), or Isaacs-Kidd (Devereux and Winsett 1953) Midwater Trawl will be used) equipped with coarser mesh (1–5 mm) targeting specific scattering layers or features in the water column that were detected using the ship-board multi-beam echo sounders. Samples were measured, enumerated, and identified to taxonomic categories based on their acoustic scattering characteristics. Net deployment and processing methods can be found in Harris et al. (2000). Wiebe and Benfield (2003) provide a review of different net methods which may also be helpful.

## 2.3. ADEON Bottom Lander Locations and Design

### 2.3.1. Deployment Locations

The ADEON mandate requires measurements of the soundscape and ecosystem between 100–1000 m water depth in the Mid and South Atlantic OCS (Virginia to mid-Florida). Considerations for the ADEON site selection include:

- Providing good north-south and east-west coverage of the project area.
- Providing an even distribution of ranges between long-term acoustic recorders (AMAPPS and ADEON) for evaluation of the portability of soundscapes.
- Locating at least two bottom landers north of Cape Hatteras, which has significantly more biologic activity than south of Hatteras.

- Locating two recorders within deep water coral areas to assess if these areas have complex soundscapes like coral reefs within the photic zone.

The selected locations, approved by BOEM, NOAA NMFS, NOAA Office of Protected Resources, and the US Navy, are shown in Figure 2. These locations provided a distribution of distances between ADEON and additional recorders (Table 3, Table 4, and Figure 3), which should allow for assessing the soundscape portability distance. Soundscape portability distance is a measure of how far from a measured location the soundscape remains similar according the soundscape metrics employed. The Wilmington and Savanah Deep bottom landers are in proximity of known deep water coral sites (lophelia at Wilmington and other corals at Savanah Deep).

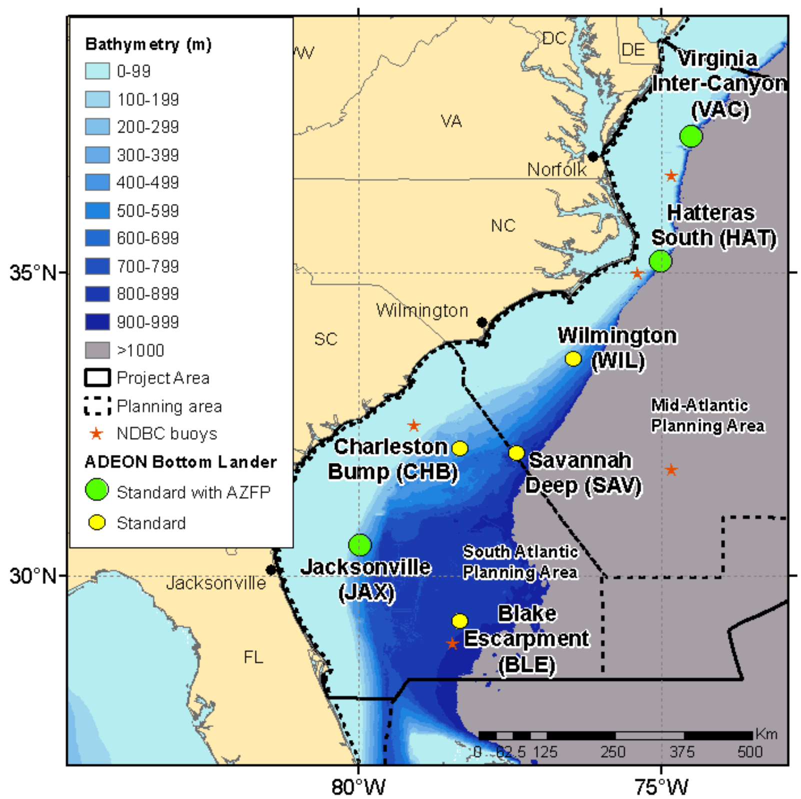



Figure 2. ADEON bottom lander locations. Locations of the NBDC buoys are shown for reference.

Table 3. ADEON bottom lander locations and water depths. Locations shallower than 400 m have the acoustic fish and zooplankton profilers. The actual lander positions will be measured by 'boxing-in' the location using the ping-response feature of the acoustic-releases.

| Location | Latitude | Longitude | Depth (m) |
|---|---|---|---|
| Wilmington | 33.57295 | −76.4614 | 461 |
| Virginia Inter-Canyon | 37.24616 | −74.5142 | 239 |
| Savannah Deep | 32.01604 | −77.401 | 802 |
| Charleston Bump | 32.1 | −78.35 | 410 |
| Hatteras South | 35.2 | −75.02 | 281 |
| Blake Escarpment | 29.25 | −78.35 | 874 |

| Location | Latitude | Longitude | Depth (m) |
|---|---|---|---|
| Jacksonville | 30.5 | −80 | 343 |

Table 4. Additional acoustic recording locations.

| Location | Latitude | Longitude | Depth (m) | Programme | Recorder type |
|---|---|---|---|---|---|
| HARP Cape Hatteras A | 35.5791 | −74.757 | 1176 | LMR | HARP |
| HARP Norfolk Canyon A | 37.1652 | −74.4666 | 1116 | LMR | HARP |
| HARP 06 | 33.6656 | −76.0013 | 961 | AMAPPS | HARP |
| HARP 07 | 32.10603 | −77.0943 | 974 | AMAPPS | HARP |
| HARP08 | 30.58378 | −77.3907 | 1010 | AMAPPS | HARP |
| NRS07 | 29.3336 | −77.9999 | 873 | NRS | PMEL |

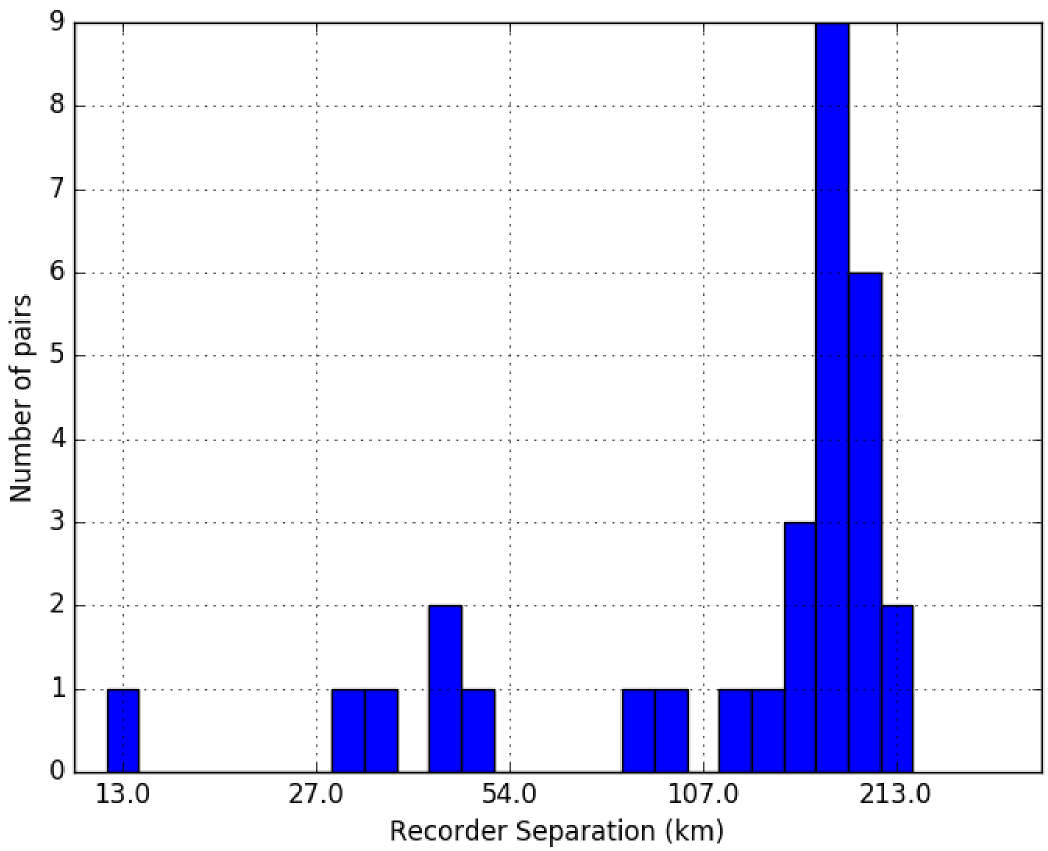



Figure 3. Histogram of ranges between all AMAPPS HARP and ADEON acoustic recorders. The X-axis is log-spaced.

## 2.3.2. ADEON Bottom Lander Design

The ADEON project area is within the Gulf Stream (e.g., Figure 4). These currents impose the following constraints on the bottom lander design:

- A fixed bottom lander is the simplest way to provide a stable platform for sensing particle velocity and/or acceleration, as well as instruments such as fish-finding sonar (AZFP).
- It is also advisable to locate pressure sensors (i.e., hydrophones) near the bottom on a fixed lander, or else large sections of a sub-surface floating mooring would need to be treated with costly fairings to reduce vortex-induced vibrations, minimize flow noise, and prevent strum.
- It must have transponders or some other method to localize the bottom lander after deployment, as significant cross-range drift may occur during deployment.
- It must have retrieval locating aids, as significant cross-range drift may be expected on retrieval, creating a large search radius.
- Acoustic propagation modeling showed that due to the generally down-ward refracting sound-speed profile the sea-bed is a desirable location for soundscape measurement (Figure 5)

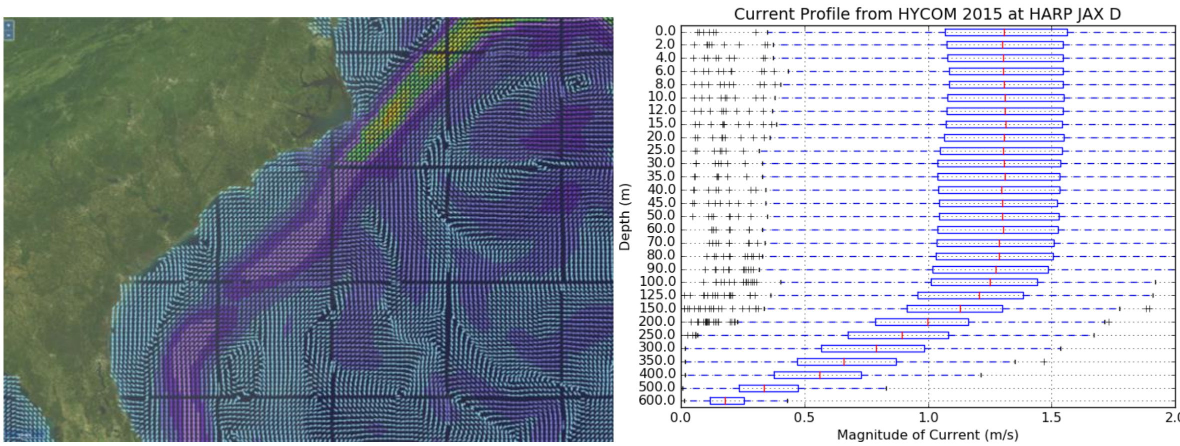
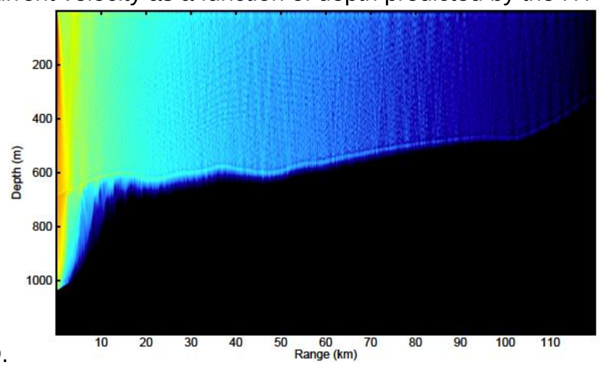



Figure 4. (Left) Sea surface currents in the project area on 18 Jul 2017 showing the Gulf Stream as purple-green-yellow and (right) distribution of daily mean current velocity as a function of depth predicted by the HYCOM model for 2015 at the site of Duke/USN recorder JAX-D.



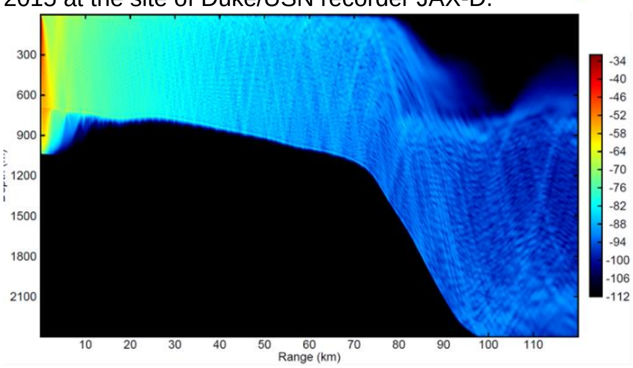




Figure 5. Acoustic propagation loss modeled for a 50-150 Hz source located at 10 m water depth above the Charleston bump. (Left) propagation to the west of the recorder location. (Right) propagation to the east of the recorder location.

To minimize flow and movement noise in the acoustic recordings from the Gulf Stream currents, ADEON used a bottom lander (Figure 6). The frame is largely composed of high-density polyethylene plastic, which will not corrode. Due to its tight pore structure, it is also a very poor substrate for biologic growth. JASCO evaluated the mechanical strength of the material and found that a four-inch section like the planned joint at the tetrahedral super-structure yields at 12,500 lbf. The bottom lander includes a dual acoustic release that holds an expendable steel anchor frame to the rest of the bottom lander (Figure 6). The bottom lander was evaluated on three separate trials to verify its mechanical and acoustic performance.

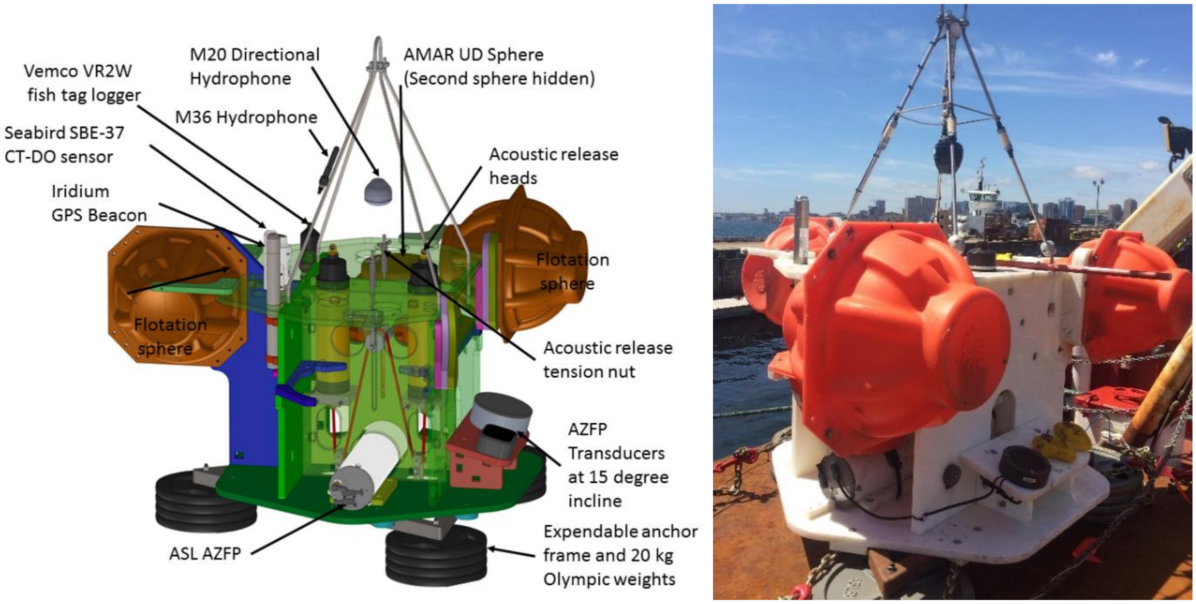



Figure 6. (Left) Bottom lander cut-away identifying the hardware components and (right) ADEON bottom lander on the deck of R/V *Odyssey* during trials in June 2017. Not shown in these images is a cylindrical flow shield around the M20 directional sensor to isolate it from flow.

# 3. Passive Acoustic Data Recorders

The objective of this section is to define the characteristics of passive acoustic data recorders that are essential for accurately measuring soundscapes. This section addresses four subjects:

1. The functional blocks of passive acoustic data recorders.
2. The distance that a hydrophone must be from typical spherical and cylindrical pressure vessels.
3. Qualitative information about minimizing self-noise when designing moorings.
4. Quantifying the performance of passive acoustic data recorders.

There are several existing Standards, Good Practice Guides, and publications concerning acoustic data terminology and metrics, passive acoustic data recorders and measurements that this section endeavors to clarify and amplify. The order of precedence is:

1. This specification.
2. The ADEON Soundscape Specification.
3. [ISO] International Organization for Standardization. 2017. ISO 18405.2:2017. *Underwater acoustics—Terminology*. Geneva. https://www.iso.org/obp/ui/#iso:std:iso:18405:ed-1:v1:en.
4. IEEE. STD-1241-2010. IEEE Standard for Terminology and Test Methods for Analog-to-Digital Converters. DOI: 10.1109/IEEESTD.2011.5692956.
5. IEEE. STD-1057-2007. IEEE Standard for Digitizing Waveform Recorders.
6. Texas Instruments. 2011. *A Glossary of Analog-to-Digital Specifications and Performance Characteristics*. TI Application Report SBAA147A. Originally published August 2006. Revised October 2011.
7. The ADEON Calibration and Deployment Good Practice Guide.
8. Robinson, S.P., P.A. Lepper, and R.A. Hazelwood. 2014. Good Practice Guide for Underwater Noise Measurement. *In* National Measurement Office, Marine Scotland, and The Crown Estate (eds.). *NPL Good Practice Guide No. 133*. National Physical Laboratory. 97.
9. Sousa-Lima, R.S., T.F. Norris, J.N. Oswald, and D.P. Fernandes. 2013. A review and inventory of fixed autonomous recorders for passive acoustic monitoring of marine mammals. *Aquatic Mammals* 39(1): 23-53. http://mhk.pnnl.gov/sites/default/files/publications/Sousa_Lime_et_al_2013.pdf.

## 3.1. Functional Blocks of Passive Acoustic Data Recorders

Figure 7 is a functional block diagram for passive acoustic data recorders. The blocks are described in the sub-sections below.

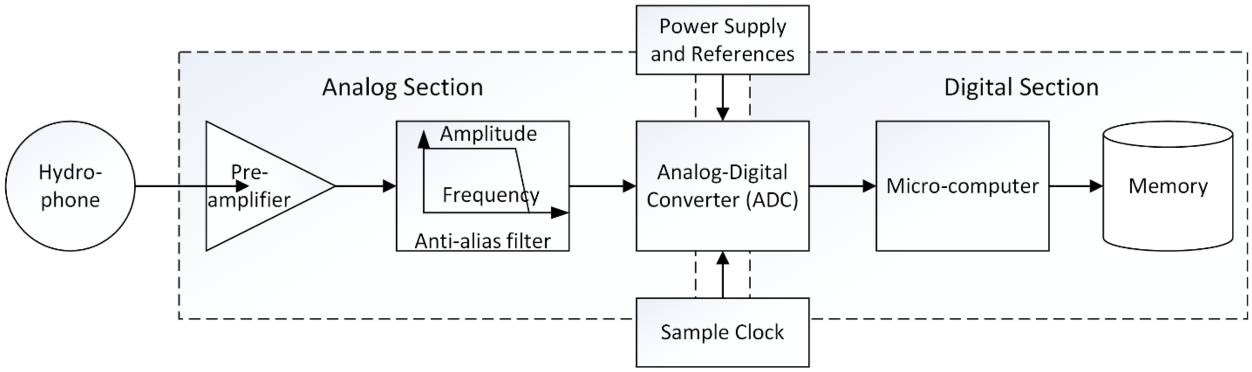



Figure 7. Block diagram of a passive acoustic data recorder.

### 3.1.1. Hydrophones

Hydrophones are the transducers that convert pressure fluctuations in the water to an electrical charge. Most hydrophones include a preamplifier that converts the charge to a voltage or current that is transmitted to the analog section of the recorder.

For hydrophones with built-in preamplifiers with voltage outputs, the voltage sensitivity is specified in units of volts per Pascal ($M_v$ in V/Pa) or as a sensitivity level in decibels relative to 1 V/µPa (dB re 1 V/µPa).

For hydrophones that use current signaling, the current sensitivity shall be specified in units of amperes per Pascal ($M_I$ in A/Pa).

The absolute sensitivity varies slightly from between hydrophones, even within the same production batch. Similarly, the sensitivity changes with frequency. Hydrophones should be purchased with a *measured* calibration curve supplied by the vendor. For accurate quantification of sound levels, the calibration curve must be included in the analysis of sound levels (see Appendix A).

The sensitivity of the sensing element impacts the overall self-noise of the hydrophone. The hydrophone preamplifier's input referred noise should be specified as an equivalent sound pressure level (SPL) in the water through the sensing element's sensitivity. The greater the sensitivity of the sensing element, the lower the hydrophone's self-noise for the same preamp input referred noise.

Hydrophones have a range of amplitudes over which their output is linearly related to the input pressure. Extreme care must be employed if the hydrophone is used outside of its linear range.

Hydrophones can be modeled as a voltage source in series with the sensor's capacitance or a charge source in parallel with the capacitance. The sensor will build a charge due to the static pressure caused by its depth or changes in depth. This charge is discharged through the preamplifier's input impedance. If the hydrophone's output is AC-coupled to the recorder's input, there is a charge time for the AC coupling during power up. For hydrophones and recorders with good low-frequency response (i.e., below 10 Hz), the input impedance is very high, and the charge and discharge times can be seconds long, during which time the hydrophone output should be discarded.

### 3.1.2. Preamplifiers

The preamplifier can be integrated into the hydrophone, and there may be a separate preamplifier that is part of the recorder. Preamplifiers can be used to:

- Buffer the sensing element from the input to the ADC.
- Amplify hydrophone signals before analog-to-digital conversion if the dynamic range of the ADC is smaller than that of the hydrophone (e.g., for the Aural M2).
- Force analog-to-digital input to exceed the maximum range of the ADC, so that the ADC reaches its maximum output before the hydrophone becomes non-linear.

The frequency response and gain of the preamplifier is required for converting the input voltage to pressure (Appendix A).

In differential input systems, the common-mode rejection ratio (CMRR) is the ratio of the signal in the output to an in-phase signal on both inputs. In an ideal system, the CMRR would be zero.

Power supply rejection ratio (PSRR) is the ratio of the signal in the output to a signal on the power supply. In an ideal system, the PSRR would be zero. When battery powered recorders write data to memory, the increased power draw can decrease the battery pack voltage enough to generate a large signal on the power supply. Hydrophone preamplifiers must buffer the outputs against this voltage change.

### 3.1.3. Analog-to-Digital Converters and Anti-Aliasing Filters

Analog-to-Digital Converters (ADC) create a digital representation of a real-world analog signal. They represent the continuously varying analog signal with the closest value from a discrete ‘stair-case’ of levels that they may generate. They are characterized by:

- The sampling rate (i.e., how many times per second the analog input is converted to a digital representation). By the Nyquist theorem, the maximum frequency that is accurately represented by the digital data is one-half the sampling rate. Frequencies above the Nyquist frequency must be filtered from the analog input signal prior to digitization, otherwise they will ‘alias’ into lower frequencies and the digital signal will not be an accurate representation of the original analog input.
- Maximum input voltage.
- Bit depth (i.e., the number of ‘bits’ of digital resolution the ADC generates). The larger the number of bits for the same maximum input voltage, the smaller the distance between the discrete levels that the ADC can represent. Thus, a higher bit depth means better representation of the data (higher resolution).

The two main types of ADCs used in digital recorders are Successive Approximation Register (SAR) and Sigma-Delta:

- SAR ADCs tend to be used for medium to high resolution applications at sample rates up to 5 MHz. They are usually a lower power option than Sigma-Delta converters for the same resolution and sample rate; however, they require external anti-aliasing filters.
- Sigma Delta ADCs use an over sampling technique whereby they sample the input with a 1-bit ADC at a very high sample rate and then digitally filter and decimate to provide an output at a lower sample rate and a higher bit width. The primary advantage of a Sigma Delta ADC is that the analog anti-aliasing requirements are greatly relaxed due to the high input sample rate.

For an ideal ADC, the number of bits in the output word places a limit on the noise floor of the converter. However, recorders with output word size greater than 16 bits, the system self-noise is usually greater than the quantization noise of an ideal ADC with that word size. Specifying an ADC with 18 or 24 bits does not necessary guarantee better system performance. An output word size may need to be specified if the processing requires a specific word length.

#### 3.1.3.1. Oversampling

With an oversampling converter, the sample rate of the ADC is at a much higher frequency than the analog bandwidth at the input. The advantages of oversampling are the lowering of the quantization noise contained within the passband, and moving sampling harmonics out of the band of interest. Increasing the Oversampling Rate by two, then filtering and decimating theoretically increases the signal to noise level ratio (SNR, see Section 3.4.4.4) by 3 dB.

The system's SNR only improves if the ADC quantization noise is the limiting factor affecting the system noise. If the limiting factor is noise from other sources, such as hydrophones or preamps, then increasing the sample rate will not improve the SNR.

It is easier to design analog anti-aliasing filters using oversampling techniques. The analog filter only needs to meet the requirements of the oversampling frequency. Digital techniques can then be used to filter and decimate to a lower output sample rate.

### 3.1.4. Sample Clocks

ADC sampling rates are set by an external sample clock. The accuracy and stability over temperature and power supply variations of the sample clock depends on the type of clock or oscillator used. The initial frequency at room temperature can have a tolerance of ±50 parts per million (ppm; i.e., 50 µHz/Hz) for a standard crystal oscillator to ±<1 ppm for a good temperature controlled crystal oscillator (TXCO) to ±<0.01 ppm for a chip-scale atomic clock (CSAC). The TCXO and CSAC hold their accuracy over the temperature range of most underwater deployments (−5 °C to +35 °C), whereas the standard crystal oscillator will vary by several additional parts per million over the temperature range.

Note that if the specified sampling rate was 1,000,000 Hz, the actual rate for a 50 ppm component could be in the range 999,950–1,000,050 Hz. Every part per million error in the sample frequency equates to an error in time of 0.604 seconds per week (i.e., 30 seconds per week for 50 ppm!). If the recorder needs to be time synchronized to other devices or external events, this clock drift must be accounted for.

### 3.1.5. Digital Sections

The digital section of a recorder assembles the digital samples into larger units that are either transmitted electronically for further use, or stored to disk or digital media (e.g., SD cards). It may also process components such as addition of error correction codes, compression, and detection of signals of interest (such as marine mammal clicks). Many recorders that employ hard disk drives stop sampling while writing from short-term buffers to the disk because the hydrophones would measure the vibrations of the disk motors and contaminate the recordings.

High-frequency switching in digital sections can create electrical noise that radiates into the hydrophone-preamp-ADC signal chain and appears in the recorded data. It can be a baseband signal or a higher frequency signal that has aliased into the bandwidth of the recorded data.

An often-overlooked noise source is acoustic noise generated by switching power supplies. Inductors in the power supplies can generate acoustic noise due to the magnetostriction from the alternating currents causing the inductor windings and cores to move and vibrate. Capacitors can generate acoustic noise due to electrostriction occurring when the ripple voltage in the input power causing the plates of the capacitors to move and vibrate. This noise is often undetectable in air due to the poor acoustic coupling to the hydrophone, but can be detected when the system is deployed in water. These issues must be dealt with by re-working the system electronics.

## 3.2. Hydrophone Mounting Relative to the Pressure Vessel

The ideal acoustic recorder is a 'point-receiver' that measures the sound field without disturbing it. Underwater passive acoustic data recorders are components of moorings that include at minimum a recorder, ropes, and anchors. They often also include flotation, other sensors, retrieval beacons, and acoustic releases. The acoustic recorder comprises at least one pressure vessel for the recorder electronics and the power source, normally batteries. These structures can reflect sound and shadow the hydrophone, resulting in measurements that inaccurately represent the soundscape. These effects increase when the size of the structure is greater than or equal to the wavelength of the sound being measured.

To mitigate these effects, mooring designs should:

- Locate the hydrophones above all pressure vessels and large mooring components;
- Orient the hydrophones vertically;
- Separate the hydrophones from all pressure vessels and horizontal flat surfaces by at least 25 cm.

Recorders whose hydrophones are located on or beside a cylindrical or spherical pressure vessel may be used for characterizing the presence of marine life. They ***should not*** be used for making calibrated ambient measurements for frequencies greater than c/(2*L), where c is the sound speed and L is the largest dimension of the pressure vessel. Figure 8 demonstrates the importance of the hydrophone being located away from the pressure vessel.

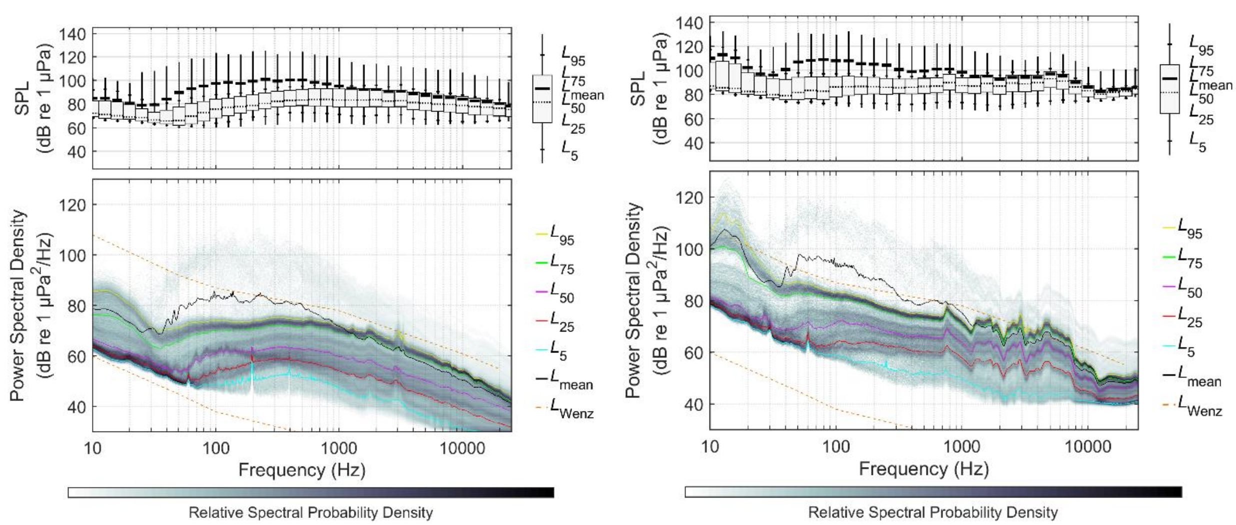



Figure 8. Percentile spectra from two recorders deployed 10 m apart for 5 days in February 2013 in 50 m of water. Only one vessel was present during the recordings for a 6 hour period. Both recorders were suspended on moorings 3 m long with a float 1 m above the recorder. The left-hand data are from a recorder with a 15-cm diameter, 70-cm long plastic pressure vessel where the hydrophone was 25 cm above the pressure vessel. The right-hand data are from a similarly shaped pressure vessel where the hydrophone was attached to the pressure vessel endcap. The deflections in the spectra are caused by constructive and destructive interference of reflected ambient sound. Similar results are obtained for recorders where the hydrophone is mounted directly beside glass sphere pressure housings. The bumps in the L95 percentile of the left-hand results at 3–5 kHz are mooring chains ~1 km from the test site. These should be visible in the right-hand side as well, but are lost in the noise artifacts.

## 3.3. Designing Moorings to Minimize Self-Noise

Acoustic recordings may be contaminated by self-noise (see Figure 1 of ISO 2017) due to mooring movement, current flow around hydrophones, and noise generated by mooring components (see Section 4.3 of Robinson et al. 2014). It is important to remember that hydrophones are pressure fluctuation sensors. Currents moving past a hydrophone can cause pressure fluctuation vortices to form behind the hydrophone, which are measured as sound, even though they are caused by the current. Similarly, vertical movement of hydrophones is a pressure fluctuation. Using the hydrostatic equation, a 1 cm vertical movement of a hydrophone results in a 100 Pa change in pressure:

$$P = \rho g h;\ \Delta P = \rho g \Delta h$$

$$\Delta P_{1\,cm} = 1040\,\frac{\text{kg}}{\text{m}^3}\cdot 9.81\,\frac{\text{m}}{\text{s}^2}\cdot 0.01\,m \sim 100\,\frac{\text{kg}}{\text{ms}^2} = 100\ \text{Pa}$$

An oscillatory vertical motion of amplitude 1 cm therefore leads to an rms pressure fluctuation of 71.7 Pa. If the same pressure fluctuation were caused by sound it would correspond to a sound pressure level of 157 dB re 1 µPa.

Vertical movement and equivalent changes in pressure may be caused by waves in shallow water or by horizontal movement of a moored hydrophone due to currents resulting in a vertical movement. The fundamental frequencies of vertical movement are usually low (< 1 Hz); however, it generally has a turbulent frequency spectrum that falls off as frequency$^{-5/3}$ and can be a significant noise source at hundreds of hertz (Figure 9). In many recordings, examining the broadband sound levels aligned with the start of the tidal cycle is an easy method of visualizing if flow noise from tidal currents are a problem (Figure 10).

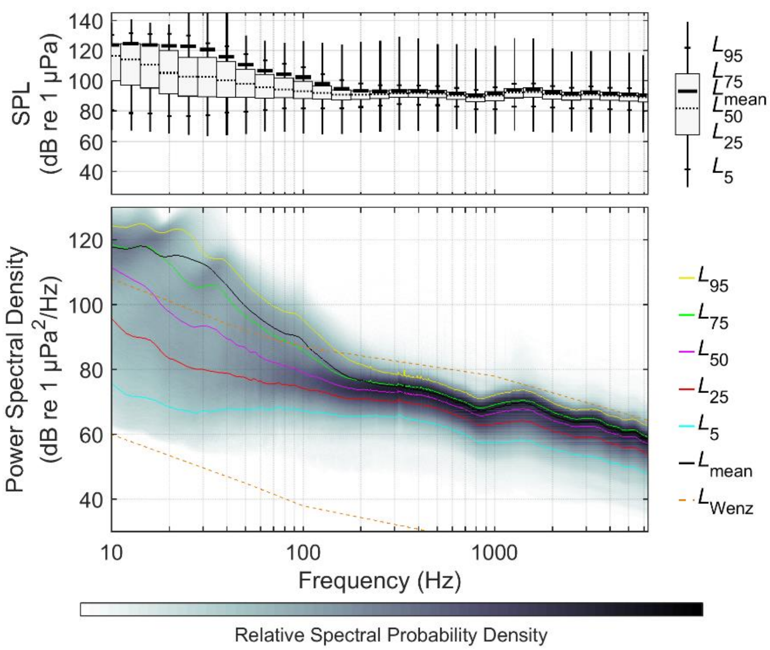



Figure 9. Example (top) 1-min decidecade SPL distributions and (bottom) percentile spectra that are dominated by flow noise. The data were collected over a four-month period using a bottom lander that floated the recorder 3 m above the seabed in an area with surface flow speeds up to 2 m/s (water depth ~150 m). These measurements can not be used to characterize the long-term soundscape below ~200 Hz.

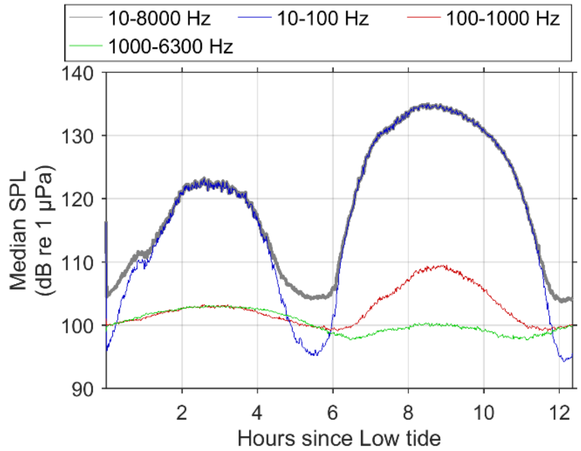



Figure 10. Data from Figure 9 aligned to the start of low tide and averaged every 5 minutes for the 4 month recording. At this location, there is more self-noise from tidal currents generated during the ebb current than the flood current, which is usual.

Moorings that fix the hydrophone position relative to the seabed, rather than suspending the hydrophone using anchors and flotation, are strongly recommended for any measurements in areas with currents greater than 0.1 m/s. The HYCOM model (see https://coastwatch.pfeg.noaa.gov/erddap/griddap/) can be used to estimate typical bottom currents at a project site.

It is best practice to protect hydrophones with flow shields and/or wraps that disrupt turbulent boundary layers. Similarly, supports and framework near the hydrophone should be wrapped.

## 3.4. Quantifying Recorder Performance

When quantifying the recorder performance, the complete system including the hydrophone should be evaluated. This section provides definitions for key acoustic data recorder performance metrics and guidance on how to measure them. Appendix B provides a recommended specification sheet as well as minimum specification values and the specifications of the AMAR recorders used by ADEON.

General guidance:

- When making measurement the test record should be long enough that the system has reached steady state and any effects of turn-on have settled out (e.g., Hydrophone AC settling times, Section 3.1.1). Additionally, the test record should have enough samples after the settling time for the chosen FFT size and number of averages. The settling time is determined by factors such as the time constant created by the low frequency roll-off pole and stabilization times of the power supplies and electronics. An initial recording should be made with the input to the recorder terminated with the equivalent impedance of the hydrophone to measure how long the recorder takes to stabilize to an error level that does not adversely affect the analysis.
- If the system performs periodic tasks such as writing to disk or memory, the test record should include samples of these periods to detect any artifacts they may introduce.

## 3.4.1. Signal Input & Hydrophone Testing

### *3.4.1.1. Noise Testing*

It can be difficult to evaluate system noise with a working hydrophone. The hydrophone must be placed in an anechoic environment with an ambient noise below the hydrophone's self-noise. An alternative is to use a dummy hydrophone that has the same preamp as the actual hydrophone, but instead of being connected to a transducer, it terminates with the equivalent transducer impedance. Should a dummy hydrophone not be available, the recorder can be terminated with the equivalent output impedance of the hydrophone and its noise measured. To obtain the total system noise, the hydrophone noise (as specified by the hydrophone vendor) should be added to the recorder noise by taking the square root of the sum of the squares of the two rms noise voltages.

The measurements must be made at the same sample rate as will be used during the deployment because sample rate can impact the quantization noise contribution of the ADC and possibly introduce undesired artifacts.

The hydrophone and recorder should be shielded from RF interference.

### *3.4.1.2. Frequency Response*

Special facilities are required to verify the frequency response of a hydrophone and recording system. Reflections of the test signal from seafloor and surface or the walls of a test tank limit the time available to make a measurement. For accurate measurements, a hydrophone-specific calibration from a specialized testing facility should be obtained from the hydrophone vendor. The calibration must then be included in the data analysis (see Appendix A).

Sensitivity testing at spot frequencies can be accomplished using calibration instruments, such as pistonphones, that generate a known source level at a specific frequency. The typical frequencies for spot calibrations are 100 and 250 Hz. The results of the spot calibration may then be used to move the entire calibration curve to account for small changes in sensitivity over time.

The frequency response of the hydrophone may change over time due to aging of the sensing element and due to moisture migrating through the protective covering. The first indication of moisture reaching the sensing element is an increase in the low-frequency roll-off due to leakage across the sensing element. As the leakage across the sensing element increases, the fundamental sensitivity of the hydrophone can be reduced.

The hydrophone sensitivity should be verified immediately after retrieving the system from the water, before the moisture can migrate out of the protective covering. The low-frequency response of the hydrophone should be verified after long deployments (greater than 2 months) for each hydrophone model until the moisture protection can be verified. The frequency response of the recorder should not change over time.

## 3.4.2. Data Analysis

The fast Fourier transform (FFT) is a mathematical method for converting the sampled data from the time domain to the frequency domain. The parameters in the following subsections should be considered when setting up the FFT analysis.

### 3.4.2.1. FFT Windowing

Windowing is required to prevent spectral leakage when analyzing the data using an FFT. The output of the FFT must be corrected for the effect of the window function. When processing the data to calculate the level of tones, the results should only be corrected for the window function, not the FFT bin width. When processing the data to calculate the spectral noise floor, the results should be corrected for both the window function and the FFT bin width. Thus, it is not possible to correctly calculate both the tone level and the noise floor with the same calculation. Additionally, different window functions are more suited to tones (flat top) and noise (Hann).

To correct for the window function, multiply the mean square value by the square root of the sum of the squared window function amplitudes divided by the number of points in the window. To correct for the FFT bin width, divide the mean square value by the square root of the FFT bin width.

### 3.4.2.2. Averaging

When using averaging to smooth the FFT data, overlapping FFTs should be used to ensure that no data is missed due to the windowing. Averaging will not change the noise floor; it will only reduce the variance of the FFT results.

### 3.4.2.3. FFT Resolution

The choice of FFT length relative to the sample rate will depend on the desired frequency resolution required by the analysis. The frequency resolution of the FFT is:

$$\mathrm{R} = \frac{F_s}{N_{FFT}}\ \mathrm{Hz}$$

where $F_s$ is the sampling rate and $N_{FFT}$ is the number of points in the FFT.

## 3.4.3. Time Series Parameters

### 3.4.3.1. Full-scale Signal

The full-scale signal of the ADC is the peak to peak value that spans the entire range of the ADC's digital output. This is used to calculate the digital sensitivity of the acquisition system.

When calculating the dynamic range (DR) the root mean square (rms) value of the full-scale signal is used.

## 3.4.4. Spectral Parameters

Figure 11 shows the relationship between various parameters of a data acquisition system.

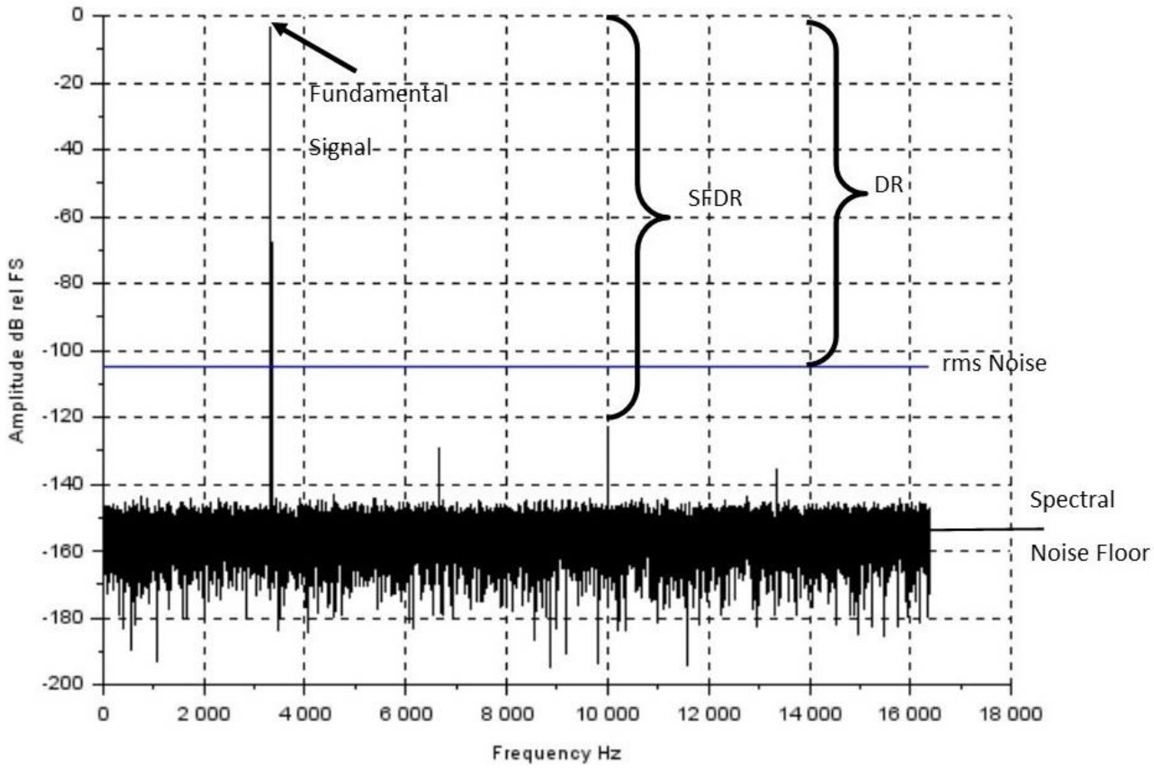



Figure 11. Frequency spectrum: Dynamic parameters.

### *3.4.4.1. Non-acoustic Self-noise*

Non-acoustic self-noise is defined as any signal in the output spectrum that is not caused by a linear time-invariant response to the input signal.

To measure the self-noise of the recorder, the recorder should be terminated with the equivalent impedance of the hydrophone. The system should be placed in an electrically shielded environment.

### *3.4.4.2. Spectral Noise*

If the noise power spectral density is being measured, the unit is volt squared per hertz. If the noise power spectral density *level* is being measured, the unit is the decibel, with a reference value of 1 $V^2$/Hz.

### *3.4.4.3. rms Noise*

The rms noise is the square root of the sum of the noise power spectral density for the frequency band of interest. In Figure 11, the broadband rms noise is shown by the blue line. The rms value of the noise is used to calculate parameters such as signal to noise ratio (SNR), dynamic range (DR), spurious free dynamic range (SFDR), signal to noise and distortion (SiNAD), and effective number of bits (ENOB).

### 3.4.4.4. Signal to Noise Ratio

The signal-to-noise ratio (SNR, symbol $\Delta L_{SN}$) is defined as the difference, in dB, between the signal power and noise power:

$$\Delta L_{SN} = 10log_{10}\left(\frac{V_s^2}{V_n^2}\right)\text{dB} = 10log_{10}\frac{P_S}{P_N}\text{dB} = 10log_{10}(V_s^2)\text{dB} - 10log_{10}(V_n^2)\text{ dB}$$

where $V_n^2$ is the sum of over the signal duration of the noise voltage squared which equals the noise power $P_N$, and $V_s^2$ is the sum of over the signal duration of the signal voltage squared which equals the signal power $P_S$.

### 3.4.4.5. Dynamic Range

The dynamic range ($R_D$) is the signal to noise ratio when the signal is the maximum possible input signal and the noise is the system electronic noise floor. Dynamic range is often incorrectly specified as:

$$10log_{10}\left(\frac{V_{signal\ peak}}{V_{spectral\ noise}}\right)^2\text{dB ,}$$

where $V_{signal\ peak}$ is peak voltage of the signal and $V_{spectral\ noise}$ is the spectral noise density. This results in a value that is 3 dB +$10\log_{10}$ (bandwidth, in Hz) dB larger than the true dynamic range, 3 dB for the peak to rms conversion and $10\log_{10}$(bandwidth, in Hz) dB for the spectral to rms noise conversion.

### 3.4.4.6. Signal to Noise Pressure Ratio

The signal to noise pressure ratio (SNPR, symbol $R_{SN}$) is defined as the ratio of the mean square signal voltage to the mean square noise voltage.

### 3.4.4.7. Total Harmonic Distortion (THD)

Total harmonic distortion (THD, symbol $D_{\text{th}}$) is the ratio of the amplitude of a pure sine wave of a specified frequency and amplitude to the square root of the sum of the squared amplitude of a specified number of harmonics. The amplitude of the input signal should be large enough that it and the generated harmonics are above the spectral noise floor, but far enough below the maximum input level that clipping does not occur. Since the THD can vary with input level and frequency, both must be specified. The number of harmonics used should include all bins where the harmonic tone level is above the spectral noise floor. Ideally the first 9 harmonics are used. THD is expressed either as a percent or in decibels.

It can adversely impact the signal processing if the THD becomes large well below the specified maximum signal. Ideally, the signal would be linear and have constant gain, until hard clipping at its maximum:

$$D_{\text{th}} = 10log_{10}\left(\frac{V_2^2+V_3^2+\cdots+V_n^2}{V_1^2}\right)\text{ dB .}$$

$V_1$ is the rms voltage of the fundamental signal. $V_2$, $V_3$, … $V_n$ are the rms voltages of the harmonics of the fundamental signal.

When testing recorders to be used for soundscape measurements, a tone of 250 Hz at a level 6 dB below full scale should be used. The THD level of the signal source should be at least 10 dB below the THD of the device under test.

### 3.4.4.8. Intermodulation Distortion (IMD)

If the input signal contains multiple tones, the generated distortion is not only the integer harmonics of the tones, but also the sums and differences to the tones. This distortion is created due to nonlinearities in the system. It is referred to as intermodulation distortion (IMD).

When testing for IMD, apply a test signal of two tones each with a level 12 dB below full scale. The magnitude of the IMD signals are found at the sum and differences of the two tones and their harmonics. The THD level of the signal source should be at least 10 dB below the THD of the device under test.

### 3.4.4.9. Spurious Free Dynamic Range (SFDR)

Spurious free dynamic range (SFDR, symbol $R_{\mathrm{sfd}}$) is the distance in decibels on an spectral plot from the fundamental input signal to the worst or highest spur. SFDR can be specified with respect to full-scale input range (in dB).

When testing recorders to be used for soundscape measurements, a tone of 250 Hz at a level 6 dB below full scale should be used. The THD level of the signal source should be at least 10 dB below the THD of the device under test.

### 3.4.4.10. Signal to Noise and Distortion (SiNAD)

Signal to Noise and Distortion (SiNAD) is the ratio of the mean-square value of the fundamental signal to the sum of all other in-band spectral components, expressed in decibels:

$$SiNAD = 10log_{10}\left(\frac{V_1^2}{V_2^2+V_3^2+\cdots+V_n^2+V_{noise}^2}\right)\ \mathrm{dB}\ .$$

$V_1$ is the rms voltage of the fundamental signal. $V_2$, $V_3$, … $V_n$ are the rms voltages of the harmonics of the fundamental signal. $V_{noise}$ is the square root of the sum of the squared in-band noise voltage.

When testing recorders to be used for soundscape measurements, a tone of 250 Hz at a level 6 dB below full scale should be used. The THD level of the signal source should be at least 10 dB below the THD of the device under test.

### 3.4.4.11. Effective Number of Bits

For an ideal ADC with no distortion and the only noise source is quantization noise, the full-scale input sine wave is:

$$V(t) = \frac{q2^n}{2}\sin(2\pi f t)\ .$$

The rms value of the full-scale input is:

$$V_{rms} = \frac{q2^n}{2\sqrt{2}}\ ,$$

where q is the value of one bit.

The uncertainty of an ADC converter bit is ±1/2 least significant bit (LSB). Assuming the error response across one bit is triangular, the rms value of the quantization noise ($V_{QN}$) of the error is equal to the magnitude of the uncertainty divided by √3:

$$V_{QN} = \frac{\frac{\pm(LSB)}{2}}{\sqrt{3}} = \frac{q}{\sqrt{12}}\ .$$

The signal to quantization noise ratio ($\Delta L_{SQN}$) is:

$$\Delta L_{SQN} = 10log_{10}\frac{V_{FS}^2}{V_{QN}^2}\ \text{dB}$$

$$\Delta L_{SQN} = 10log_{10}\left[\frac{q2^{2n}/2\sqrt{2}}{q/\sqrt{12}}\right]\text{dB} = 10log_{10}2^{2n}\text{dB} + 10log_{10}\sqrt{\frac{3}{2}}\text{dB} = (6.02n + 1.76)\ \text{dB}$$

where ‘n’ is the effective number of bits of the analog-to-digital system.

### 3.4.5. System-level Parameter - Crosstalk

In multichannel systems, crosstalk is the undesired signal level in an undriven channel due to the signal level in a driven channel. Crosstalk causes errors when bearings are calculated from the relative signal strengths in the different channels. Crosstalk is often frequency dependent, an usually increases with frequencies.

To measure crosstalk, terminate the channel to be tested with equivalent impedance of the hydrophone. Place the unit in an electrically shielded environment. Inject an in-phase signal into all other channels at a level 6 dB below full scale. Measure the signal level in the terminated channel. This test should be repeated at multiple frequencies across the band of interest. The test should be repeated for each channel.

## 3.5. System Performance

### 3.5.1. Maximizing Dynamic Range

To maximize the dynamic range of the system, the maximum linear output of the hydrophone should be matched to the maximum input of the ADC. Often the gain of the hydrophone becomes non-linear before it hard limits, or clips. Matching the maximum linear output of the hydrophone to the maximum input of the ADC causes the ADC to hard limit before the hydrophone becomes non-linear. Hard limiting makes it easier to identify overload conditions in the data.

### 3.5.2. Overload

The hydrophone sensitivity should be selected to prevent it from overloading from expected signal levels (both in and out of band). It is not only the peak signal at one frequency that can cause overloading. The total energy that the hydrophone is exposed to must not exceed the maximum level of the hydrophone. Once a stage in the signal chain overloads, filtering later in the signal chain will not correct the problem, it will only mask that the problem has occurred.

Recovery from overload is important. If a signal larger than the system can handle occurs, it is important to know how quickly the system recovers from the overvoltage event.

### 3.5.3. Dominant Noise Source

The dominant noise source is determined by comparing the output referred noise of the hydrophone to the ADC input referred noise. The larger of the two is the dominant noise source. Since the ADC spectral noise can depend on sample rate (the spectral noise floor reduces by 3 dB for every doubling of the sample rate), the dominant noise source may depend on the sample rate. At lower sample rates, the ADC may be the dominant source. At higher sample rates, the hydrophone may be the dominant source.

If the recorder noise floor is measured without the hydrophone, it is important to know how the hydrophone noise contributes to the noise floor of the system. The system noise can be referred to as an SPL in the water through the sensitivity of the hydrophone.

# 4. Active Acoustic Recorders

This section defines the characteristics of echo sounder systems that are essential for accurately measuring fish and zooplankton biomass using acoustic backscatter from the water column and to describe the hardware selected for ADEON. This section discusses:

1. Remotely deployed echo sounder systems
2. Vessel mounted echo sounder systems

Echo sounders measure and record acoustic returns from the ocean bottom and scatterers in the water column. Scatterers can be biological (fish, zooplankton) or geophysical (sediment, gas plumes) in nature. A time clock triggers pulses at a specified rate to the transmitter (Figure 12 (1)). The transmitter produces an electrical ping of specified duration and frequency (Figure 12 (2)). The transmitter output is received by the transducer as electrical energy and is converted to acoustic energy (or pressure). The acoustic energy is emitted from the transducer into the water column and propagated within the echo sounder beam (Figure 12 (3)). The width of the echo sounder beam is inversely proportional to the frequency of the pings generated. Nominal 3 dB beam widths for single beam echo sounders is typically 5–15$^{o}$. When the propagating pulse encounters a target in the water column, reflected energy (or echo) is bounced back to the transducer. This backscattered energy or echo is received by the transducer and converted to electrical energy (Figure 12 (4)). The receiver generates the time difference between the electrical signal emission and return for determining distance, and the signal is amplified for display or storage (Figure 12 (4–5)).

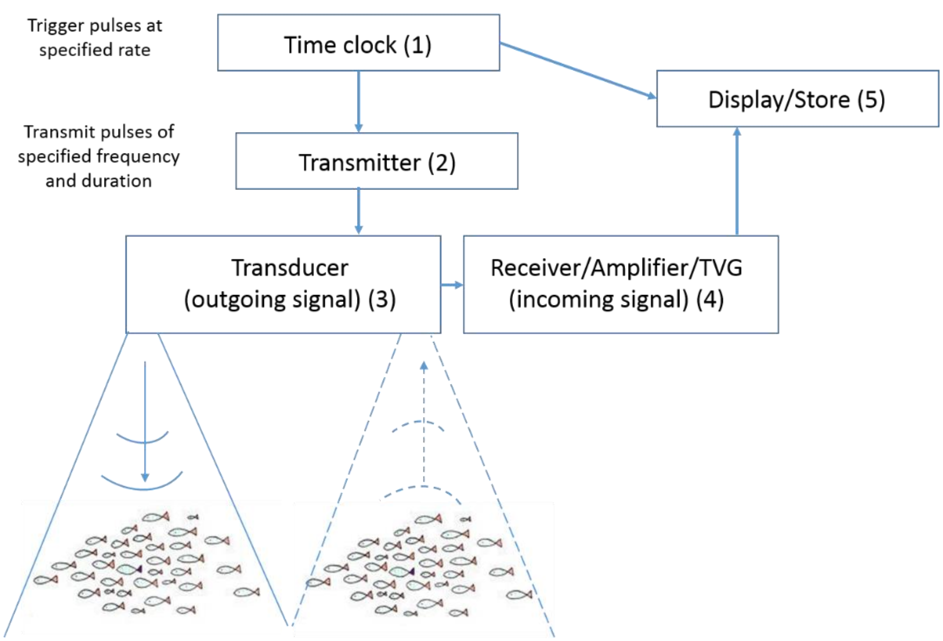



Figure 12. Generalized concept of a downward looking echo sounder. Remotely deployed echo sounders can also be positioned looking upward or sidewards. Returning echoes ca be viewed as an echogram on a display or stored within the system for future analysis.

There are three basic categories of scientific echo sounder transducers: single-beam, split-beam, and multi-beam. Single-beam systems are widely-used and cheaper than the other two systems. The data they collect is used to estimate volume backscatter strength ($S_v$ =10log10($s_v$), where $s_v$ is the volume backscattering coefficient in $m^{-1}$), which is the integrated measure of echo energy for a volume of water at a specific range from the transducer. Split-beam systems are more expensive, but the received signal is measured along 4 (or in some cases 3) sub-sections of the transducer face. This approach allows split-beam systems to measure the phase difference in the echoes received by the different quadrats, which produces backscatter measurements of single targets within the volume of water ensonified. Thus split-beam systems can collect target strength (TS) measurements (including the 3-D position of these targets) in addition to $S_v$ data. The positional information of the TS measurements can be very powerful and may allow for deeper analysis of the data such as tracking the movement of individual targets over multiple pings thus providing information on the behavior of some targets. Multi-beam systems are usually thought of as bottom-mapping sonars; however, there are several models that can collect water column backscatter data ($S_v$). Many national fishery survey vessels are equipped with these systems. These systems can collect 3-D swaths of the water column, sampling much larger volume of water compared to the smaller beamwidth single- and split-beam systems. However, these systems are larger, more expensive, require fine-scale position and attitude sensor integration, and since targets may be ensonified at angles off-of-vertical (relative to single- and split-beam systems), the interpretation of multi-beam water column backscatter data can be challenging.

## 4.1. Remotely Deployed Echo Sounder Systems

### 4.1.1. Remote Deployment Hardware Limitations and Trade-offs

Remotely deployed echo sounder systems can be deployed in a downward, upward, or sideward looking position. In deployment regions where a surface expression increases overall risk to the instruments, echo sounder systems are typically deployed on a bottom lander looking up or within a sub-surface mooring line oriented slightly off vertical to minimize interference from sensors higher up on the mooring line. ADEON is integrating a single-beam echo sounder system into 3 of the 7 bottom lander platforms. The transducers are mounted at an approximate $15^{o}$ angle off vertical to eliminate interference from the lander sensors and flotation mounted above the transducers (Figure 6).

The remote deployment of an archival echo sounder system requires a trade-off between power and storage space. Flexibility in battery power comes from balancing the instrument duty cycle, ping rate per sampling cycle, ping duration, and onboard processing (i.e., averaging before storing). Internal storage is maximized through the balance of duty cycle, ping rate per sampling cycle, sampling range, averaging (temporal and spatial resolution). The maximum possible sampling range is determined by the size of the internal data buffer and internal analog-to-digital (A/D) sampling rate. Storage space can also be conserved in some systems by specifying a lockout range. A lockout range can be specified for the region directly in front of the transducer where electronic “ringdown” renders the data unusable. Alternatively, if the user is only interested in a specific depth of the water column, a lockout range can be specified to exclude unwanted regions of the water column.

### 4.1.2. The Selected Remote Deployed Echo Sounder System: Acoustic Zooplankton Fish Profiler (AZFP)[1]

The AZFP (ASL Environmental Sciences) is a self-contained instrument designed to measure and record acoustic returns from the water column. The AZFP can be deployed in depths up to 600 m in its anodized aluminum underwater pressure housing and will operate for extended periods up to a year with its internal battery. A deep-water version is available up to 6000 m with advance special order. The instrument is equipped with up to 4 echo sounder channels, each operating at a different acoustic frequency. The ADEON AZFPs will contain transducers operating at 38, 125, 200, and 455 kHz. A four-frequency system was selected to maximize the amount of information provided for determining community structure from multiple scattering groups. The transducers for each frequency all have similar nominal beamwidth of 7–8 degrees, except for the 38 kHz beam, which has a beamwidth of 12 degrees (Table 5). Because the attenuation of the emitted sounds increases with distance to the surface (Table 5), the AZFPs were only

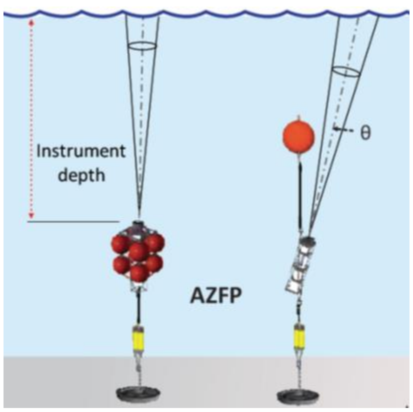
[1] All technical specifications, tables, and figures related to the AZFP were obtained from the AZFP Operator’s Manual and compiled here for simplicity. AZFP Operator’s Manual GU-100-AZFP-01-R27

deployed on the three shallowest ADEON bottom landers (Table 3) so that at least three of the frequencies sampled the full water column.

For each frequency, the AZFP transmits a series of acoustic pulses of programmable duration. In between each pulse the instrument listens for the echoes from targets in the water column up to a programmable distance from the instrument. The AZFP stores acquired data within its non-volatile 32 GB Compact FLASH memory. Communicating with the AZFP and downloading of data occurs via an RS-232 (or optional RS-422) interface through a bulkhead connector on the pressure housing. An alternative download method is to remove the instrument from its pressure case, eject the Compact FLASH, and use a USB card reader to transfer the data to a PC.

#### 4.1.2.1. Deployment Configuration Options

The AZFP systems can be deployed in multiple configurations: upward, downward, or sideward looking orientations (Figure 13). ADEON deployed the AZFPs on bottom landers where the main sensor housing was deployed lying down in a horizontal position, while the transducers were deployed in an upward looking orientation 15$^{o}$ off vertical to eliminate interference from the lander floatation mounted above the transducers (Figure 6).



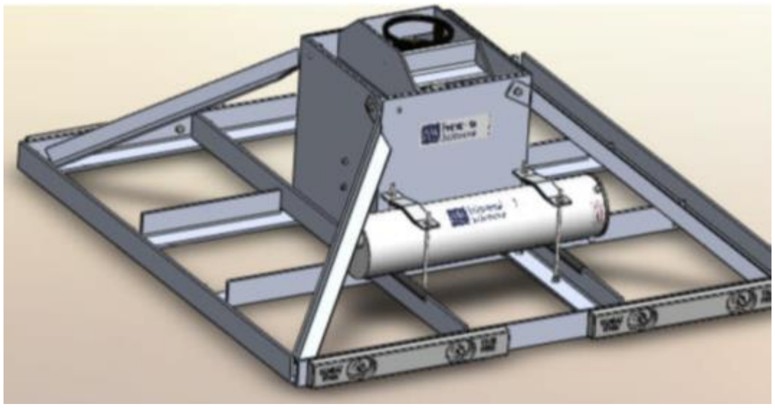


Figure 13. (Right) Two typical sub-surface bottom mooring deployment configurations. (Left) bottom lander deployment configuration where the AZFP instrument is deployed in a horizontal position, while the transducers are deployed in an upward looking orientation. ADEON deployed the AZFPs in a bottom lander mode with transducers deployed 15$^{o}$ off vertical to eliminate interference with the lander floatation. Note that this right-hand figure is a typical deployment, however, for this project the AZFP is deployed as shown in Figure 6.

The AZFP units properly measure instrument orientation when the instrument is “upright” (i.e., the end cap of the pressure case is oriented toward the surface when the instrument is submerged). This orientation is referred to as the “Upward-Looking Pressure Case” orientation. The instrument properly senses and records orientations that differ ± 45$^{o}$ from this orientation with an accuracy of ± 3$^{o}$. It is important to note that instrument orientation data is recorded, not transducer orientation (which may differ if the transducer is remotely located). Specific to ADEON, the AZFPs are in a bottom lander with the orientation sensor aligned horizontally with the pressure casing. This renders the orientation information of the sensor void.

### 4.1.2.2. Sensors

The ADEON AZFPs are equipped with 4 transducers (38, 125, 200, and 455 kHz). The transducer elements are manufactured by AIRMAR Inc and have nominal source levels and beam angles shown in Table 5. Each echo sounder channel is equipped with a high-dynamic-range, logarithmic-response receiver that eliminates the requirement for time-varying gain. The receiver dynamic range is >85 dB for each channel of the selected ADEON transducers. The estimated minimum detectable volume backscattering strength ($S_v$ in dB re 1 $m^{-1}sr^{-1}$) for each transducer frequency is shown in Table 5. A Certificate of Calibration was provided by the manufacturer for each transducer upon delivery (e.g., Figure 14).

Table 5. AZFP acoustic characteristics given by transducer frequency. Spatial sidelobes suppression is 15 dB or better outside the nominal beam widths. Limits of detectable volume backscatter strength are estimates, and individual units may vary by ± 3 to 4 dB. Receiver dynamic range is >85 dB for each channel (* receiver dynamic range is 75 dB for 2000 kHz).·Volume backscatter is calibrated to ± 1 dB, and Sv resolution is ±−0.1 dB. Reference values are 1 μPa m for source level and 1 $m^{-1}$ $sr^{-1}$ for volume backscattering strength.

| | | | Estimated Minimum Detectable Volume Backscatter Strength (dB) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Frequency (kHz) | Nominal Source Level(dB) | Nominal -3dB Beam Angle | 1m | 2m | 5m | 10m | 20m | 50m | 100m | 200m | 300m | 500m |
| 38 | 208 | 12 | -136 | -130 | -122 | -116 | -110 | -101 | -94 | -87 | -82 | -74 |
| 67.5 | 205 | 10 | -131 | -125 | -117 | -110 | -104 | -95 | -87 | -77 | -70 | -58 |
| 125 | 210 | 8 | -136 | -129 | -121 | -115 | -108 | -98 | -88 | -75 | -64 | - |
| 200 | 210 | 8 | -130 | -124 | -115 | -109 | -102 | -91 | -79 | -63 | -48 | - |
| 333 | 211 | 8 | -121 | -115 | -106 | -100 | -92 | -79 | -65 | -43 | - | - |
| 455 | 210 | 7 | -116 | -110 | -101 | -94 | -86 | -71 | -54 | - | - | - |
| 769 | 210 | 7 | -106 | -99 | -90 | -81 | -71 | -48 | - | - | - | - |
| 2000* | 212 | 7 | -80 | -71 | -55 | - | - | - | - | - | - | - |

**AZFP Certificate of Calibration Version : 12.0**

| | | | | |
|---|---|---|---|---|
| 10/26/2016 | Operator: | Jay Milligan | Unit Serial Number: | 55127 |

**Sonar Channel #1:**

| | | | | | |
|---|---|---|---|---|---|
| Frequency: | 38.0 KHz | Transducer Part#: | E23D20 | Transducer Serial#: | 157 |
| **OCV:** Voltage on reference: | 8.8 | Reference TVR: | 145.9 | Transducer Voltage: | 0.248 |
| **TVR:** Voltage on transducer: | 173 | Reference OCV: | -213.2 | Reference Voltage: | 2.0 |

**System Gain and Linearity:**

| Voltage on Reference | A/D Counts (N) |
|---|---|
| * | 65000 |
| -10dB | 59000 |
| -20dB | 53040 |
| -30dB | 47080 |
| -40dB | 41100 |
| -50dB | Not Measured |

| Calibration Values | | Units |
|---|---|---|
| TVR | 174.5 | dB |
| VTX | 61.2 | $V_{RMS}$ |
| BP | 0.02 | Sr |
| Echo Level | 144.3 | dB |
| Slope | 0.0228 | V/dB |

| Sphere Check | | Units |
|---|---|---|
| Water Temp | 10.12 | °C |
| Range | 310 | cm |
| Measured | -51.3 | dB |
| Expected | -51.0 | dB |
| Error | -0.3 | dB |

*This voltage is adjusted to bring N between 64950 and 65050 counts
All measurements with 1.0 meter separation in 20°C fresh water unless otherwise noted.

Figure 14. Example Certificate of Calibration provided for a 125 kHz transducer within the AZFP system. OCV (for "open-circuit voltage") is the hydrophone sensitivity level in dB re 1 V/µPa. The "Calibration Values" are integrated into the AZFP operation software as unique instrument parameters. The "Sphere Check" lists the results of a target strength calibration measurement, comprising the water temperature (10.12 °C), the distance from the sonar to the target, the measured target strength (−51.3 dB re 1 $m^2$/sr), and the target strength of the calibration sphere (−51.0 dB re 1 $m^2$/sr). The error value (−0.3 dB) is the difference between the "Measured" and "Expected" values of target strength.

The AZFP also includes the following context sensors for interpreting the data:

- EClock: The AZFP contains a real-time clock adjusted to be accurate within several parts per million (ppm) at room temperature. The EClock value is the measured period of microprocessor clock. It is used as the time base for various post-processing calculations and coefficients. The nominal EClock value is $2.50 \cdot 10^{-7}$ seconds.
- Orientation sensor: The two tilt channels are calibrated during manufacture and are expected to stay stable for many years. Tilt coefficients are measured by ASL by operating the AZFP at 20 different tilt angles, ranging from −45 degrees to +45 degrees, as independently measured using a high-precision inclinometer. The calibration coefficients are computed using a least-squares fitting method to a third-order polynomial equation.
- Tilt X Calibration Coefficients:
  - X_a; X_b; X_c and X_d (X_c and X_d may be zero)
  - Tilt_x (degrees) = X_a + X_b (NX) + X_c $(NX)^2$ + X_d $(NX)^3$
  - Where NX is the raw counts out of the A/D converter. Counts range from 0 to 65535
- Tilt Y Calibration Coefficients
  - Y_a; Y_b;Y_c and Y_d (Y_c and Y_d may be zero)
  - Tilt_y (degrees) = Y_a + Y_b (Ny) + Y_c $(Ny)^2$ + Y_d $(Ny)^3$
  - Where Ny is the raw counts out of the A/D converter. Counts range from 0 to 65535

- Thermistor: A thermistor is used to record temperature during an AZFP deployment. The thermistor is calibrated with respect to an ice bath at the factory. The thermistor bridge coefficients are ka, kb, and kc. The calibration coefficients are A, B, and C. To convert recorded counts to temperature, first convert counts to volts according to:
  - $V_{in}$ = 2.5 * (counts / 65535), then calculate the equivalent bridge resistance
  - R = (ka + kb * $V_{in}$) / (kc - $V_{in}$).
  - Finally, the temperature (in $^{o}$C) is T = 1 / (A + B * (ln(R)) + C * (ln($R^3$))) - 273

### *4.1.2.3. Programming/Processing Specifications*

The AZFP has multiple user-selected operation parameters to maximize data collection for a pre-defined mission. The AZFP is programmed using the custom AZFP communication software (AZFPLink) to start data collection immediately, or to wake up at a future time. The AZFP offers the pre-programming of deployment phases (12 max) by date or duration with repeat and sleep features. Pulse lengths are selectable from 100 to 1000 ms. The ping rate within each phase is also user specified up to 1 Hz depending on frequency and range. Figures 15 and 16 illustrate sample user-specified deployment phases using the AZFPLink terminology for programming burst interval, pings per burst, pulse length, digitization rate, ping period, lockout range, maximum range, and averaging options (see Appendix D for parameter definitions).

The AZFP offers three A/D digitization rates: 64, 40, or 20 kHz. The maximum possible sampling range is determined by the size of an internal data buffer and the internal analog-to-digital (A/D) sampling rate: it is ~160 m at a sampling rate of 64 kHz, 255 m at 40 kHz, and 510 m at 20 kHz. The effective maximum range may be much less than the nominal maximum, depending on the acoustic frequencies used by the instrument. The maximum range for the higher frequencies will be limited by the dynamic range of the sounder detection system and acoustic propagation effects (see Table 5). The AZFP is also equipped with a range lockout feature to disregard transducer ringdown or close targets.

The AZFP has the capability to perform received data averages in range (minimum bin size is 0.011 m), time, or both. Recorded counts are related to the target strength or volume backscattering strength in the water column that produced the echo signals recorded by the instrument. Frequently, considerations of data storage space or power consumption make it advantageous to store averaged data rather than the individual digitized values. The user may specify averaging over a specified range interval or number of samples, time-averaging over all the pings in a burst, or a combination of the two. Since the recorded values of *N* are proportional to the logarithm of the echo intensity, they cannot be directly averaged (the result would in that case be the geometric rather than the arithmetic mean). The AZFP performs a true arithmetic average of the signal amplitude data and stores the result as the data are being collected. The individual raw samples are not saved. Because of the limitations of the on-board processor and integer arithmetic, the conversion between logarithmic and linear values is done using a look-up table, which has a resolution of 0.013 dB. The averages are stored in linear form on board.

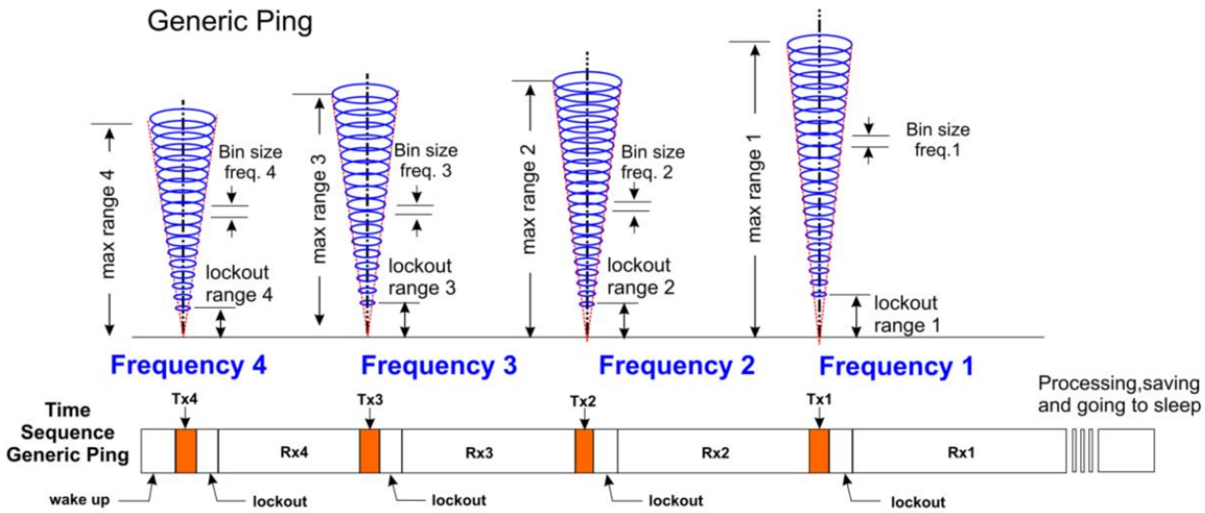



Figure 15. Illustration of a generic ping for a 4-channel AZFP and its associated timing.

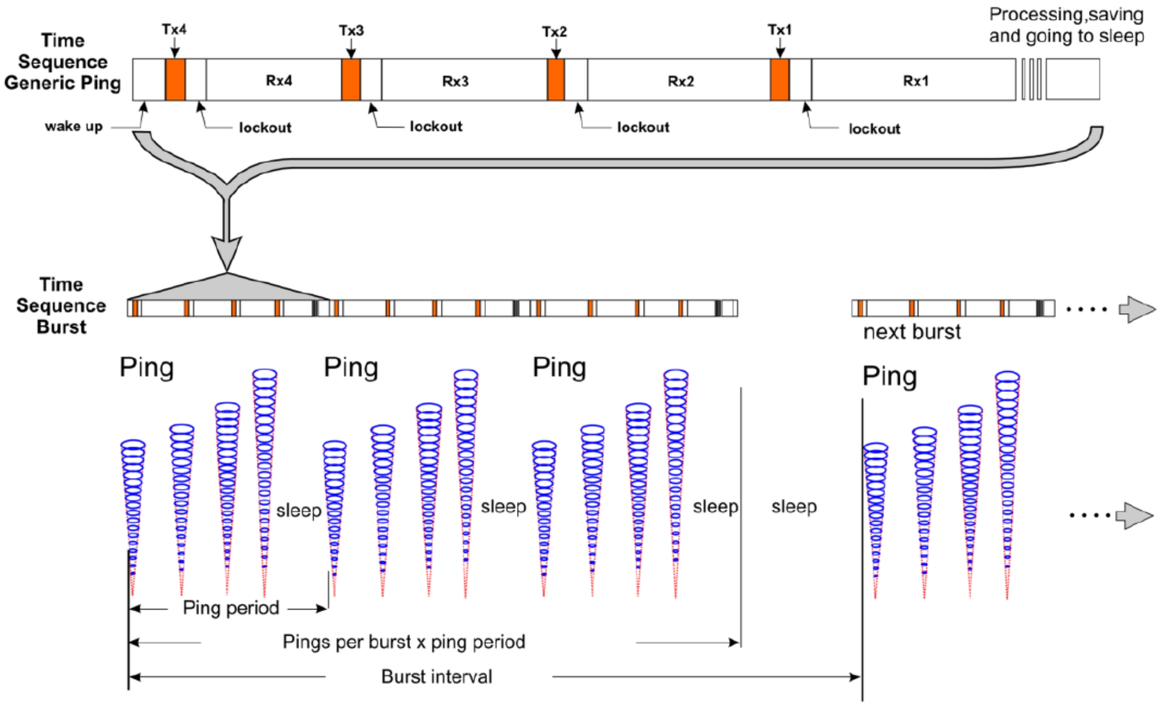



Figure 16. Illustration of burst interval sampling over a single deployment phase.

## 4.2. Vessel mounted echo sounder systems

### 4.2.1. Vessel-mounted Hardware Limitations and Trade-offs

Vessel-mounted systems allow for greater spatial survey coverage at the expense of only sampling at a small number of time intervals. Vessel mounted systems are also not constrained for power or storage and therefore can provide higher resolution measurements, especially when multi-beam systems are employed. There are three methods of deploying vessel mounted systems:

- Hull-mounted systems offer many benefits including: fixed position of the transducers relative to the ship; protected location; and cable-runs are in protected space. In addition, lower frequency, narrow-beamwidth transducers (i.e., 18 and 38 kHz, < 20$^{o}$ beamwidth; beamwidth is the angular extent of the beam, in degrees, that has at least one-half of the power in the middle of the beam) can be very large and heavy, so hull-mounting is the only practical approach for using these systems. Their drawbacks include installation/removal of transducers requires drydocking the vessel from the water; transducer position is difficult to alter post-installation so bubbles, turbulent boundary layer sweepdown and other noise sources can be difficult to fix, and hull-mounted systems (especially on larger vessels) are located at depths of 5–10 m below the sea surface so the “blind zone” of these installations can be quite large. Most manufacturers provide instructions and recommendations for hull-mounting their systems, but even when these are followed challenges may be encountered.
- Pole-mounted systems can provide flexibility in that transducers can be used from different platforms. However, the engineering design of the pole can be challenging depending on the number and size of transducers, the sea-conditions expected, and the ship being used. Attachment points to decks, gunwales, or other fixed structures on the ship are necessary and raising and lowering the pole-mount system can require the use of cranes or winches. There may be speed limitations to how fast surveys can be done due to mechanical limitations of the pole-mount. A key advantage of pole-mount systems is that the transducers can be placed closer to the sea-surface reducing the “blind zone” of the system.
- Tow-fish deployments are advantageous when there are no suitable structures for mounting a fixed pole-mount system or there is a need for near-surface measurements. Towfish systems can be deployed quite close to the sea-surface, however there are challenges in designing a towfish that flies straight and at constant depth, maintains distance from the vessel during ship movements and turns; and in running the mechanical and electrical connections between the towfish, the transducers, the echo sounders, and the ship without putting strain or wear on power and data cables.

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### 4.2.2. ADEON Shipboard Acoustic Systems

This project used a combination of Simrad EK60 and EK80 echo sounders (depending on which ship performed the bottom lander service cruises) operating with split-beam transducers at multiple frequencies including: 18, 38, 70, 120, and 200 kHz. The choice of these frequencies are for historical reasons since sonar companies only built transducers at specific frequencies and a trade-off in detecting deep fishes using lower frequencies that propagate further versus smaller organisms that scatter energy better at higher frequencies.

These systems received a GPS input from the survey vessel and (when available) attitude/directional information. Multiple frequencies of transducers were connected to a single computer for data acquisition. A second computer, connected to the data acquisition computer via Ethernet, was used for real-time data processing and verification.

Normal operation of these systems is in narrow bandwidth (bandwidth < 10% of center frequency) mode (i.e., traditional EK60 system). However, for some portions of the acoustic survey track, when EK80 systems are available, we will operate them in broadband (bandwidth > 10% of the center frequency)

mode. This provides improved vertical resolution and improved target identification, although at the expense of much larger data sets being collected.
Unlike the fixed systems, ship-based echo sounders may have varying ping rates (due to changes in water depth), but typically will operate with a ping interval between 0.5 to 5 seconds. Pulse lengths vary depending on the operating frequency of the transducer (lower frequencies usually have longer pulse lengths) and the vertical resolution needed in the water column (shorter pulse lengths provide finer vertical resolution), but typical values are 0.128 ms to 4 ms. Power settings are usually set at the maximum value provided by the manufacturer, but can be lowered by the user when in shallow water.

Specific details on the data collection and processing done by the EK60 and EK80 systems can be found in the users guides to these systems provided by the manufacturer.

# Acronyms

| | |
|---|---|
| AC | alternating current |
| ADC | analog to digital converter |
| ADEON | Atlantic Deepwater Ecosystem Observatory Network |
| CHL-a | Chlorophyll-a |
| CMRR | common mode rejection ratio |
| CSAC | chip-scale atomic clock |
| dB | decibel |
| DR | dynamic range |
| DV | digital values |
| ENOB | effective number of bits |
| ESA | Endangered Species Act |
| FFT | fast Fourier transform |
| FS | full scale |
| IEEE | Institute of Electrical and Electronics Engineers |
| IFREMER | Institut français de recherche pour l'exploitation de la mer |
| ISO | International Organization for Standardization |
| LSB | least significant bit |
| MMPA | Marine Mammal Protection Act |
| MSFD | Marine Strategy Framework Directive (European Union) |
| OCS | Outer Continental Shelf |
| PSRR | power supply rejection ratio |
| RF | radio frequency |
| rms | root mean square |
| SD | secure digital |
| SFA | Sustainable Fisheries Act |
| SFDR | spurious free dynamic range |
| SiNAD | signal to noise and distortion |
| SNR | signal to noise ratio |
| SPL | sound pressure level |
| SST | Sea Surface Temperature |
| TCXO | temperature controlled crystal oscillator |
| THD | total harmonic distortion |
| UNH | University of New Hampshire |
| UNOLS | University-National Oceanographic Laboratory System |

Table 6. Abbreviations used in this report.

| Term | Definition | Notes |
|---|---|---|
| AAF | anti-alias filter | |
| abbr. | abbreviation | |
| ADC | analog-to-digital converter | |
| IEV | International Electrotechnical Vocabulary | IEC 60500:1994[2] |
| rms | root-mean-square | |
| sym. | symbol | |
| syn. | synonym | |

[2] See http://www.electropedia.org/iev/iev.nsf/index?openform&part=801.

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# Appendix A. Calculating Sound Levels from Acoustic Recordings

## A.1. Converting Digital Values to Acoustic Pressure

To convert the digital values (DV) in the WAV files to acoustic pressure units, the following shall be accounted for:

- Digital sensitivity ($M_{ADC\_D}$) of the ADC, which depends on the bit depth $N_{\text{bit}}$ (=16 or 24): $M_{ADC\_D} = 1/2^{N_{\text{bit}}}$. Unit: 1.
- Voltage range of the ADC ($V_{ADC}$) = $V_{max}$-$V_{min}$ where $V_{min}$ is the minimum voltage the ADC can convert, and $V_{max}$ is the maximum voltage the ADC can convert. Unit: 1 V.
- Gain of the hydrophone preamplifiers is *G*. Unit: 1 V/V.
- Voltage sensitivity of the hydrophone is $M_v$. Unit: 1 V/Pa. (Voltage sensitivity is often expressed in units of 1 V/µPa because the reference sound pressure in underwater acoustics is 1 µPa.)

The preamplifier gain *G* is an amplification applied to the hydrophone signal before the ADC. This gain is the ratio of the output voltage to the input voltage: $G = V_{out}/V_{in}$, where $V_{in}$ is the input voltage to the amplifier from the hydrophone and $V_{out}$ is the output voltage from the amplifier.

A hydrophone converts acoustic pressure to voltage. The hydrophone sensitivity is the ratio of the output voltage to the input acoustic pressure. The sensitivity is customarily given as a sensitivity level in decibels relative to 1 V/µPa, which usually results in a negative number. The sensitivity depends on frequency, but it is usually approximately constant over a nominal bandwidth. The nominal sensitivity is usually provided by the manufacturer based on factory calibration. The sensitivity in decibels, $H_{dB}$, is related to the sensitivity in linear units, *M*, by:

$$M_{\text{V,dB}} = 10 \log_{10} \frac{M^2}{1\ \text{V}^2/\mu\text{Pa}^2}\ \text{dB}\ .$$

For example, for a hydrophone sensitivity level of $M_{v,dB}$ = −165 dB re 1 V/µPa, the voltage sensitivity is:

$$M_{v,} = 10^{M_{V.dB}/20} = 5.623 \times 10^{-9}\ \text{V/µPa}\ .$$

A less negative sensitivity corresponds to a more sensitive hydrophone. For example, a hydrophone with a sensitivity of −165 dB re 1 V/µPa is more sensitive than one with −180 dB re 1 V/µPa.

These values may be combined into a total sensitivity value:

$$M_{tot}[1/\mu\text{Pa}] = \frac{1}{V_{ADC}[\text{V}]} \cdot M_{ADC_D}[1] \cdot M_V[\text{V}/\mu\text{Pa}] \cdot G[\text{V/V}]\ .$$

For example, for a 24-bit channel with an ADC input range of ±2.5 V, a gain of 2 V/V, and a hydrophone sensitivity of −165 dB re 1 V/µPa, $M_{tot}$ is:

$$M_{tot} = \frac{1}{5\ \text{V}} \cdot 2^{24} \cdot 5.623 \times 10^{-9} \frac{\text{V}}{\mu\text{Pa}} \cdot 2 \frac{\text{V}}{\text{V}} = 0.0377 \frac{1}{\mu\text{Pa}}.$$

A digital value from the ADC is converted to sound pressure by dividing by $M_{tot}$. For the example above and an ADC digital output of 10000, the pressure is 265,003 µPa, which is equivalent to 108.4 dB re 1 µPa.

### Frequency response

In the examples above, the hydrophone sensitivity was assumed to be constant for all frequencies, which is generally untrue. The recorder often also has a low-frequency roll off that must be accounted for, especially if analyzing frequencies below ~10 Hz.

The frequency response of the hydrophone and recorder are generally combined into a single gain-vs-frequency response curve. The response is applied in the frequency domain (after a Fourier transform), instead of the fixed value shown in the equations above.

If a frequency calibrated time series is required (e.g., for directional sensors), the gain must be applied to the complex Fourier transformed data and then the inverse Fourier transform must be used to revert to the time domain. The input time series length must be doubled with zeroes to eliminate circular convolution in the output time series.

# Appendix B. Sample Specification Sheet for Autonomous Recorders

Tables 7 and 8 provide the standardized metrics that should be provided by manufacturers of acoustic recorders that are intended for soundscape quantification. The values for the AMAR G4 recorder and M36-V35-100 hydrophones used on ADEON bottom landers and the towed array system are provided as examples. The specifications for the directional sensor, whose purpose is directionality rather than quantifying the sound levels, are similar but not provided.

Table 7. Recorder metrics.

| Reporting metric | Unit | Minimum requirement | AMAR G4 | Towed array |
|---|---|---|---|---|
| Sample rate | kHz | 200 | 512, 256, 128, 64, 32, 16, 8 | |
| Output word size (number of bits) | bit | 16 | 24 | |
| Sample clock accuracy–standard clock | Parts per million (ppm) | 5 | 2 (better with higher resolution clocks) | |
| Number of channels | | 1 | 4 | |
| Synchronous sampling between channels in a multichannel recorder | (yes/no) | yes | yes | |
| −3 dB Frequency response of recorder electronics | Hz | 10 Hz to 100 kHz | 2 Hz to 200 kHz | |
| Minimum peak amplitude that may be recorded | dB re 1 µPa | 160 | 165 | |
| Recorder dynamic range | dB | 96 | 110 | |
| Recorder spectral noise floor assuming a −165 dB re 1 V/µPa hydrophone and 16 kHz sample rate (lower is better) | dB re 1 µPa²/Hz | 35 | <15 | |
| Storage capacity | TB | 1 | 12 TB | |
| Power draw for 1 channel at maximum sampling rate (does not include hydrophone) | mW | | 540 mW | |
| Power draw for 1 channel sampling rate of 16 kHz (does not include hydrophone) | mW | | 340 mW | |
| Power draw for 4 channels at maximum sampling rate (does not include hydrophone) | mW | | 985 mW | |
| Power supply capacity at 4 °C | W h | | 61.5 W h to 2916 W h | |
| Maximum operating depth | m | | 250 m, 6700 m | |
| Operating temperature range | °C | −5 to 40 °C | −5 to 50 °C | |
| Storage temperature range | °C | −10 to 50 °C | −18 to 55 °C | |
| Recording schedule options (duty cycling, different sample rates, etc.) | | Duty cycling with different sample rates | Duty cycle, sample rate, delay start, schedule of schedules | |
| Input gain control | | | Fixed gain to match hydrophone | |

Table 8. Standard hydrophone metrics.

| Reporting metric | Unit | GTI M36-V35-100 | Towed array |
|---|---|---|---|
| Sensitivity level (if including hydrophone in specification) | dB re 1 V/μPa | −165 dB re 1 V/μPa | |
| Frequency response | Hz | 17 Hz to 180 kHz | |
| Maximum operating depth | m | 2500 m | |
| Hydrophone spectral noise floor | dB re 1 μPa$^2$/Hz | 34 dB re 1 μPa$^2$/Hz | |

# Appendix C. Specification Sheets for Equipment

## C.1. SBE-37 CT-DO Sensor

The following specification is verbatim from: http://www.seabird.com/sbe37smpodo-microcat-ctd-do.

> The SBE 37-SMP-ODO pumped MicroCAT is a high-accuracy conductivity and temperature (pressure optional) recorder with Serial interface (RS-232 or RS-485), internal batteries, Memory, integral Pump, and Optical Dissolved Oxygen. The MicroCAT is designed for moorings or other long-duration, fixed-site deployments.
>
> Data is recorded in memory and can be output in real-time. Measured data and derived variables (salinity, sound velocity, specific conductivity) are output in engineering units.
>
> Memory capacity exceeds 380,000 samples. Battery endurance varies, depending on sampling scheme and deployment temperature and pressure. Sampling every 15 minutes (10 °C, 500 dbar), the MicroCAT can be deployed for almost 9 months (25,000 samples).
>
> **Features**
>
> - Moored Conductivity, Temperature, Pressure (optional), and Optical Dissolved Oxygen, at user-programmable 10-sec to 6-hour intervals.
> - Integral pump.
> - RS-232 or RS-485 interface.
> - Internal memory and battery pack (can be powered externally).
> - Expendable anti-foulant devices, unique flow path, and pumping regimen for bio-fouling protection.
> - Adaptive Pump Control for high-accuracy oxygen data.
> - 7000 m titanium housing.
> - Seasoft©V2 Windows software package (setup, data upload, and data processing).
> - Field-proven MicroCAT family, with more than 10,000 instruments deployed.
> - Five-year limited warranty.
>
> **Components**
>
> - Unique internal-field conductivity cell permits use of expendable anti-foulant devices, for long-term bio-fouling protection.
> - Aged and pressure-protected thermistor has a long history of exceptional accuracy and stability.
> - Oxygen sensor is field-proven, individually calibrated SBE 63 Optical Dissolved Oxygen sensor
> - Pump runs for each sample, providing improved conductivity and oxygen response, bio-fouling protection, and correlation of CTD and oxygen measurements.
>
> **Options**
>
> - Titanium (7000 m) housing.
> - RS-232 interface.
> - Wet-pluggable MCBH connector.

**Notes added by authors of ADEON Hardware Specification**

- 1 bar = 100 kPa
- 1 dbar = 0.1 bar = 10 kPa

## C.2. VEMCO VR2-W Fish Tag Logger

The following specification is verbatim from: https://vemco.com/products/vr2w-69khz/?product-specifications.

| Specifications | |
|---|---|
| Dimensions | 308 mm long x 73 mm diameter |
| Weight | 1190 g in air, 50 g in water |
| Power supply | 1–3.6 V Lithium D cell battery |
| Battery life | ~15 months |
| Maximum depth | 500 m |
| Receive frequency | 69 kHz standard |
| Storage | ~1.6 million detections (16 MBytes non-volatile flash memory)<br>~1 million detections (8 MBytes non-volatile flash memory) |
| Attachment | Standard: Cable ties |

# Appendix D. Terms and Definitions

This appendix describes the terminology used in the ADEON hardware specification. The description includes a list of concepts (Table 9), followed by a sequence of tables listing the terminology used for characterizing the properties of a hydrophone (Table 10), a pre-amplifier and an anti-alias filter (AAF) (Table 11), an ADC converter (Table 12), a passive acoustic recorder system (comprising one hydrophone, one pre-amplifier, one AAF, and one ADC; Table 13), the levels associated with different measurements (Table 14), and the terminology related to active acoustic echo sounders (Table 15).

Table 9. Acoustical terminology for ADEON hardware specification: Concepts.

| Term | Definition | Notes |
|---|---|---|
| Hydrophone | Transducer designed to convert sound to electricity | hydrophone input = system input |
| Pre-amplifier | Electronic component that increases the amplitude of an electric current or voltage | |
| Anti-alias filter (AAF) | Low-pass filter that avoids aliasing by removing frequencies above the Nyquist frequency of the analog-to-digital converter | |
| Analog-to-digital converter (ADC) | Electronic component that samples an analog electric current or voltage into a digitized representation of that electric current or voltage | ADC output = system output |
| System | Sequence of electronic components comprising (in this order) a hydrophone, a pre-amplifier, an AAF, and an ADC | system input = hydrophone input<br>system output = ADC output |
| ADC input | Generic term referring to an analog representation of the ADC input such as current or voltage | |
| ADC output | Generic term referring to a digital representation of the ADC input, suitable for storage in a digital storage medium or processing on a digital computer | |

Table 10. Acoustical terminology for ADEON hardware specification: Quantities used to characterize a hydrophone.

| Preferred term | Syn. | Unit | Sym. | Definition | Notes |
|---|---|---|---|---|---|
| Free-field voltage sensitivity | Pressure Sensitivity Voltage sensitivity | $\mathrm{Pa}^{-1}$ | $M_{\mathrm{hp},V}$ | Ratio of the rms open-circuit output voltage to the rms spatially-averaged sound pressure in the undisturbed plane-progressive free field | Property of a voltage hydrophone, for a specified frequency band and a specified direction of sound incidence<br>Adapted from IEV 801-25-53 |
| Free-field current sensitivity | | $\mathrm{A}^{-1}$ | $M_{\mathrm{hp},I}$ | Ratio of the rms short-circuit output current to the rms spatially-averaged sound pressure in the undisturbed plane-progressive free field | Property of a current hydrophone, for a specified frequency band and a specified direction of sound incidence<br>Adapted from IEV 801-25-56 |
| Equivalent rms hydrophone noise sound pressure | | Pa | $p_{\mathrm{N,eq}}$ | Ratio of the rms open-circuit output voltage to the free-field voltage sensitivity | Adapted from ISO 18405 (3.6.1.15) |
| Hydrophone non-acoustic self-noise voltage | Self-noise voltage | V | | Open-circuit output voltage in the absence of sound pressure at the hydrophone input | |
| Hydrophone mean-square non-acoustic self-noise voltage spectral density | Self-noise voltage spectral density | $V^2$/Hz | | Ratio of mean-square hydrophone non-acoustic self-noise voltage in a specified frequency band to the width of the frequency band | |
| Equivalent hydrophone mean-square non-acoustic self-noise sound pressure spectral density | Hydrophone self-noise sound Pressure spectral density | $Pa^2$/Hz | | Ratio of hydrophone mean-square non-acoustic self-noise voltage spectral density to the squared free-field voltage sensitivity | |

Table 11. Acoustical terminology for ADEON hardware specification: Quantities used to characterize a pre-amplifier and anti-alias filter (AAF).

| Preferred term | Syn. | Unit | Sym. | Definition | Notes |
|---|---|---|---|---|---|
| Pre-amplifier voltage gain | | 1 | $G_{\mathrm{pA},V}$ | Ratio of rms pre-amplifier output voltage to rms pre-amplifier input voltage | |
| AAF voltage gain | | 1 | $G_{\mathrm{AAF},V}$ | Ratio of rms AAF output voltage to rms AAF input voltage | |

Table 12. Acoustical terminology for ADEON hardware specification: Quantities used to characterize a digital sampling system.

| Preferred term | Syn. | Unit | Sym. | Definition | Notes |
|---|---|---|---|---|---|

| Preferred term | Syn. | Unit | Sym. | Definition | Notes |
|---|---|---|---|---|---|
| Integer ADC output | | 1 | $N$ | Integer representation of ADC output, defined such that a unit change in integer ADC output corresponds to a change in the lowest significant bit from 0 to 1 or from 1 to 0 | The integer ADC output is equal to the product of ADC sensitivity to voltage and ADC input voltage |
| Maximum integer ADC output | Full-scale ADC output | 1 | $N_{\mathrm{max}}$ | Largest possible value of the integer ADC output | |
| Minimum integer ADC output | | 1 | $N_{\mathrm{min}}$ | Smallest possible value of the integer ADC output | |
| Bit depth | Word size | bit | $N_{\mathrm{bit}}$ | Amount of digital memory available at ADC output to digitize one value of ADC input | |
| ADC sensitivity to voltage | | $\mathrm{V}^{-1}$ | $M_{\mathrm{ADC},V}$ | Ratio of rms integer ADC output to rms ADC input voltage | |
| ADC voltage conversion factor | | V | $\mu_V$ | Reciprocal of ADC sensitivity to voltage | |
| Maximum unsaturated voltage | Full-scale voltage | V | $v_{\mathrm{max}}$ | Maximum absolute value of ADC input voltage for which the ADC sensitivity to voltage is independent of ADC input | |
| Minimum unsaturated voltage | | V | $v_{\mathrm{min}}$ | Minimum ADC input voltage for which the ADC sensitivity to voltage is independent of ADC input | Minimum unsaturated voltage is equal to $-V_{\mathrm{max}}$ |
| Voltage relative to full-scale | | | $v_{\mathrm{reFS}}(t)$ | Ratio of ADC input voltage to full-scale voltage | |
| ADC self-noise voltage | | | | Ratio of the integer ADC output to the ADC sensitivity to voltage | |
| Dynamic range | DR | | $\Delta L_{\mathrm{DR}}$ | Level of the ratio of the full-scale mean-square voltage to the mean-square ADC self-noise voltage | |

Table 13. Acoustical terminology for ADEON hardware specification: Quantities used to characterize the passive data recorder acquisition system.

| Preferred term | Syn. | Unit | Sym. | Definition | Notes |
|---|---|---|---|---|---|

| Preferred term | Syn. | Unit | Sym. | Definition | Notes |
|---|---|---|---|---|---|
| Total system sensitivity | | $\mathrm{Pa}^{-1}$ | $M_{\mathrm{tot}}$ | Ratio of rms integer ADC output to the rms spatially-averaged sound pressure in the undisturbed plane-progressive free field | For a voltage hydrophone, the total system sensitivity is related to the hydrophone and ADC sensitivities according to $M_{\mathrm{tot}} = M_{\mathrm{hp},V} G_{\mathrm{pa},V} G_{\mathrm{AAF},V} M_{\mathrm{ADC},V}$ |
| System non-acoustic self-noise output | System self-noise output<br>ADC self-noise output | 1 | | System output in the absence of sound pressure at the hydrophone input | System output = ADC output |
| System mean-square non-acoustic self-noise output spectral density | System self-noise output spectral density<br>ADC self-noise output spectral density | 1/Hz | | Ratio of mean-square ADC non-acoustic self-noise output in a specified frequency band to the width of the frequency band | |
| Equivalent system mean-square non-acoustic self-noise sound pressure spectral density | System self-noise sound pressure spectral density | $\mathrm{Pa}^2/\mathrm{Hz}$ | | Ratio of system mean-square non-acoustic self-noise output spectral density to the squared total system sensitivity | |
| Noise power | | W | $W_{\mathrm{N}}$ | Time-averaged product of noise current and noise voltage | In an electrical circuit of resistance $R$, noise power is given by mean-square noise voltage divided by $R$ or mean-square noise current multiplied by $R$.<br>The noise power depends on the position in the processing chain at which it is determined.<br>The position in the processing chain at which the noise is determined shall be specified. |
| Signal power | | W | $W_{\mathrm{S}}$ | Time-averaged product of signal current and signal voltage | In an electrical circuit of resistance $R$, signal power is given by mean-square signal voltage divided by $R$ or mean-square signal current multiplied by $R$.<br>The signal power depends on the position in the processing chain at which it is determined.<br>The position in the processing chain at which the signal is determined shall be specified. |
| Signal to noise power ratio | | 1 | $R$ | Ratio of signal power to noise power | The signal to noise power ratio depends on the position in the processing chain at which it is determined.<br>The position in the processing chain at which the signal to noise power ratio is determined shall be specified. |

Table 14. Levels and other logarithmic quantities usually expressed in decibels

| Quantity (preferred name) | Syn. | Abbr. | Sym. | Reference value | Definition | Notes |
|---|---|---|---|---|---|---|
| Voltage sensitivity level | | | $L_{M,V}$ | 1 V/μPA | Level of the free-field voltage sensitivity | In equation form, $L_{M,V} = 10 \lg M_{\text{hp},V}^2$ dB |
| Signal to noise ratio | | SNR | | 1 | Level of the signal to noise power ratio | In equation form, $\text{SNR} = 10 \lg R$ dB |
| Hydrophone spectral noise floor level | | | | 1 μPa$^2$/Hz | Level of the equivalent hydrophone mean-square non-acoustic self-noise sound pressure spectral density | |
| System spectral noise floor level | Recorder spectral noise floor level | | | 1 μPa$^2$/Hz | Level of the electronics mean-square non-acoustic self-noise sound pressure spectral density, assuming a standard hydrophone were generating the noise instead of the electronics | The sensitivity of the assumed hydrophone must be provided. |

Table 15. Terminology related to the operation and configuration of active acoustic echo sounders.

| Quantity (preferred name) | Unit | Definitions | Notes |
|---|---|---|---|
| Ping | | A single transmission (at multiple frequencies for capable instruments) from the sonar channels in the instrument. | |
| Burst | | Sequence of pings closely spaced in time over which the measured backscattering is averaged to reduce noise. | |
| Pings per Burst | | This is the number of individual pings in each burst or the number of pings in a profile if ping averaging has been selected. (Pings may be averaged, but this is not mandatory.) | |
| Burst Interval | s | The time between bursts (or between pings if the burst interval has been set equal to the ping period). | |
| Pulse Length | s | Duration of the transmitted acoustic excitation pulse, usually expressed in ms. | |
| Digitization Rate | Hz | For echo sounders this it the rate at which samples are processed by the A/D converter when digitizing the returned acoustic signal. | |
| Ping Period | s | Time between pings in a profile set. | |
| Bin Size | m | The depth range, in m, that is sampled by an echo sounder. It is the sound velocity / 2 * digitization rate. | |

| Quantity (preferred name) | Unit | Definitions | Notes |
|---|---|---|---|
| Bin Definition | m | This describes the division of the water column into discrete “bins” that contain range-averaged samples. The actual number entered into the AZFPLink software is the bin size in meters or samples | |
| Maximum Range | m | Distance, rounded to the nearest bin size that the sounder listens for returns. Acoustic returns from objects further away than the Maximum Range will not be recorded by the instrument. | |
| Lockout Range | m | (User selectable from 0 to Maximum Range – 1 m). This is the distance, rounded to the nearest Bin Size after the pulse is transmitted that over which AZFP will ignore echoes. | |
| Volume Backscattering Strength | dB. Reference value = 1 $m^{-1}$ $sr^{-1}$. | The volume scattering strength evaluated in the backscattering direction. | |