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Design and Development of Persistent Harmonic Acoustic Detector (PHAD) Sensor System

by Joydeep Bhattacharyya, David J Gonski, Leng K Sim, Hao Q Vu, and WC Kirkpatrick Alberts II

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14. ABSTRACT

Detection and characterization of multiple near-ground, slow-moving high-value targets is a critical need for the Department of Defense (DOD). The detection and tracking of such targets, using sparse networks and in mixed urban and rural environments, can be carried out using acoustic sensing over a wide range of frequencies. In Persistent Harmonic Acoustic Detection (PHAD), the US Army Combat Capabilities Development Command (CCDC) Army Research Laboratory developed a novel acoustic sensor system with capabilities and performance that mirror the larger footprint of low-frequency acoustic systems that are in the current military inventory while providing the form factor and ease of use for field installation by one Soldier. The Army can use this system to address unattended acoustic sensor needs for numerous applications ranging from activity detection to ground- and air-traffic monitoring to battlespace situational awareness, among others. Given the high sample rate available for PHAD, we can also connect multi-component seismic, electric-field, and/or magnetic-field sensors and collect data contemporaneously with the aforementioned eight-channel acoustic array, making PHAD a deployable multimodal sensor. The PHAD is composed of two independently operable, but slightly different, acoustic arrays, the small array (SA) and the large array (LA). The SA is easier to deploy while the LA is expected to have a better performance in monitoring low frequency targets at standoff. For both arrays, the CCDC Army Research Laboratory packages the electronics inside the environmentally hardened sensor box. The range of DOD targets capable of being detected, tracked, and located using the PHAD system continues to grow, showing the system's efficacy as a multi-role acoustic detection system.

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1. Introduction

Detection and characterization of multiple near-ground, slow-moving high-value targets is a critical need for the US Department of Defense (DOD). The detection and tracking of such targets, using sparse networks and in mixed urban and rural environments, is carried out using acoustic sensing over a wide range of frequencies. However, for this application to be effective, significant capabilities in sensor technologies, advanced understanding of signal propagation, physics-based signal processing, and utilization of all-source information is critical. The US Army Combat Capabilities Development Command (CCDC) Army Research Laboratory (ARL) has recently developed acoustic arrays and associated exploitation algorithms that provide both detection and tracking of targets of interest to DOD. The CCDC Army Research Laboratory's acoustic modelers can support both pre-deployment planning and post-deployment event understanding. Improved sensors and processing will enable detection, tracking, cueing, and classification of diverse ground and airborne targets at extended ranges. Due to the higher noise levels expected for battlefield acoustics, increasing the number of acoustic sensors by using arrays is beneficial as they can potentially decrease background noise and thereby increase the signal-to-noise ratio (SNR) of the target. Arrays can potentially limit the impact of local manmade clutter sources (e.g., heating ventilation and air conditioning units, vehicular traffic) on the collected data. Having more than one physically separated sensor array allows us to distinguish such clutter from the data, associate them across the arrays based on our knowledge of the clutter signatures, and thereby decrease their impact on downstream sense-making. Lastly, decreasing the form-factor and improving the ease of deployment is always preferable in any urban or austere environment.

As part of a customer-funded effort, the Acoustic and Electric Field Sensing Branch of ARL engaged the DOD funding agency to understand requirements unique to their areas of operational responsibility (AORs). ARL identified a technology gap for an environmentally robust, hand-emplaced remote microphone array that we can optimize to be target-specific spectral and temporally varying acoustic signals. In Persistent Harmonic Acoustic Detection (PHAD), ARL developed a novel acoustic sensor system with capabilities and performance that mirror the larger footprint of low-frequency acoustic systems that are in the current military inventory while providing the form factor and ease of use for field installation by one Soldier. DOD's interest in an acoustic sensor system that can detect a large number of both broadband and narrowband at standoff is obvious. Due to the difficulties with hand-emplacing sensors in remote and hostile areas, a self-contained sensor system that includes the sensor, digitizer, and GPS receiver in the same package is preferred. PHAD, which we can deploy in both urban and rural settings without any modifications, provides these capabilities.

ARL has focused the PHAD development efforts for the initial sensor design toward a specific set of requirements (i.e., narrowband tones and their harmonics at frequencies less than 100 Hz). However, PHAD includes sensors with a known response over a wide-range of frequencies (5–50,000 Hz) and a digitizer that can sample up to 50,000 samples/second. The spiral array of eight microphones in PHAD provides good angular resolution on all directions (0°–360°). Therefore, the Army can use this system to address unattended acoustic sensor needs for numerous applications ranging from activity detection to ground- and air-traffic monitoring to battlespace situational awareness, among others. Furthermore, in its current configuration, PHAD has eight unused data-collection channels. Given the high sample rate available for PHAD, we can easily connect multicomponent seismic, electric-field, and/or magnetic-field sensors and collect data contemporaneously with the aforementioned eight-channel acoustic array, making PHAD a deployable multimodal sensor. Expanding its use beyond the military, ARL can leverage the PHAD technology in homeland defense, border protection, and commercial applications.

The PHAD is composed of two independently operable, but slightly different, acoustic arrays, the small array (SA) and the large array (LA). In the SA, we mount the microphones directly on top of the sensor box. The suggested use of the SA is for situations when the physical space for deployment is limited to less than 1-m square. In the LA, the microphones are located outside the sensor box and can take up to 6-m square of physical space. The SA is easier to deploy while we expect the LA to have a better performance in monitoring low frequency targets at standoff. For both arrays, ARL packages the electronics inside the environmentally hardened sensor box. ARL delivered six SAs and two LAs to the DOD customer and trained a number of their personnel in its installation. ARL has subsequently collaborated with the customer to carry out additional field tests against manmade targets of interest to DOD. The range of DOD targets capable of detect, track, and locate using the PHAD system continues to grow, showing the system’s efficacy as a multirole acoustic detection system.

2. Methods, Assumptions, and Procedures

2.1 System Requirements

The PHAD development team derived a set of design parameters for the sensor system following discussions with potential users. The following were the primary design considerations:

- Acoustic sensors (i.e., microphones)
- Sensors arranged in an array for estimating bearing to the target and false alarm mitigation
- Efficient emplacement of sensors
- All-weather, all-terrain applications
- Human emplaced
- Placed on the ground or elevated surfaces like rooftops and towers
- Waveform data to be exfiltrated out via Ethernet cable to a communications relay available at the deployment location
- Powered by an electrical outlet, worldwide
- Include wind-noise reduction device for the microphones
- Available additional channels, available for additional microphones or other phenomenologies like seismic and magnetic-field sensors
- High sample rate recording, to allow for multitude of targets
- Broadband recording to detect both transient and harmonic signals
- GPS timing of data
- Exfiltrated data will not include location information
- Two separate systems, depending on the available spatial extent for deployment

2.2 Operational Concept

The primary purpose of PHAD is for wide area monitoring under a range of geographical, terrain, and vegetation conditions. The Concept of Operations (CONOPS) for PHAD is that it is hand emplaced at a physically secure location near a region of interest. Depending on the type of target and its signature, we can install PHAD at standoff distances of hundreds of meters to more than 100 km. The sensors are sensitive to atmospheric acoustic signals and the system can record from 200 samples-per-second (sps) to 50,000 sps; it is currently set at 200. The PHAD waveform data is available to the user in physical units (i.e., pascals). Depending on the exploitation algorithm used, we can leverage the PHAD data to detect and track movement of one or more targets. With multiple PHAD sensors, the user has the ability to geolocate the targets, incorporate algorithms to mitigate false alarms, and provide pattern of life analysis. Over time, we expect new use cases to emerge for PHAD.

As we will show in this report, the PHAD sensor system can incorporate multiple sensing modalities to address multiple applications. The current configuration specifically includes acoustic sensors focused on monitoring manmade activities at standoff, including the following:

- Vehicles
- Moving targets
- Loiter detection of targets of interest
- Urban infrastructure
- Perimeter protection

3. Mechanical Design

The PHAD system, to meet the requirements of long-term outdoor deployment coupled with robust data collection and dissemination, needed a robust enclosure for the data-acquisition (DA) hardware. The PHAD system consists of three SA enclosures and an LA enclosure. Each enclosure is similar in its base construction and differences will be described in the process of discussing the major components of the system. This section describes the mechanical drawings used to build the system and the decision process for each major component. Major components of the system are discussed in separate subsections

3.1 Small Array (SA)

3.1.1 Hardware Enclosure

The steel box chosen for enclosing the PHAD array electronics was 61 cm × 61 cm × 30 cm in length, width, and height, respectively. These boxes were selected to maintain survivability of the enclosed hardware when subjected to outdoor conditions and were used for both the LA and SAs. In the case of the SAs, the boxes are raised a further 10 cm to protect from torrential rainfall and standing water while also allowing for leveling using three feet.

As shown in Fig. 2, handles on the sides of the SA allow for easy loading, unloading, and setup of the array. All cable connections and switches on the SA, in order to protect them from water infiltration, are on the bottom of the box. As is clear in Fig. 2, the SA contains, in its top, all of its sensors. This array top plate is discussed in detail in Section 3.1.2.

As mentioned, the same steel boxes used to enclose the hardware in the SAs were used to house the hardware for the LAs, Fig. 3. Because the LAs needed conduit for sensor connections and the arrays would need to be set up and taken down multiple times over their useful lifetimes, nearly straight conduit runs were selected for ease of manufacture and ease of running cable. Therefore, the LA boxes have short leveling feet and all cable connections and switches were mounted on one side of the box, Fig. 3. The LA enclosures still have lifting handles on the sides for reasons stated previously. Although the SA system can be placed and functioned quickly, for target tracking purposes, it is suited for frequencies greater than 20 Hz. That is why an LA must be desired if lower frequencies are preferred. Note that the target-detection algorithm applied in this study works equally well for the SAs and the LAs.

3.1.2 Microphone Plate

To provide accuracy in sensor placement, rigidity once mounted, and strong weather resistance, a 1.3-cm thick aluminum plate was chosen for mounting the microphones on the SA (Fig. 1). The microphone plate for the small PHAD array is a modified design based on an existing logarithmic spiral acoustic array having 16 elements. Due to the limited allowable data transmission bandwidth specified in the original system requirements, the 16-element spiral array was limited to 8 elements. In post-processing after a prior risk-reduction focused field test, the 16-element spiral was shown to yield good detection and tracking results on low-frequency targets. Thus, the size of the SA was chosen to remain 61 × 61 cm (Fig 2). While the SA was shown to perform well, a larger array was also shown to perform well at larger standoffs to the target. Thus, the LA, within the PHAD system, was designed and developed.

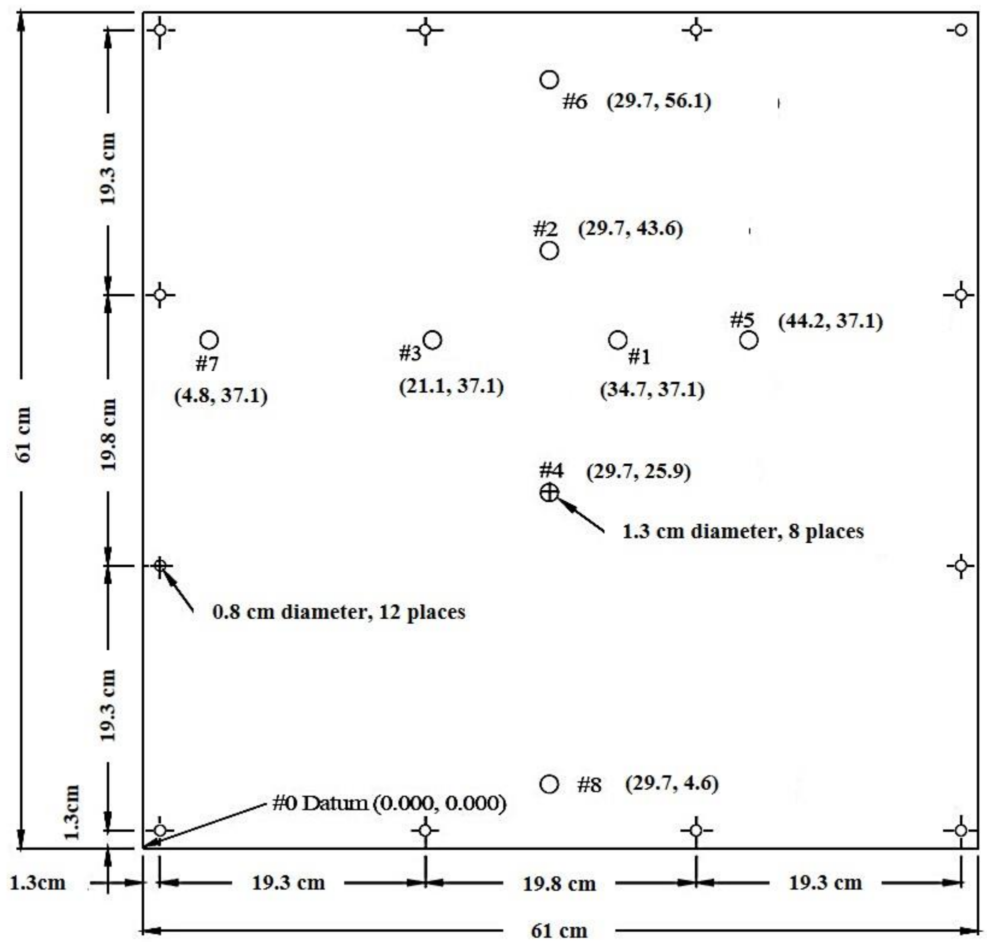

Fig. 1 Microphone mounting plate for the PHAD SAs, dimensions in cm to the nearest mm

Fig. 2 Completed microphone array plate installed on SA hardware enclosure

3.2 Large Array (LA)

The LA within the PHAD system was selected for its angular beamforming performance. The LA is 16 times larger than the SA. As such, placement of the microphones required special handling to ensure long-term weather resistance. To accomplish this, each microphone was mounted on a dedicated 25.4 × 25.4 by 10.16 cm steel box. Between each microphone and the main hardware enclosure, 5 cm diameter, galvanized electrical conduit was used to both encase the microphone cables and maintain separation between the microphones. Compression fittings on the end boxes, middle boxes, and hardware enclosure help maintain water resistance. An installed LA is shown in Fig. 3 where the conduits, microphone boxes, and side-mounted connections, discussed in Section 1.2, are all visible. To aid in array assembly, each conduit was stamped with its number (e.g., the conduit that goes between microphone boxes 2 and 6, Fig. 4, was stamped *6:1.68m*).

Fig. 3 Large PHAD array installed for testing

The microphone boxes, Figs. 3 and 4, as mentioned previously, are 25.4- × 25.4- × 10.16-cm steel enclosures. These boxes come in two configurations, as shown in Fig. 3; the first has conduit connections on opposing sides and sits near the middle of the array and the second has a single conduit connection and sits at the edges of the array. Cables run through the conduit from connections at the analog-to-digital converter, inside the hardware enclosure, to each microphone, so the center boxes act as pass-through for cables going to the outer microphones. In addition, all the microphone boxes support a machined microphone holder, Figs. 3 and 4, and house a microphone preamplifier.

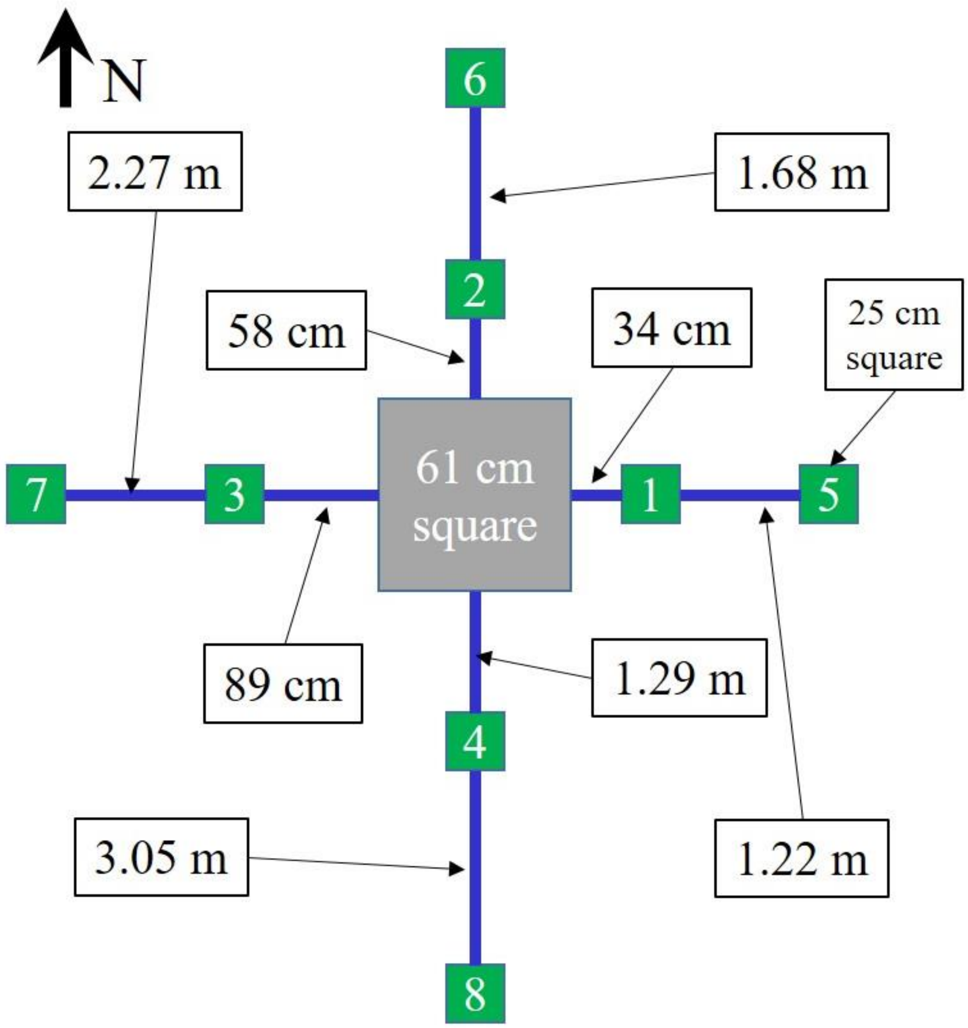

Fig. 4 **Drawing of the LA (not to scale); all dimensions are to the nearest cm**

3.3 Wind Noise Reduction

As described by Alberts et al.,[1] wind can be the critical component that contributes to background noise in outdoor acoustics. In the PHAD system, there were three separate types of mechanical wind noise filters used to reduce the wind noise on the microphones in order to allow data collection and processing at the lower audible frequency range. The SAs had two nested mechanical filters while the LA used standard 9 cm open cell foam spheres. We will discuss each mechanical filter more thoroughly in Sections 3.3.1–3.3.3.

3.3.1 Perforated Metal Filters

The SAs have all microphones almost flush-mounted with the surface of the microphone plate. This presents significant challenges when considering the optimal method needed to reduce the wind noise mechanically at the microphone. Generally, the most efficient and successful wind-noise reduction filter is a spherical open cell foam filter placed over a microphone such that the face of the microphone is approximately near the center of the filter. Since a spherical open cell foam filter of sufficient size was impractical for long-term deployment, the PHAD system took a page from the infrasound community and utilized perforated metal enclosures as mechanical filters (Fig. 5).

Fig. 5 Perforated metal windscreen as installed over a small PHAD array

The angled portion of the perforated metal enclosure in Fig. 5 is an example of a filter designed and produced by the University of Mississippi (UM) for long-term deployments of infrasound sensors.[2] In the UM example, a single infrasound sensor is placed under the dome. In the case of the SAs in the PHAD system, an entire SA is placed under a perforated metal enclosure. As each of the SAs was approximately 61 cm wide × 61 cm deep × 61 cm tall, a standard UM-designed perforated metal enclosure was too short to cover the small PHAD arrays. This necessitated an additional skirt of perforated metal to raise the height of the dome-shaped upper portion of the enclosure, Fig. 5.

By drastically increasing the height of the perforated metal enclosure, the enclosure became too large for standard shipping methods. Therefore, the ARL-modified design incorporated a method for splitting the enclosure in half, such that minimal personnel at the deployment site could quickly assemble it. To split the enclosure, the underlying steel framework of the enclosure was doubled along the centerline of the enclosure and locating pins (drilled and tapped to accept screws) were welded to one side of the enclosure. Matching holes were placed in the other side of the enclosure. To reassemble, the pins and holes were aligned, the two halves were held together, and screws were inserted to lock the halves. After installing the screws, tool holes in the perforated metal were then plugged with removable plastic inserts. The completed perforated metal windscreen was then placed over the SA.

Initial testing with the SA within its windscreen showed that there was still significant wind noise present when gusts were passing the array. This could potentially lead to false or missed targets. Therefore, the nested solution discussed in the next subsection is deployed with the perforated metal enclosure.

3.3.2 Vinyl Mat Filters

To reduce the wind noise arriving at the microphones on the small PHAD arrays further during high wind conditions, a secondary windscreen needs to be employed. In similar systems used by ARL, an approximately 2-inch-thick sheet of open cell foam is placed over the microphone plate to reduce wind noise. In experiments with higher frequency targets, the wind noise appeared to be sufficiently reduced to allow detection and tracking of certain harmonic targets to ranges where the signal-to-noise level was very low. Therefore, a similar type of windscreen has been determined to be sufficient for increasing the overall wind noise reduction of the small PHAD arrays. However, experience with spherical open-cell foam windscreens on deployed systems has shown that the windscreens have a lifetime of three to six months, which is not sufficient for the deployments for which the PHAD is designed. As such, a different material is selected for the sheet to be placed over the microphone plate.

The vinyl material shown in Fig. 6 was chosen for use as a windscreen for the PHAD system because it has random porosity, Fig. 6b, and because, by virtue of its preferred use, appears to be robust to environmental conditions. Figure 6a is a front-lit photograph of a roughly 5-cm-square section of mat showing the outward-facing construction of the material. Figure 6b is a backlit view of the same piece of material. Figure 6b serves to illustrate the random porosity of the material that should help further reduce wind noise making it through the perforated metal. Figure 6c is a side view of the same piece of material and shows the thickness of the vinyl threads, and how the various threads are semirandomly aligned within the material section. The mat used to create the nested windscreen for the small PHAD arrays was approximately 1-cm thick and covered the entire 61- × 61-cm top plate of the array.

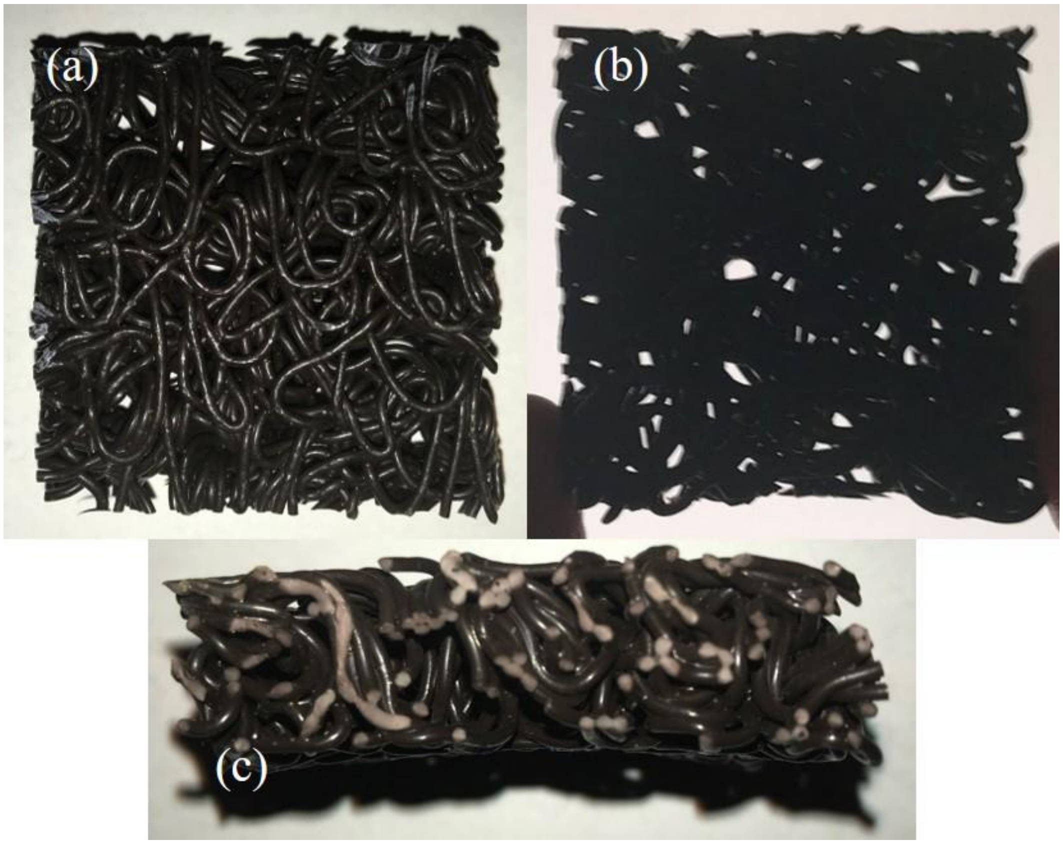

Fig. 6 Front-lit view of vinyl mat (a), back-lit view of mat showing porosity (b), and side view of mat showing semirandom placement of vinyl threads (c)

3.3.3 Spherical Open-Cell Foam Filters

The large PHAD array, because of the separation between the microphones, necessitated a more compact, per sensor, wind-noise mitigation. Therefore, a commercial solution is purchased to provide wind noise reduction for the LA. The 9-cm, spherical, open cell, foam windscreen available from Brüel and Kjær[3] (part no. UA0237) is chosen for the PHAD system for its availability and ease of use. Figure 7 shows a spherical open cell foam windscreen as installed on one of the microphone boxes in the LA.

Fig. 7 Spherical, open-cell foam windscreen installed on a microphone in the LA

4. Electronic Design

This section describes the electronic design of the PHAD sensor. The large and small PHAD sensor arrays have some distinctive differences that will be addressed here, but many aspects of the two arrays are the same. The main electronics unit is functionally the same for both arrays, but the mechanical design has some differences that we describe in this section.

4.1 Overview

The purpose of the PHAD sensor is to detect low-frequency acoustic signals of interest at a distance. The LA and SAs both contain eight acoustic sensors and have the same geometric shape, with the LA having a much larger sensor spacing. The PHAD SA is completely contained within the main electronics unit. All acoustic sensors, along with the electronics related to signal conditioning, signal acquisition, GPS, and data exfiltration, are contained within the main electronics unit, which is a metal enclosure approximately 24 inches in length and width and 16 inches in height. The main electronics unit for the PHAD LA contains everything mentioned previously except for the acoustic sensors. The LA has the acoustic sensors distributed along a larger baseline using electrical conduit to define the array geometry. Due to the LA geometry and longer sensor cabling, we integrate a preamplifier into each microphone assembly to increase the SNR and reduce electromagnetic interference pick up during the cable runs back to the main electronics unit.

4.2 PHAD Acoustic Sensor

We used the same acoustic sensor in both the large and small PHAD arrays. The Knowles Electronics Model no. VEK-H-30320-000 microphone assembly contains a microphone element, Knowles Model no. EK-30436-PO3, packaged in a plastic housing.[4] A sintered metal windscreen on the top of the housing allows the acoustic signal to reach the microphone element and helps to make the entire assembly weather resistant. The microphone element power and signal leads egress from the bottom of the assembly inside a shielded cable using an epoxy-based potting compound to seal the assembly and provide weather protection and strain relief of the cable. The microphone assembly as delivered from the manufacturer contains an 8-inch-long pigtailed cable that allows for easy integration based on the application.

4.3 PHAD Main Electronics Unit

The main electronics unit is controlled by a National Instruments CompactRIO (cRIO)[*] real-time embedded industrial controller, which utilizes precision analog to digital converters for DA. The controller runs a LabView VI[†] program to set the operating parameters including sampling rate, filtering, data egress, precision timing, positioning, and communications. The controller has a unique IP address so that each PHAD array is uniquely identified.

The controller requires a GPS signal that is acquired using a GPS antenna, located near the top center of the main electronics unit. The GPS antenna cable connects to the controller using a feedthrough bulkhead connector located on the main electronics unit housing.

The main electronics unit contains signal conditioning electronics consisting of a variable gain amplifier with the gain being user selectable values of 1, 10, 100, or 1000 using a rotary switch mounted to the housing of the main electronics unit. The gain is selected based on the expected signal level, any known noise sources, and estimated noise from wind or turbulence. The data analyst can provide guidance on the optimal gain once the sensor is on site and operational so that any environmental and noise issues can be addressed for best performance of the sensor.

The controller outputs the digitized acoustic signals, time, and position through an RJ-45 network connection. A bulkhead mounted RJ-45 feedthrough connector

[*] https://www.ni.com/en-us/shop/compactrio.html
[†] http://www.ni.com/pdf/manuals/321778c.pdf

located on the main electronics unit housing passes the signals to a hub/router using a CAT-6 cable.

Power for the main electronics unit is provided through a connector mounted to the main electronics unit housing. The electronics unit requires approximately 1-amp at 12 VDC, but any power source from 9–18 VDC can be used.

4.4 PHAD SA

The PHAD SA has the sensor array integrated into the top plate of the main electronics unit. The sensors connect directly to the variable gain amplifier by splicing an additional cable and connector to the microphone assembly provided by the manufacturer.

The amplifier gain-control switch and the connectors for power, GPS, and data egress are located on the bottom face of the main electronics unit. There are holes drilled at each corner and the center of the bottom face of the main electronics unit to allow for drainage of moisture should leakage or condensation within the unit become an issue. The electronics unit sits atop a leveling stand so that the bottom of the electronics unit is approximately 3 inches above the ground.

The average sensitivity of the SA sensors is 18 mV/pascal within the frequency of interest at an amplifier gain setting of 1. The gain can be set to 1/10/100/1000 (initial value of 100 is recommended) based on expected signal and noise levels as part of the installation procedure. We calibrate each microphone in the array to compensate for variations in sensor responses for the signal of interest.

4.5 PHAD LA

The PHAD LA passes the microphone signals from a distributed array through electrical conduit into the main electronics unit. The signals connect to the variable gain amplifier through a bulkhead harness mounted on the amplifier housing. The final connection from the array cable to the bulkhead harness must be completed on site during installation and assembly of the array by removing the lid from the main electronics unit.

The amplifier gain-control switch and the connectors for power, GPS, and data egress are located on a sidewall of the main electronics unit. The main electronics unit sits directly on the ground with a conduit connector close to the bottom on each of the four sides. The LA main electronics unit is a sealed enclosure.

The microphone assemblies contain a preamplifier that amplifies the signal by 20. Including the preamplifier gain, the average sensitivity of the LA sensors is 360 mV/pascal within the frequency of interest at an amplifier gain setting of 1 (additional details available in Appendix C of this report). The gain can be set to 1/10/100/1000 (initial value of 10 is recommended) based on expected signal and noise levels as part of the installation procedure. We calibrate each microphone in the array to compensate for variations in sensor responses for the signal of interest. Additionally, we advise performing this calibration process after installation as the LA final assembly is done on site.

5. Hardware Implementation

The heart of the PHAD system is the DA within each array. For ease of use and robustness, the PHAD system uses the industrial-grade National Instruments cRIO DA system. Specifically, the chassis used in the PHAD system is the Linux-based version of the cRIO, Model 9068. Inserted into the chassis are four 4-channel DA units, Model 9239,[5] and a GPS timing module, Model 9467.[6] Using Labview, an existing ARL-developed software package is modified to manage the process of acquiring analog acoustic data and disseminating packetized data as a server over Transmission Control Protocol/Internet Protocol (TCP/IP) to a data client computer. For details of the TCP/IP software, refer to Section 6. Greater details regarding the hardware and software are included in the subsections that follow.

5.1 Chassis

As we intend to use the PHAD system for multiyear deployment in outdoor conditions, the DA chassis needs to be robust to large swings in temperature while also having a processing speed capable of sustained TCP/IP streaming of up to 16 channels of data at sampling rates of up to several kHz. The NI cRIO Model 9068[7] is rated for industrial temperature range (–40 °C to 70 °C) and, thus, should be capable of remaining in operation during most diurnal and seasonal changes that might be encountered in typical DOD field applications.[1] In addition, the cRIO consists of a Field Programmable Gate Array (FPGA) coupled to a local embedded computer. In the case of the 9068, this is a Linux-based operating system. This coupled nature of the chassis allows for hybrid operations so that data acquisition speeds can be higher, if necessary.

5.2 DA and Timing Modules

In order to acquire analog sensor data through the cRIO, DA modules have been required. As the possible deployment scenarios required the ability to resolve low amplitude, near the noise floor, as well as high amplitude, near the maximum DA voltage sources, the DA modules needed to be 24 bit and have as high a maximum signal voltage as possible. Thus, the DA modules chosen for the PHAD system were the NI Model 9239, which are 4-channel, 24-bit DA modules that are capable of simultaneously recording ±10-V signals at up to 50 kHz. The 9239 modules are also compliant with the necessary temperature range of –40° C to +70° C, have several configurable sampling rates, and have built in anti-aliasing filters.[5] For the PHAD system, the sampling rate is initially set to 2 kHz, though it can be changed as necessary.

The module required to acquire data at a known time is the GPS Model 9467. This module complies with the –40 °C to 70 °C temperature range and, via a separate GPS antenna, delivers GPS date, time, and position. The 9467 also delivers a pulse-per-second output accurate to 100 ns in time.[6] This allows the cRIO chassis to be accurately timed relative to other chassis in the system and to be able to report its GPS position, if required. Accurate GPS timing across the PHAD system guarantees that intersystem signal processing is accomplished. If the system loses GPS lock, the system clock onboard the cRIO is no longer disciplined by the pulse-per-second output of the GPS and will likely experience some drift. This will also change a status flag within the header so the data client computer will note that the packets with the switched flag are not properly disciplined in time. Once GPS lock is re-established, the drift and flag are removed.

5.3 DA Software Details

As mentioned previously, the DA software used for the PHAD system was modified from an existing ARL-developed software package for the cRIO. The existing software package was written in NI Labview in order to create a hybrid FPGA–host DA system. With this architecture, the FPGA handles the timing and sampling of data for the system while the host, the embedded Linux-based computer, handles packaging, light signal processing, and distribution of the data.

The original software package has been written for TCP/IP streaming at moderate sampling rates (up to 4 kHz) with no signal processing and only short-haul TCP/IP communications. In addition, the data stream contained two timing channels, the Linux epoch time in seconds and the microseconds past the nearest second. For the PHAD system, this architecture was not sufficient since the maximum data-rate requirements for long-haul TCP/IP communications necessitated that the sampling rate be low and that only raw sensor data from eight channels and a small header be sent in each packet. To meet these requirements, two major software changes were necessary:

- The sampling rate is reduced to 200 Hz, based on PHAD user input

- The additional two timing channels had to be removed from the TCP/IP stream

Addressing the sampling rate issue was the most critical of the above tasks. The DA modules have user-selectable sampling rates. However, the available choices are determined by dividing the internal sampling clock by an integer factor and result in a minimum sampling rate of 1.613 kHz, which was not sufficient for the PHAD system, as per user request. In order to reach the required sampling rate of 200 Hz, the DA modules were set to sample at 2 kHz (an available user selection), and to send eight channels of raw data in 1-s blocks via First In First Out (FIFO) buffer to the host. Upon reading the data from the FIFO, the host would then apply an anti-aliasing filter and downsample the data by a factor of ten to reach the desired sampling rate of 200 Hz. This data at the reduced sampling rate is then integrated with a packet header and forwarded over TCP/IP in 1-s data packets.

Removing the additional timing channels from the data stream initially proved to be the most trivial of the three tasks. Within the FPGA software, the two channels are removed from the data array going out of the FPGA through the FIFO buffer. The data-packet timestamp is then retrieved from a subroutine within the host software. An issue has been encountered, however, that necessitated returning the time stamp to the data coming from the FPGA through the FIFO; if the cRIO lost its TCP/IP socket connection with the data client computer, the timestamp would fall to a nonsensical Linux epoch time and never recover without a cRIO reboot. This appeared to arise within the timestamp software module, but no obvious software faults have been found that would generate the observed behavior. Therefore, the time channels are added back into the data coming from the FPGA, the first time point (Linux epoch in seconds and milliseconds past last full second) in the packet was then removed after downsampling, and the two time values were then sent to the software module that generates the packet header. Thus, each packet is guaranteed to have an absolute timestamp at the beginning of the packet so any missing data packets can be reviewed on the client side in postprocessing. With the above changes, the cRIO DA portion of the PHAD system has been successfully generating eight channels of raw sensor data sampled at 200 Hz and broadcasting that data over TCP/IP.

6. Firmware Architecture

The PHAD firmware architecture is divided into two distinct functions, a data server and a data client. The data server is a collection of Labview applications running on a National Instruments cRIO A/D system. The client contains applications capable of running on either Linux-based or Windows-based operating systems.

6.1 Data Server

The data server is designed to acquire raw signature data from up to 16 individual analog channels with each channel connected to an analog sensor; the PHAD uses eight analog Knowles microphones. The raw signatures are acquired continuously in the background while waiting for a connection request from a client. The server communicates with a client via a TCP/IP socket.

Once the data server has established a TCP/IP socket connection with the client, it begins continuously transmitting raw data packets to the client until the socket connection is closed. Each raw data packet contains a header followed by a packet of raw data acquired from the eight analog input channels. Please refer to Appendix A for a detailed packet format.

6.2 Data Client

The Data Client can operate on either a Linux-based or a Windows-based computer. Its main purpose is to retrieve the raw signature data from the Data Server and to store the retrieved data on its local host for postprocessing.

The Data Client consists of two distinct tasks, a Driver and a Logger. The Driver handles a TCP/IP socket connection and converts the retrieved raw signature data from the Data Server into ARL format signatures. Please refer to Appendix B for the ARL data format; each ARL format file is packetized so that data corruption does not occur in the event of a power failure or loss of connection. The Logger stores the converted data on its local host for postprocessing. The two tasks used shared memory as the Inter Process Communication (IPC) to synchronize their communication. The Driver stores the converted ARL format signatures data packets onto a shared memory Data Queue, which is 1000 packets deep. Once the Driver places a data packet onto the queue, it uses a semaphore to signal the Logger of the data being placed on the queue. Upon receiving the semaphore signal, the Logger retrieves the data packet from the queue and stores it into a file. The Logger continues to log the data into a file until a top-of-the-hour alarm goes off, which signals the Logger to close the old file and create a new one. The interaction between the two tasks continues until the Data Client is disconnected from the Data Server.

7. PHAD Installation Procedure

In this section, we describe the installation procedure for the SAs and LAs as part of the PHAD sensor system.

7.1 Small Acoustic Array

7.1.1 Overview

This portion of the document describes the installation, setup, and operation of the small acoustic array. Three of the arrays will be positioned in a triangular pattern at the desired location. While the arrays are GPS timed, positions will not be recorded. Therefore, each array's position must be surveyed during installation. The personnel on site will be responsible for the orientation of the arrays as a magnetic declination correction is determined based on the exact geophysical location of the array. The orientation tools (i.e., compass or survey equipment) have not been provided as part of the delivered hardware.

Each of the deployed arrays has a unique IP address. Two arrays have each been assigned the same IP address so that one is the primary and the second one is the backup should a hardware failure occur; that is, the primary is labeled with the last three digits of the IP address (133) and the secondary has a "-B" appended to the last three digits (133-B). Make sure the three arrays being installed have unique IP addresses. Each array has the IP address engraved on the microphone array plate opposite the "N" marking, which is under the protective cover plate. Both N and the IP address are visible without removing the protective cover plate.

It is assumed that standard 120-V AC power is available near the array site. A 50-foot outdoor extension cord has been provided with each array along with a standard US 3-prong plug that can be field installed onto the end of the extension cord. The factory mounted plug can be cut off the end of the extension cord if the cord needs to be run through a smaller conduit or electrical box opening. A full set of tools has been included for installation and setup of the array.

A Power Conditioning Unit (PCU) is provided for each array. The PCU serves as a stable DC power source and surge suppressor in the event of power line surges, nearby lightning strikes, or faulty wiring. The PCU connects to 120-VAC line power and then outputs 12 VDC to the array. Each PCU has a 60-foot cable providing the 12 VDC to the array, so the arrays can be spaced a maximum of 60 feet from the geometric center of the three arrays.

Before connecting the PCU to line power, open the lid of the PCU and verify that the red rocker switch on the right side is set to the position marked "120V". Close the lid and secure. The hardware kit contains a 3-way splitter so that the 120-VAC line power can be split to go to the three PCUs. The splitter junction can be wrapped or covered to provide weather protection. Each PCU has a short power cord that connects to the splitter with a standard 3-prong plug and to the PCU connector marked “AC POWER IN” with a 3-pin Military connector. The three PCUs will be placed next to each other in the center of the three arrays.

The following procedure describes how to deploy, connect, and turn on the hardware for proper operation:

1) Place each of the three arrays in the desired location and orient each array to true North relative to the “N” engraved on the array plate.

2) Remove the four corner screws from the protective plate and remove the protective plate and spacers. Save the screws, spacers, and plate for future use. Install provided 1/4-20 × 1-inch screws in the corner holes.

3) Use the leveling feet and level to verify that each array is level.

4) Place a latex finger cot over each microphone for weather protection.

5) Connect the GPS antenna cable to the SMA connector on the bottom of the array box. The GPS antenna will be placed on the top center of the array windscreen later.

6) Connect the Military connector end of the Ethernet data cable to the RJ45 connector on the bottom of the array box. The other end of the cable will be connected to the Ethernet switch/router.

7) Connect the end labeled “SPU +12V” of the DC power cable from the PCU to the 3-pin MIL connector on the bottom of the array box. Connect the end labeled “PCU Power Out” to the connector on the PCU marked “Power Out +12VDC”.

8) The signal gain of the array amplifier is controlled by the four-position rotary switch on the bottom of the array box. It is preset to a gain of 100 and can be adjusted as needed depending on expected signal and background noise levels. Looking at the switch from the bottom of the box, the switch set to fully counterclockwise is switch position 1 with a gain of unity (1), the next clockwise position is 2 with a gain of 10. The switch has been delivered in position 3 with a gain of 100. Switch position 4 is a gain of 1000. The most likely gain settings will be 100 or 10, so do not change the switch settings unless instructed to by the data analyst. The maximum output signal voltage of the array is +/–10 V.

The following procedure describes initial checks:

1) At this point all array cables are connected and the PCUs have been connected to 120Vac line power. Set the toggle switch on the PCU marked "POWER" to "ON". Look at the "VOLTAGE OUT" gauge on the PCU and verify that the gauge reads 12V.

2) The system should be running at this time and streaming the data out continuously.

3) To verify that each channel is operating as expected, boot the supplied field laptop, remove the long Ethernet cable from the array, and connect the short Ethernet cable from the laptop to the array. Run Internet Explorer on the laptop and open the front panel (using the favorites bar) of the array to which the laptop is connected.

4) After the laptop connects to the front panel, right click on the panel and select "Request Remote Operation." This will allow the laptop to control the plotting of data as it streams out. Select each channel to verify that each microphone is operating correctly.

5) Once the verification procedure is complete, disconnect the laptop and reconnect the regular Ethernet cable. Repeat steps 1–4 for each deployed array.

6) To change the gain of the array, adjust the gain switch based on feedback from the data analyst. The array does not need to be powered off to change the gain.

7) To shut down the operation of the array, toggle the "POWER" switch on the PCU to "OFF". Turning the power back on will restart the array and proper operation will resume.

8) In the event of a hardware failure, replace the entire array box with the spare box containing the same IP address. There are no user/operator-serviceable parts inside the array box and the array box lid should not be removed.

9) Critical step: *Always install the spacers and protective cover plate when storing or shipping the arrays to protect the microphones.*

The following procedure describes our preferred process to deploy the perforated metal windscreen:

1) The windscreen halves are mated pairs from the manufacturer. Under the top edge of each windscreen-half are two to four bumps. Match numbers of bumps to form a complete windscreen.

2) Each windscreen half has pins that mate with holes in the opposite half. Remove plastic covers on access holes on each half and push the pins into their respective holes.

3) Using the provided screws and tools, attach the two halves and replace the plastic access port covers.

4) On the top of the windscreen, attach, via the included screws, the round mating plate.

5) Set the windscreen over the top of the array and run the three cables under the bottom edge of the windscreen.

6) Set the GPS antenna on the top center plate of the windscreen and the magnetic mount will hold the antenna in place.

7.2 Large Acoustic Array

7.2.1 Overview

This subsection describes the installation, setup, and operation of the large acoustic array. The personnel on site will be responsible for the orientation of the array as a magnetic declination correction is determined based on the exact geophysical location of the array. The orientation tools (i.e., compass or survey equipment) have not been provided as part of the delivered hardware. Two LAs have been assigned the same IP address so that one is the primary and the second one is the backup should a hardware failure occur.

It is assumed that standard 120 VAC power is available at the array site. A 50-foot outdoor extension cord has been provided along with a standard US 3-prong plug that can be field installed onto the end of the extension cord. The factory mounted plug can be cut off the end of the extension cord if the cord needs to be run through a smaller conduit or electrical box opening. A full set of tools has been included for installation and setup of the array.

A PCU is provided for the array. The PCU serves as a stable DC power source and surge suppressor in the event of power line surges, nearby lightning strikes or faulty wiring. The PCU connects to 120-VAC line power and then outputs 12 VDC to the array. The PCU has a 60-foot cable providing the 12 VDC to the array, so the PCU can be conveniently located.

Before connecting the PCU to line power, open the lid of the PCU and verify that the red rocker switch on the right side is set to the position marked “120V”. Close the lid and secure. The PCU has a short power cord that connects to the extension cord and to the PCU connector marked "AC POWER IN" with a 3-pin Military connector.

The following procedure describes how to prepare the eight microphone boxes prior to installation:

1) Remove the lid from the microphone box using a flat tip screwdriver.

2) Attach the microphone assembly to the stub with flange by sliding the stub first over the connector and into the matching threads on the microphone assembly. Hand tighten.

3) Attach the microphone and stub assembly to the lid. Place a gasket between the flange and the lid. Attach the flange using four 8-32 × 1-inch screws with sealing washers and locknuts.

4) Set the lid on the box, but do not screw the lid to the box at this time.

5) Repeat steps 1–4 for the remaining seven boxes. There should be four boxes with one conduit connector and four boxes with two conduit connectors.

The following procedure describes how to install, connect, and operate the array hardware:

1) Set the array electronics box in the center of the desired location and remove the lid.

2) Set a microphone box with two conduit connectors at the North, South, East, and West headings relative to the array electronics box.

3) Refer to the Excel spreadsheet regarding the conduit length for each connection. Conduit no. 1 goes to the East box for microphone no. 1, no. 2 to the North box, no. 3 to the West box, and no. 4 to the South box for microphone no. 4.

4) Install the conduit into the connectors on the microphone box and the array electronics box. Make sure the conduit goes all the way into the connector. Tighten using the slip joint pliers.

5) Set a microphone box with one conduit connector at the North, South, East, and West headings relative to the array electronics box.

6) Refer to the spreadsheet and place conduit no. 5 at the East heading, no. 6 to the North, no. 7 to the West, and no. 8 to the South. Conduit no. 7 and no. 8 are made up of two pieces of conduit with a coupler in the middle. Mate these prior to installing in the box connectors.

7) Install the conduit into the connectors on the microphone boxes. Make sure the conduit goes all the way into the connector. Tighten using the slip joint pliers.

8) Remove the microphone box lids and set them aside.

9) Refer to the spreadsheet for the cable lengths for each microphone. Run the cables from each microphone box to the array electronics box using the fish tape. The shortest cable (marked "6") goes to microphone no. 1 and the longest cable (marked "20") goes to microphone no. 8. Run the cable so that the marking on the cable end is inside the array electronics box.

10) Connect the cables inside the array electronics box according to Table 1:

    a. Cable marked "6" goes to 1 on the amplifier box

    b. Cable marked "7" goes to 2 on the amplifier box

    c. Cable marked "8" goes to 3 on the amplifier box

    d. Cable marked "9" goes to 4 on the amplifier box

    e. Cable marked "11" goes to 5 on the amplifier box

    f. Cable marked "13" goes to 6 on the amplifier box

    g. Cable marked "16" goes to 7 on the amplifier box

    h. Cable marked "20" goes to 8 on the amplifier box

11) Connect the other end of the cables to the microphone/stub assembly connector in each of the microphone boxes. Make sure the microphone assembly fits neatly in the box and no stress is on the preamp or cable. Create a service loop at each end of the cable as needed.

12) Secure the lids on the microphone boxes.

13) Place a foam ball windscreen over each of the microphone/stub assemblies. Make sure it goes on completely so that the microphone tip is at the center of the windscreen. The windscreen should be replaced every 3 months during normal operations. Do not use the microphone without a windscreen.

14) Install the lid on the array electronics box.

15) Check the orientation of the array to ensure the North microphone boxes are facing true North and the other boxes are correctly aligned. Adjust if necessary by carefully rotating the array or moving the boxes/conduit.

16) Connect the GPS antenna cable to the SMA connector on the side of the array electronics box. The GPS antenna will be placed on the top center of the array electronics box.

17) Connect the Military connector end of the CAT-6a Ethernet data cable to the RJ45 connector on the side of the array electronics box. The other end of the cable will be connected to the Ethernet switch/router.

18) Connect the end labeled “SPU +12V” of the DC power cable from the PCU to the 3-pin MIL connector on the side of the array electronics box. Connect the end labeled “PCU Power Out” to the connector on the PCU marked “Power Out +12VDC”.

19) The signal gain of the array amplifier is controlled by the four-position rotary switch on the side of the array electronics box. It is preset to a gain of 10 and should only be adjusted if needed after looking at the output signals. Looking at the switch from the outside of the box, the switch set to fully counterclockwise is switch position 1 with a gain of 1. Rotating the switch clockwise one-click will set the switch to position 2 with a gain of 10. Switch position 3 is a gain of 100 and position 4 is a gain of 1000. The most likely gain setting is 10, so do not change the switch settings unless instructed to by the data analyst. The maximum output signal voltage of the array is +/-10 V.

The following procedure describes initial checks:

1) At this point all array cables are connected and the PCUs have been connected to 120-VAC line power. Set the toggle switch on the PCU marked “POWER” to “ON”. Look at the “VOLTAGE OUT” gauge on the PCU and verify that the gauge reads 12V.

2) The system should be running at this time and streaming the data out continuously.

3) To verify that each channel is operating as expected, boot the supplied field laptop, remove the long Ethernet cable from the array, and connect the short Ethernet cable from the laptop to the array. Run Internet Explorer on the laptop and open the front panel (using the favorites bar) of the array to which the laptop is connected.

4) After the laptop connects to the front panel, right click on the panel and select “Request Remote Operation.” This will allow the laptop to control the plotting of data as it streams out. Select each channel to verify that each microphone is operating correctly.

5) Once the verification procedure is complete, disconnect the laptop and reconnect the regular Ethernet cable.

6) To change the gain of the array, adjust the gain switch based on feedback from the data analyst. The array does not need to be powered off to change the gain.

7) To shut down the operation of the array, toggle the “POWER” switch on the PCU to “OFF”. Turning the power back on will restart the array and proper operation will resume.

8) In the event of a hardware failure, the operator must determine if a single microphone box/cable assembly needs to be replaced or if the array electronics box needs replacing.

9) Typically, if all channels stop producing data then the array electronics box has failed and needs replacing. If a single channel stops producing data then the corresponding microphone box or cable assembly will need to be replaced.

Table 1. LA conduit and cabling

Conduit no.	From	To	Conduit length (in)	Conduit notes	Use cable marked (length in ft)	Cable connects to amplifier channel	Mic heading relative to box
1	Center box	Mic 1	13.266	…	6	1	East
2	Center box	Mic 2	22.640	…	7	2	North
3	Center box	Mic 3	34.884	…	8	3	West
4	Center box	Mic 4	50.875	…	9	4	South
5	Mic 1	Mic 5	48.135	…	11	5	East
6	Mic 2	Mic 6	66.039	…	13	6	North
7	Mic 3	Mic 7	89.424	2 pieces w/ coupler	16	7	West
8	Mic 4	Mic 8	119.967	2 pieces w/ coupler	20	8	South

9. PHAD Data and Processing

The PHAD sensor system has been built to collect time-tagged acoustic waveform data. Both types of PHAD systems, SA and LA, consist of eight broadband microphones (5 Hz–50 kHz). All eight channels are recording acoustic data continuously and are time-tagged to the same GPS clock. Thus, each PHAD sensor has its own GPS clock. The PHAD systems are capable of recording data at up to 50 kHz sampling rate. However, the ones described in this report are sampling at 200 Hz to focus on the low frequency (5–100 Hz) acoustic signals. In Section 6 we have discussed the data-collection architecture of the PHAD systems and in Appendix D we discuss the process to convert the raw data to physical units. In this section, we provide examples of PHAD data under different environmental conditions and manmade clutter sources.

9.1 Data Examples

9.1.1 Consistency of Recorded Data

In this section, we first show the reproducibility of waveforms for all sensors in an array in both time- and frequency-domains. Figure 8 shows the data collected on all of the eight microphones at the PHAD sensor array 134. We have converted the data to physical units and the Sound Pressure Level (SPL) of the whole waveform is noted. The data contains a number of high SNR manmade signals of unknown origin, which let us visually compare the waveform amplitudes. Allowing for the slight variations in the wind noise at each array, we see that the amplitudes and arrival times of the signals coincide between the different channels.

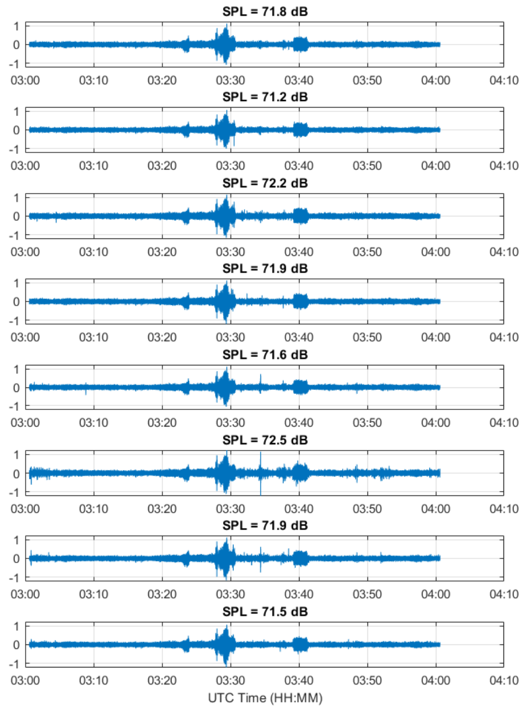

Fig. 8 Waveform recorded at microphones in the PHAD array 134

Next, we plot the power spectral density (PSD) of the waveform data shown above in Fig. 9. We note that the spectral features are consistent in both frequency and amplitude across all the channels.

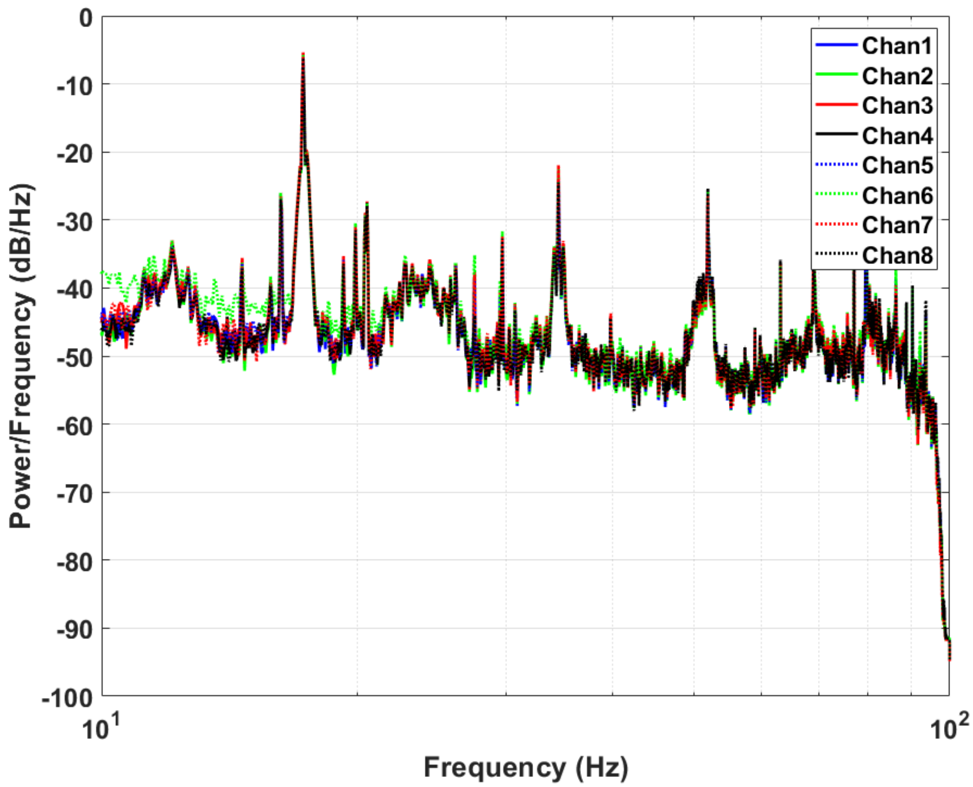

Fig. 9 PSD of microphone data from PHAD array 134

We have carried out the same exercise with the other PHAD arrays, namely SAs (133, 135) and LA (136), and concluded that the waveforms and spectra correlate across all channels. Next, we plot the PSD of one channel from each of the four PHAD arrays (Fig. 10). In this case, we chose channel 2 from each array for consistency. For this data collection, the arrays are located approximately at the vertices of a 20-m-sided equilateral triangle. We expect some variation between the channels due to small-scale variations in background wind. We can conclude that the signals correlate well between nearby arrays in both frequency and amplitude, as expected.

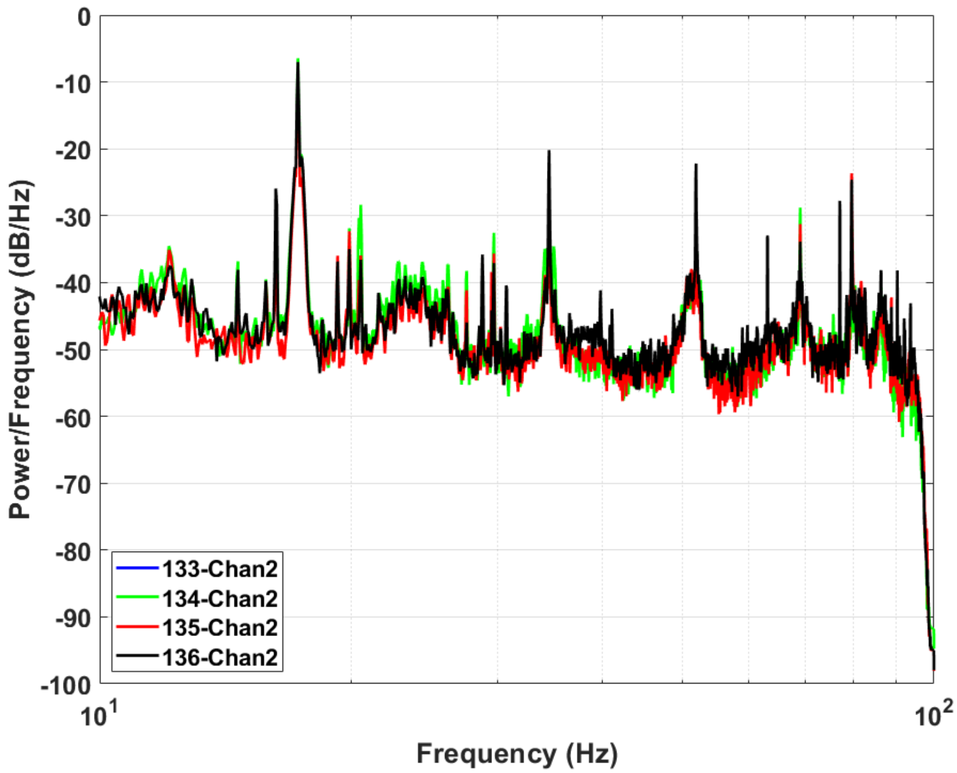

Fig. 10 Comparison of the PSD of microphone data for all four PHAD arrays. The signals correlate well.

9.1.2 Evaluating the Impact of Background Noise

Various studies have shown that the noise levels for low-frequency outdoor acoustics due to wind is usually higher during the day.[8] We expect to see variation in noise levels across an array even when they are small. The windscreen developed for PHAD, as described in Section 3, decreases the impact of wind noise, but does not eliminate it. We note that the closer the sensor is to the windscreen, the larger is the windnoise.[1] For example, typically, channel 8 will be noisier compared with channels 1 or 2. Secondly, manmade activities can also decrease at night that can lead to a lowering of the background noise. As we typically detect signals based on their SNR, the background noise directly influences our ability to detect manmade signals of interest. In this section, we show examples of this variation, which the PHAD used need to be cognizant of during processing of the acoustic data. In the top panel of Fig. 11 we show the spectrogram from a typical nighttime recording (i.e., 0200–0300 local time, on PHAD array 133). The background noise is low, which lets us clearly identify a number of narrow-band tones at approximately 18 Hz, 20 Hz, 30 Hz, 78 Hz, and so on. We also see a number of time-limited signals at approximately 35–40 Hz, 60 Hz, and 90 Hz. Given the high SNR of the signals and having observed no visible sound sources near the array, we conjecture that the signals emanate from buildings that are within 30–50 m of the array and we expect most of these signals to continue throughout the day. In the lower panel of Fig. 11, we show the data from a typical daytime recording (i.e., 0815–0915, on PHAD array 133). Since the sensor location is the same for both panels in Fig. 11, we expect some of the signals to overlap between the sensors. When we compare the two panels of Fig. 11, we can confirm that several of the continuous harmonics and time-limited harmonics are coincident in both waveforms. However, for the daytime recording as shown in the lower panel, the wind-noise is observed in time-limited signals below 50 Hz, which are much larger than those during nighttime (upper panel). This variation in background noise needs to be taken into account when detecting signals at frequencies below 50 Hz. We also note that variations in wind noise between nearly placed PHAD arrays are expected due to their separation, and are a normal part of outdoor acoustic measurements.[9]

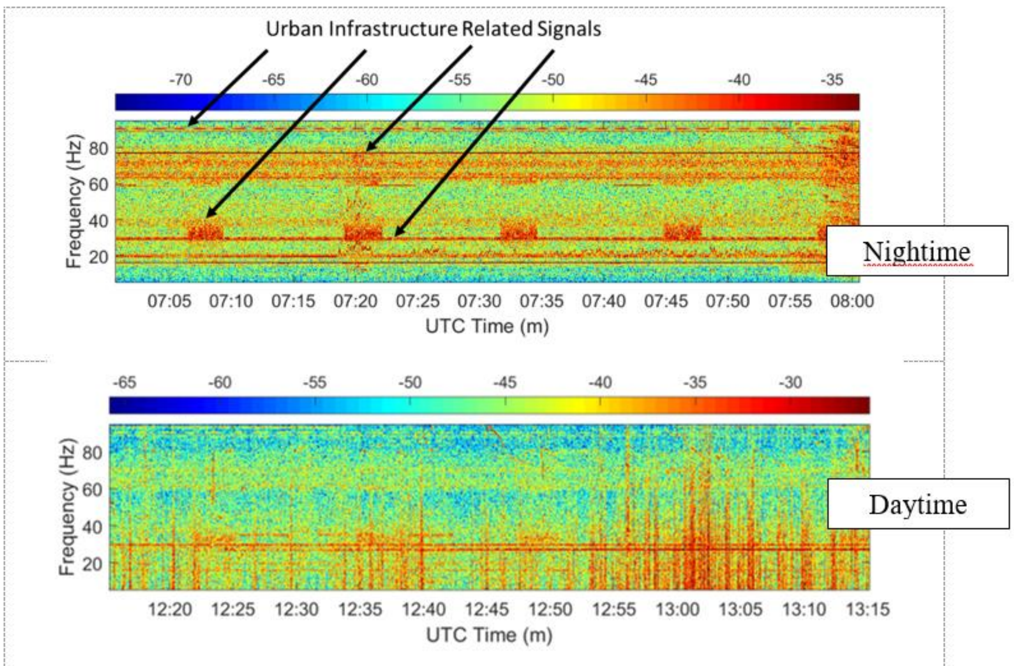

Fig. 11 Acoustic data collected on PHAD array 133 during local nighttime (top panel) and local daytime (lower panel). Infrastructure related signals are consistent between the panels, though higher wind-noise is evident during local daytime.

9.2 PHAD Detector

The microphones in the PHAD system are designed to record signals between 5 Hz –10 kHz, and as such are expected to detect impulsive (e.g., explosions), continuous waveform (e.g., urban infrastructure), and time-limited harmonics (e.g., moving targets in the air and ground). For unattended ground sensors (UGS) like the PHAD system, automated detection algorithms for impulsive and harmonic signals exist. Here, we show examples of harmonic signals in the frequency band of the data, namely, 5 Hz–100 Hz. Focusing on manmade signals, we can expect the acoustic spectrum to contain several harmonically related spectral peaks. The harmonic structure will typically consist of a number of fundamental frequencies, which can persist from seconds to hours. The detector that we describe below only reports the fundamental frequency, which decreases the number of signals to analyze for target classification. As we have shown earlier, each microphone data within each PHAD array correlates well with each other. Therefore, we choose one sensor close to the center of each array, namely channel no. 4, for detection processing for that array. Following the methodology of Mays et al.,[10] the harmonic detector consists of the following steps:

1) Identify candidate spectral peaks, which we examine for harmonic relationships. The spectral resolution is approximately 0.2 Hz.

2) Estimate the SNR of each of the spectral peaks.

3) Extract all spectral peaks that have an SNR value above the threshold of 6 dB.

4) Determine if the spectral peaks are harmonically related.

5) Report all the fundamental frequencies. If the narrowband peak does not have overtones, we report that frequency.

In Fig. 12, we show some of the signal detections during local nighttime. PHAD arrays 133, 134, and 135 are of the SA type and 136 is of the LA type and are placed about 20 m from each other. In this case, the data is recorded local midnight to 0100 AM (UTC – 5 hours). The top panels in each plot show the spectrogram of the data (5–95 Hz). In the lower panel, each point is a separate detection, as a function of time in minutes. If a signal persists for more than 2 min, we consider it a valid detection. We detect signals from nearby buildings and a ground vehicle pass-by around 0540 UTC. It is important to note that, though the signals are slightly different because of variations in local noise, the detector results are similar and can be correlated in time and frequency. Also, note the narrowband tone near 0525 UTC, which we suspect was an airplane flying close to the arrays, in the spectrogram data. However, since the narrowband tone wanders in frequency, presumably due to acoustic Doppler effects, our detector does not flag it as a detection. In Fig. 13, we show detections on the four PHAD arrays similar to Fig. 12, but for local daytime (0815–0915 local). As expected, the background noise levels are higher during the daytime, which leads to a lower consistency of detections over time.

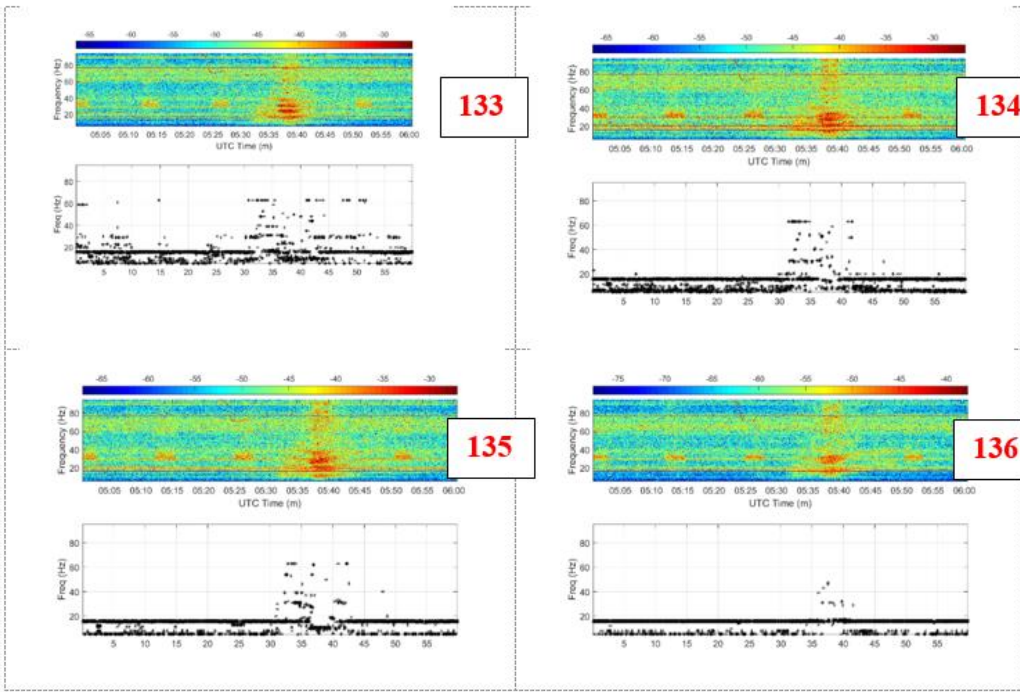

Fig. 12 Narrowband detector for the same window for the four PHAD arrays; signal features in the spectrogram of data (top panel) and detections (bottom panel) are consistent across arrays

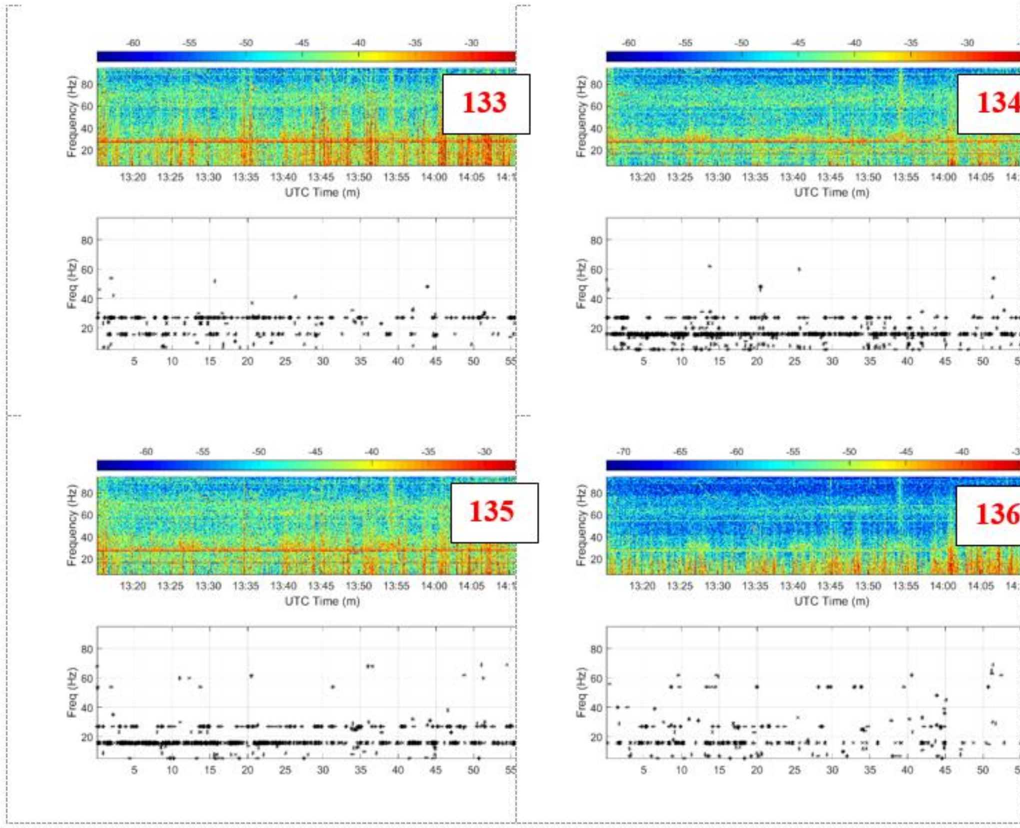

Fig. 13 Similar to Fig. 12, but for local daytime (0815 – 0915 local); detections are less consistent over time because of lower SNR

9.3 PHAD Tracker

We use the well-known Time Difference of Arrival (TDOA) beamformer for narrowband PHAD detections, following the formulation of Goldman and Reiff.[11] Though MVDR beamformers can be more robust against background noise, in our case, TDOA is more efficient and is sufficient for target cueing for a multitude of missions. In our case, we use differential time delays between all eight microphones in a single PHAD array using cross-correlation and Wiener filtering. We then combine the time delays to generate bearing-to-target as a function of time. Note that, for each time interval, our TDOA estimates the bearing to the target with the highest signal amplitude. Next, using a Kalman Filter tracker, we combine the bearing estimates to provide a bearing-versus-time for each array. In the future, we plan to combine the tracker results with time-tagged target locations to evaluate the capability of the PHAD tracker.

10. Conclusion and Future Developments

As we have discussed in this report, the high sampling rate of its digitizer and the broadband sensitivity of its acoustic sensor allows us to leverage the man-portable PHAD systems against a range of targets and operational concepts. Further developments can include a Linux-based processor and a local data-storage system so that there is no requirement for a continuous data exfiltration. By making that processor accessible from outside the metal enclosure, we will be able to change the sampling rate and gain settings and readily adapt PHAD for multiple CONOPS. Additionally, we can connect PHAD to solar panels, and thus use it for long-term field deployments, without the need for uninterrupted access to an electrical outlet. Based on the needs of PHAD users, future developments can include developing an Analyst Work Station with sensor fusion and georeferenced situational awareness capabilities.

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Appendix A. Broadcast Data Packet

This appendix shows the format of each raw data packet that is broadcast from the Data Server to the client computer. It consists of a packet start identifier ($HDR>) followed by a packet header containing data information to include timing and packet count. Note that gpsLat, gpsLong, and gpsAlt are all set to 9999 within the cRIO for the data to remain unclassified. The timing and packet count are sent to allow for filling in any data gaps during postprocessing. Following the packet header is a full second of data. In the case of the PHAD, the second of data contains 8 × 200 samples.

cRio Raw Data packet

```
{
 $                                                            // Begin
Marker of raw data packet
   H
  D
  R
  >
  File Separator (28 decimal)                                 // End
Marker of raw data packet
  unsigned char gpsStatus                                     // Begin data
packet Header
   unsigned char numOfChans
  unsigned char fpgsTimeLockStatus
  unsigned char utcOffset
  float gpsLat
    float gpsLong
    float gpsAlt
    unsigned long long epochSec
    unsigned int cRioPktCnt                                   // End
data packet Header
    float sample1                                             // Begin
raw binary data
    float sample2
    float sample3
     …
     …
     …
    Float sample(NUM_OF_CHANS(8)xSAMPLE_RATE(200))     // End
raw binary data
}
```

Appendix B. Stored Data Format

This appendix shows the packet format for each packet stored within each hourly ARL format data file. Each packet contains all of the useful information from the raw data packet described in Appendix A as well as some checksums for filling in any missing data within the finalized format.

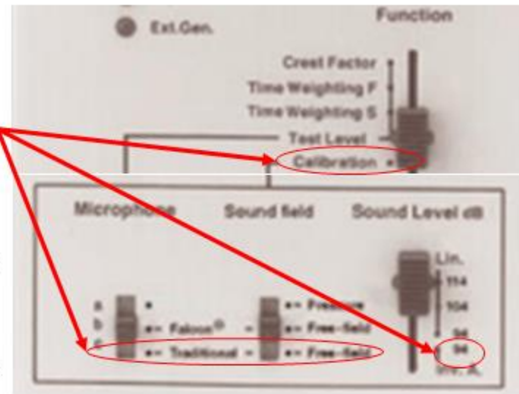
ARL Raw Data Packet

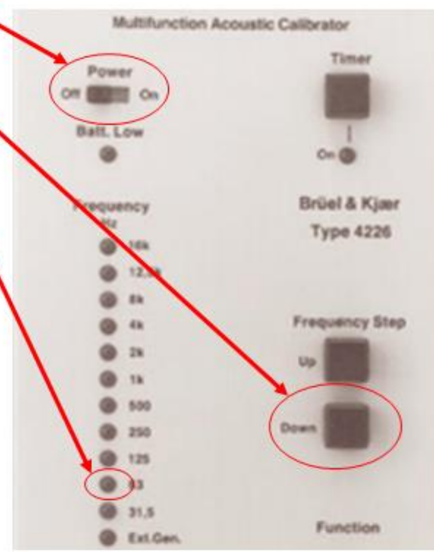
```
{
  double ActualSps                                         // Begin raw data header
    time_t time_sec
    unsigned short time_msec
    int site_id
    int num_channels
    int num_samples
    int data_valid
    unsigned long artPktCnt
    struct lowResA2D_info lowResA2D                        // Legacy format Not used
    int nav_status
    usigned long sequence_counter                          // End raw data header
  float sample1                                            // Begin raw binary data
    float sample2
    float sample3
     …
     …
     …
    float sample(NUM_OF_CHANS(8)xSAMPLE_RATE(200))         // End raw binary data
}
```

Appendix C. Acoustic Sensor Calibration

The procedures below detail the two-tone amplitude calibration to be performed on the PHAD system. We assume that the PHAD system is powered and connected to a data-retrieval laptop that is actively collecting acoustic data. We use the Brüel and Kjær Multifunction Acoustic Calibrator (MAC) Type 4226 for this purpose.

1. Configure the MAC for c-weighted, free field calibration with a sound pressure level (SPL) of 94 dB (1.0024 Pa)**
2. Ensure that the SMA-type connector is secure from the body of the MAC to the piston
3. Firmly place the piston on the microphone to be calibrated
4. Release hand from piston and ensure that the piston does not move
5. Switch on the MAC, which will power up set to a frequency of 1 kHz
6. Press the down button to reach the desired frequency for the calibration; for the PHAD system, the frequencies to calibrate are 31.5 and 63 Hz
7. The red LED next to the desired frequency will initially flash and then transition to a steady on condition
8. If the LED remains flashing, the calibrator is experiencing poor coupling due to placement, to wind noise, or both; adjust piston position or shield piston from wind until the LED remains steady
9. Allow the calibrator to run for 30 seconds at each frequency, noting the start time of the calibration in UTC, before switching to the next frequency
10. Repeat Steps 6-9 for each of the remaining microphones in the system
11. A calibration on a single microphone of the PHAD system will take approximately 1.5 - 2 minutes to complete.





**NOTE: There are subtle differences between versions of the MAC. Thus, the pictures here may not represent all models but should give an understanding of the proper setup before calibration.

Appendix D. Converting Persistent Harmonic Acoustic Detector (PHAD) Data to Physical Units

D.1 Overview

In this section, we discuss the procedure for converting the recorded Persistent Harmonic Acoustic Detector (PHAD) sensor data to useable units. Typically, sensor systems do not record the acoustic pressure in physical units. To exploit the PHAD data fully, we would like to convert the recorded data to pascals (Pa). The recording system can be understood as a linear system where the input is the acoustic pressure and the output is the number (i.e., count) in the digital recording. For a given sensor system, if we can estimate the frequency-dependent response function *Q(f)*, the given acoustic pressure *P(f)* can be computed from the recorded data *Z(f)* as a function of frequency, *f*:

$$Z(f) = P(f)\, Q(f) \tag{D-1}$$

Q(f) is the combined effect of all elements in the acoustic system, which includes the sensor, amplifier, filter, and digitizer. *Q(f)* is usually a complex number and comprises the amplitude response (*A(f)*) and the phase response *(Φ(f))*.

General Form of PHAD Instrument Response

For the PHAD small arrays (SAs) and large arrays (LAs), the amplitude response term, *A(f)*, can be put together from the following information:

1) *S*, the microphone sensitivity as a function of frequency, as provided to ARL by the manufacturer, Knowles (units = V/V)
2) f_0, the lowest frequency for stable measurement = 5 Hz
3) *G*, the pre-amplifier gain (units = V/V)
    a. Pre-set values:
        1) SA: 1
        2) LA: 20
4) *L*, anti-aliasing filter function for the digitizer (= 1)
5) *D*, digitizer gain given in V/V.
    a. *D* = 1 ± 0.0009, at frequencies 0 – 0.453×f_s , where f_s is the sampling rate of the data (http://www.ni.com/pdf/manuals/375939b_02.pdf)
    b. Stopband frequency = 0.547 f_s
    c. Stopband rejection = 100 dB
    d. For PHAD, f_s = 200 Hz.
6) *F*, the digitizer scale factor that is a frequency-independent multiplier applied to the output data. The user can set this value, usually by balancing the amplitude of the expected signals and the dynamic range of the digitizer (= ± 10 V).
    a. Scale factors in PHAD are 1, 10, 100, and 1000
    b. Same set of scale factors are available for the PHAD SAs and LAs.
    c. At times of high background anthropogenic noise or wind conditions, using a scale factor of 1000 might saturate the digitizer.

d. The suggested user-settable values for a typical outdoor collection are:
    1) SA: 100
    2) LA: 10

For typical use, we analyze the data between 5 – 100 Hz and factors that influence the PHAD instrument response are: 1) microphone sensitivity, 2) pre-amplifier gain, and 3) digitizer scale factor.

D.2 Estimating the Microphone Sensitivity Function

The sensitivity of the Knowles microphone is available to us in the form of the amplitude spectra in the frequency range of 5 Hz–50 kHz. We have designed the PHAD system to detect narrowband frequencies over a frequency range of 5–100 Hz. For use in routine processing, we need to estimate an analytical form of this sensor response over the 5–100 Hz range. We compute this by fitting an eighth-order polynomial to the amplitude spectrum, as a function of frequency f (Hz), and at a sample spacing of 0.01 Hz. First, we scale the frequencies to improve the robustness of the fit (*F* in Eq. D-1), and then we compute the coefficients of the polynomial from the manufacturer-provided microphone sensitivity (*P* in Eq. D-2). Figure D-1 shows the fit of our functional form to the sensitivity values obtained from the manufacturer.

$$F(f) = (f - 39.605)/\,33.549, \qquad \text{(D-2)}$$

$$S(f) = P(8)*F^8 + P(7)*F^7 + P(6)*F^6 + P(5)*F^5 + P(4)*F^4 + P(3)*F^3 + P(2)*F^2 + P(1)*F + F, \qquad \text{(D-3)}$$

where,

$$f = 5 – 100\ Hz,$$

P = [-0.27323 1.6528 -3.4082 2.2105 0.82565 -0.054303 -3.1995 3.9068 -54.015],

and, *S(f)* is in units of dB V/0.1 Pa.

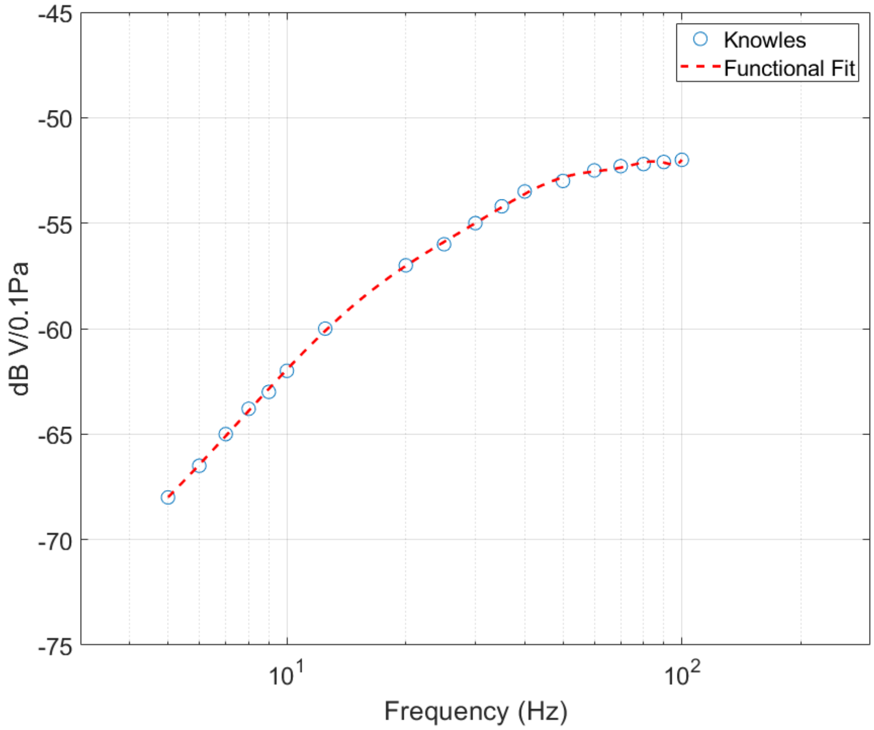


Fig. D-1 Estimating an analytical form of the sensitivity of the microphone used in PHAD

For ease of use, we convert the analytical form of the microphone response to mV/Pa using the following equation:

$$\hat{S}(f) = 10^{(S(f)/20)} * 1000 * (1/0.1) \tag{D-4}$$

Figure D-2 shows the variation of the sensitivity, which can be used with the PHAD data, to convert the sensor data in *Volts* to acoustic data in *Pascals*. Note that the microphone sensitivity, $\hat{S}(f)$, is tabulated in the ASCII file *KnowlesFit.txt* and is included with PHAD system.

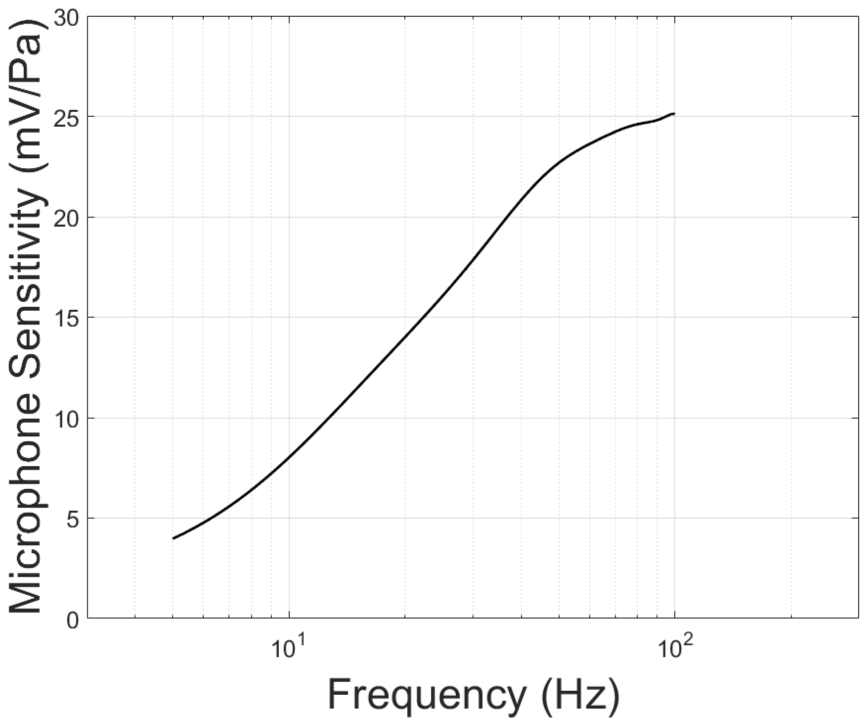


Fig. D-2 Sensitivity of the Knowles microphone used in converting PHAD data to physical units

The previously mentioned equation, however, only corrects for amplitude. Sensors and filters also generate phase shifts of the signals, which can be mathematically represented by using a complex system response. To calculate the phase shifts, we would also need to know the phase response of the component parts, especially the microphone response and the digitizer. For PHAD, we hypothesize that the phase shifts are small and neglect them in the analysis of the data.

D.3 Procedure for Converting PHAD Data to Physical Units

We can, thus, convert the recorded sensor data, Z(f), to calibrated acoustic data, P(f) for the PHAD sensor by rewriting Eq. D-1:

$$P(f) = \frac{Z(f)}{Q(f)} \times \left(1/_G\right) \times \left(1/_F\right), f = 5 - 100\ Hz \qquad \text{(D-5)}$$

We note that Eq. D-4 is in the frequency domain. Based on our experience in analyzing geophysical data, it is preferable to present the calibrated data in the time domain. Importantly, since all the microphones in the SA and LA are identical, we can use the following procedure for all of the PHAD data channels:

1) We extract the recorded data, *s(t)*.

2) We divide the timeseries data by the two frequency-independent gains (*G* and *F*).

3) Given a real signal $s(t)$, we compute the Fourier transform of the gain removed data in terms of frequency (f), $W(f) = x(f)+iy(f)$, *where* $f = [0\ Nyquist]$

4) Compute the magnitude of $W(f)$, $|W| = \sqrt{(x^2+y^2)}$

5) Divide the magnitude |W|, frequency by frequency, by the microphone's amplitude response, Ŝ(f), to reach the deconvolved magnitude, H(f).

6) Calculate the phase angle, $\Phi(f)$ of the data: $\Phi(f) = arctan\ (y/x)$. We assume that the Knowles microphone does not introduce any phase shifts to the data.

7) Reconstruct the scaled signal: : $Q(f) = H(f)*e^{(i\Phi(f))}$

8) Compute the Inverse Fourier transform to convert the scaled signal to a time series for analysis using existing time-domain analysis tools.

9) Obtain the calibrated time series in physical units (= pascals).

Appendix E. Evaluation of Persistent Harmonic Acoustic Detector (PHAD) Sensor Deconvolution Using Calibrated Signals

E.1 Overview

In Appendix D, we have described the process to convert the recorded Persistent Harmonic Acoustic Detector (PHAD) microphone data to physical units, namely, pascals. In this section, we evaluate the accuracy of this process using calibrated narrow-band sources. Appendix C describes the calibrated source used by ARL; however, narrowband calibrators can also be used to evaluate the conversion process. We compare the RMS amplitude of the converted data to the calibrated source. It is important to note that here we are testing the transfer function (i.e., the mathematical formulation that converts recorded microphone data to pascals) of the PHAD system. This function includes the contribution of the microphone sensor, the digitizer, and the amplitude gains, as we describe in detail in Appendix D. One factor we do not consider here is the broadband amplitude reduction from using a mechanical wind-noise reduction device, as it is specific to the user.

E.2 Acoustic Data Collection Using a Calibrated Source

Following the process described in Appendix D, we employ the calibrated narrowband acoustic at two frequencies (31.5 and 63 Hz) and two separate gain settings (1 and 10). We carry out the calibration on a subset of microphones used in PHAD. In this section, we show results from a PHAD large array (LA), which includes a preamplifier gain of 20. Note that for both the frequencies, we expect a recorded amplitude of approximately 74 dB for a gain setting of 1 and 94 dB at a gain setting of 100.

Figure E-1 shows the recorded narrowband data, extracted to match the time of calibrated signal (63 Hz at 94 dB). Figure E-2 shows the recorded waveform with the frequency-independent gain factors removed. Using the procedure described in Appendix D, we first deconvolve the complex sensor response in the frequency domain, and then compute the inverse Fourier Transform to generate the time-series that an analyst can use for sense-making. We compute the Sound Pressure Level (SPL) using the following well-established equation:

$$SPL = 20*\log_{10}(RMS(Deconvolved\_Data)/(2*10^{-5})) \quad \text{(E-1)}$$

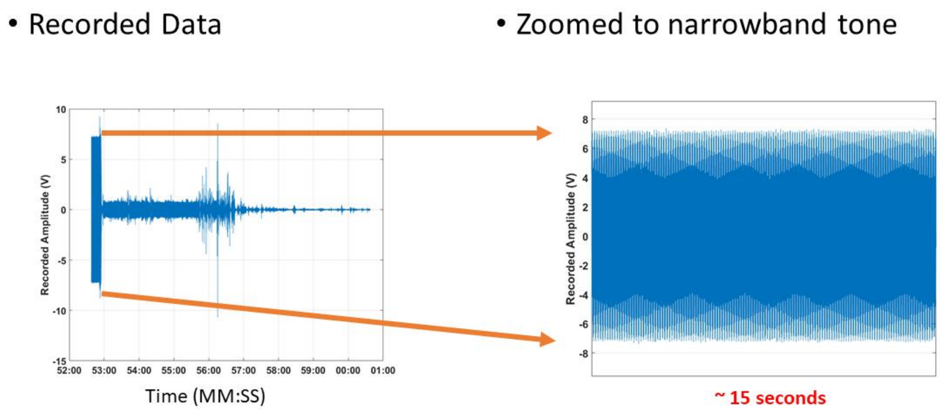


Fig. E-1 Recorded narrowband data

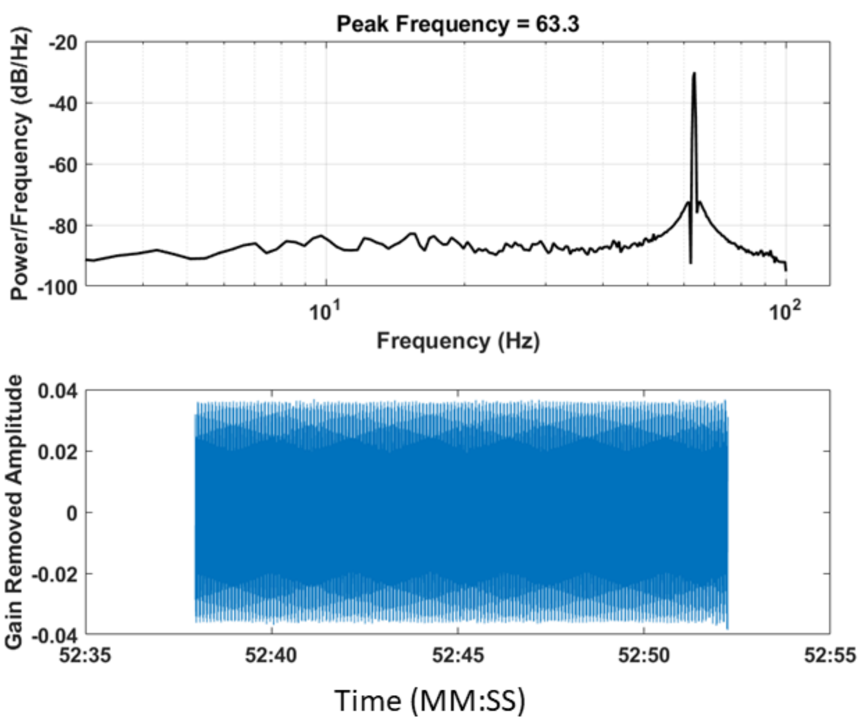


Fig. E-2 Narrowband data used for sensor calibration. The lower panel shows the recorded data with the preamplifier gain (= 20) and digitizer gain (= 10) removed. The PSD in the top panel shows the frequency of the narrowband input signal (= 63 Hz).

The SPL value for the data in this example is 94.5 dB, which is close to the expected value of 94 dB (Fig. E-3).

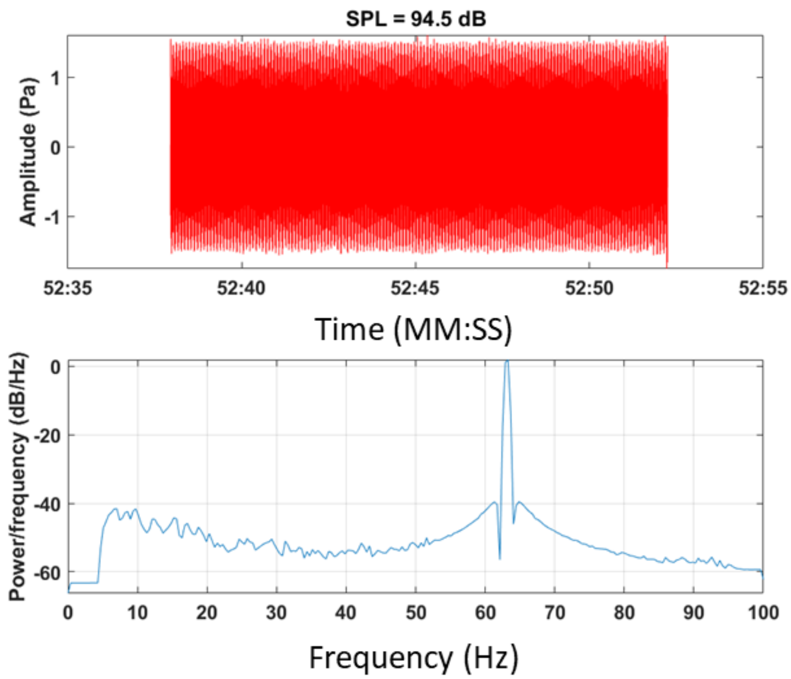


Fig. E-3 Instrument deconvolved data in physical units (= pascals) with an SPL value of 94.5 dB, which is close to the expected value of 94 dB. The PSD shows the extracted frequency of 63.3 Hz is close to the input frequency of the calibrator, 63 Hz.

In our second example, we show the data from a different microphone where the calibration frequency is set at 31.5 Hz and the gain factor is set at unity. Therefore, the expected SPL value in this case is 74 dB. Figure E-4 shows that the estimated value of 74.8 dB is close to the expected value. Note that the waveform plot in Fig. E-4 shows that broadband wind noise is present in the data that we expect in an outdoor sensor-calibration test. We hypothesize that the presence of wind noise generates the slightly higher than expected SPL value shown in Figs. E-3 and E-4.

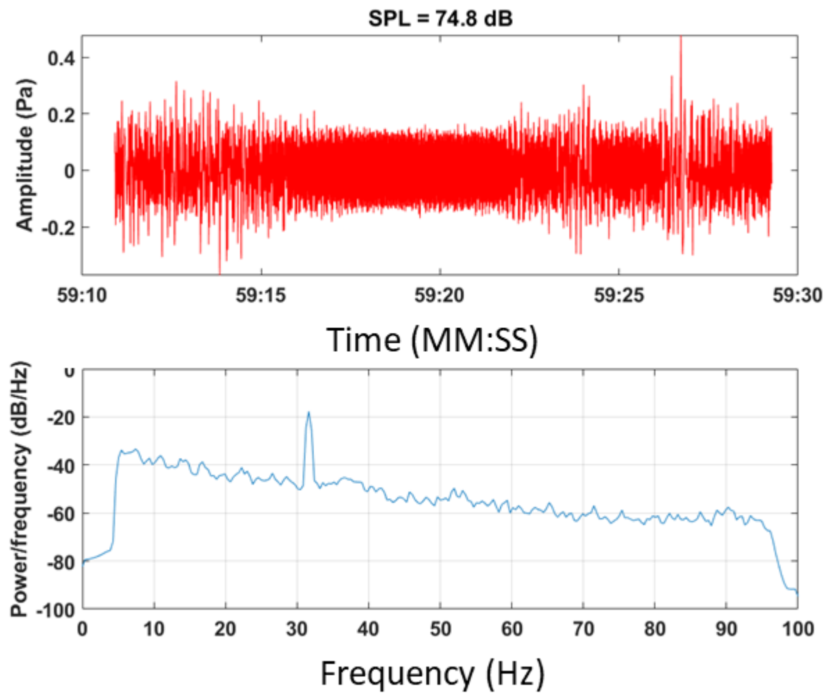


Fig. E-4 Instrument deconvolved data in physical units (= pascals) with an SPL value of 74.8 dB, which is close to the expected value of 74 dB. The PSD shows the extracted frequency of 31.8 Hz is close to the input frequency of the calibrator, 31.5 Hz.

Appendix F. Persistent Harmonic Acoustic Detector (PHAD) Schematics

F.1 Persistent Harmonic Acoustic Detector (PHAD) Amplifier Schematic

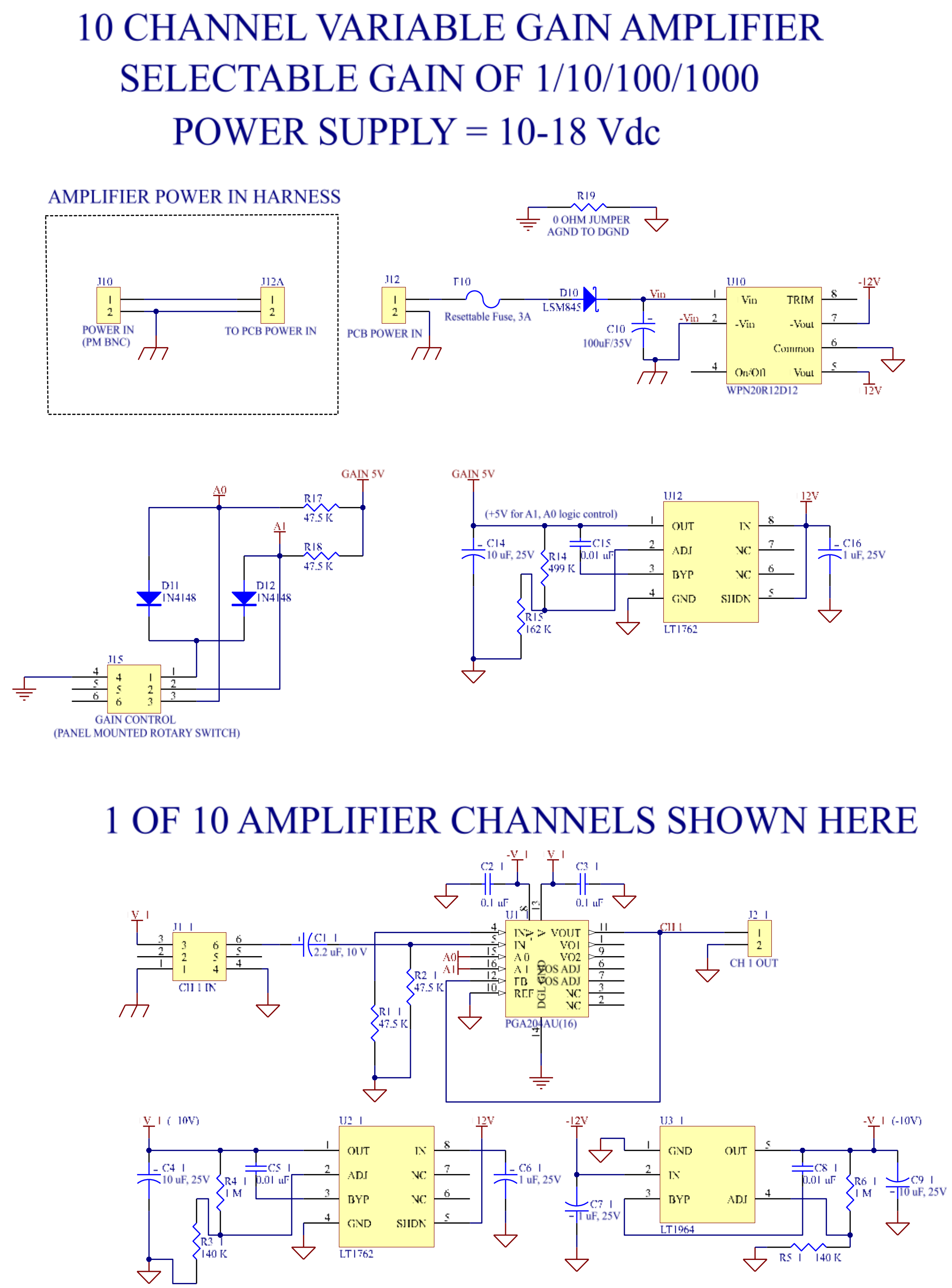


Fig. F-1 Schematic of variable gain amplifier

F.2 PHAD Amplifier Printed Circuit Board

Only the top side view of printed circuit board (top copper layer and top silk layer) is shown for clarity (Fig F-2).

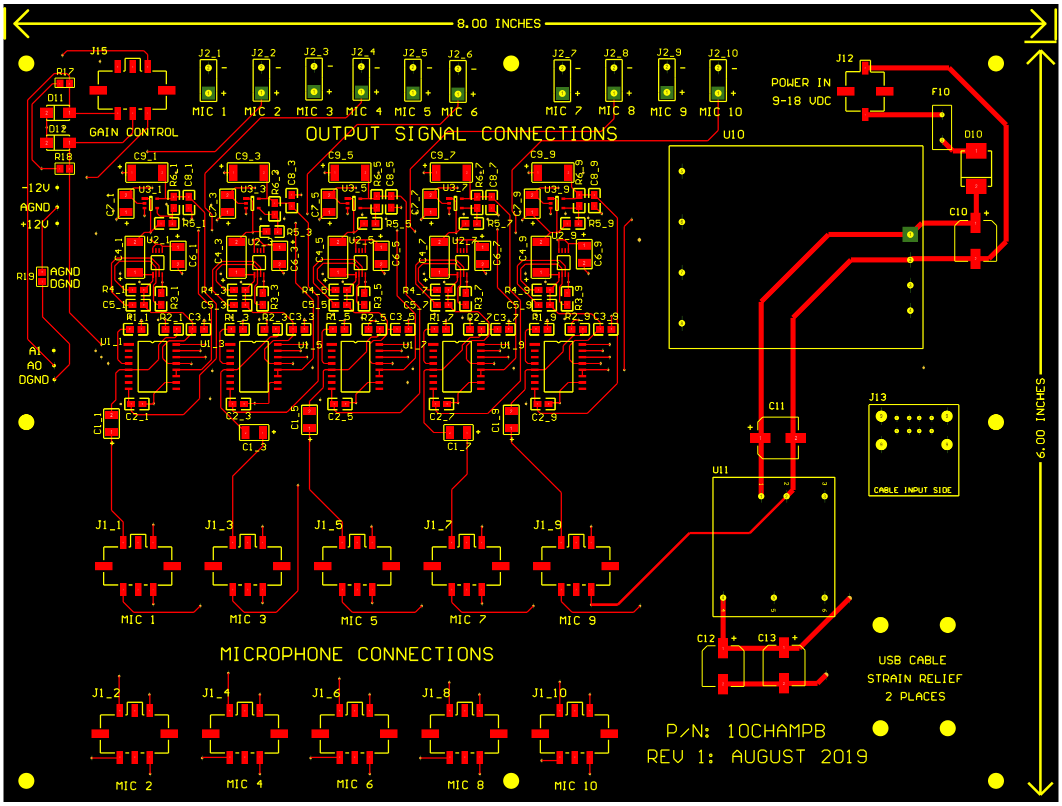


Fig. F-2 Printed circuit board

NOTE FOR ALL ASSEMBLIES: Follow the manufacturer-provided assembly instructions for all connector assemblies. Specialty tools and fixtures may be needed for crimping of contacts and assembly of the connectors. The model number of any required tools and fixtures will be specified in the manufacturer-provided instructions.

F.3 Microphone Cable Assembly for the PHAD Small Array

This section describes the assembly and testing of the microphone/cable assembly that connects the microphones mounted on the top plate of the small array (SA) and the variable gain amplifier's printed circuit board located inside the electronics box.

1) Attach microphone, Knowles P/N VEK-H-30320-000, to cable, 36 in length, Alpha P/N 3222, (3 conductor shielded cable, 22 AWG). Do not trim the factory supplied 8-inch microphone leads. Cover each splice with heat shrink tubing and shrink using a heat gun, being careful not to melt the PVC

insulation on the wires. Place heat shrink tubing over the insulation and conductors of the cable to provide strain relief (Fig. F-3).

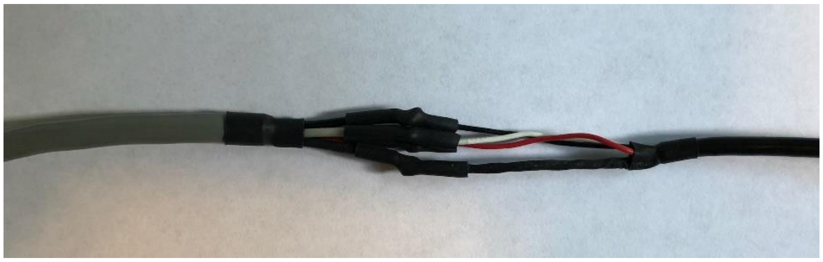


Fig. F-3 Close-up of strain relief (left) and splices (right)

2) Attach the other end of the cable to a 6-pin receptacle, Molex P/N 43025-0600 using female contacts 20-24 AWG, Molex P/N 43030-0009. Place heat shrink tubing over the insulation and conductors of the cable to provide strain relief.

3) The overall length of the microphone cable assembly is about 45 inches using a 36-inch length of Alpha P/N 3222 cable. Assemble according to the wiring specifications shown in Table F-1.

Table F-1 Microphone cable assembly wiring table

Microphone leads wire color	Alpha 3222 wire color	Molex 43025-0600 contact no.
Shield	Shield	1
Red (Vmic,+10V)	Red	3
Black (GND)	Black	4
White (Signal)	White	6

F.4 PHAD Microphone Preamplifier Schematic

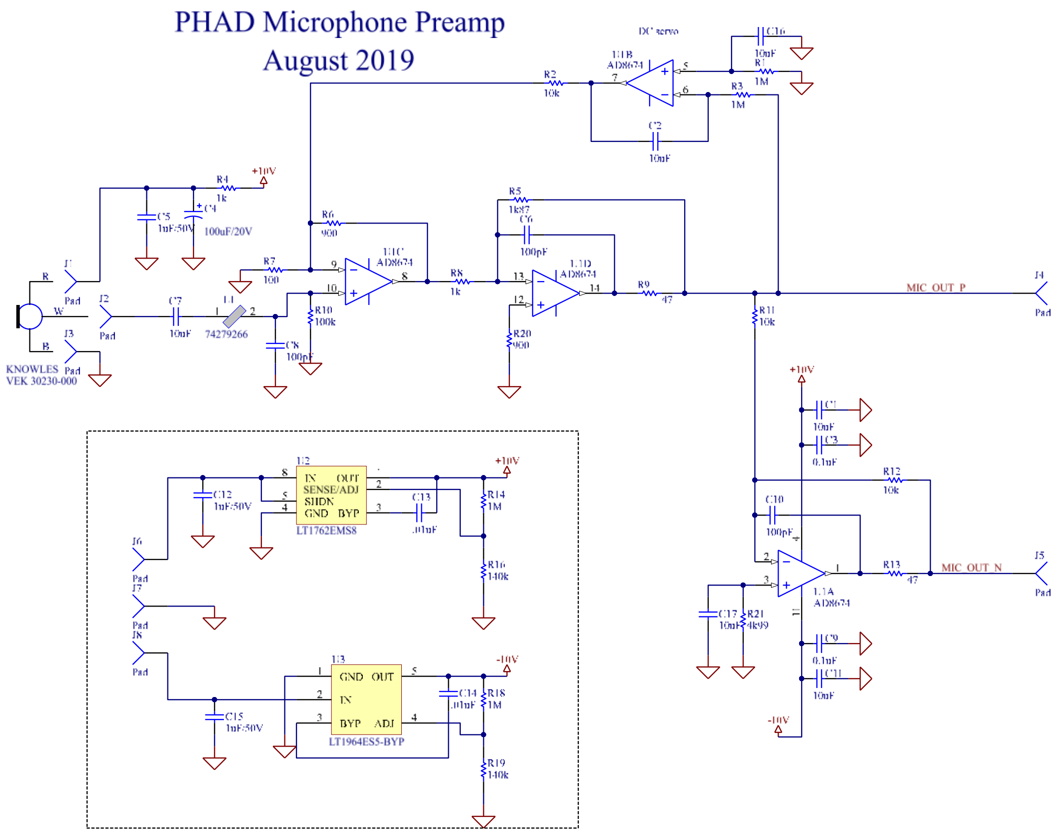


Fig. F-4 Microphone preamplifier schematic

F.5 PHAD Microphone Preamplifier Printed Circuit Board

Only the top side view of printed circuit board (top copper layer and top silk layer) is shown for clarity (Figs. F-4 and F-5).

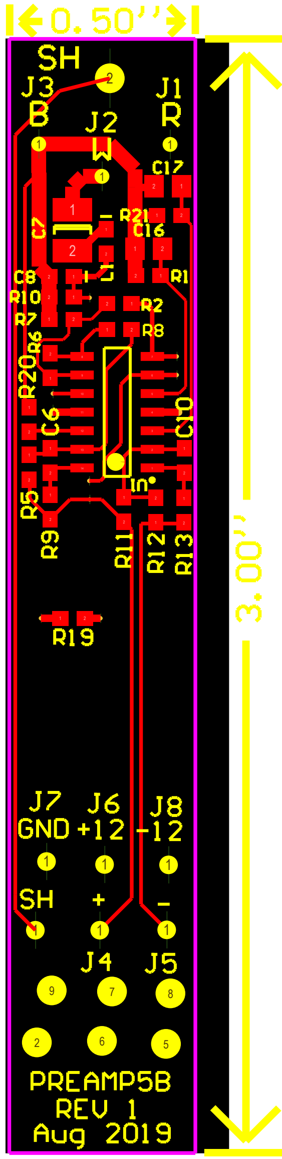


Fig. F-5 Preamplifier printed circuit board

F.6 PHAD Microphone Preamplifier Wiring and Assembly Instructions

This section describes the assembly and testing of the microphone preamplifier assembly for use in the PHAD large array (LA).

1) Attach a 6-pin connector jack, Hirose P/N LF07WBJ-6P, to the preamplifier using a 1 inch–3 inch cable, Belden P/N 9535 (5-conductor shielded cable, 24 AWG) according to the specifications shown in Table F-2.

Table F-2 Microphone preamplifier wiring table

Hirose LF07WBJ-6P contact no.	Belden 9535 wire color	Preamplifier connection pad designator
1	Red	J6 (+12V)
2	Green	J7 (GND)
3	Brown	J8 (-12V)
4	Black	J5 (-)
5	White	J4 (+)
6	Shield drain wire (connector body)	SH

2) Attach microphone, Knowles P/N VEK-H-30320-000, to the preamplifier using the 8-inch factory supplied microphone leads according to the specifications shown in Table F-3. Trim the leads only if required to make the wiring neater.

Table F-3 Microphone-lead wiring table

Microphone leads wire color	Preamplifier connection pad designator
Red (Vmic,+10V)	J1 (R)
Black (GND)	J3 (B)
White (SIGNAL)	J2 (W)
Shield	SH

3) Apply conformal coating to both sides of the preamplifier PCB according to instructions and let it cure completely before going on to the next step (Fig. F-6).

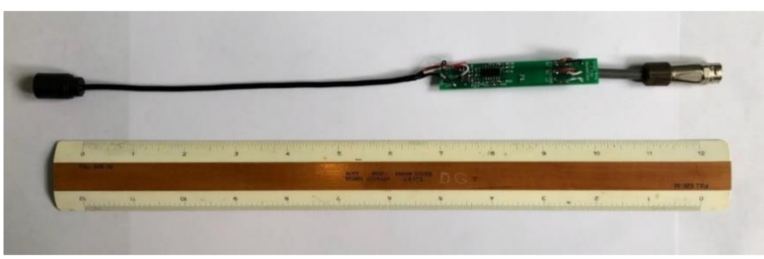


Fig. F-6 Microphone preamplifier assembly after steps 1–3

4) Cover the preamplifier PCB with heat shrink tubing 4 inches long × 0.75-inch starting diameter. Shrink tubing using a heat gun.

5) Test all microphone assemblies using a harness built from a mating connector plug, Hirose P/N LF07WBP-6S, according to the wiring table shown here (Table F-4). Use 24-inch length 24 AWG hookup wire. Use benchtop DC power supplies, an oscilloscope, and a B&K calibrator Model 4226 set to Calibration Function, Pressure response, 94 dB SPL at 31.5 Hz. After all microphones have been tested, match the microphones into groups of eight with the most similar calibration voltages (sensitivities) grouped together. Approximately 10% extra assemblies should be built to allow for some that do not match well.

Table F-4 Harness wiring table

Hirose LF07WBJ-6P contact no.	Belden 9535 wire color	Preamplifier connection pad designator
1	Red	+12 VDC
2	Green	Ground
3	Brown	–12 VDC
4	N/A	No connect
5	White	Signal
6	N/A	No connect

6) Mount microphone assembly in metal stub and coupler.

   a. Install microphone assembly into microphone stub and coupler so that the top edge of the microphone extends 0.25 inch beyond the non-coupler end of the stub. Install three set screws to hold the microphone in place.

   b. Apply RTV/silicone to seal the gap between the microphone housing and the stub, being careful not to get any silicone on the top of the microphone. Wipe off any excess and make sure the gap is completely sealed. Wait for RTV/silicone to fully cure according to product instructions (Fig. F-7).

Fig. F-7 Microphone preamplifier assembly without heat shrink tubing on stub

c. Place a piece of heat shrink tubing 1 inch long × 1 inch starting diameter over the end of the stub so that the screws are fully covered but the tubing does not extend beyond the end of the stub. Shrink tubing using a heat gun.

NOTE: The microphone preamplifier assembly is now ready for integration into the PHAD LA setup.

F.7 PHAD LA Cable Assembly Instructions

This section describes the assembly and testing of the array cables used to connect the microphone preamplifier assembly to the main electronics box used in the PHAD LA. All cables are wired the same, but the length varies for each as shown in Table F-5. The lengths as built provide approximately 3 feet of extra length to allow for a service loop in the microphone box and PHAD electronics box. One cable of each length should be built for each PHAD LA.

Table F-5 Cable lengths for LA

Cable for microphone no.	Cable length (feet)
1	6
2	7
3	8
4	9
5	11
6	13
7	16
8	20

1) Attach a 6-pin plug, Hirose P/N LF07WBP-6S to both ends of cable, Belden P/N 9535 (5 conductor shielded cable, 24 AWG) according to the specifications shown in Table F-6. The length of each cable is listed in Table F-5.

Table F-6 LA wiring table

Hirose LF07WBJ-6S contact no.	Belden 9535 wire color
1	Red
2	Green
3	Brown
4	Black
5	White
6	Shield drain wire (Connector body)

2) Test each cable for continuity and for potential shorts between contacts.

3) Label each cable at both ends with the cable length for easy identification.

F.8 PHAD LA Cable to Amplifier Bulkhead Harness

This section describes the assembly and testing of the harness that connects the array cables to the PHAD amplifier printed circuit board.

1) Attach a 6-pin bulkhead receptacle, Hirose P/N LF07WBR-6P to cable, 6-inch length, Belden P/N 9535 (5 conductor shielded cable, 24 AWG).

2) Attach a 6-pin receptacle, Molex P/N 43025-0600 to the other end of the cable using female contacts 20–24 AWG, Molex P/N 43030-0009. Assemble the harness according to the specifications shown in Table F-7.

Table F-7 Harness wiring table for LA

Hirose LF07WBR-6P contact no.	Belden 9535 wire color	Molex 43025-0600 contact no.
1	Red	2
2	Green	4
3	Brown	5
4	Black	N/C
5	White	6
6	Shield drain wire (Connector body)	1

3) Test the harness for continuity and for potential shorts between contacts.

F.9 PHAD Main Electronics Unit Assembly Instructions

This section describes the final assembly procedure for the PHAD main electronics unit. At this point, all PCBs, cables, harnesses, and subassemblies have been fabricated and tested. Most of the procedure is the same for both the LAs and SAs with differences being noted during the individual steps.

1) Attach three isolated BNC connectors to the equipment plate with BNC side facing up. On the terminal side, connect center conductors together and connect to red wire of DC Power Input harness (3-pin Military Connector that mates with the Power Conditioner Cable and goes to red/black pigtails inside the main electronics unit). Connect ground tabs together and connect to black wire of DC Power Input harness.

2) Attach the amplifier and the cRIO controller to the equipment plate using #8 screws and nylon locknuts. Use four 0.25-inch length spacers between

the amplifier enclosure and equipment plate. For the LA only, install the lid on the amplifier enclosure using eight no. 8 × 3/8 inch length sheet metal screws.

3) Connect the twisted pairs from the amplifier to the cRIO A/D modules with the red wire going to the "+" terminal and black wire going to the "–" terminal. The A/D module closest to the ports on the controller is A/D channels 1–4.

4) Install the equipment plate in the main electronics unit using four hex bolts, which go through the equipment plate, then through the unthreaded short standoff, then through a sealing washer with the rubber side on the bottom. The hex bolts then go through holes in the bottom of the main electronics unit and screw into the threaded long standoff.

5) Attach the leveling plate with the single hole nearest the front face of the electronics box.

6) Attach the leveling legs. Replace the thin nut with a thick nut so that there is one nut on each side of the leveling plate.

NOTE: Steps 7–10 apply to both the LA and SA, except the connectors are mounted to the sidewall of the LA main electronics unit rather than the bottom as described here for the SA main electronics unit.

7) Install a panel mount RJ-45 receptacle on the bottom of the main electronics unit with the exterior tab facing towards the front face of the electronics box. Make sure the sealing gasket is installed between the receptacle flange and the main electronics unit. Install a connector cap.

8) Grease the O-Ring and install the DC Power Input connector (3-pin MIL connector) on the bottom of the main electronics unit.

9) Install the amplifier-gain control switch and gain control knob on the bottom of the main electronics unit.

10) Grease the O-Ring and install the GPS connector (SMA feedthrough F/F) on the bottom of the main electronics unit.

11) Connect a BNC patch cable between the equipment plate mounted BNC and the "DC Power In" BNC connector mounted to the amplifier enclosure.

12) Connect an isolated BNC connector with red/black wire pigtails between the equipment plate mounted BNC and the "Power Connector" of the cRIO controller.

13) Connect an SMA (M/M) patch cable between the main electronics unit mounted GPS connector and the cRIO "GPS Input".

14) Install a CAT-6 patch cable between the main electronics unit mounted RJ-45 receptacle and the cRIO "Ethernet Port".

15) For the LA only, install weather stripping to the bottom side of the main electronics unit lid and then install the lid using the supplied bolts.

NOTE: The LA is ready for shipment or installation. The lid will need to be removed during installation to make the final connections between the LA microphone cables and the bulkhead connectors on the amplifier enclosure.

NOTE: The remaining steps apply to the SA only. It is highly recommended that a second person help with steps 16–20 to avoid personal injury or damage to the array.

16) Install weather stripping to the wire side of the microphone array plate.

17) While propping up the microphone array plate, run the microphone cables through the 1.25-inch hole in the lid of the amplifier enclosure. Connect the Molex-6 connectors to the corresponding "Microphone Connections" J1_1 thru J1_8 on the amplifier PCB (Fig. F-8). The Hirose connector is shown in Fig. F-9.

18) Place tie wraps on both sides of the amplifier enclosure lid to keep the microphone cables from moving inside the enclosure once the lid is secured.

19) Secure the amplifier enclosure lid using four no. 8 × 3/8-inch length sheet metal screws.

20) Place the microphone array plate on the main electronics unit such that the "North" marking on the array plate points towards the rear of the main electronics unit. The rear side of the main electronics unit should have two leveling feet along that side.

21) Secure the microphone array plate to the main electronics unit by first clamping the four corners using 0.75-inch length standoffs and 2-inch length bolts. Tighten securely.

22) Install 1-inch length bolts with sealing washers to remaining holes on all sides.

23) Replace the corner bolts with 1-inch bolts and sealing washers. Tighten all bolts.

NOTE: The SA is now ready for testing and installation. If the SA is going to be transported or stored, the following steps should be taken to prevent damage to the microphones.

24) Remove the four corner bolts. Place a 0.75-inch length standoff used in step 21 over each corner hole and then place the protective metal cover on top of the standoffs. Secure cover with the 2-inch length bolts that were used in step 21.

25) Once the SA is transported to the installation location, remove the four corner bolts and the protective cover. Set the cover plate, 2-inch bolts and 0.75-inch standoffs aside for future transportation or storage of the SA. Install the 1-inch length bolts with sealing washers from step 23 into the four corners and tighten. The PHAD SA is now ready for installation.

Top View (Wire Side)

43025-0200

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43025-0600

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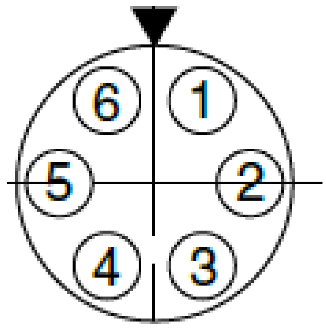
Fig. F-8 Molex connector contact arrangement

View from Plug Connector Mating End

Or

Receptacle/Jack Solder Pot Side



Note: The ▼ symbol indicates polarizing key position.

Fig. F-9 Hirose connector contact arrangement

List of Symbols, Abbreviations, and Acronyms

ALC	Adelphi Laboratory Center
AOR	area of operational responsibility
ARL	Army Research Laboratory
CAT-6	Category 6 Ethernet cable
CCDC	US Army Combat Capabilities Development Command
CONOPS	Concept of Operations
COTS	commercial off-the-shelf
cRIO	CompactRIO
DA	data acquisition
DOD	US Department of Defense
FIFO	First In First Out
FPGA	Field Programmable Gate Array
GPS	global positioning system
LA	large array
MIL	Military
NI	National Instruments
PCU	Power Conditioning Unit
PHAD	Persistent Harmonic Acoustic Detector
PSD	Power Spectral Density
SA	small array
SMA	Sub-Miniature version A
SNR	signal-to-noise ratio
SPL	Sound Pressure Level
sps	samples per second
TCP/IP	Transmission Control Protocol/Internet Protocol

TDOA	Time Difference of Arrival
UM	University of Mississippi
UTC	Coordinated Universal Time

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