Naval Submarine Medical Research Laboratory

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Guidelines for Characterization of Sounds Produced by Underwater Active Acoustic Technologies for Human Exposure

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This guide was developed as a reference for vendors and/or manufacturers of active acoustic technologies (e.g., UUV, Sonar, and Acoustic Modem systems) to appropriately characterize the sound produced by their systems. These acoustic characterizations will be used by experts to provide guidance for the protection of divers. NSMRL created this guide at the request of NAVSEA, which intends to distribute the guide as a step in the technology approval process. With a standard measurement and characterization methodology, we hope to streamline the safety evaluation step in the technology approval process.

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Technical Note

This technical memorandum contains a document prepared by NSMRL at the request of NAVSEA, who intend to distribute this guide as a step in the technology approval process for the ANU list.

Introduction

In recent years, the military diving community has seen a surge of new technologies intended to improve the safety, situational awareness, and efficacy of divers. Many of these technologies operate by transmitting sound energy through the water while being in close proximity to divers. For example, acoustic modem technologies have been developed to provide a way for a top-side dive supervisor to wirelessly obtain information about deployed divers through communications between a boat-mounted modem and diver-mounted modems. This communication is facilitated by the transmission of acoustic signals underwater. Diver-held SONAR systems allow divers to image their surroundings, enabling divers to navigate low visibility environments and create spatial maps of underwater environments. This imaging is done by projecting high-frequency sound energy, and measuring reflected energy. Unmanned underwater vehicles (UUVs) also employ active acoustic technology for imaging and communication purposes. Divers sometimes must operate in the same environment as these UUVs. Specialized UUVs have also been proposed for man-machine dive teams where UUVs may augment divers' capability or efficiency. All of these technologies are in use or under consideration for use by the fleet.

High-level underwater sound is a known hazard to human divers, causing negative impacts including hearing loss, tinnitus, vestibular stimulation, and heating or direct mechanical damage to the tissue[†,‡]. Thus, any intended benefits of active acoustic technologies must be considered in conjunction with potential risks. Accurate characterization of the acoustic energy of underwater sound produced by these technologies is necessary to assess the risks of human exposure. Standard practice to report risk is computation of a permissible exposure limit (PEL)[‡], the length of time to which a diver can be safely exposed (i.e., exposed with mitigated risk) to the sound energy produced by the device. PELs can be computed by measuring projected acoustic signals and calculating several different sound level indices, which are representative of the expected levels of exposure a diver may experience.

This guide was developed as a reference for vendors and/or manufacturers of active acoustic technologies (e.g., UUV, Sonar, and Acoustic Modem systems) to appropriately characterize the sound produced by their systems. These acoustic characterizations will be used by experts to provide guidance for the protection of divers. With a standard measurement and characterization methodology, we hope to streamline the safety evaluation step in the technology approval process.

† United States Department of the Navy. (2016). U.S. Navy Diving Manual, Revision 7. Washington, DC: Naval Sea Systems Command.

‡ United States Department of Health and Human Services. (2019). Marketing Clearance of Diagnostic Ultrasound Systems and Transducers. Rockville, MD: U.S. Department of Health and Human Service - Food and Drug Administration – Center for Devices and Radiological Health.

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Characterization of Underwater Active Acoustic Technologies for Human Exposure

Guidelines for Providing the Acoustic Information Necessary to Inform Navy Use of Novel Technologies and Systems

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Prepared For: **Naval Sea Systems Command (NAVSEA)**
Supervisor of Diving & Salvage (00C)

Prepared By: **Naval Submarine Medical Research Laboratory (NSMRL)**

Disclaimer

This guidance document does not establish legally enforceable responsibilities. Instead, this document is a set of recommendations for the acoustic characterization process a manufacturer/vendor of active acoustic technologies should follow to improve the likelihood of their product being accepted into the Authorized for Navy Use (ANU) technologies list. Any deviations from the recommendations in this document should be noted in the manufacturer's/vendor's final report. The use of the word "should" throughout this document means that something is suggested or recommended, not required.

Objective

Underwater, high-level sound waves produced by unmanned underwater vehicles (UUVs) and other active acoustic technologies pose hazards to human divers. Measuring the intensity of these sound waves across a broad frequency range is important to assess potential impacts to humans, which could include hearing loss, tinnitus, vestibular stimulation, and heating or direct mechanical damage to tissue. The objective of this guide is to provide a standard methodology that vendors and/or manufacturers of acoustic technologies can follow to characterize the sounds produced by their systems. Following the methodology presented herein will provide decision makers (i.e., NAVSEA 00C) with the information necessary to inform safe Navy use of these technologies/systems.

This guide is organized into five sections:

1. **General Recording Equipment:** lists and describes the appropriate recording equipment to capture the sound energy of the system being characterized;
2. **Projector – Hydrophone Set-Up**: provides technical recommendations for the physical set-up of the system being characterized and the recording hydrophone;
3. **What to Record:** outlines the active acoustic signals that should be recorded and analyzed from the system being characterized;
4. **Analysis:** provides a detailed guide for the computation of the acoustic metrics that can be used by NAVSEA to inform safe Navy use of the technology/system; and
5. **Presenting Results:** details the information that should be included in the final report to NAVSEA, with formatting recommendations.

This guide was developed as a reference for vendors and/or manufacturers of active acoustic technologies (e.g., UUV, Sonar, and Acoustic Modem systems) that may be used with or adjacent to divers and swimmers to appropriately characterize the sound produced by their systems.

This guide is focused primarily on the *typical* cases for these technologies. Some technologies may have functions/settings that fall outside of the scope of this characterization guide. If you believe your system or any of its settings falls under this category at any step in the characterization procedure, contact the Technical Warrant Holder at NAVSEA 00C3 to determine the best path forward.

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1. General Recording Equipment

Figure 1 shows a general outline of recording equipment expected to be used to record sound waves originating from the acoustic projector. The acoustic projector (green box 1.1) emits an acoustic signal through the water (striped arrow). The acoustic energy is measured via the hydrophone as a voltage signal (solid arrows) that is amplified by the signal conditioner/preamp, digitized by the analog-digital converter, and finally stored on a computer.

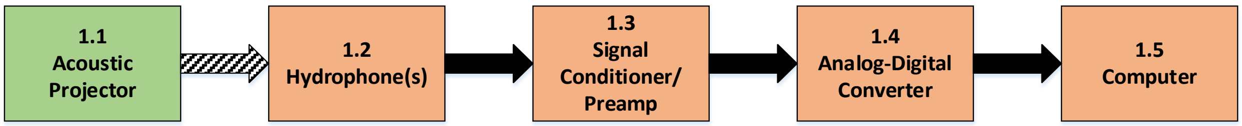

Figure 1: General equipment outline. The acoustic projector (green) emits an acoustic signal (striped arrow) that is captured by the components of the recording system (orange).

Equipment for characterizing active acoustic technologies falls into five categories:

1.1 Acoustic Projector (System being characterized)
1.2 Hydrophone(s)
1.3 Signal Conditioner/Preamp
1.4 Analog-Digital Converter
1.5 Computer

1.1 Acoustic Projector

The "acoustic projector" (or just "projector") is the specific component of the system being characterized, such as a UUV or handheld SONAR system, that produces an acoustic signal. Many systems have a wide range of settings with multiple configurations available to the user (e.g., pulse length, pulse shape, bandwidth, power). The ideal characterization would be to measure sound production for each possible configuration. However, because the time investment to accomplish this is likely prohibitive, you, as the manufacturer or vendor, must decide the most feasible number of configurations and decide the most important settings to characterize. Guidelines to help you determine which settings to characterize are provided in detail in Section 3.

1.2 Hydrophone

The three major considerations for selecting a hydrophone[1] are:

1.2.1 Frequency response,
1.2.2 Receiving sensitivity, and
1.2.3 Directionality.

[1] *Some systems being characterized may require the use of multiple hydrophones to capture the full range of acoustic energy.*

1.2.1 Frequency Response

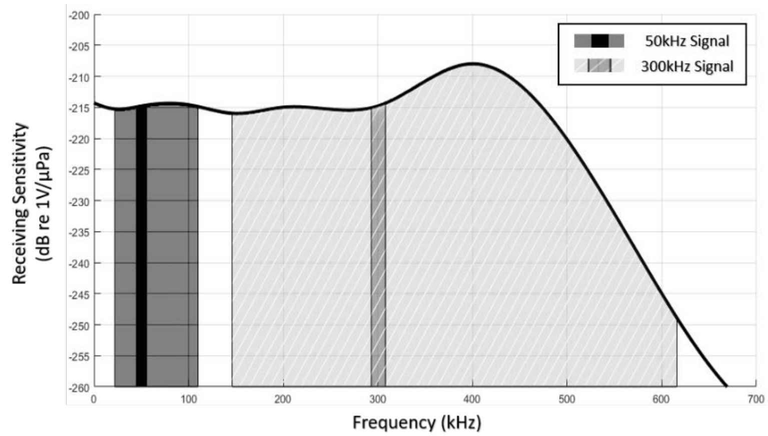

Figure 2: Example of a hydrophone frequency response plot with ideal measurement ranges for two hypothetical signals. The darker, un-textured, shaded area indicates the frequency range (22.5-110 kHz) wherein you should measure energy for a signal with an expected bandwidth of 10 kHz centered at 50 kHz (black bar). The lighter, textured, shaded area indicates the frequency range (146-615 kHz) wherein you should measure energy for a signal with an expected bandwidth of 15 kHz centered at 300 kHz.

The desired frequency response for the recording equipment is determined by the expected center frequency (f_0), and the expected bandwidth (B) of the transmitted acoustic signal[2]. With the expected frequency band of the signal $\left(f_0 \pm \frac{B}{2}\right)$ determined by the signal's expected center frequency and bandwidth, the desired measurement frequency range is an additional octave beyond these bounds: $\left[\frac{1}{2}\left(f_0 - \frac{B}{2}\right),\ 2\left(f_0 + \frac{B}{2}\right)\right]$.

If the hydrophone has a relatively flat response within the desired frequency range, then the hydrophone is appropriate for the system to be characterized. Hydrophone vendors typically include a frequency – sensitivity plot (Figure 2) in the specification sheet of their products. Examples 1 and 2 (below) illustrate instances when the frequency response of a hydrophone is and is not appropriate for a given frequency range[3].

[2] *You are expected to have an estimate of the center frequency and the approximate bandwidth of the acoustic signal before testing.*

[3] *If you encounter significant difficulties finding an appropriate hydrophone, please contact the Technical Warrant Holder at NAVSEA 00C3 for recommendations.*

Example 1: *Consider a projector with an expected center frequency of 50 kHz, and an expected bandwidth of 10 kHz. The desired frequency range would then be 22.5 – 110 kHz (Figure 2; un-textured dark gray area). The receiving sensitivity in this frequency range is relatively flat. This hydrophone* ***is appropriate*** *for this frequency range.*

Example 2: *Consider a projector with an expected center frequency near 300 kHz, and an expected bandwidth of 15 kHz. The desired frequency range would then be 146 – 615 kHz (Figure 2; textured light gray area). The receiving sensitivity in this frequency range varies greatly. This hydrophone* ***is not appropriate*** *for this frequency range.*

1.2.2 Receiving Sensitivity

The receiving sensitivity of a hydrophone (k_{dB}; typically presented in units of decibels referenced to 1 volt per micropascal (dB re 1 V/µPa)), should be appropriate for the level of acoustic signal you plan to record. Knowledge of the receiving sensitivity allows you to convert the recorded voltage signal to a pressure signal representing the measured pressure. Equation 1 presents a simple method to compute *a minimum signal level*, in volts, that you should observe in your recordings, assuming an absence of environmental noise[4]. This minimum signal level will ensure recordings are made with a signal-to-noise ratio (SNR) of at least 40 dB (recommended). If the level of the recorded signal you are observing is lower than the minimum level computed, you should use a more sensitive hydrophone.

$$V_{min} = (V_{max} - DR_{ADC}) + SNR_{min} \qquad (Eq\ 1)$$

V_{min} is the minimum signal level needed to meet the desired SNR threshold (dB re 1 Volt), V_{max} is the maximum voltage level of the analog-to-digital converter (ADC) system (dB re 1 Volt), SNR_{min} is the desired *minimum* SNR (recommend 40 dB), and DR_{ADC} is the dynamic range of the ADC system (dB).

1.2.3 Hydrophone Directivity

Directivity refers to the relative sensitivity of a hydrophone as a function of the incoming pressure waveform's propagation direction. Omnidirectional hydrophones are recommended.

Directional hydrophones are acceptable but require precise orientation relative to the projector. The advertised sensitivity of most directional hydrophones is defined in the direction of greatest sensitivity. Therefore, you can determine the proper orientation using a "peaking" strategy, in which multiple short recordings are made while rotating the hydrophone in azimuth and elevation (i.e., yaw and pitch). The angle of the hydrophone that produces the highest-level recording is the orientation you should use for further recordings.

Positioning of the hydrophone is addressed in Section 2.

1.3 Signal Conditioner/Pre-amplifier

The signal conditioner/pre-amplifier applies filters and/or gain to the incoming voltage signal. Similar to hydrophone selection (section 1.2.2), signal conditioners should have a relatively flat response

[4] *The presence of environmental noise in excess of the quantization noise of the ADC will increase V_{min} required to achieve SNR_{min}.*

level in the frequency range that is to be characterized. Any filters/gain applied to the signal should be noted in the characterization report.

1.3.1 Recording System Bandwidth

Any system used for recording should meet the following criteria:

1. The corner frequency (-3 dB) of low-pass filters should be set at or below ½ the sample rate (i.e., Nyquist frequency as discussed in section 1.4.1).
2. The corner frequency (-3 dB) of high-pass filters should be set to 500 Hz or lower so that it does not compromise later aspects of analysis.

Some signal conditioners have filters that are configurable by the user. Filtering is not required for characterization, however every signal conditioning system has an inherent frequency response.

1.3.2 Gain application

The best way to determine how much gain to apply to the incoming voltage signal is to start at the minimum gain setting of your system and slowly increase the gain after repeated test trials. It is important to apply enough gain to obtain a clean signal that stands out from the noise floor (refer to section 1.2.2 for minimum signal levels) to ensure a good SNR. Keep in mind that increased gain does not always have a 1:1 relationship with increased SNR; gain applied will also increase noise originating from the acoustic environment and from any electronics prior to the gain stage.

Example 1: *Consider an ADC system with a max voltage level of 10V (20 dB re 1V), a dynamic range of 80 dB, and a minimum SNR goal of 40 dB. Using equation 1, the minimum signal level is:*

$$V_{min} = 20\ dB\ re\ 1V - 80\ dB + 40\ dB = -20\ dB\ re\ 1V$$

Converting from decibels to linear units to get:

$$10^{\frac{V_{min}}{20}} = 0.1\ V$$

If the recorded signal is above the level of 0.1 V, then the minimum SNR of 40 dB has been met. The gain applied to the signal is appropriate.

1.4 Analog-to-Digital Converter

The Analog-to-Digital Converter (ADC) is the component of the recording setup that receives the voltage signal from the signal conditioner, discretizes it at a defined sample rate (F_s), and sends the digitized signal data to a computer for processing and characterization.

1.4.1. Determining sample rate

Sample rate requirements are dependent on the system being characterized, specifically the upper frequency bound of the signal emitted by the projector (recall the "one octave above the upper bound of the expected band" recommendation in 1.2.1). Therefore, the minimum sample rate for recording should be 4x the expected upper bound of the band, making the upper bound frequency established in section 1.2.1 the Nyquist frequency[5].

Example: Consider a system projecting a signal centered at 24 kHz with an 8 kHz bandwidth. Following the guidelines in 1.2.1 we expect energy within a band up to 28 kHz. Next, following the guidelines 1.4.1, you should aim to make 2x the upper bound (56 kHz) the Nyquist frequency by multiplying this upper bound by 4 to obtain the minimum recommended sample rate: 112 kHz.

$$f_0 = 24\ kHz \qquad (Expected\ Center\ Frequency)$$

$$B = 8\ kHz \qquad (Expected\ Bandwidth)$$

$$f_0 + \frac{B}{2} = 28\ kHz \qquad (Expected\ upper\ limit)$$

$$F_{Nyquist} = 2\left(f_0 + \frac{B}{2}\right) = 56\ kHz \qquad (Nyquist\ Frequency)$$

$$F_s = 2F_{Nyquist} = 112\ kHz \qquad (Minimum\ Sample\ Rate)$$

Figure 3 (LEFT) shows the example waveforms of this signal sampled at 1 MHz, 112 kHz, and 50 kHz to represent the ideal, minimum, and below minimum cases of the sample rate. Note that the signal is the smoothest in the ideal, over-conservative case of the 1 MHz sample rate, and that the signal is significantly obscured with the 50 kHz sample rate.

Figure 3 (RIGHT) shows the power spectra of the signal sampled at 1 MHz, 112 kHz, and 50 kHz to demonstrate that greater sample rates allow for more energy to be measured across the spectra. While the spectra shown for the 112 kHz sample rate case captures most of the energy, the 1 MHz case does capture energy missed by the lower sample rate.

[5] *This is the recommendation for the* ***minimum sample rates*** *that should be used. Using higher sample rates allows for a greater range of frequencies to be characterized and more accurately captures the peak pressures of pulsed signals, therefore enabling a more thorough characterization of the system.*

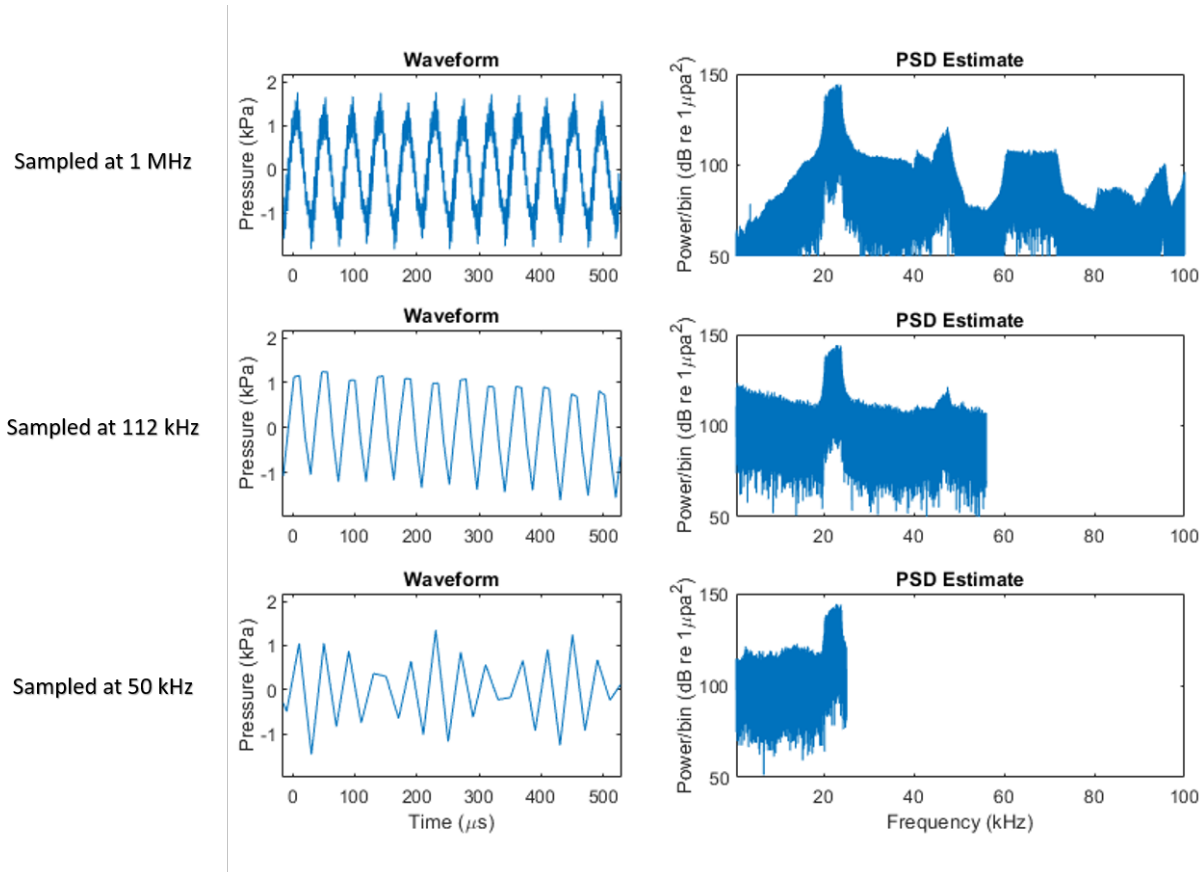

Figure 3: LEFT: Example waveforms of a signal expected to be centered at 24 kHz, with a 8 kHz bandwidth, sampled at 1 MHz (conservative oversample rate), 112 kHz (minimum recommended sample rate), and 50 kHz (not recommended). RIGHT: Corresponding power spectral density (PSD) estimates of the example waveform. Note the waveform envelope degradation and spectral inaccuracies present in the lower sample rate recording.

1.5 Computer and Processing Software

The digitized signal is sent by the ADC to a computer with recording software (e.g., LabView, MATLAB), where the digitized signal is processed and characterized for the final report. Characterization/Analysis (As detailed in section 4) can be completed using any numerical computing environment (e.g., MATLAB, Python).

2. Projector – Hydrophone Set Up

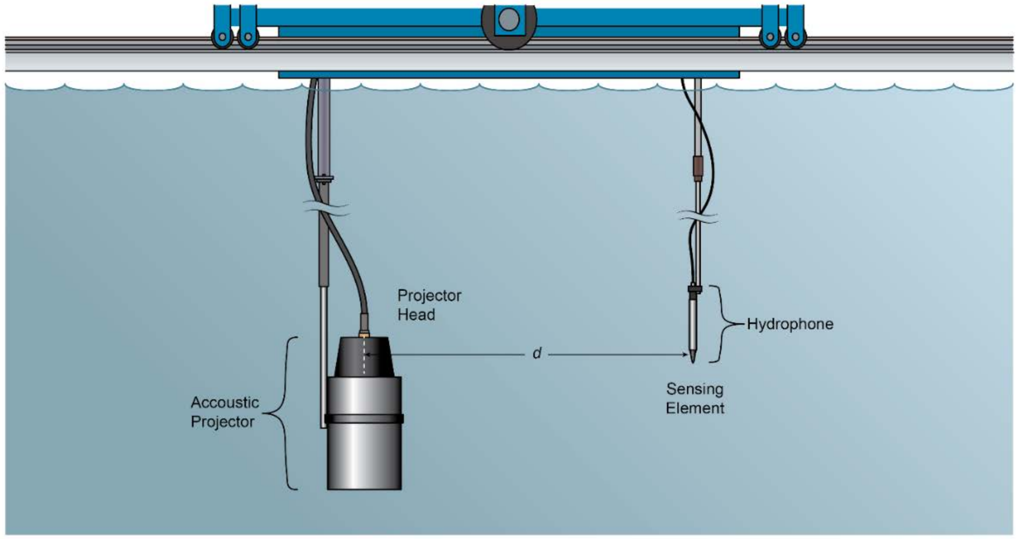

Figure 4: Acoustic Projector - Hydrophone setup

When submerging the system being characterized for recording of active acoustic signals there are two major considerations for the placement of the projector and the hydrophone:

2.1 Projector Depth
2.2 Projector – Hydrophone Arrangement

2.1 Projector Depth

The projector depth for recording should be selected to minimize interference from past/present pulses (reflections). Mid-water is recommended as it provides maximum distance from both surface and bottom reflections. Measure the distance of the projector from any reflective surface (surface, bottom, and, if in a pool/tank, walls), the dimensions of the specific environment in which recordings were made[6]. The depth of the center of the projector head is the depth to be included in the report.

2.2 Projector – Hydrophone Arrangement

Two methods of determining distance are presented here; "Standard Distance" and "Diver-mounted Distance." The objective of "Standard Distance" is to present the acoustic levels with the standard "referenced to 1 meter" protocol, and should always be used for a set of recordings. These measurements will allow for safety evaluations for divers at any range from the system. The "Diver-mounted distance" is only for projectors that are intended to be attached to, carried, or handled by a diver and should be treated as a second set of recordings. These measurements will allow for safety evaluations for these specific scenarios, since near-field effects can alter the expected sound field at such close working ranges.

[6] *Precise knowledge of the projector-hydrophone distance during recording is critical for the accurate characterization of a system (precision should be within one-tenth the total approximate distance). Please ensure great care when positioning the projector and hydrophone.*

2.2.1 Standard Distance

While the primary set of measurements should be referenced to 1 meter, it may not be practical to place the hydrophone at exactly 1 meter from the projector. In this case, the measured pressure can be corrected to account for the actual projector-hydrophone arrangement to obtain a metric referenced to 1 meter (sections 4.4-4.8).

The goal of the standard distance arrangement is to maximize the SNR of the recording while minimizing interference from reflections. To accomplish this, the distance between the hydrophone and projector should be greater than the boundary of the near-field of the emitted sound, but less than the distance between any reflecting surface and the hydrophone or projector. The hydrophone and projector should have approximately equivalent distances from the nearest reflecting surface in order to maximize the distance of either device to any reflecting surface.

The appropriate range for the distance, d_{ph}, between the projector and the hydrophone during recording can be determined using equation 2; $\frac{D^2}{4\lambda}$ represents the boundary of the near-field and, thus, the smallest recommended distance, while $d_{hs} \approx d_{ps}$ represents largest recommended distance.

$$\frac{D^2}{4\lambda} < d_{ph} < d_{hs} \approx d_{ps} \qquad (Eq\ 2)$$

D is the diameter of the projector head, λ is the expected wavelength of the acoustic signal in water (Equation 3), d_{hs} is the shortest distance between the hydrophone and any reflecting surface (e.g., floor, walls, surface) and d_{ps} is the shortest distance between the projector and any reflecting surface.

$$\lambda = \frac{c_{water}}{f_0} \qquad (Eq\ 3)$$

Where c_{water} is sound speed in water (approximately 1500 m/s), and f_0 is the expected frequency of the signal in hertz.

2.2.2 Diver-mounted Distance

If the projector is intended to be mounted to, carried, or handled by a diver (e.g., acoustic modem, handheld sonar), then a second set of recordings should be performed *in addition to* recordings made using the "standard distance" protocol. "Diver-mounted distance" should be representative of the distance and orientation of the projector relative to the diver's head during use.

3. What to Record

To characterize the sound production of your acoustic system, you should take both a noise floor recording and active acoustic recording(s)[7]. The objective of this section is to describe how to determine what needs to be recorded.

[7] *A single system may require multiple recordings given its configurable parameter options.*

3.1 Noise Floor

With all projectors and hydrophones in position, gain levels set, and filters selected – make a recording with no active sounds present. This provides a base level recording to compare active sound recordings to throughout the analysis. This step also ensures the recording setup is functioning properly and SNR goals are being met.

3.2 Active Acoustics

The number of active acoustic recordings you should make depends on the number of configurations of signal parameters (e.g., power, frequency, bandwidth, pulse length) available in the system being characterized. The more configurations of parameters you characterize, the more detailed guidance NAVSEA 00C3 can provide for your system. The ideal situation would be to characterize all possible combinations (i.e., full factorial design), however this process is likely prohibitively time-consuming. In the interest of finding a balance between an adequate amount of information conveyed, and a reasonable amount of time spent on characterizing, the following are two recommended strategies to select parameter configurations to characterize:

One-factor-at-a-time testing: In this strategy, all but one parameter are set as constants, with the remaining one treated as an ‘experimental’ parameter that is characterized through a range of its possible values. This is repeated, using a different parameter as the ‘experimental’ condition, until all parameters gone through this testing. This method can require a large time investment, but it can be used to determine how each individual parameter affects the final characterization. This is the preferred strategy to follow. At a minimum, ***one-factor-at-a-time testing should always be performed for gain/power settings*** *(i.e., “Linearity Testing”)*.

Typical use-case: In this strategy, you select and test the combinations of parameters that are most likely to be used in realistic diving scenarios. The goal of this strategy is to use a moderate number of tests to characterize the most commonly used configurations. Although this strategy will not convey the full relationship of each parameter to the sound pressure levels exhibited by the projector, it will provide enough information for guidance in those specific use-cases.

When selecting parameter configurations for characterization, keep in mind that guidance can only be made using the available information. For example, *using the ‘typical use case’ method is much more time efficient than the ‘one-factor-at-a-time’ method, but would result in guidance only being available for the use cases represented in the documentation, which could limit the usability of the system*. Conversely, one-factor-at-a-time testing will consume more time for recording and processing. However, it provides more information that can result in guidance for a broader set of use-cases of the system. The number of use-cases for which guidance can be provided determines the likelihood and scope of approved Navy use of the system. It is not practical to perform thousands of characterizations for a given system. In cases where the number of possible configurations would result large numbers (thousands) of characterizations, you should focus on the extremes of parameter selection and/or combinations that might produce the highest level of peak or average sound pressure levels.

4. Analysis

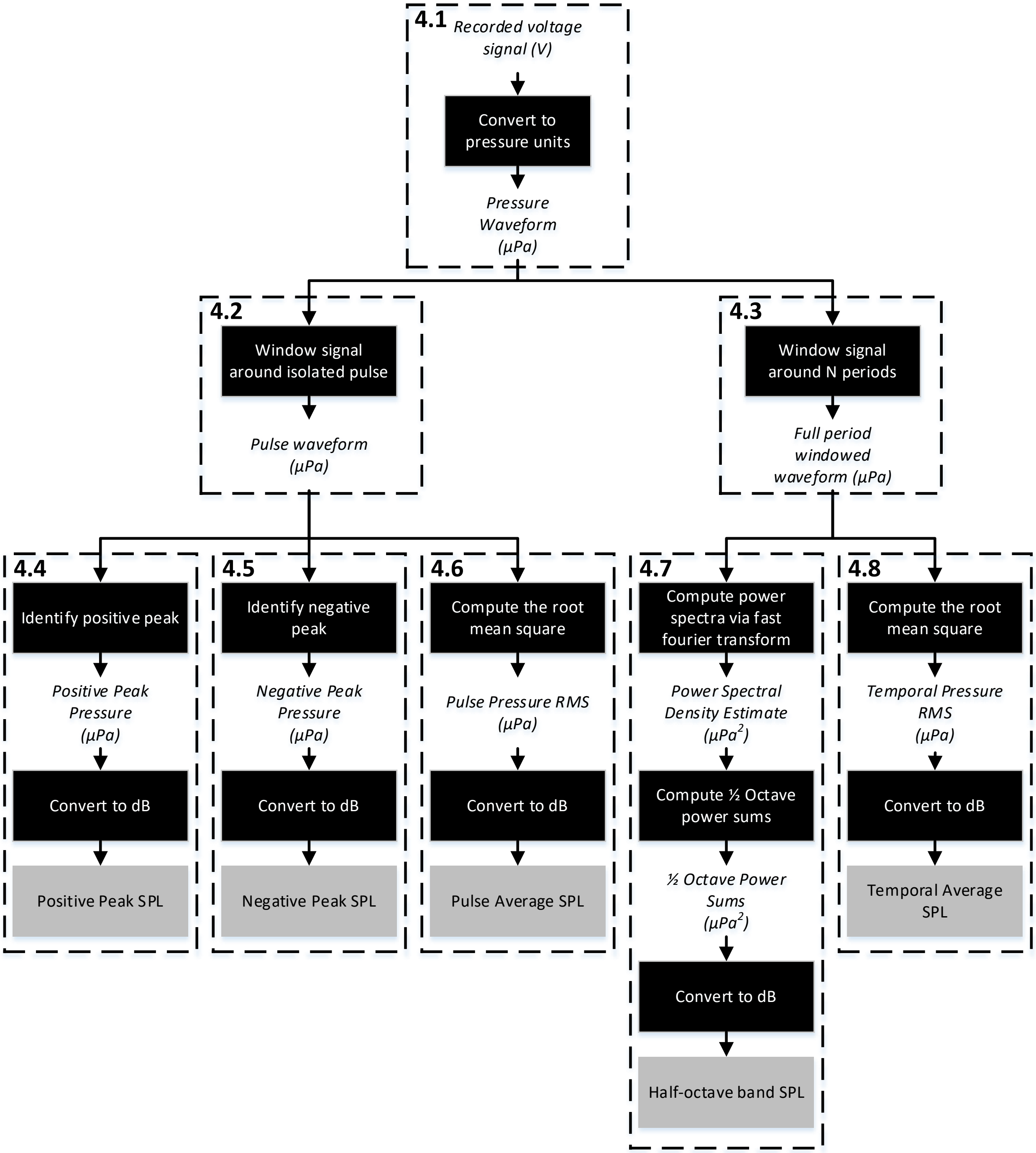

Figure 5: Analysis flow chart. Arrows indicate the flow of computation steps, Italicized text represents intermediate stages of the data, black boxes describe the signal preprocessing actions, gray boxes are the final SPL indices, and boxes with dashed outlines represent the subsections within this document that describe their respective phases of analysis (subsection number in the upper left of each box).

This section provides steps you should follow to obtain the following set of sound pressure level (SPL) indices:

- **Positive peak SPL** SPL_{Pk+} – The maximum positive pressure of the system achieved during a pulse.
- **Negative peak SPL** SPL_{Pk-} – The minimum negative pressure of the system achieved during a pulse.
- **Pulse average SPL** $SPL_{RMS(PA)}$ – The RMS of single acoustic pulses transmitted per duty cycle period. For a system that sends a single pulse (e.g., handheld sonar) per period, only one pulse need be characterized. For a system that sends multiple types of pulses during a single period of communication (e.g., acoustic modems), the signal should be divided into its component pulses and the PA-SPL computed for the pulse with the largest expected RMS.
- **Temporal average SPL** $SPL_{RMS(TA)}$ – The root-mean-square (RMS) of a positive integer number of periods (active signal pulse transmission plus inactivity) of the system.
- **Half-octave band SPL** $SPL_{(f_L,f_U)}$ – Power sums in half-octave intervals spanning 500 Hz to the Nyquist frequency.

This section includes signal processing steps (Figure 5; black boxes), which are required to obtain the intermediate data stages (Figure 5; italicized text) and index computation steps, which result in the final indices of sound pressure level (Figure 5; gray boxes). The numbers in the dashed boxes in Figure 5 correspond with the section in this document that describes how to make a particular calculation. Some of these calculations are for intermediate data values needed to compute the final index. For example, to calculate Negative Peak Pressure, you would first convert your voltage to a pressure waveform as described in Section 4.1. Then you use your calculated pressure waveform to determine the pulse waveform (described in Section 4.2). Finally, to determine the negative peak pressure, you follow the steps in Section 4.5 for the sound pressure level of the negative peak pressure.

The following sections (4.1-4.8) correspond to the numbers in the dashed boxes in Figure 5.

4.1 Convert to pressure

Inputs: voltage waveform ($v[n]$)*, pre-amp gain, and hydrophone receiving sensitivity*

Outputs: Pressure waveform ($p[n]$)

This step is required to compute all final sound pressure level indices (Sections 4.4-4.8).

Where $v[n]$ is the digitized voltage signal (Units = Volts), A_{dB} is the gain from the pre-amp in dB, and k_{dB} is the sensitivity of the hydrophone in $dB\ re\ \frac{1\,V}{1\,\mu Pa}$. Calculate the digital pressure signal ($p[n]$) using equation 4:

$$p[n] = v[n] * 10^{-\left(\frac{k_{dB}+A_{dB}}{20}\right)} \qquad (Eq\ 4)$$

The resulting waveform ($p[n]$) is in units of µPa.

4.2 Window signal around isolated pulse

Input: Pressure waveform ($p[n]$*; section 4.1)*

Output: Pulse waveform(s) $\left(p_{pulse}[n]\right)$

This step is required to compute the final indices of positive peak SPL, negative peak SPL, and pulse average SPL (Sections 4.4-4.6).

Within a signal's period there should be one pulse or one set of pulses. This section details how to window a signal around an isolated pulse in order to compute the positive peak, negative peak, and pulse average sound pressure level. The number of pulses within a period will vary across systems. Examples provided show cases where there is only one pulse per period. Some systems, such as acoustic modems, will have multiple different pulses per period; in these cases the following process should be applied to each of the pulse types within a period. Briefly, the process of windowing a signal to an isolated pulse is:

1. Create a conservative estimate window around the pulse.
2. Compute the 'analytic signal' by performing Hilbert transform on the waveform.
3. Compute the envelope of the waveform by using the absolute value of the analytic signal.
4. Compute the max value of the envelope.
5. Identify the first and last data points of the Hilbert transform to cross 50% of the max value of the envelope. The location of these points are the pulse boundaries (edges of the window).

Example: Consider a system that produces a single pulse per period, such as the one presented in Figure 6. Figure 6A shows the waveform with one full period, and one pulse per period. Figure 6B is a conservative estimate of the window around the pulse. Figure 6C shows the envelope computed from the Hilbert transform of B, the max value of the envelope (black line), and the recommended boundaries for the pulse window (blue circles). Figure 6D shows the isolated pulse waveform based on the bounds set in Figure 6C.

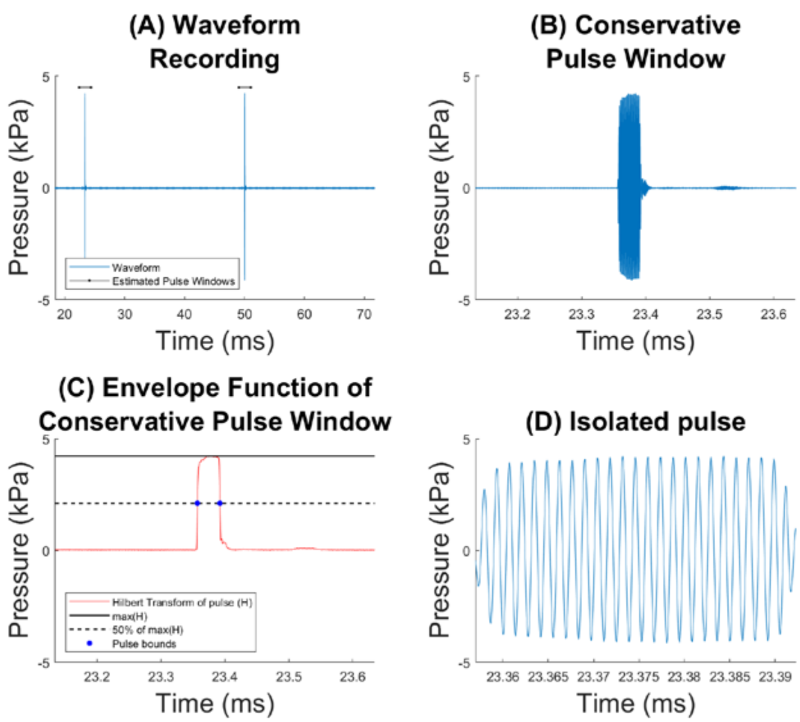

Figure 6: (A) Waveform with 1 full period. Potential conservative estimates of pulse windows are shown as black dots above the pulse. (B) Zoomed in conservative estimate of the pulse window. (C) Hilbert transform of the waveform within the conservative window used to identify the bounds of the pulse. (D) The isolated pulse as defined by the bounds determined in C.

4.3 Window signal around N pulse repetition periods

Input: Pressure waveform ($p[n]$) *(Section 4.1)*

Output: Full period waveform $(p_{period}[n])$

This step is required to compute half-octave band SPL and temporal average SPL (Sections 4.7-4.8).

Analysis: Window signal around around N periods

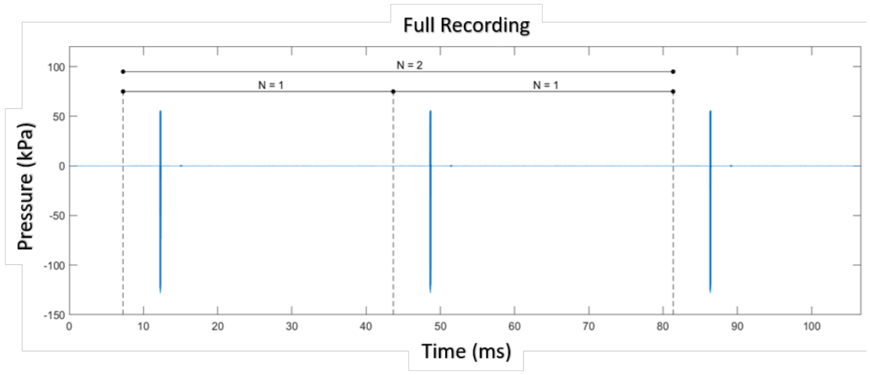

Figure 7: Full recording with signal periods outlined by vertical dashed lines. Horizontal lines show the span of two periods (N = 1), and the span of the two periods aggregated together (N = 2). Periods are defined as starting ~5ms before the start of a given pulse.

1. A signal's period is defined as the time period between the onset times of instances of a repeating pulse pattern. Therefore, a period usually contains one set of pulses and a period of inactivity. For this stage of processing, you should:
2. Observe your recorded signal in full (Figure 7).
3. Define the onset of a pulse repetition period as some constant amount of time prior to the signal pulse (Figure 7; vertical lines indicate ~5 ms prior to pulse start)
   - The amount of time prior to the pulse used to define the start of a period is arbitrary, the only requirements are that it should be constant and should allow for complete inclusion of the pulse shape.
   - In Figure 7, the example shows a recorded signal that captured 3 pulses, and two complete pulse repetition periods; the boundaries of which are illustrated with vertical dashed lines. This example captures two full periods, so you can limit the signal to precisely capture these two periods (Figure 8).
4. Window the signal by aligning the start and end to some integer number of periods (Figure 8).
   - Windowing the signal around multiple periods allows for better characterization of low frequency energy that may arise from factors such as pulse rate.

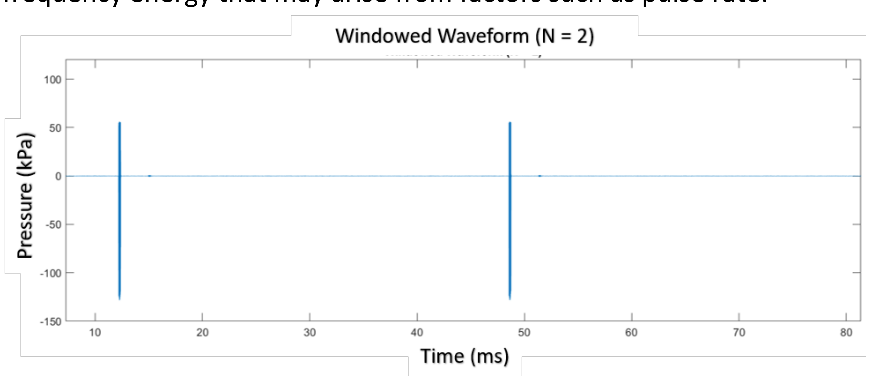

Figure 8: Windowed version of the waveform presented in Figure 7.

4.4 Identify Positive Peak Pressure

Inputs: Pulse waveform ($p_{pulse}[n]$; [section 4.2](#)), distance between projector and recording hydrophone (d_{ph}).

Output: Sound pressure level of the positive peak pressure ($\boldsymbol{SPL_{Pk+}}$; example shown in Figure 9)

This calculation results in a final SPL index.

To compute the sound pressure level of the positive peak pressure of $p_{Pulse}[n]$, denoted $\boldsymbol{SPL_{Pk+}}$:

1. Identify the positive value with the greatest magnitude, $\max\{p_{pulse}[n]\}$, using peak detection.
2. Ensure your peaks are in units of micropascals (μPa), convert as necessary, and
3. Convert the peak pressure values to decibels.
   a. *Convert to decibels referenced to 1m* ($dB\ re\ 1\mu Pa\ @\ 1m$) using equation 5.

$$\boldsymbol{SPL_{Pk+}} = 20\log_{10}\left(\frac{\max\{p_{pulse}[n]\}}{1\ \mu Pa}\frac{d_{ph}}{1\ m}\right) \qquad (Eq\ 5)$$

   b. *If the projector is intended to be held/worn/used by a diver, convert to decibels referenced to the measured distance* ($dB\ re\ 1\mu Pa\ @\ d_{ph}\ m$) using equation 6 in addition to being calculated with a reference to 1m (Equation 5).

$$\boldsymbol{SPL_{Pk+}} = 20\log_{10}\left(\frac{\max\{p_{pulse}[n]\}}{1\ \mu Pa}\right) \qquad (Eq\ 6)$$

4.5 Identify Negative Peak Pressure

Inputs: Pulse waveform ($p_{pulse}[n]$; [section 4.2](#)), distance between projector and recording hydrophone (d_{ph}).

Output: Sound pressure level of the negative peak pressure ($\boldsymbol{SPL_{Pk-}}$; example shown in Figure 9)

This calculation results in a final SPL index.

To compute the sound pressure level of the negative peak pressure of $p_{Pulse}[n]$, denoted $\boldsymbol{SPL_{Pk-}}$:

1. Identify the negative value with the greatest magnitude ($\max\{-p_{pulse}[n]\}$), using peak detection.
2. Ensure your peaks are in units of micropascals (μPa), convert as necessary, and
3. Convert the peak pressure values to decibels.
   a. *If the projector is NOT intended to be held/worn/used by a diver, convert to decibels referenced to 1m* ($dB\ re\ 1\mu Pa\ @\ 1m$) using equation 7.

$$\boldsymbol{SPL_{Pk-}} = 20\log_{10}\left(\frac{\max\{-p_{pulse}[n]\}}{1\ \mu Pa}\frac{d_{ph}}{1\ m}\right) \qquad (Eq\ 7)$$

b. *If the projector is intended to be held/worn/used by a diver, convert to decibels referenced to the measured distance* $(dB\ re\ 1\mu Pa\ @\ d_{ph}\ m)$ using equation 8 in addition to being calculated with a reference to 1m (Equation 7).

$$\boldsymbol{SPL_{Pk-}} = 20\log_{10}\left(\frac{\max\{-p_{pulse}[n]\}}{1\ \mu Pa}\right) \qquad (Eq\ 8)$$

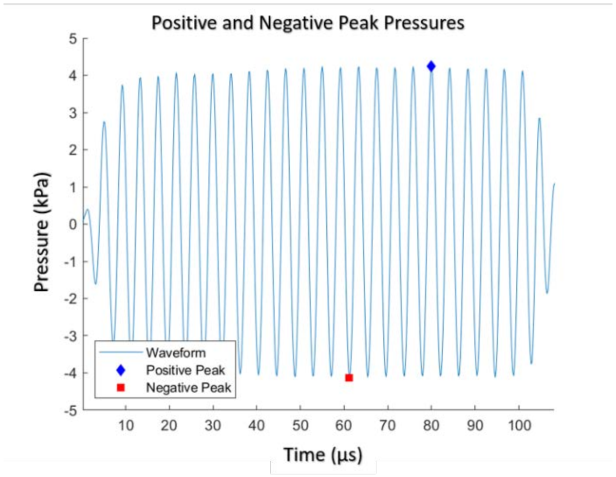

Figure 9: Pulse waveform with labeled positive (blue diamond) and negative (red square) peaks. The value of these points is used to compute the peak positive and peak negative sound pressure level indices.

4.6 Compute Pulse Pressure Root Mean Square

Inputs: Pulse waveform (p_{pulse}[n]; [section 4.2](#)), distance between projector and recording hydrophone (d_{ph}).

Output: Pulse average sound pressure level ($\boldsymbol{SPL_{RMS(PA)}}$; example shown in Figure 10)

This calculation results in a final SPL index.

1. Given, $p_{pulse}[n]$ is the pulse pressure waveform, and N is the total number of data points in $p_{pulse}[n]$. The root mean square (RMS) value of $p_{Pulse}[n]$ is computed with equation 9.

$$\mathrm{RMS}(p_{pulse}[n]) = \sqrt{\frac{1}{N}\sum_{n=1}^{N} p_{pulse}^2[n]} \qquad (Eq\ 9)$$

2. Convert $\mathrm{RMS}(p_{pulse}[n])$ to decibels.
   a. *Convert to decibels referenced to 1m* $(dB\ re\ 1\mu Pa\ @\ 1m)$ using equation 10.

$$\boldsymbol{SPL_{RMS(PA)}} = 20\log_{10}\left(\frac{\mathrm{RMS}(p_{pulse}[n])}{1\ \mu Pa}\frac{d_{ph}}{1\ m}\right) \qquad (Eq\ 10)$$

b. *If the projector is intended to be held/worn/used by a diver, convert to decibels referenced to the measured distance* $(dB\ re\ 1\mu Pa\ @\ d_{ph}\ m)$ using equation 11 in addition to being calculated with a reference to 1m (Equation 10).

$$\boldsymbol{SPL_{RMS(PA)}} = 20\log_{10}\left(\frac{\mathrm{RMS}\left(p_{pulse}[n]\right)}{1\ \mu Pa}\right) \qquad (Eq\ 11)$$

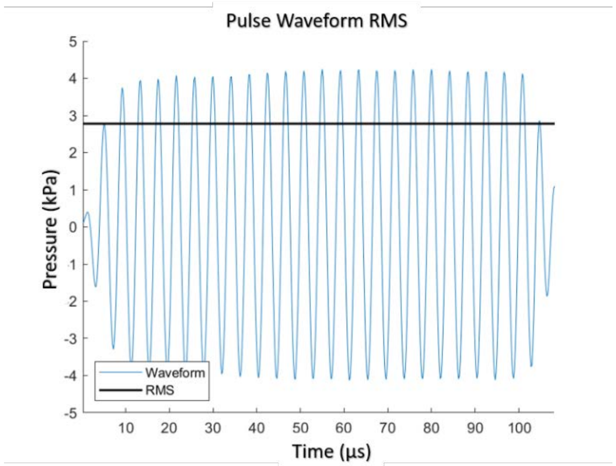

Figure 10: Pulse waveform (blue line) and the root mean square (RMS) of the pulse waveform (solid black line). The RMS value is used to compute the pulse average sound pressure level.

4.7 Compute Power Spectral Density Estimate and ½ Octave Power Sums

Input: Full period waveform ($p_{period}[n]$*; section 4.3)*

Output: Half-Octave Band Sound Pressure Levels $\left(\boldsymbol{SPL}_{(f_L,f_U)}\right)$

This calculation results in a final SPL index.

1. Power spectral density (PSD; $\frac{\mu Pa^2}{Hz}$) estimates, $P[f]$, are obtained by computing the fast Fourier transform (FFT) of the pressure signal. Given $X[f]$ is the FFT of the pressure signal, $p_{period}[n]$, the PSD is computed using equation 12.

$$PSD[f] = \frac{1}{N * Fs}|X[f]|^2 \qquad (Eq\ 12)$$

Where N is the number of samples in the signal, and Fs is the sample rate.

Note that, for real signals, $PSD[f] = PSD[-f]$. Therefore, to account for energy from both positive and negative frequency components, limit analysis to one side of the frequency spectrum and multiply power values by 2. You can do this by discarding the negative frequencies and multiplying values by 2 for all frequencies greater than zero.

Analysis: Compute power spectral density and ½ octave power sums

2. Power band sums $\left(P_{(f_L,f_U)}\right)$ are computed for ½ Octave bands between lower and upper bounds (f_L and f_U, respectively; equation 13) (Table 1). The constant $\frac{Fs}{N}$ is required to convert power density units ($\frac{\mu Pa^2}{Hz}$) to power units (μPa^2).

$$P_{(f_L,f_U)} = \frac{Fs}{N} \sum_{f=f_L}^{f_U} PSD[f] \qquad (Eq\ 13)$$

a. *Convert to decibels referenced to 1m* ($dB\ re\ 1\mu Pa\ @\ 1m$) using equation 14.

$$\boldsymbol{SPL}_{(\boldsymbol{f_L},\boldsymbol{f_U})} = 10\log_{10}\left(\frac{P_{(f_L,f_U)}}{1\ \mu Pa^2}\frac{d_{ph}}{1\ m}\right) \qquad (Eq\ 14)$$

b. *If the projector is intended to be held/worn/used by a diver, convert to decibels referenced to the measured distance* ($dB\ re\ 1\mu Pa\ @\ d_{ph}\ m$) using equation 15 in addition to being calculated with a reference to 1m (Equation 14).

$$\boldsymbol{SPL}_{(\boldsymbol{f_L},\boldsymbol{f_U})} = 10\log_{10}\left(\frac{P_{(f_L,f_U)}}{1\ \mu Pa^2}\right) \qquad (Eq\ 15)$$

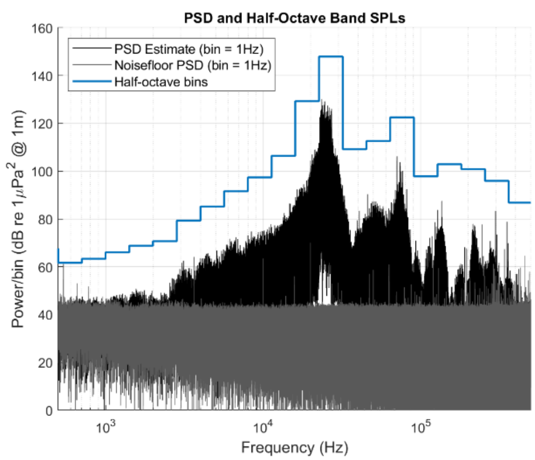

Figure 11: The power spectral density (PSD; black line) of a given acoustic signal, PSD of a noise floor recording, and the half-octave power sums (purple step-lines). The x-axis is spaced logarithmically such that the width of each half-octave band appears equivalent on this scale.

Equations for computing bounds and center frequencies:

$$f_L(r) = 500 * 2^{\frac{r}{2}};\quad r \in \mathbb{Z} \qquad (Eq\ 16: Lower\ Bound)$$

$$f_U(r) = f_L(r+1) \qquad (Eq\ 17: Upper\ Bound)$$

$$f_0(r) = \sqrt{f_L(r) * f_U(r)} \qquad (Eq\ 18: Center\ Frequency)$$

Analysis: Compute power spectral density and ½ octave power sums

Units	Lower Bound (f_L)	Center Frequency (f_0)	Upper Bound (f_U)
Hz	500.00	594.60	707.11
Hz	707.11	840.90	1000.00
kHz	1.00	1.19	1.41
kHz	1.41	1.68	2.00
kHz	2.00	2.38	2.83
kHz	2.83	3.36	4.00
kHz	4.00	4.76	5.66
kHz	5.66	6.73	8.00
kHz	8.00	9.51	11.31
kHz	11.31	13.45	16.00
kHz	16.00	19.03	22.63
kHz	22.63	26.91	32.00
kHz	32.00	38.05	45.25
kHz	45.25	53.82	64.00
kHz	64.00	76.11	90.51
kHz	90.51	107.63	128.00
kHz	128.00	152.22	181.02
kHz	181.02	215.27	256.00
kHz	256.00	304.44	362.04
kHz	362.04	430.54	512.00
kHz	512.00	608.87	724.08
kHz	724.08	861.08	1024.00
MHz	1.02	1.22	1.45
MHz	1.45	1.72	2.05
MHz	2.05	2.44	2.90

Table 1: Center frequencies and associated bounds. This table shows bounds ranging from 500 Hz to 2.90 MHz, however power sums need only to be performed to a range warranted by the system.

4.8 Compute Full Period Pressure Root Mean Square

Inputs: Full period waveform ($p_{period}[n]$; section 4.3), distance between projector and recording hydrophone (d_{ph}).

Output: Temporal average sound pressure level $\left(\boldsymbol{SPL_{RMS(TA)}}\right)$

This calculation results in a final SPL index.

1. Given, $p_{period}[n]$ is the full period pressure waveform, and N is the total number of data points in $p_{period}[n]$. The root mean square (RMS) value of $p_{period}[n]$ is computed using equation 19.

Analysis: Compute full period pressure root mean square

$$\mathrm{RMS}\big(p_{period}[n]\big) = \sqrt{\frac{1}{N}\sum_{n=1}^{N} p_{period}^{2}[n]} \qquad (Eq\ 19)$$

2. Convert $\mathrm{rms}\big(p_{period}[n]\big)$ to decibels.
   c. *Convert to decibels referenced to 1m* $(dB\ re\ 1\mu Pa\ @\ 1m)$ using equation 20.

$$\boldsymbol{SPL_{RMS(TA)}} = 20\log_{10}\left(\frac{\mathrm{RMS}\big(p_{period}[n]\big)}{1\ \mu Pa}\,\frac{d_{ph}}{1\ m}\right) \qquad (Eq\ 20)$$

   d. *If the projector is intended to be held/worn/used by a diver, convert to decibels referenced to the measured distance* $(dB\ re\ 1\mu Pa\ @\ d_{ph}\ m)$ using equation 21 in addition to being calculated with a reference to 1m (Equation 20).

$$\boldsymbol{SPL_{RMS(TA)}} = 20\log_{10}\left(\frac{\mathrm{RMS}\big(p_{period}[n]\big)}{1\ \mu Pa}\right) \qquad (Eq\ 21)$$

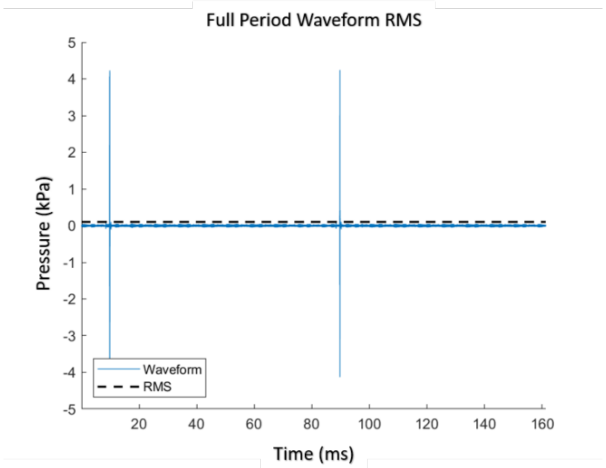

Figure 12: Two full periods of the waveform (blue line) and the root mean square (RMS) of the waveform (dashed black line). The RMS value is used to compute the temporal average sound pressure level.

5. Presenting Results

This section describes the expected contents of the final report of the characterization(s). This should include a brief summary of the recording and experimental setup, choice of parameter configurations (if applicable), indices of sound pressure levels (per parameter configuration), and graphs of the waveform and PSD estimates (per parameter configuration).

The following checklists will help ensure you have all the information that should be included in your report:

5.1 Recording and experimental setup information to include:

- ☐ Hydrophone manufacturer/model
- ☐ Hydrophone receiving sensitivity
- ☐ Signal condition/pre-amp manufacturer/model
- ☐ Signal condition/pre-amp filters used
- ☐ Signal condition/pre-amp gain level used
- ☐ Analog-to-digital converter manufacturer/model
- ☐ Depth of projector and hydrophone during testing
- ☐ Distance between projector and hydrophone during testing
- ☐ Distance between projector and any potentially acoustic reflective surface (ground, walls, etc.)
- ☐ Distance between hydrophone and any potentially acoustic reflective surface (ground, walls, etc.)
- ☐ Brief rationale of parameter configuration choices for characterization (if applicable)

5.2 Characterization(s) information

- ☐ Parameter settings (e.g., power, pulse shape)
- ☐ Pulse duration and inter-pulse period
- ☐ Example waveform plots of pulse waveforms (Section 4.2) and period waveforms (Section 4.3)
- ☐ Plots of the PSD estimates and the ½ Octave sound pressure levels (Section 4.7)
- ☐ Table of results including peak positive SPL, peak negative SPL, pulse average SPL, temporal average SPL, and ½ Octave sum SPLs (Example in section 5.2.2)

5.2.1 Plot preferences

There are two types of plots that should be included in a final report: waveform plots, and power spectrum density (PSD) plots.

Consider using units for pressure and time that make the plot intuitive to read. Consider the waveform plots used to present RMS values in sections 4.6 and 4.8 (shown side by side in Figure 13). In both of these cases the pressure is presented on the y-axis as kilopascals (kPa), despite all sound pressure index computations being done with micropascals (μPa), because it is more intuitive to read the pressure as "$2.8\ kPa$," than it is to read it as "$2.8 * 10^9 \mu Pa$." Similar considerations should be taken when determining the appropriate units for the x-axis of the plot. Note that the pulse waveform is presented in microseconds (μs), and the period waveform is presented in (ms) in order to make each axis easier to read.

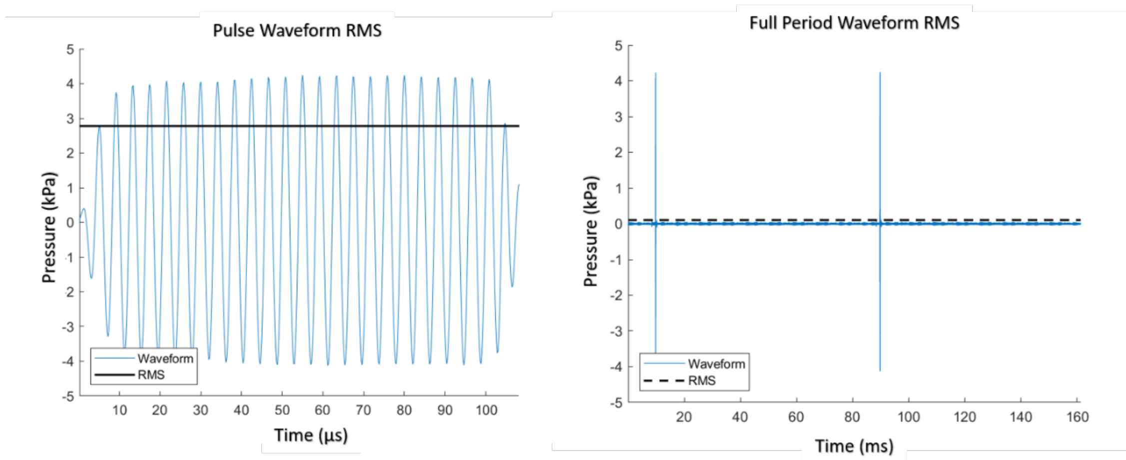

Figure 13: Side by side view of pulse waveform and full period waveform. Note that the y-axes are the same, however the x-axes differ in units and magnitude.

PSD plots, used to present spectral power and half-octave power sums, similarly require special considerations. The y-axis should be presented in decibels referenced to $1\mu Pa^2$ at an appropriate distance. The x-axis should span 500 Hz to the Nyquist frequency and be logarithmically spaced – logarithmic spacing of the x-axis allows for half-octave bounds to be viewed as equally sized (Figure 14 shows a comparison of a PSD plot with half-octave sums on linearly and logarithmically spaced x-axes). Additionally, it is recommended that the PSD of the noise floor is included in the plot for comparison to the PSD of the active signal.

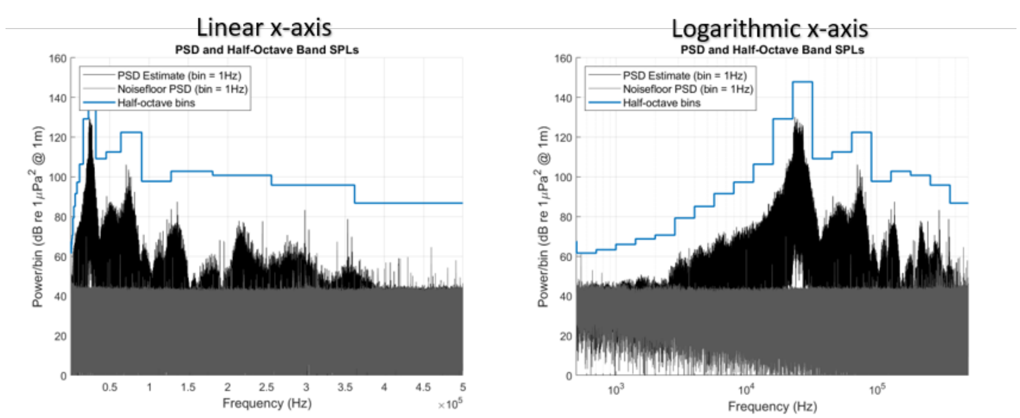

Figure 14: Example PSD plots with linearly spaced (left) and logarithmically spaced (right - preferred) x-axes. PSD plots should include the PSD estimate of the active sound recording (black), PSD of the noise floor recording (gray), and the ½ octave sound pressure levels (magenta). Note that the relative widths of the half-octave sums consistently grow larger in the linear spaced plot, and are equally sized throughout the logarithmically spaced plot; logarithmic spacing is preferred.

5.2.2 Presenting Sound Pressure Level Indices

Sound pressure level indices should be presented in a simple, readable way; it is recommended that positive peak sound pressure level, negative peak sound pressure level, pulse average sound pressure level, and temporal average sound pressure level be simply listed in a basic table or bullet points.

Projector Tested	**Reference Distance (m)**	**Parameter Configuration**	**SPL Indices** $(dB\ re\ 1\mu Pa\ @\ Reference\ Distance)$				
				SPL_{pk+}	SPL_{pk-}	$SPL_{RMS(PA)}$	$SPL_{RMS(TA)}$
Top-side	1	*A*					
Top-side	1	*B*					
Diver-mount	1	*A*					
Diver-mount	1	*B*					
Diver-mount	0.1	*A*					
Diver-mount	0.1	*B*					

Table 2: Example tabular layout of single value SPL indices for a system consisting of two projectors ("Top-side" and a "Diver-Mounted"). Each Projector was tested with two parameter configurations labeled "A" and "B."

Lastly, half-octave band sound pressure levels should be presented in a table clearly listing the bounds of the half-octave and the sound pressure level within that band (e.g., Table 3). The number of bands used in this example is not a definite number that should be used for all characterizations; it is recommended that you use as many half-octave bands as necessary to reach the Nyquist frequency.

Lower Bound (f_L)	**Upper Bound** (f_U)	$SPL_{(f_L,f_U)}$ $(dB\ re\ 1\mu Pa\ @\ d\ m)$
500 Hz	707 Hz	
707 Hz	1.00 kHz	
1.00 kHz	1.41 kHz	
1.41 kHz	2.00 kHz	
2.00 kHz	2.83 kHz	
2.83 kHz	4.00 kHz	
4.00 kHz	5.66 kHz	
5.66 kHz	8.00 kHz	
8.00 kHz	11.3 kHz	
11.3 kHz	16.0 kHz	
16.0 kHz	22.6 kHz	
22.6 kHz	32.0 kHz	
32.0 kHz	45.3 kHz	
45.3 kHz	64.0 kHz	
64.0 kHz	90.5 kHz	
90.5 kHz	128 kHz	
128 kHz	181 kHz	
181 kHz	256 kHz	
256 kHz	362 kHz	
362 kHz	512 kHz	

Table 3: Example tabular layout of half-octave band sound pressure levels for a generic signal sampled at 1MHz.

Final Recommendations

As stated at the start of this document, this guidance does not establish legally enforceable responsibilities. The purpose of this document is to serve as a set of recommendations for the acoustic characterization process that may assist active acoustic technology manufacturers/vendors in getting their system accepted into the ANU technologies list. The recommendations here are methods the authors have expressed as important and think should be used. The use of the word "should" throughout this document means that something is suggested or recommended, not required.

In general, more information is better for providing guidance on the use of active acoustic technologies with divers. Recommendations for *minimums* are provided throughout this document (e.g., minimum sample rate, minimum testing set up, minimum frequency bands); however, you, as the manufacturer or supplier interested in characterizing the sound production of your underwater acoustic equipment should use your judgement to exceed these minimums whenever appropriate to ensure guidance is provided with maximum accuracy and fidelity.

Glossary

General Terms

- Acoustic Projector – refers to the component of the system being characterized responsible for emitting acoustic energy. The "Acoustic Projector," or just "Projector," specifically refers to the component of the system responsible for emitting the acoustic signal.
- Analog-to-Digital Converter (ADC) – Component of the recording system responsible for receiving the voltage signal from the signal conditioner and discretizes it at a defined sample rate.
- Characterization – Process of recording acoustic signals and computing sound pressure level indices.
- Directivity – Refers to the angle(s) and path of emittance from a projector and/or receiving area for a sensor.
- Diver-mounted distance – Distance of recording intended to mimic the distance between the projector and the head of the diver for systems that are meant to be mounted to, carried, or handled by a diver.
- Full period waveform – Result of windowing the pressure waveform around a whole number of pulse repetition periods.
- Gain – Ratio of power of output to the power of input.
- Hydrophone – Piezoelectric sensor produces a voltage signal that can be converted to pressure according to the sensitivity of the sensor.
- Noise Floor Recording – Ambient recording made with all equipment in place but no active sounds being transmitted.
- Nyquist Frequency – Defined as ½ the sample rate. The maximum frequency measurable in spectral analysis.
- Parameter (or "Configurable parameter") – Properties of the emitted acoustic signal that may be controlled by the user (e.g., Power, frequency, bandwidth, pulse length, pulse shape).
- Positive peak pressure – Value of a pressure waveform with the largest positive magnitude.
- Negative peak pressure – Value of a pressure waveform with the largest negative magnitude.
- Power Spectral Density (PSD) – Description of the distribution of power of a signal into the frequency components composing that signal.
- Power sum – Process of summing the power within a given frequency band (i.e., half-octave).
- Pressure waveform – Result of converting voltage waveform to pressure units (preferably μPa) using the hydrophone's receiving sensitivity to scale the waveform.
- Pulse waveform – Result of windowing the pressure waveform around a single pulse of the acoustic signal.
- Receiving Sensitivity – Property of the hydrophone indicating the volt-to-pressure relationship of the output signal. Receiving sensitivity may be presented as a function of frequency (i.e., frequency response), a general relationship, or both.
- Reflection – change in direction of an acoustic wave at the interface between two different media (i.e., water & air, water & ground).
- Root Mean Square (RMS) – Value computed to represent the 'average' power of the time series waveform.

- Sample Rate – Rate at which the raw voltage signal is measured and discretized. Presented as samples/second (Hz).
- Signal Conditioner/Pre-Amp – Device used in recording active signals intended to filter and scale the input signal prior to analog-to-digital conversion.
- Pulse Repetition Period – Time length spanning from the onset of one pulse to the onset of the next. For systems producing repeating sequences of pulses (e.g., acoustic modems), this time length spans from the onset of the first pulse in the sequence to the onset of the first pulse in the next sequence.
- Signal-to-noise ratio (SNR) – The ratio of signal power to the level of background noise.
- Standard Distance – Distance of recording intended to maximize the signal-to-noise ratio, minimize interference from reflections, and be referenced to 1-meter distance computationally.
- System – Technology being characterized that contains at least one acoustic projector.
- Voltage waveform – Recorded signal in voltage units.
- Windowing – Action of trimming the bounds of a recorded signal (e.g., isolating the 10ms pulse in a 5s recording).

SPL Indices

- **Positive peak SPL,** $\boldsymbol{SPL_{Pk+}}$ – The maximum positive pressure of the system achieved during a pulse.
- **Negative peak SPL,** $\boldsymbol{SPL_{Pk-}}$ – The minimum negative pressure of the system achieved during a pulse.
- **Pulse average SPL,** $\boldsymbol{SPL_{RMS(PA)}}$ – The RMS of single acoustic pulses transmitted per duty cycle. For a system that sends a single ping (e.g., handheld sonar) per cycle, only one pulse need be characterized. For a system that sends multiple signals during a single cycle of communication (e.g., acoustic modems), the signal should be divided into its component pulses and the PA-SPL computed for the pulse with the largest expected RMS.
- **Temporal average SPL,** $\boldsymbol{SPL_{RMS(TA)}}$ – The root-mean-square (RMS) of a positive integer number of periods (active signal pulse transmittance plus inactivity) of the system.
- **Half-octave band SPL,** $\boldsymbol{SPL_{(f_L,f_U)}}$ – Power sums in half-octave intervals spanning 500 Hz to the Nyquist frequency.

Equation variables

- Fs –Sample Rate
- f_0 – Center frequency of a given signal and/or given band
- B –Bandwidth
- $F_{Nyquist}$ – Nyquist frequency
- V_{min} –Minimum signal level to achieve a given SNR
- V_{max} –Maximum voltage level a given ADC system is capable of
- DR_{ADC} –Dynamic range of a given ADC system
- SNR_{min} –Desired signal-to-noise ratio of a recording setup (recommend 40 dB)
- D –Diameter of the projector head
- d_{ph} – Distance between the projector (p) and the hydrophone (h)
- d_{hs} – Distance between the hydrophone (h) and the nearest reflective surface (s)

Glossary

- d_{ps} – Distance between the projector (p) and the nearest reflective surface (s)
- λ – Expected wavelength of the acoustic signal in water
- c_{water} – Soundspeed in water (approximately $1500 \frac{m}{s}$)
- N – number of samples in a given signal
- $n = 1,2, \dots N$ – Sample Index
- $v[n]$ – Recorded voltage waveform (V)
- $p[n]$ – Recorded pressure waveform (μPa)
- A_{dB} – Gain applied by the preamp (dB)
- k_{dB} – Receiving sensitivity of the hydrophone $\left(dB\ re \frac{1V}{\mu Pa}\right)$
- $p_{pulse}[n]$ – Pulse Waveform
- $p_{period}[n]$ – Full period Waveform
- $X[f]$ – Fast Fourier Transform (FFT) of $p_{period}[n]$
- $PSD[f]$ – Power Spectral Density of $p_{period}[n]$ $(dB\ re \frac{\mu Pa^2}{Hz})$
- $P_{(f_L, f_U)}$ – Total average power in half-octave bands $(dB\ re\ \mu Pa^2)$
- f_L –Lower bound frequency used in power summing
- f_U –Upper bound frequency used in power summing