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FINAL TECHNICAL REPORT

Underwater Active Acoustic Monitoring Network For Marine And Hydrokinetic Energy Projects

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ABSTRACT

This project saw the completion of the design and development of a second generation, high frequency (90-120 kHz) Subsurface-Threat Detection Sonar Network (SDSN). The system was deployed, operated, and tested in Cobscook Bay, Maine near the site the Ocean Renewable Power Company TidGen™ power unit. This effort resulted in a very successful demonstration of the SDSN detection, tracking, localization, and classification capabilities in a high current, MHK environment as measured by results from the detection and tracking trials in Cobscook Bay. The new high frequency node, designed to operate outside the hearing range of a subset of marine mammals, was shown to detect and track objects of marine mammal-like target strength to ranges of approximately 500 meters. This performance range results in the SDSN system tracking objects for a significant duration - on the order of minutes - even in a tidal flow of 5-7 knots, potentially allowing time for MHK system or operator decision-making if marine mammals are present. Having demonstrated detection and tracking of synthetic targets with target strengths similar to some marine mammals, the primary hurdle to eventual automated monitoring is a dataset of actual marine mammal kinematic behavior and modifying the tracking algorithms and parameters which are currently tuned to human diver kinematics and classification.

KEYWORDS

Marine mammal, active sonar, MHK, detection, tracking

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1. EXECUTIVE SUMMARY

Marine and hydrokinetic (MHK) energy projects, and for that matter offshore renewable energy projects in general, may not meet current or future regulatory requirements without real-time monitoring of the surrounding underwater environment. This might not be true in the very long-term as we learn how marine life and debris in the water column interacts with the devices deployed. However, at this point there are unknown risks associated with harm to marine life, including endangered species, and risks associated with floating debris interacting with moving parts of the device. The risks can occur during operation, such as for turbines deployed in a tidal stream, and during construction such as the pile driving necessary to install offshore wind farms. For the foreseeable future monitoring may be required to determine and measure the risks, as well as to mitigate those risks through shut down or other procedures if deemed necessary.

The primary technical goals of this project involved the development, deployment, and demonstration of an active acoustic monitoring (AAM) system based on the Subsurface-Threat Detection Sonar Network (SDSN). The two primary components were the design and development of a second generation sonar node operating in the 90-120 kHz frequency range and the demonstration of this device in an MHK relevant environment.

This project saw the completion of the design and development of a second generation, high frequency (90-120 kHz) Subsurface-Threat Detection Sonar Network (SDSN) sonar node. Although an issue with the communications cable required an adjustment in the deployment location, the system was deployed, operated, and tested in Cobscook Bay, Maine near the site the Ocean Renewable Power Company TidGen™ power unit.

This effort resulted in a very successful demonstration of the SDSN detection, tracking, localization, and classification capabilities in a high current, MHK environment as measured by results from the detection and tracking trials in Cobscook Bay. The new high frequency node, designed to operate outside the hearing range of many marine mammals, was shown to detect and track objects of marine mammal-like target strength to ranges of approximately 500 meters. This performance range results in the SDSN system tracking objects for a significant duration on the order of minutes even in a tidal flow of 5-7 knots, potentially allowing time for MHK system or operator decision-making if marine mammals are present.

These results support the viability and feasibility of the SDSN as a technology for MHK projects. Having demonstrated detection and tracking of synthetic targets with target strengths similar to some marine mammals, the primary hurdle to eventual automated monitoring is a dataset of actual marine mammal kinematic behavior and modifying the tracking algorithms and parameters which are currently tuned to human diver kinematics.

If that additional modification were successful, the SDSN would likely be a suitable technology for MHK projects in multiple possible roles:

- Marine mammal monitoring during MHK installation projects for animal avoidance data and protection.
- Short-term marine mammal monitoring during MHK operation to determine animal response and behavior in the presence of MHK devices.

- Long-term marine mammal monitoring during MHK operation, possibly as a system or operator decision-making aid, if short-term observations determine there is a measurable impact that should be monitored or mitigated.

As a result, this project supports the larger objective of facilitating MHK installations and the advancement of renewable energy technologies by mitigating the significant barrier that is the potential impact of MHK devices on their environment – specifically marine mammals in this instance.

The original objective of this project involved deploying the SDSN system on the MHK device directly. However, installation difficulties led to a modified approach. The SDSN system was deployed near-shore and oriented towards the area in front of the MHK device. Although not the exact same monitoring region or installation configuration, this allowed for operation and collection of a rich dataset that includes synthetic target detection and tracking, nuisance alert data, and target strength as a function of the variable environmental conditions in the desired MHK environment.

Based on the deployment and operation of a high frequency version of the SDSN system in a relevant environment, and the ability to detect and track synthetic targets with target strengths relevant to marine mammal observation, the system has surpassed TRL 4 and reached TRL 5. Commercialization of the SDSN technology for MHK applications is likely still difficult in the near term. The SDSN system itself will require an additional degree of productization to allow it to be an off-the-shelf option for MHK installations. This would include improving the deployability, maintainability, and speed of manufacture. It would also require some form of standardization or common use case with respect to a typical MHK installation to define installation requirements and have those installations prepared to accept an SDSN system for mounting and cabling. In the interim, however, it is quite conceivable to manufacture individual SDSN specific installations or applications as the industry matures.

2. INTRODUCTION

Marine and hydrokinetic (MHK) energy projects, and for that matter offshore renewable energy projects in general, may not meet current or future regulatory requirements without real-time monitoring of the surrounding underwater environment. This might not be true in the very long-term as we learn how marine life and debris in the water column interacts with the devices deployed. However, at this point there are unknown risks associated with harm to marine life, including endangered species, and risks associated with floating debris interacting with moving parts of the device. The risks can occur during operation, such as for turbines deployed in a tidal stream, and during construction such as the pile driving necessary to install offshore wind farms. For the foreseeable future monitoring may be required to determine and measure the risks, as well as to mitigate those risks through shut down or other procedures if deemed necessary.

For some region around an MHK system, likely on the order of hundreds of meters, there may be a need to detect that a moving object is present, track the object to determine its trajectory and speed, localize it to a range and bearing, and classify it to determine what the object is and whether there is a danger to it or the MHK system. These capabilities are commonly referred to as detection, tracking, localization, and classification (DTLC) in the context of tracking systems, be it sonar, radar, or other means [1]. An MHK system deployed in a high current environment may be susceptible to moving debris if it is large enough to cause damage or otherwise interfere with normal operation. Conversely, the system itself may present a danger to marine life if it is determined that marine life is either unable to avoid or unable to recognize a need to avoid the system, or if marine life is attracted to the system.

Active acoustics is where sound transmitted by an acoustic source travels out to a target, reflects off the target, and travels to and is detected by one or more receivers. At least one receiver is usually co-located with the source. Through measurements of travel time and a plethora of characteristics of the return signal, sonar systems are able to perform DTLC. The level of performance depends on the specifics of the system and the environment. Given a requirement of suitable detection ranges for automated or manual decision-making for the dangers presented in the previous paragraph, active acoustics or active sonar is truly the only viable solution to meet MHK marine mammal monitoring needs.

Of course, sonar is a well-developed and well-understood technology. Active sonar systems exist to track submarines, find fish, detect and map the marine substrate (depth sounders and side-scan sonar), and even provide imaging of the underwater environment. However, their capabilities depend greatly on the system configuration and the operating frequency. There are no sonar systems on the market that provide a comprehensive solution to meet MHK marine mammal monitoring needs. Imaging sonars would seem to be one solution and are available. However, they do not have sufficient range and are not generally intended for long-term deep-water deployment. They also lack real-time DTLC capabilities and are not easily integrated with other systems. The technology with the closest fit to meet MHK marine mammal monitoring needs is likely related to the military sonar systems now available on the market for DTLC of threat swimmers and underwater vehicles in the harbor environment. However, these systems are generally very expensive, the operating parameters such as frequency, detection range, and ping rate are not optimized to meet MHK marine mammal monitoring needs, and these sonars are not necessarily designed for integration into an MHK system.

An active acoustic system to monitor marine life and floating debris must be designed specifically for the MHK-type installations. There are a variety of reasons including higher current velocities in more open water and differences in marine life kinematics relative to the anti-swimmer problem. Automatic DTLC in the far-field at ranges on the order of hundreds of meters is a must if the system is to provide information that is adequate and timely enough for decision-making. Although the initial objective may simply be to track and understand the behavior, if negative interactions do occur then there is likely a minimum time window for decision-making. Given currents on the order of 5-8 knots (separate from any independent movement of the marine life), the likely detection range of an AAM system (order 500 m @ 100 kHz), and any time required to safely and nondestructively stop or alter the movement of something the scale of MHK devices (such as the order 100 ft long ORPC TidGen™ unit) it is likely this time window is on the order of minutes rather than seconds.

The potential impact on the MHK industry is likely to be largest if the initial monitoring determines that there is no negative interaction between MHK installations and marine life and debris of the size detected by these sonar systems. This could reduce or eliminate monitoring requirements in future installations, thereby mitigating installation and operating costs. Although possibly counterintuitive, the observed behavior in efforts such as this would ideally demonstrate that this type of system and the associated *permanent* and *continuous* monitoring at many or all future installations are *not* necessary due to a lack of negative interactions. On the other hand, if there is cause for concern over long-term adverse effects or this form of monitoring is otherwise deemed necessary, this project represents an important opportunity to begin to transition this form of DTLC technology to the MHK environment and operational requirements.

The commercialization of this technology for MHK installations will be a function of the results of data collection efforts such as the one completed in the project, where the detection and tracking capabilities of an AAM system is evaluated in MHK environments, and where they are evaluated with a statistically significant number of marine mammals rather than synthetic targets (primarily due to kinematic differences). If these systems prove suitable for MHK environments, and regulators determine that monitoring is a permanent and required component of these installations, then we would anticipate commercialization for something close to off-the-shelf use in MHK installations. In the near-term, individual and customized projects for the evolving MHK installations that are research-oriented, despite the maturity of the sonar technology itself, is a more viable approach to determine both the need and optimized operation of the DLTC systems for this application.

3. BACKGROUND

The enabling sonar technology used for the AAM system in this project is the Subsurface-Threat Detection Sonar Network (SDSN), which is an anti-swimmer/diver sensor system that has been under development since 2004. SDSN is an Office of Naval Research (ONR) Small Business Innovative Research Program (SBIR).

Most swimmer detection sonar systems have a single sonar head that "looks" in either a 180 or 360 degree-wide window. They generally have a single source that transmits in a very wide beam and a phased-array receiver that is typically composed of hundreds of individual receive elements. They are often very complex and expensive as the signals from each element are typically individually digitized and amplified, and then combined from multiple elements for beam-forming [2].

SDSN uses a distributed network of single narrow-beam sonar systems. If each of these sources of sound were instead a source of light, one might picture each single-beam sonar system as a single flashlight shining in a fixed direction. The total system would be made up of hundreds of these "flashlights" pointing in different directions to "illuminate" the entire area.

Individual single-beam sonar systems are combined into units referred to as "nodes". A node contains multiple single-beam sonar systems in a single housing with each beam oriented in a slightly different direction, and provides for shared electronics. The original operational node had 12 beams. Each beam covers an angle of 4.5 degrees for a total angular coverage of 54 degrees for the node. The next generation (G2) node completed during this project has four beams. Each beam still covers an angle of 4.5 degrees for a total angular coverage of 18 degrees per node; however multiple four-beam nodes can be assembled together. Each additional node expands the view by 18 degrees, with 20 nodes providing full 360-degree coverage if necessary.

Figure 1: SDSN nodes. On the left is the original production node that has 12 round parabolic reflector transducers. On the left center is the second-generation (G2) node that has 4 rectangular parabolic reflectors transducers. On the right center is a comparison of the size of the current node and G2 node (black foam has not been installed in the G2 node). The new node is roughly 1/8 the size and has the same or better performance. On the right is a mock-up of the G2 node with high frequency rectangular flat plate transducers. This would operate between 90 and 120 kHz and is similar to what was developed for this project.

Figure 1 shows the original production node as compared to the second-generation (G2) node. In addition to size and weight, there are many significant advances in the G2 node related to cost, signal generation, data acquisition, and networking. Both the original production node and the first iteration of the G2 node operate between 45 kHz and 75 kHz. However, the G2 node can be configured to operate at frequencies up to 200 kHz with a change of transducers and tuning components. The nodes are designed to operate at a source level between 210 and 215 dB re 1 µPa @ 1m.

The design philosophy of the SDSN is to combine all of the individual single-beam sonar systems and signal processing computers together with information shared across an entire network of sensors and support equipment. Significant software is used to transfer, process, and fuse all the information into a robust DTLC system (Figure 2 and Figure 3). One or more human-machine interface (HMI) displays provide control and monitoring of the system and the display of all target track information over the coverage area. As an example of scale, an existing operational SDSN installation has a total of 240 beams across 20 nodes. There are roughly 70 processors working together to collect, transfer, and process the data. DTLC ranges are on the order of 1000 m for objects the size of a human diver.

To summarize, the principles of the SDSN system architecture and design are:

- Each individual beam is very simple. In fact, each single-beam sonar system is no more sophisticated then a depth sounder. The power of the system is in the shared information over the network and distributed processing.
- Unlike similar underwater harbor surveillance systems, the SDSN both transmits and receives in narrow beams. Each sensor can be assigned and detect its own unique transmit signal. This can dramatically reduce interference between sensors and from reverberation, thereby improving system performance.
- In regions where beams overlap the system performance improves as the system has multiple views of the target. Multistatic processing is possible where the signal from one beam can be processed by other receivers. The system timing was designed from inception to allow this.
- The system is easily expanded. Adding a node requires mounting the node, providing power and a network connection, and updating simple system configuration data with the location and aiming of the new node.
- The system uses standard network interfaces and communications and is easily integrated with other systems.

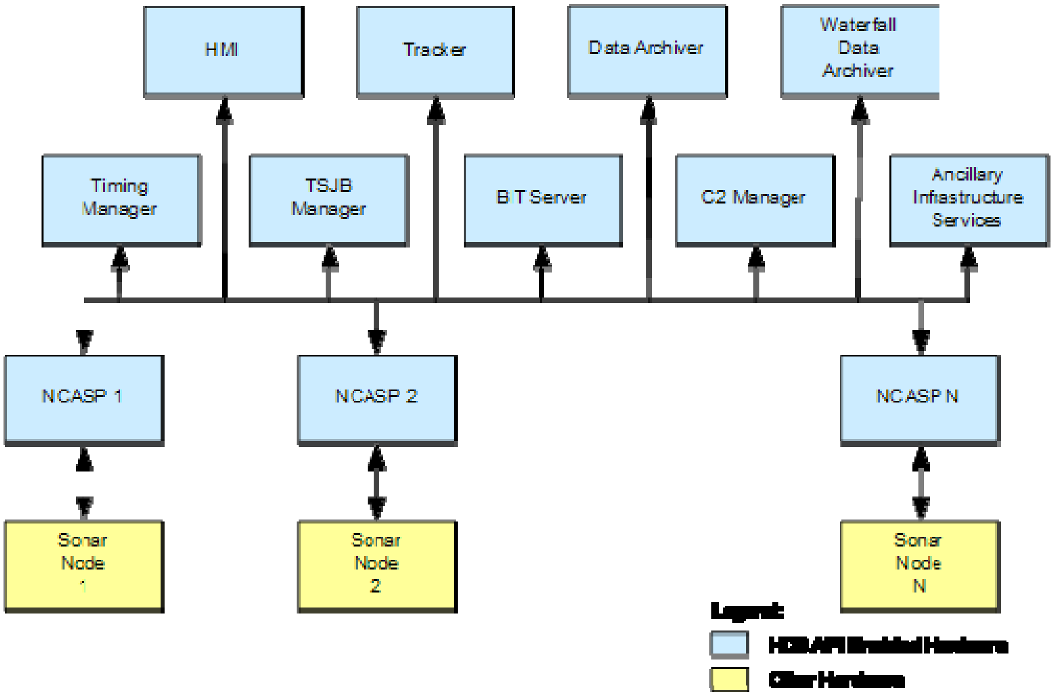


Figure 2: SDSN software architecture. The SDSN software has been developed to operate the system, share data on the network, and process and display the information. Each sonar node has a dedicated control and processing computer referred to as the NCASP (node control and signal processing). In addition there are computers running applications associated with timing, top-side junction box (TSJB) control, built-in-test function (BIT), data archiving, tracking, and the human machine interface (HMI).

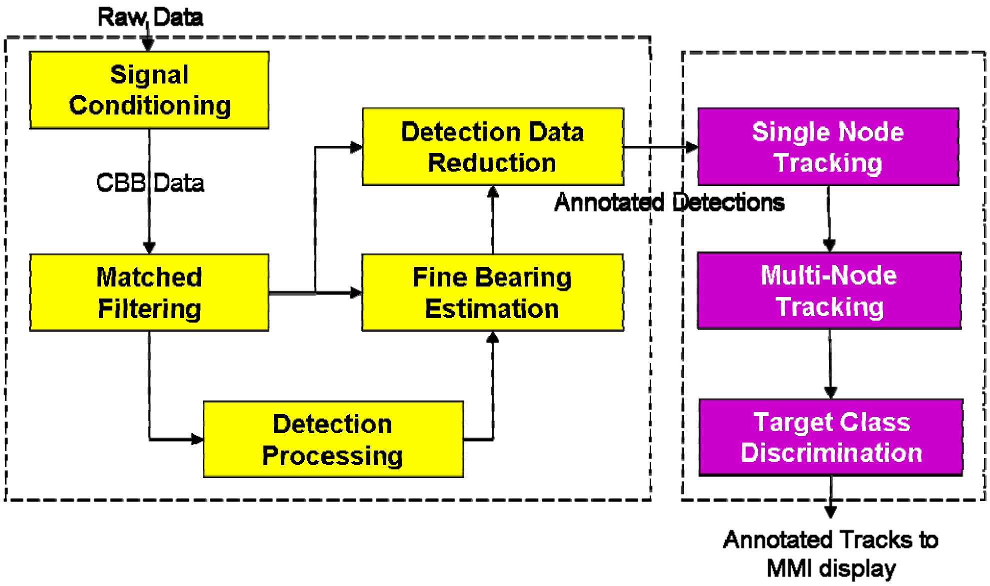


Figure 3: SDSN signal processing overview. Algorithms have been developed to detect, track, localize, and characterize divers. These algorithms likely require significant modifications and testing to alert on and classify marine life and floating debris.

3.1. Using SDSN to Track Marine Life and Floating Debris

The greatest challenge in the current SDSN operational system is distinguishing between swimmers or divers that might be threats and the marine life and debris that the system also tracks at times. In the context of threat swimmer or underwater vehicle detection, these tracks may result in “nuisance alerts” where action is taken for an object that is not a threat.

Figure 4 shows two objects being tracked by the SDSN system during one trial. One is a diver and the other is an unknown object, often later determined to be a large fish, marine mammal, or a school of fish. At times the system also tracks considerable amounts of what we presume is floating debris. During one nuisance alert a target was investigated and found to be a floating log.

The SDSN tracking and classification algorithms were not specifically developed or optimized to track and classify marine life and floating debris, and statistical performance data regarding how well the system works against these types of targets is not yet available. However, visual inspections of false alerts over the course of many threat-diver related trials have confirmed false alerts to be debris or marine life on several occasions. The goal of this effort was to develop a version of the system that is capable of detecting, tracking, localizing and classifying these objects in an acceptable operating frequency range, and gather data though could facilitate future algorithm development to enable high alert probabilities that would provide adequate monitoring and decision-making capabilities for MHK systems.

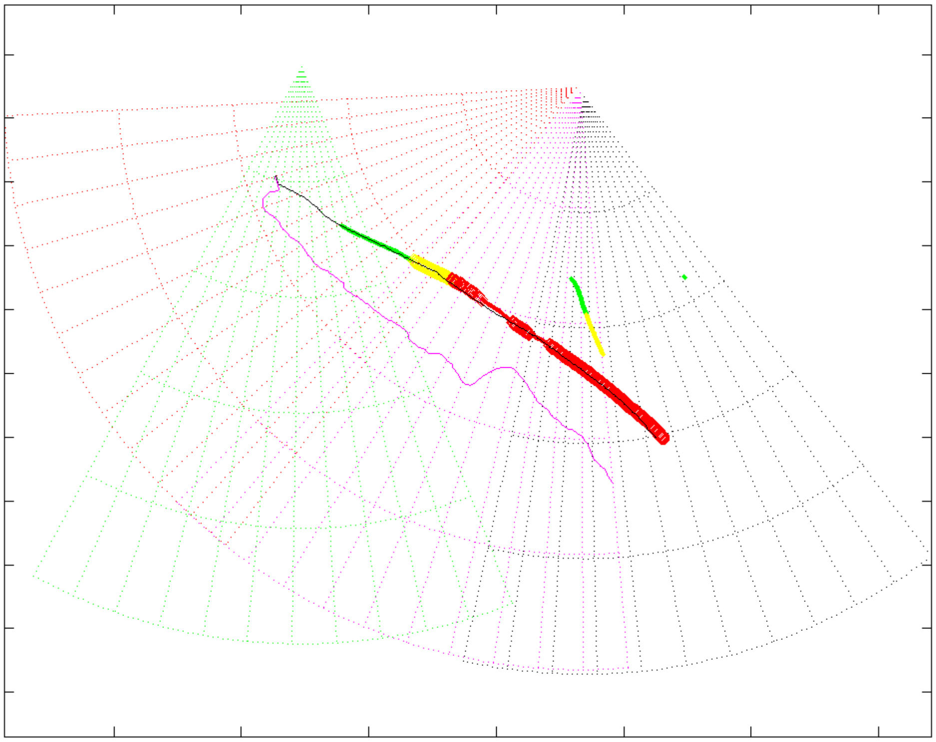


Figure 4: The SDSN system tracking both diver (track that turns red) and an unknown target (track that turns yellow), which is presumed to be a marine mammal or large fish.

3.2. Modifying SDSN for an MHK Active Acoustic Monitoring System

Due to the rapid increase of sound absorption with frequency in seawater, the detection range of a system is highly dependent on frequency [3]. The original SDSN production nodes, operating at a frequency of 45-75 kHz, achieved a DTLC range of over 1000 m. This is expected to be more than is necessary for MHK applications where 300-500 m is likely adequate. In MHK applications the most apt response, if any, would be to stop or otherwise alter the state of the MHK device. The time window for decision-making only needs to be wide enough to allow for such a change in state to occur, whereas in the original anti-swimmer context, one can imagine responses that may be moderately time consuming, such as manning and launching a vessel to intercept a threat.

Further, in the case of the current anti-swimmer system, there were no concerns about the effects of the transmitted sound on marine mammals due to the locations where the system has been deployed. For widespread deployment there is a need to operate outside the hearing range of as many marine mammals as possible, while achieving sufficient detection range. The convergence of these issues suggested an operational frequency in the range of 90-120 kHz. This places the system above the estimated auditory bandwidth of pinniped and low-frequency cetacean functional hearing groups [4]. In addition, the higher absorption at 90-120 kHz that inhibits further detection ranges also limits the region where sounds levels may exceed any current or future guidelines for peak sound pressure or sound exposure levels. If those levels must be exceeded due to a greater danger of interaction with the MHK device, one objective would be to limit that exposure region to just what is required for an adequate decision-making window. Thus the primary hardware modification to the system was to modify the G2 node to operate at higher frequencies.

The existing, operational, low frequency, anti-swimmer SDSN system was implemented in a tropical environment, whereas MHK systems will likely be deployed in a variety of climates, including temperate ones. This is an important difference in that during the summer months the surface water is warm and there could be downward refraction that limits range. This might be solved with additional nodes using a different vertical aperture. However, the MHK systems are also deployed in strong tidal flows and the mixing might keep the temperature and the sound speed within the water column fairly uniform, removing this as an issue.

The SDSN system had not been deployed in the 5-7 knot currents where some MHK systems are installed. Although preliminary results from this test demonstrated successful detection and tracking of the synthetic target, there may be acoustic propagation effects in some locations due to the turbidity of the water that also limit performance. This might suggest a lower operating frequency.

4. RESULTS AND DISCUSSION

4.1. Next Generation Sonar Node Design and Development

This project saw the completion of the G2 high frequency (G2HF) design and development as planned. This involved completion of the common aspects of the G2 design (common to both low and high frequency versions), as well as the high frequency specific aspects. The majority of the common design and development had been completed; however significant components completed as a part of this effort involved development of the node firmware for startup, data uploads, and built in test features.

The key design elements that are specific to the high frequency version include the analog filtering components for the receive electronics and the transducer and associated baffling. The original analog filtering components for the G2 low frequency (G2LF) design were selected for the 45-75 kHz operation of that design. For the G2HF design this was expanded to up to 200 kHz. The lower limit was not changed and the upper limit set well above the G2HF operational frequency range (90-120 kHz) for two reasons.

The first reason is to allow the updated receive analog electronics design to be applicable to any variation of the G2 node between 45 kHz and 200 kHz. All of the other electronics other than the transducer tuning components now share a common design. The second reason is to allow the G2HF nodes to receive signals from G2LF nodes. It is unlikely that G2 low frequency nodes would be applicable in many MHK contexts given the operating frequency range relative to the hearing range of most marine mammals. However, multistatics (transmitting and receiving acoustic signals on different sensors) is such a key area of possible system improvement that it is sensible to not proactively prohibit the interaction of different node variations.

The most important design element involved the transducer selection for 90 – 120 kHz operation. It is necessary to change the transducer design when the operating frequency changes by such a significant amount (relative to the G2LF version) for two reasons. The first is that the transmit voltage response and receive sensitivity of the transducer ceramics are generally maximized and nominally flat for an approximately 30 kHz wide window. To make the 45 kHz jump in operating range required the selection of a new transducer.

The second reason involves the beamwidth for each channel. As the frequency increases the beam width, given the same transducer elements and baffle design, will decrease [2]. A new transducer was required in order to increase the operating range by 45 kHz and maintain the required horizontal and vertical beamwidths. This modification turned out to be one of the more challenging aspects of the project prior to installation and testing. A number of variations were considered and tested before final components from International Transducer Corporation (ITC) were chosen.

As part of the selection and testing of the G2HF design and transducer selection, SSI conducted a test of a new G2HF node as well as a new G2LF node off of the ORPC barge in Eastport, Maine in May 2011 under its own internal funding. This test was intended to verify the performance of the G2 design and components in both frequency ranges prior to finalizing the physical node design for the G2HF version.

The following list summarizes the primary mechanical, electronic, and firmware developments completed as a part of this effort.

- **Mechanical Hardware**
  - Physical node design, material selection, and fabrication.
  - Selection of new transducer elements and baffle design.
- **Electronics**
  - Redesign of receive filtering components and transducer tuning components. This involves the redesign and replacement of various components to support both the higher frequency transducer and to support anti-aliasing over the higher operating frequency range of the G2 node.
  - In-house tank test to verify electronic receive levels. These tests are required to ensure the analog receive filtering and preamplifier responses are as intended for the higher frequency range.
  - Transmit signal measurement and evaluation to assess and confirm the performance of the new transducer elements.
- **Firmware**
  - New interfaces were developed for the following node firmware components. These are basic elements of functionality that were required for the node to function.
    - Boot Startup
    - Data uploads
    - Built in Test status

4.2. Software

As noted in the introduction, a significant component of the SDSN is the topside software infrastructure and components that allow for system control and multi-sensor detection, fusion, and tracking. Although many of the high-level components are insulated from the change from the original production node to the G2, a number of components that interact directly with the node or are dependent on specific node features required changes. Portions of those updates were completed as a part of this effort including updates to the data archiver, node control, detection processing, node status, and built-in-test manager applications.

4.3. Tests and Data Collection

The primary objective of the installation and data collection of this effort involved mounting the SDSN system on the ORPC TidGen™ unit to monitor the region fore and aft depending on the tidal flow. A significant deviation from the plan occurred when the fiber optic cable which was to connect the SDSN system to the shore station broke during the initial installation attempt. After careful consideration of several options an alternative was chosen where the SDSN was installed near-shore close to the TidGen™ operating region. The initial installation attempt and modified deployment plan are detailed in subsequent Sections 4.3.1 and 4.3.2.

4.3.1. Initial Deployment Attempt

The original plan for this effort called for mounting the SDSN system on the ORPC TidGen™ device. The SDSN deployment was to be accomplished by having divers retrieve the required shore cable from the installed TidGen™ device (at the bottom), bring it to a surface vessel, mate it with the SDSN system, and then lower the SDSN system by crane and installing it on the TidGen™. The procedure was required due to a fiber optic connection that could not be performed underwater.

After successfully retrieving the cable and beginning the mating process the cable snapped. It was later determined that a portion of the cable had been caught on the TidGen™ device and there was less slack available than expected. After evaluating the cable and available resources it was determined that options such as re-terminating the connector and running an alternate shore cable were not feasible. This was due to a combination of factors including cost, available cable lengths, likelihood of successful cable termination, and unknown cable integrity in the remaining portion of the cable.

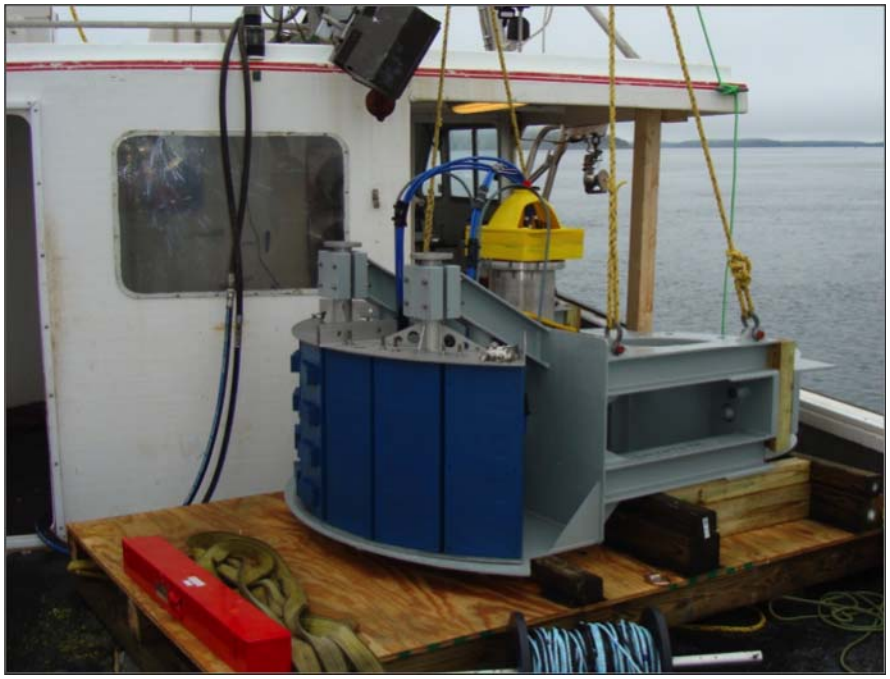


Figure 5: Nodes and mounting bracket ready for initial deployment in Cobscook Bay, Maine.

4.3.2. Final Deployment and Data Collection

An alternative deployment approach was devised whereby the natural tide cycle would facilitate the SDSN deployment in a region close to the original monitoring region. The location was chosen because it was the closest possible position to the original monitoring region given the available length of cable to connect the SDSN to the shore station and topside equipment.

The location of the system, the monitoring region, and the location of the TidGen™ and original deployment location are shown in Figure 6. The bathymetry is also shown in Figure 7. The location allowed the monitoring region to still include a relatively unobstructed portion of the high current area.

The photos in Figure 8 through Figure 10 show the updated SDSN deployment method. At low tide a crane on a barge lowered the SDSN system on to a platform of blocks that created a level surface and the cable run to the shore station. As the tide rose the barge was moved away and moored. Eventually, once the tide was 3-5 feet above the top of the SDSN system, operation could commence until after high tide and the levels receded back to 3-5 feet above the system. The final deployment and data collection schedule is shown in Table 1.

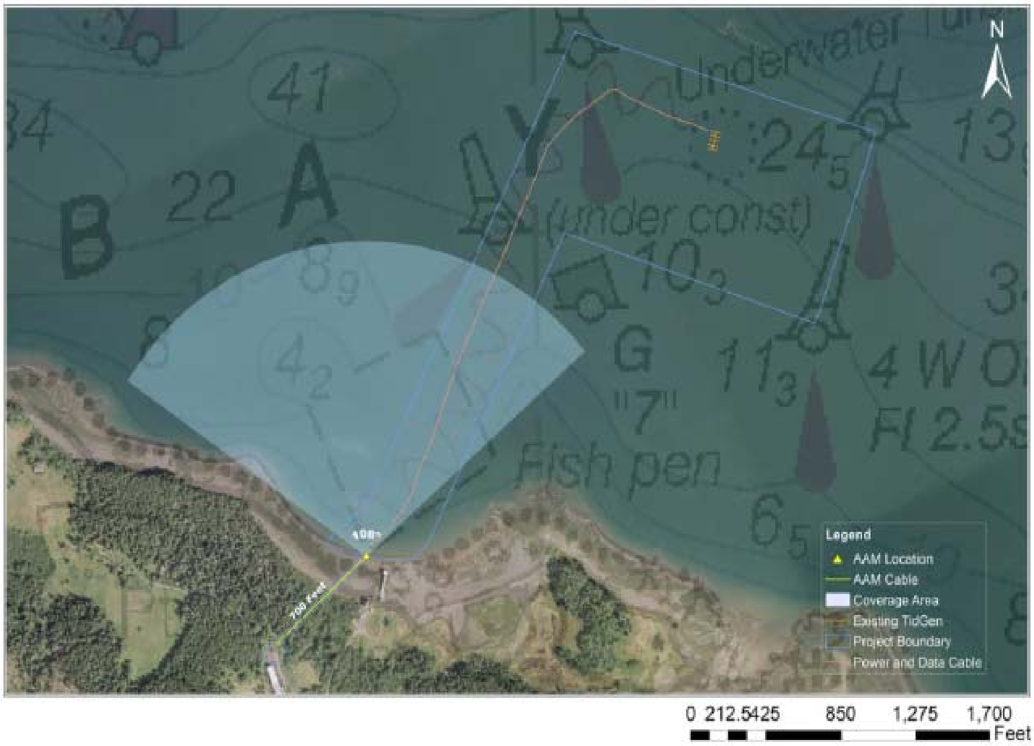


Figure 6: The final location of the system, monitoring region, and the location of the TidGen and original deployment location.

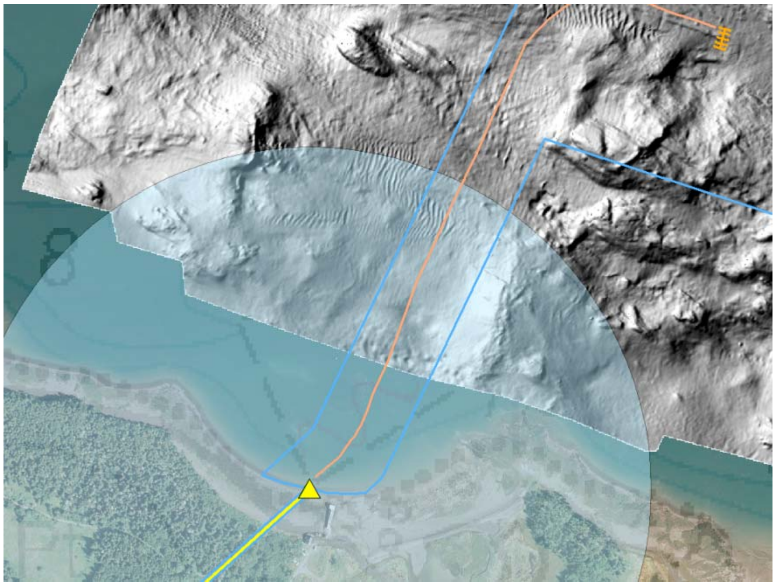


Figure 7: Partial bathymetry of the monitoring region.

Figure 8: SDSN deployment procedure at low tide.

Figure 9: SDSN nodes deployed on leveling blocks at low tide.

Figure 10: SDSN system nearly covered as the tide rises prior to operation.

Table 1: Final Deployment and Data Collection Schedule

Date	Action
Monday June 17, 2013	Deployment and 1 hour of system operation verification
Tuesday June 18, 2013	Three hours of test target practice trials
Wednesday June 19, 2013	Four hours of large synthetic target test trials
Thursday June 20, 2013	Four hours of small synthetic target test trials
Friday June 21, 2013	Moored target and nuisance alert data collection

4.4. Data Analysis and Tracking Results

The June 2013 deployment results fall into five general categories:

- *Ambient data levels* – demonstrates overall background levels and is an indicator of what target strength is required for sufficient signal-to-noise ratio for detection and tracking.
- *Towed synthetic target tracking* – assess performance of detection and tracking algorithms and parameters for a marine mammal-like target strength object.
- *Moored synthetic target measurements* – can provide insight into variability of target returns ping-to-ping which can impact detection and tracking. This may be especially important in an environment with significant currents, tide changes, weather, and other environmental variability.
- *Nuisance track and alert data* – assess the number of tracks and alerts that are not actual objects of interest. A system with too many nuisance alerts may be impractical for mitigation or decision-making.
- *Marine mammal sightings and associated tracking* – were marine mammals in the monitoring region and if so were they detected and tracked.

4.4.1. Ambient Data

Ambient data measurements are used to determine overall background levels and can be an indicator of what target strength is required for sufficient signal-to-noise ratio for detection and tracking. It also exposes background features, such as those related to the bathymetry, which may cause areas of high clutter and potentially weak areas of detection and tracking. Figure 11 shows A-scan data (amplitude modulation scan - a measure of the acoustic return signal as a function of range or time) for a single ping for all node channels. These plots are the effective target strength (dB re 1m) as a function of range. They provide some sense of the background levels, however as a snapshot for just a signal ping they include many transients as well.

The B-scan plot (brightness scan - a measure of the acoustic return signal as a function of range or time across multiple beams or channels) shown in Figure 12 provides a slightly different view of the background. First, the data is shown as a top down view where each channel is plotted over the area covered and the overall shape therefore matches the coverage shown in the earlier layout figures. Here the color scale is also effective target strength; however the values are an average of ten consecutive pings of data. In addition, the data between adjacent channels and as a function of range in each channel is smoothed.

This removes much of the transient background elements and provides better insight as to the static background elements. In conjunction with Figure 6 and Figure 7 the fact that the first channel of node 1 (the left side of the pie) hits the small jetty on the shoreline is apparent in Figure 12 by the high (red) returns along that left edge. Similarly, the rise seen in the topography of Figure 7 just left of center approximately 300 meters away from the yellow triangle indicating approximate cluster location is seen in Figure 12 in the same general location.

Overall the background is very encouraging. Although measurements of marine mammal target strength are not comprehensive, measurements on the order of -5 to +5 dB re 1µPa @ 1m are available for northern right whales, sperm whales [5, 6], and mean values for odontocetes such as bottlenose dolphins of -20 dB re 1µPa @ 1m [7], indicating that Minke whales, sometimes seen in Cobscook Bay, may fall somewhere in between. This suggests that outside of some strong returns due to physical features, detection on a per-ping basis and subsequent tracking should be feasible.

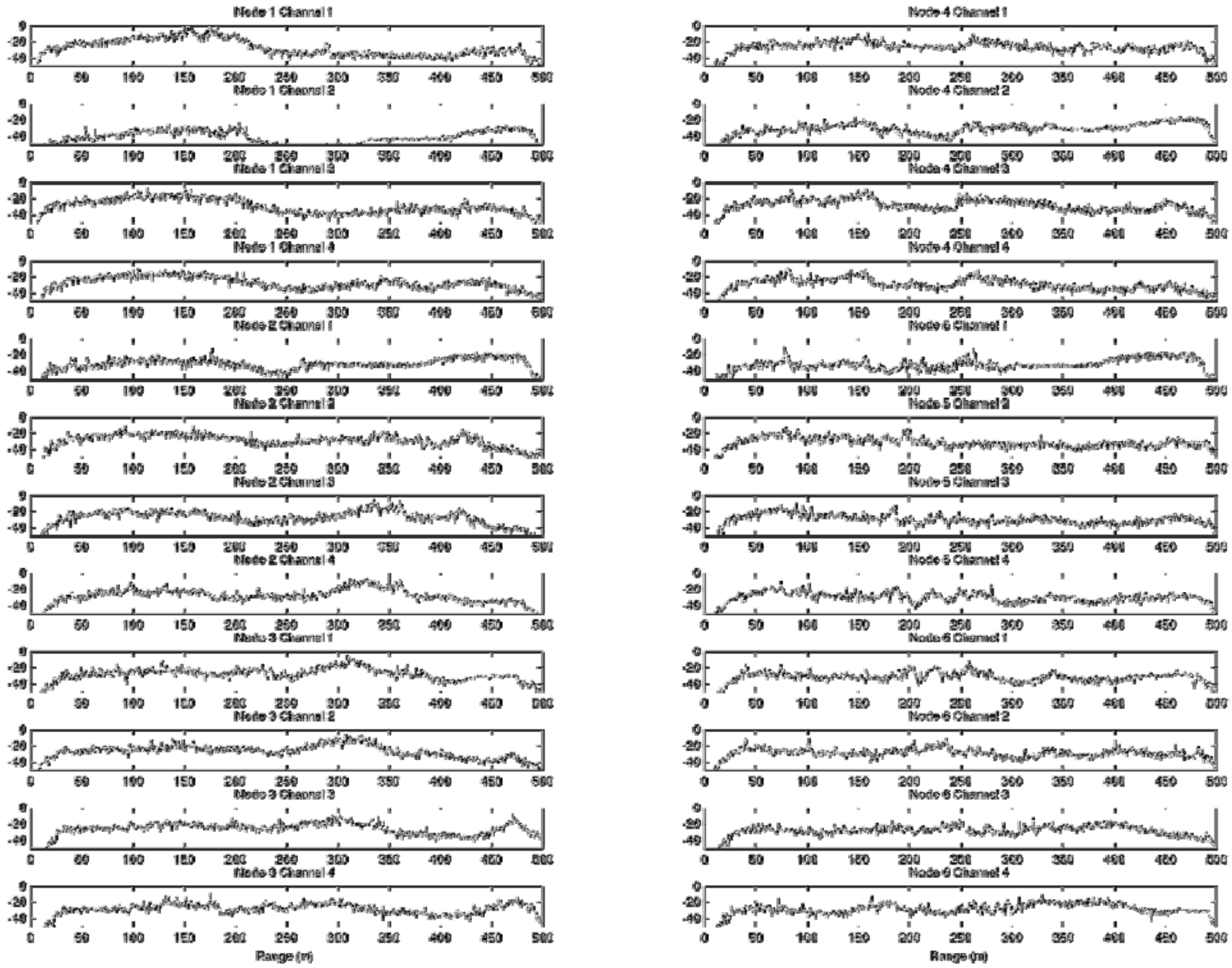


Figure 11: Example A-scan data for a single ping for all node channels. These plots are the effective target strength (vertical axis, dB re 1µPa @ 1m) as a function of range.

4.4.2. Towed Synthetic Target Tracking

The towed synthetic target tracking exercises assess the performance of the detection and tracking algorithms and parameters for a marine mammal-like target strength object. The data is also collected and archived so that it can be reprocessed at a future date with new algorithms or parameters to quantify improvements in the signal processing. Synthetic targets are designed to have a target strength similar to the object of interest and allow controlled trials where the target passes through the SDSN monitoring region at a known time and with a known path, as recorded by a handheld GPS.

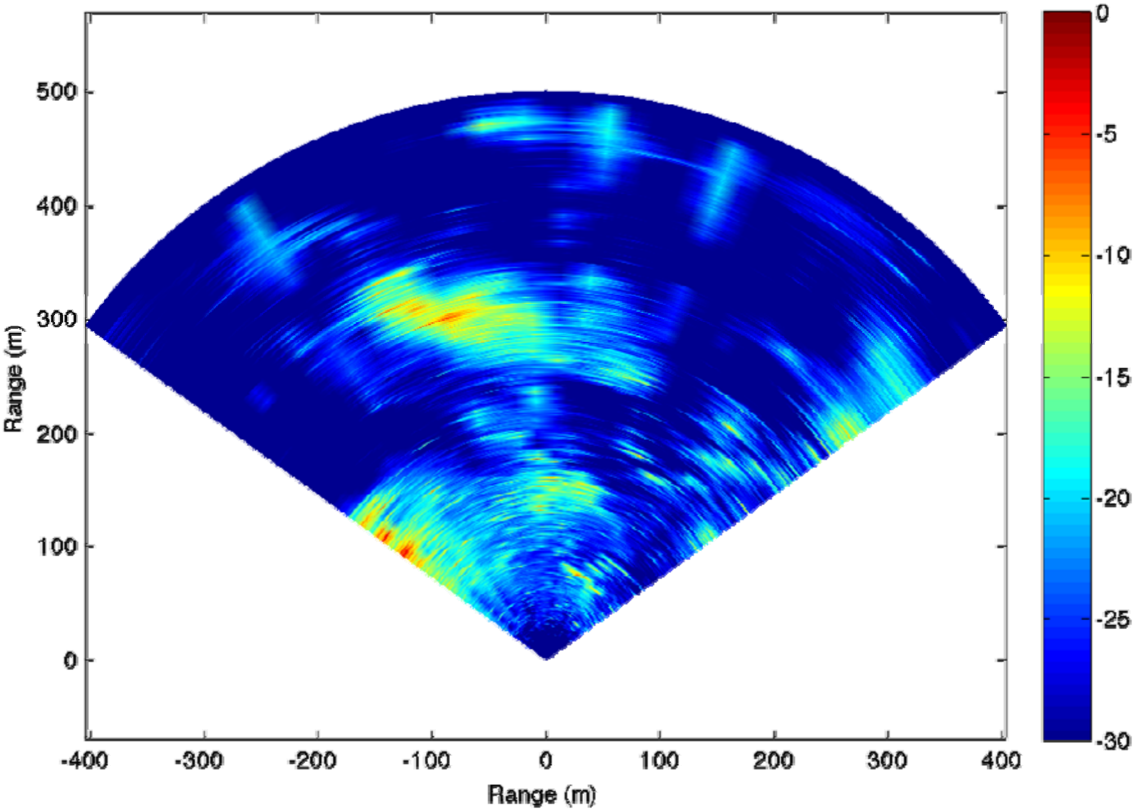


Figure 12: Example B-scan data for ten averaged pings for all node channels. The color level represents the effective target strength (dB re 1µPa @ 1m) as a function of range in each beam. Node and channel boundaries cannot be seen directly, however node 1 channel 1 is the leftmost and the 24 channels progress to node 6 channel 4 as the rightmost.

Figure 13 shows the large and small synthetic targets. The large target is the yellow corner reflector on the left with four counterweights attached to prevent it from rising in the water column. The small target is the silver sphere on the right. It is shown next to the float that the sphere hangs from so that it can be deployed ~ 50 meters from the boat itself.

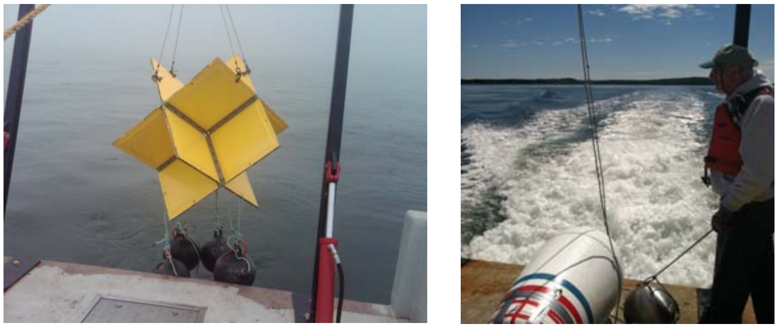


Figure 13: The high target strength (~0 dB re 1 µPa, left) and lower target strength (~ -10 dB re 1 µPa, right) synthetic targets.

Figure 14 is an example A-scan with the return from the large synthetic target (indicated with the black arrow). As expected the target strength is approximately 0 dB and has a very strong signal to noise ratio. Acoustic returns such as that seen in Figure 14 lead to individual detections from each ping, which in turn lead to the tracking seen in Figure 15. Figure 15 shows the real-time SDSN system tracking over time for three separate trials. On the left the trial began in the center of the SDSN cluster at 500 m range and drifting in toward the node. In the center example the trial began on the left side of the monitoring region and moving mostly across and somewhat out from the cluster location. On the right, the trials started a bit less than two hundred meters from the cluster and moved out.

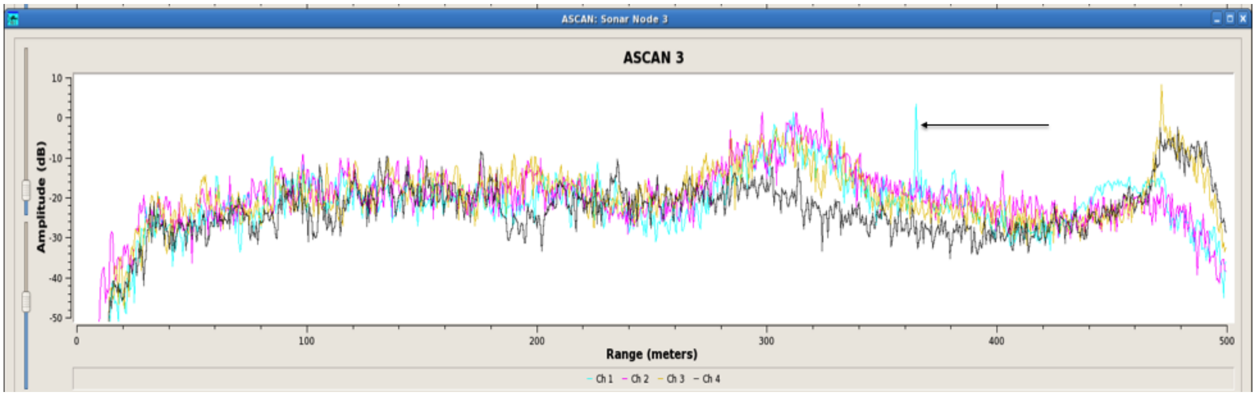


Figure 14: A-scan with the return from the large corner reflector synthetic target (indicated with the black arrow).

The progression from blue to green to yellow and to red on each track is the progression of the system confidence that it is tracking something real. In general blue is low confidence and does not appear on the screen unless the track reaches a higher level of confidence. At that point the full track including the early low confidence portion is shown. In an anti-swimmer application, yellow or red would typically indicate a response point. For the MHK application this could also be used as part of a decision-making scenario by an operator, or simply used as a threshold to limit how much information (*e.g.*, how many tracks) is shown to the operator. The important result for this test is that the system was able to detect and track in this environment, at this frequency, for ranges up to 500 meters. It is also important to note that there are no other red or yellow tracks at the same time, *i.e.*, there are no nuisance tracks or alerts.

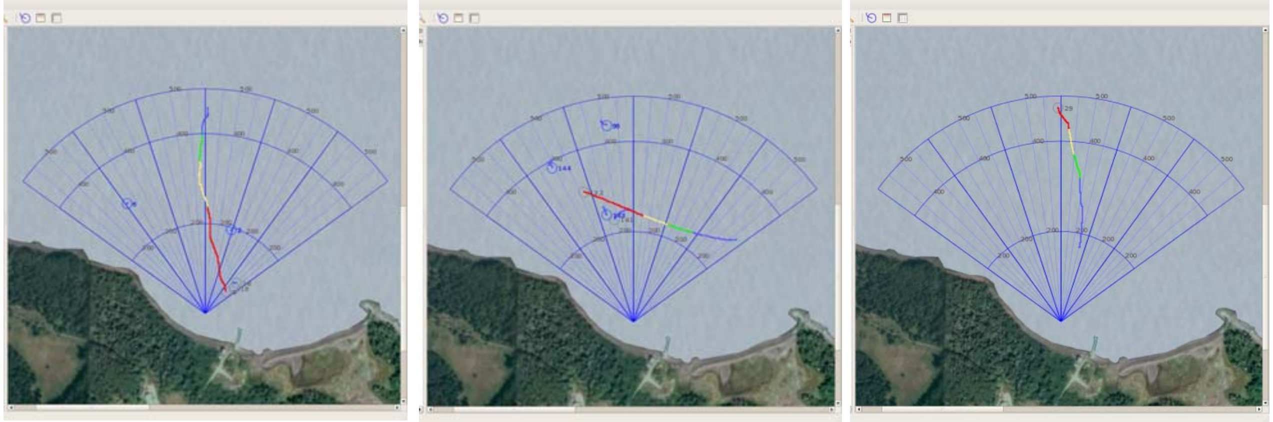


Figure 15: Real-time SDSN system tracking for three separate trials using the large synthetic target.

Figure 16 shows an example A-scan with the return from the smaller synthetic target (indicated with the black arrow). As expected the target strength is approximately -10 dB and also has a very strong signal to noise ratio, and examples of the tracking are shown in Figure 17. The smaller target tracking results are shown in the post-processing display so that ground truth information can be shown.

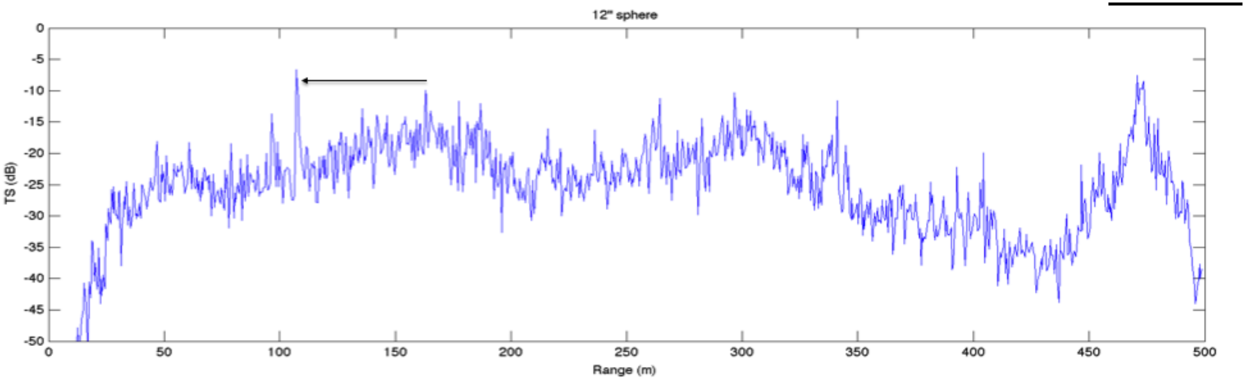
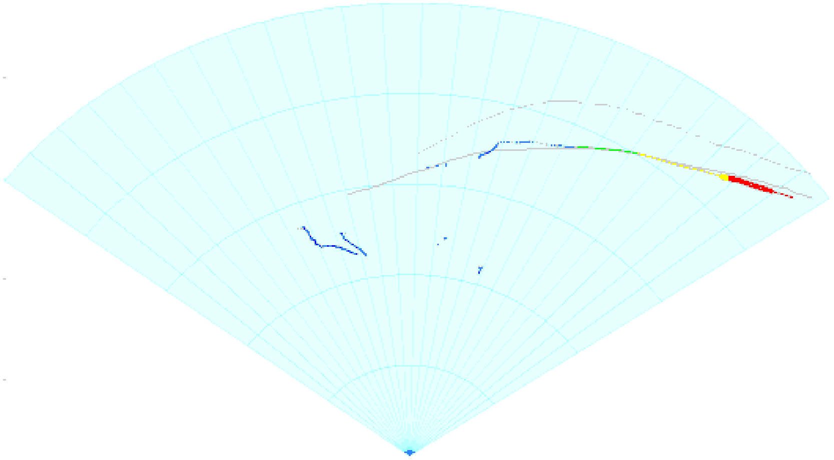


Figure 16: A-scan with the return from the smaller synthetic target (indicated with the black arrow).

The black lines in the plots in Figure 17 come from the ground truth data of the handheld GPS attached to the float that supports the target sphere. The magenta lines are from GPS units on the boat itself, showing the ~50 meter offset and demonstrating that the tracks are of the target sphere and not the boat itself. The results highlight that the tracking is more intermittent with the smaller, weaker target.

Although not shown in Figure 15 because it is the live display without ground-truth overlay, the large target tracks occur from very near the start of the trial and continue through the end without breakage. The top plot of the smaller sphere tracking shows that the sphere drifting for a couple of hundred meters before the system began tracking. In the plot on the bottom, tracking began fairly close to deployment, however after reaching the green level of confidence there is a gap and track appears blue again. This indicates that the old track died and new track began and therefore there was a period of time where the system was not tracking. There is also a further gap and track break after the second blue track before a new and final track starts that does track strongly enough to reach the higher levels of green, yellow, and red confidence.



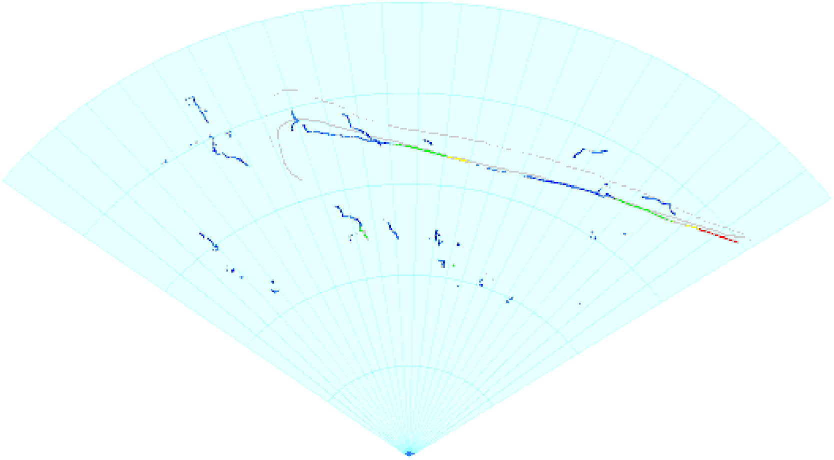


Figure 17: Reprocessed SDSN system tracking for two trials using the smaller synthetic target. Each ring represents 100 meters.

These results are consistent with expectations for a lower target strength object. The tracking results, while not perfect, are encouraging and suggest that higher current is not substantially impacting the SDSN detection and tracking performance in this environment – for objects that travel in nominally straight line segments. The SDSN system will track movements that curve or change direction (as seen in the trial plots), however the existing kinematics that are based on human diver targets do make assumptions regarding the velocity and acceleration limits those divers can perform and the extent of those curves and course changes. It is probably a good assumption that a number of species have different movement capabilities as compared to a human diver. Therefore, further algorithm and parameter modifications will be required to tune and test the performance against an AAM dataset that includes actual marine mammal kinematics.

4.4.3. Moored Synthetic Target Measurements

Moored synthetic target measurements can provide insight into variability of target returns ping-to-ping which can impact detection and tracking. This may be especially important in an environment with substantial currents, tide changes, weather, multipath, and other environmental variability. Figure 18 shows before (left) and after (right) B-scan data for the moored synthetic targets, averaged over ten pings for each plot. The 12” synthetic target sphere (~ -10 dB) was moored 5 meters off of the bottom at 110 meters from the cluster and is highlighted with the black arrow in the plot on the right. A smaller, 6” sphere (~ -15 to -20 dB, not used in towed target trials) was moored at a similar depth at 60 meters range and is highlighted with a white arrow.

Figure 19 through Figure 21 show the variability in the acoustic return and associated apparent target strength as a function of time. The top plot in each figure is the target strength as a function of time in the node and channel where the target should be moored. The middle plot is the range location of the peak target strength in a 10 meter window around the expected location. The bottom plot is the tide height as a function of time during the capture of the top two plots.

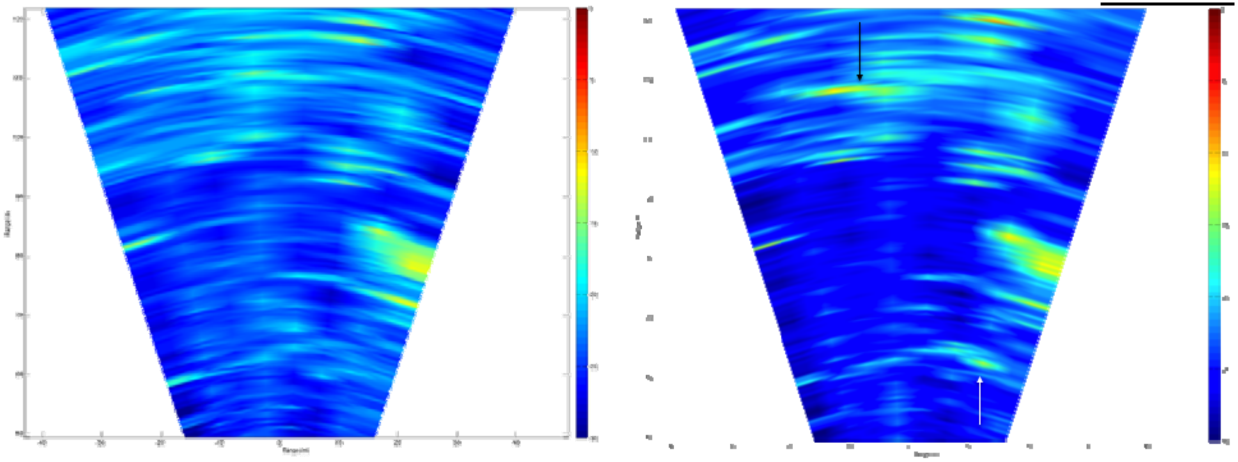


Figure 18: Before (left) and after (right) B-scan data for the moored synthetic targets averaged over ten pings.

For each top plot, the expectation would be a lower background level prior to target deployment and a higher level as the return comes from target. This is seen in the top plot of Figure 19 where the return is lower (~ -18 dB) for the first few minutes prior to deployment. There is a spike as the boat comes in and moors the target, followed by over two hours where the returns are higher (avg. ~ -10dB) while the target is present.

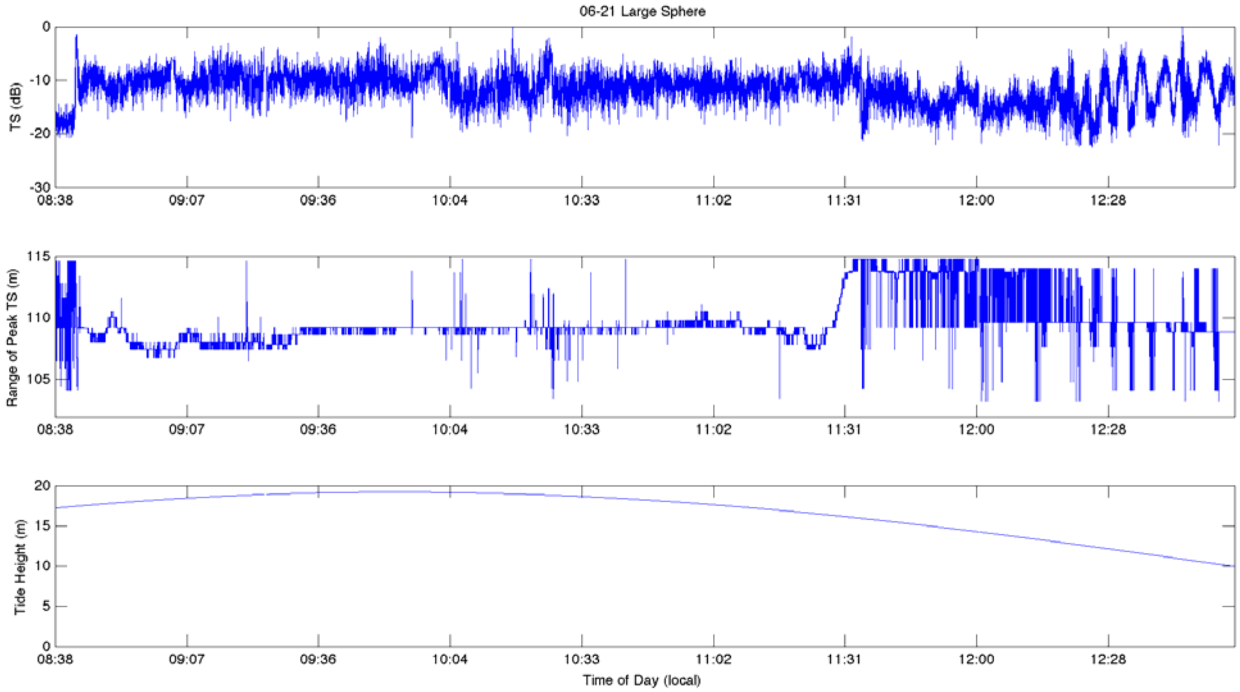


Figure 19: Variability of returns from the moored 12” target sphere as a function of time for the initial channel where the sphere was deployed.

At just after 11:30 AM the tide has dropped enough that the combination of the slack in the line and the tidal flow allows the target to wander in and out of the channel resulting in the drop in response and oscillations shortly after 11:30. Figure 20 shows the same time period of the adjacent channel. Here, the response in the top plot is relatively low, due to just the ambient background, until shortly after 11:30 at which point the target drifts into the channel, raising the return and eventually oscillating back and forth between the channel in Figure 19.

The middle plot helps to confirm the presence of the moored target where it is expected. For random background clutter one would expect the location of the peak return in an arbitrary 10 meter window to be similarly random, unless there are specific features present in the bathymetry. However, when a strong target is present at a relatively fixed location the peak return should arrive from a relatively fixed location.

This can be seen in Figure 19 and Figure 20 where the middle shows a maximum response throughout in the 10 meter through the first few minutes. The target is then deployed and peak response is at a relatively fixed location in Figure 19. The randomness continues in Figure 20 until the slack allows the target to drift into that channel at which point the roles are reversed.

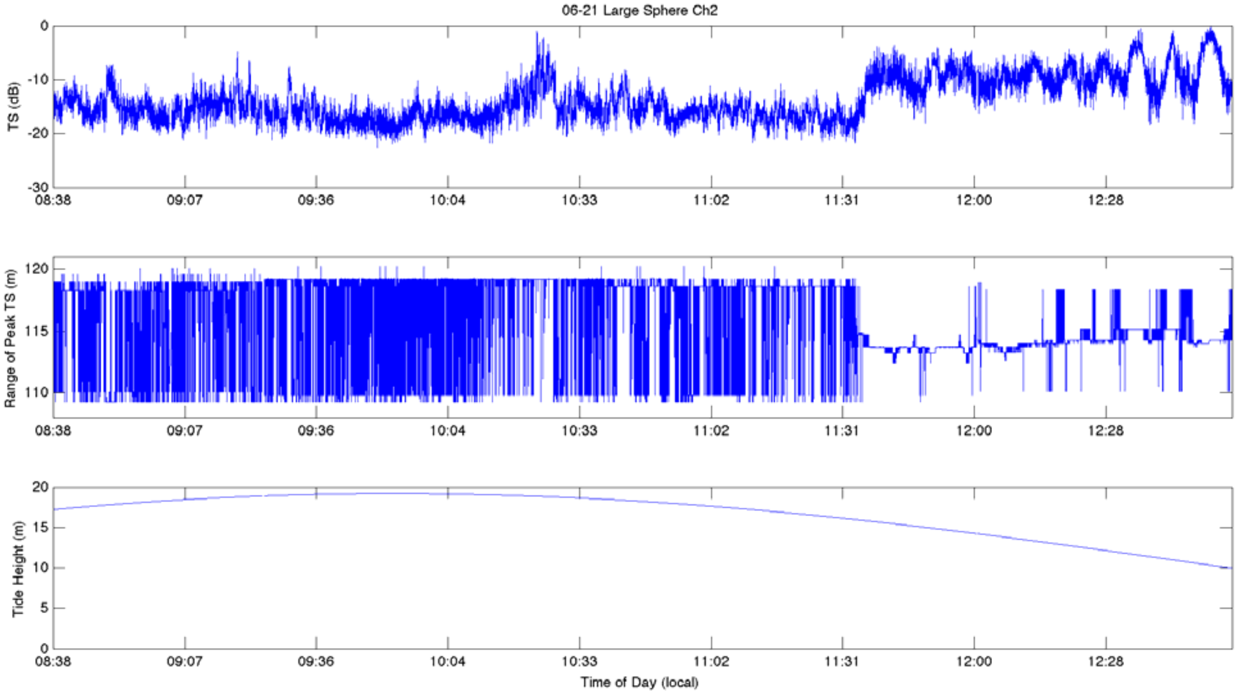


Figure 20: Variability of returns from the moored 12” target sphere as a function of time for the channel where the sphere moved due to slack as the tide fell.

These plots highlight two important features. The first is the variability in the apparent target strength of the target seen in the top plot. Although the average value is consistent with what is expected, the ping-to-ping value varies, and as seen from the middle plots is not always the peak value. The second is that the variability in the background clutter means the target is not always the strongest return, even in a small window just around the target, as seen by the data points in the middle plot that appear as spikes away from the general trend. These can present challenges in the detection and tracking. However, the overall consistency seen in the middle plots suggest that any additional variability due to higher currents may be sufficiently low.

Figure 21 illustrates the same phenomena for the smaller 6” synthetic target sphere. The difference here is the lower target strength results in greater variability in the middle plot as it is more likely that background clutter can rise above the target strength of the target on any given ping.

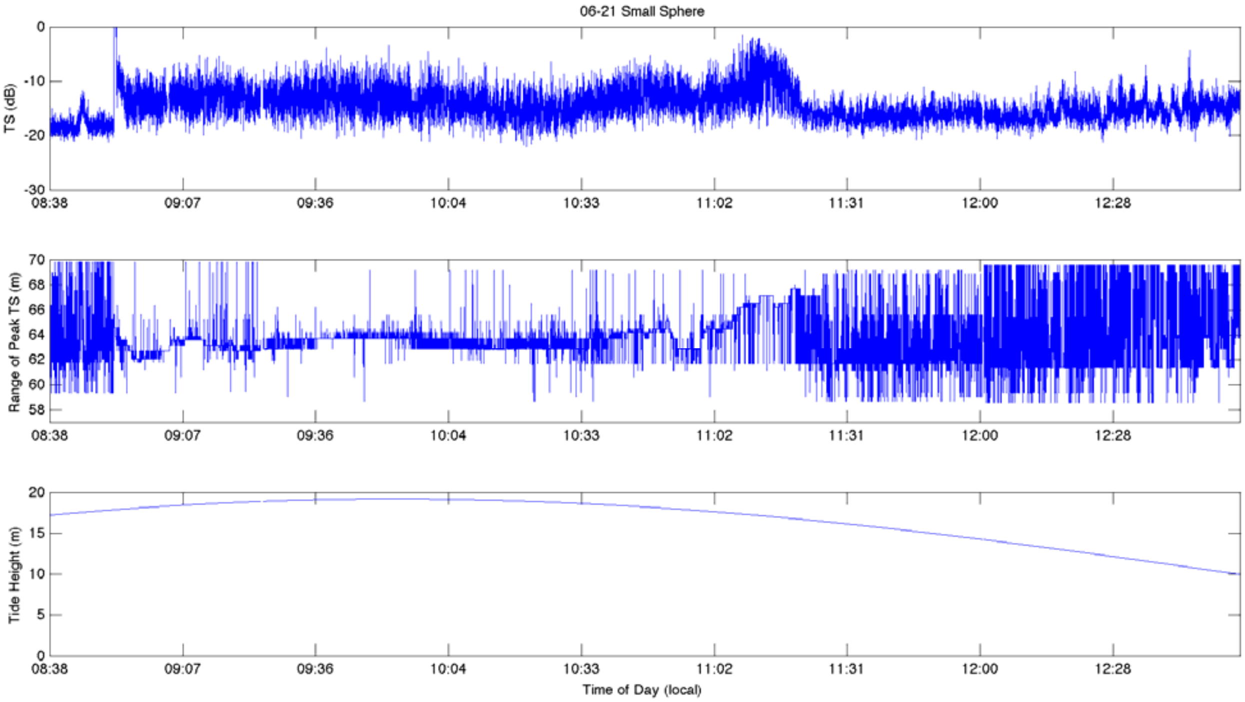


Figure 21: Variability of returns from the moored 6” target sphere as a function of time for the initial channel where the sphere was deployed.

4.4.4. Nuisance Track and Alert Data

Nuisance track and alert data is used to assess the number of tracks and alerts that are not actual objects of interest. A system with too many nuisance alerts may be impractical for mitigation or decision-making. For a permanent deployment site this data is often collected over a period of 24 continuous hours for daily variations as well as over a period of 2-4 weeks for 1 hour per day. Due to time constraints, and the requirement for marine mammal observation in daylight hours, the data here was collected over a single 4 hour time period. Although it does not represent the results over a variety of conditions at this site, it does provide insight into nuisance alert behavior.

Figure 23 shows all tracks generated by the SDSN system for a 4 hour period of continuous operation, including very low confidence (blue) tracks. A positive result would generally involve a moderate level of low confidence tracks (typically indicates that the sensitivity should be sufficient for detection of targets above the background level) with as few reaching a yellow or red confidence level, which can be interpreted as nuisance alerts.

For the 4 hour period shown here one track reach the nuisance alert level. It is possible that this track was not a nuisance alert and represented a real object, such as debris, marine mammal, or school of fish. However, in the absence of an observation otherwise it is assumed to be a nuisance alert. This result would translate into a nominal value of 6 nuisance alerts per 24 hours if we can assume that the 4 hour window was a representative sample of typical conditions. It may have been an exceptionally low or high period nuisance alert activity, however that can only be definitely established through long-term data collection as described earlier. Although it is always desirable to minimize these nuisance alerts, all active acoustic systems generate nuisance alert – the question is typically whether the number is manageable. The demands for a system or operator to react to 6 in a 24 hour period is unlikely to be high.

This is encouraging as these results are using the same setting and parameters that resulted in the positive synthetic target tracking shown earlier.

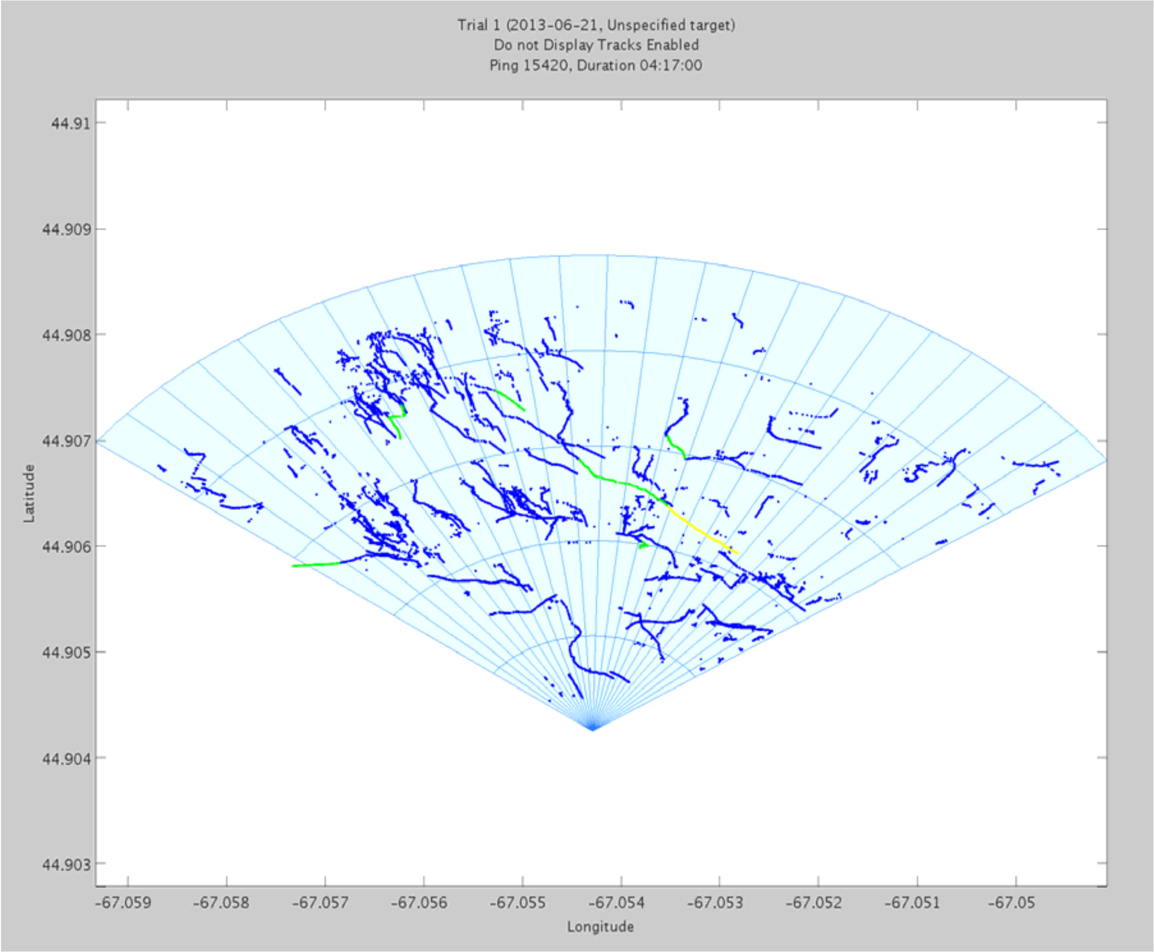


Figure 22: All tracks generated by the SDSN system for a 4 hour period of continuous operation, including very low confidence (blue) tracks.

4.4.5. Marine Mammal Sightings and Associated Tracking

The primary objective of this effort was the design, development, deployment, and testing of a high-frequency SDSN system in a realistic MHK environment. An associated goal was that the timing of the system operation and data collection would coincide marine mammal activity in the monitoring region. This would have provided an initial dataset of known and observed marine mammal activity with the G2HF system.

Figure 23 shows the monitoring region of the SDSN system and marine mammal observations during operation for the entire week of deployment. In most cases marine mammals were observed outside of the monitoring region or in a few cases within the region while the system was not operating (marine mammal observation occurred during pre- and post- operation periods per the NMFS Letter of Concurrence).

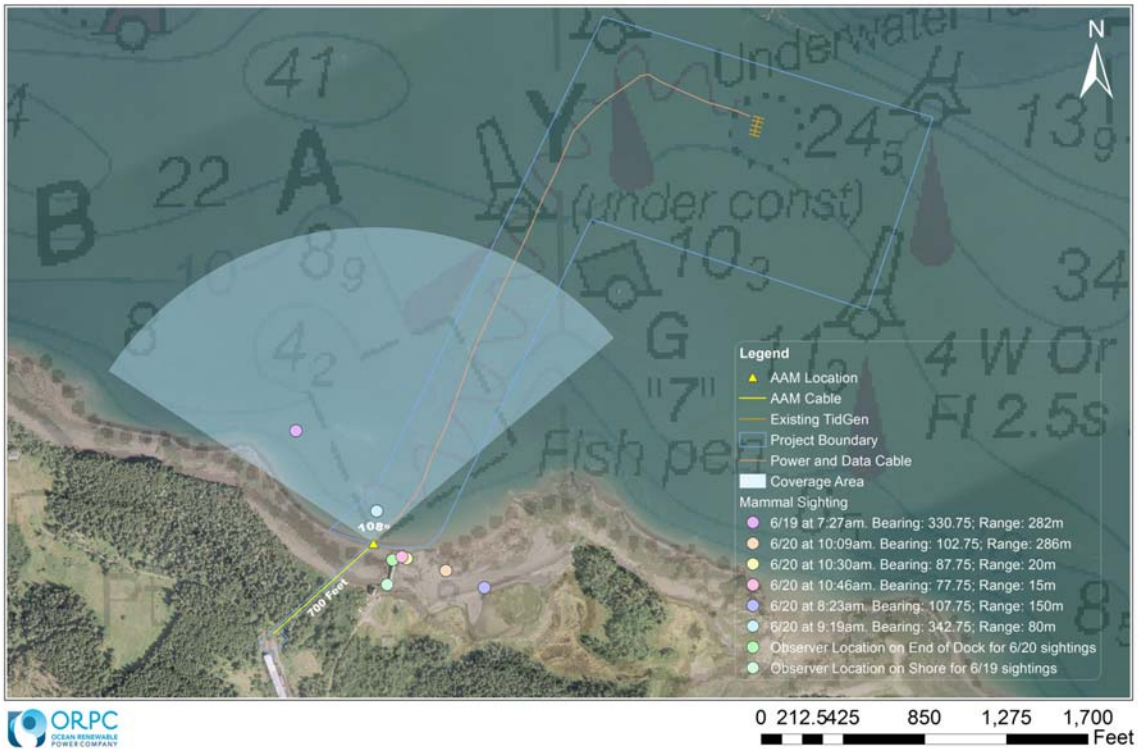


Figure 23: Marine mammal activity observations during system deployment.

In two instances there were singular observations of marine mammal activity in the monitoring region while the system was operating. Analysis of the data did not show tracks in the associated region that could be definitively associated with the observations. There are several possible reasons for this:

- The system tracks movement and animals may be been largely or intermittently stationary while the system was operating.
- Observations were relatively close to the edges of the monitoring zone. If the animal directly exited the region it may not have been tracked.
- Due to range-bearing uncertainty in the visual observations, a track may have existed but not been definitely associated during analysis due to the error in location.
- The system may have failed to track the animals, particularly these small harbor seals.

This result speaks to the need to conduct tests where these is a much higher level of marine mammal activity. Only by doing this will we be able to properly assess and improve the detection and tracking performance of the SDSN system for marine mammals. The synthetic target results strongly suggest detection and tracking is possible, and even likely if the system is optimized for the movement behavior of these mammals, however that movement behavior must be observed and quantified in the context of acoustic returns.

4.5. Additional Issues

In addition to the deployment challenges, the following items were the major issues encountered during the project:

- NEPA approval and associated delays
- Delays in the TidGen™ deployment
- Delays in transducer delivery from ITC
- Cost of the mounting bracket for SDSN connection to TidGen™

These issues did not ultimately impact the objectives of the project other than restrict the available deployment and testing calendar to a very limited time window.

5. ACCOMPLISHMENTS

5.1. System Design, Development, and Delivery

A six-node, G2HF SDSN system has been tested and delivered to the Ocean Renewable Power Company. This system includes all subsurface and topside hardware required for additional deployments and testing or operation.

5.2. Data Collection

All data collected during the June 2013 has been archived and is available for further analysis. This includes ambient conditions, synthetic target tows (large and small mammal equivalent), and fixed target data collection.

In addition, all data collected during the G2HF prototype testing conducted under SSI internal funding in May 2011 has been archived and could be made available if beneficial to the further analysis of the June 2013 data.

5.3. Publications and Conference Proceedings

The following publications, conference proceedings, and presentations were specifically focused on the Eastport system and testing or included information from those tests or the G2HF system development:

- P. Edson, P.J. Stein, N.A. Rotker, "Marine life detection and tracking using a swimmer detection sonar network," J. Acoust. Soc. Am. 128 (4 pt. 2), 2333 (2010).
- P.J. Stein, "Development of Active Acoustic Monitoring (AAM) for Marine Mammals around MHK Devices," FERC and DoE MHK Environmental Seminar, (2013).
- P.J. Stein, P. Edson, "Active acoustic monitoring of aquatic life," 3rd International Conference on the Effects of Noise on Aquatic Life, Budapest, Hungary (2013).
- P.J. Stein, P. Edson, "Active acoustic monitoring of aquatic life," in "The Effects of Noise on Aquatic Life II," A. Popper and A. Hawkings (Eds.), Springer (Forthcoming 2014).
- P. Edson, P.J. Stein, "Practical applications of track segment association algorithms to an active sonar network for underwater port surveillance.," 166th Meeting of the Acoustical Society of America, San Francisco, CA (2013)

6. CONCLUSIONS

Although it was necessary to choose an alternate installation location for the SDSN system, this effort resulted in a very successful development and deployment of the SDSN detection, tracking, localization, and classification in a high current, MHK environment. The new, high frequency node that operates outside the hearing range of many marine mammals was shown to detect and track objects of marine mammal-like target strength to ranges of approximately 500 meters. This range allows the system to track objects for a significant duration, potentially allowing time for MHK system or operator decision making if marine mammals are present. A significant remaining hurdle is the development of DTLC algorithms for the specific kinematic behavior of marine mammals as opposed to human divers for which the SDSN system was originally designed.

Commercialization of the SDSN technology for MHK applications would require a significant investment. The SDSN system itself will require some level of productization to allow it to be an off-the-shelf option for MHK installations. This would include improving the deployability, maintainability, and speed of manufacture. It would also require some form of standardization or common use case with respect to a typical MHK installation to define installation requirements and have those installations prepared to accept an SDSN system for mounting and cabling. In the interim, however, it is quite conceivable to manufacture individual SDSN specific installations or applications as the industry matures.

7. RECOMMENDATIONS

The primary recommendation of this report is for further testing at a site with more frequent marine mammal activity. Performing the initial testing that was a part of this effort in Cobscook Bay, Maine was an appropriate choice for this phase of development. It allowed for testing in a realistic MHK environment with the potential for marine mammal activity, but with a low enough likelihood, particularly for endangered species, that long periods of operation within the limits of the NMFS letter of concurrence were practical. These long periods were necessary to determine system viability in these high current environments and to perform the synthetic target data collection. However, as described below, substantial data collection with actual marine mammals is a major component of tuning the system for marine mammal DLTC.

The additional recommendations below are intended to both improve the SDSN system individually, as well as develop a more comprehensive system for detecting and monitoring marine mammal activity near MHK installations or during MHK installation.

7.1. Further Studies with Marine Mammals

Having demonstrated the system’s ability to detect and track synthetic targets in this environment, the next logical step is to collect data where marine mammal activity is frequent and reasonably predictable (insofar as it can be) such as that data collection times can be chosen with some reasonable likelihood that marine mammal activity will be captured on the system. The step is essential for development of the signal processing algorithms and parameters. Larger marine mammals (i.e., whales) would likely lead to a better first dataset as the high target strength increases the likelihood of detection and the opportunity to evaluate and modify the tracking algorithms for kinematics that can be reasonably expected to be different from human divers. A subsequent dataset would likely involve smaller marine mammals whose movement capabilities and kinematics will be substantially different. Although difficult, but feasible to permit, we would suggest testing against either right whales in Massachusetts Bay or Nova Scotia, or beluga whales in Alaska since protecting these animals, in particular, is of primary importance.

The data collected with the synthetic towed targets was important as it allows us to verify the detection and tracking for a target of similar target strength to marine mammals in an MHK environment in a controlled manner. However, a towed synthetic target is not likely to have the same kinematics as a marine mammal. In addition, the signal characteristics used for classification will be significantly different for real marine mammals, as well as between different species of marine mammals, and between marine mammals and other entities such as debris and schools of fish.

The primary deliverable of this type of effort would be a more comprehensive dataset than could be acquired in Cobscook Bay, one that could be used for modifying and tuning the existing signal processing algorithms and parameters for marine mammal tracking.

7.2. Deployment in Additional Relevant Locations

One motivation for deployment in additional locations is to obtain data with greater marine mammal activity, as described above. However there are other reasons to seek additional deployment opportunities. Although the Cobscook Bay site is a “characteristic site” in that it has high tidal flows suitable for MHK installations, the specific bathymetry, environmental parameters such as sound velocity profile, and other features may vary significantly. The effects of these variations (possible degradation or variation in system performance) have been observed in the anti-swimmer applications of SDSN-type technology and would most likely be applicable in the MHK context as well. Techniques that are used in a moderately sheltered anti-swimmer environment such as a harbor with piers and breakwaters may or may not be applicable in the high current environments of MHK installations.

7.3. Integration with Additional Sensors

The SDSN system can provide coverage for the subsurface activity of marine mammals near MHK installations. As with all detection and tracking systems, the SDSN system will have less than 100% detection and tracking (missed targets) as well as some number of nuisance alerts (tracking of objects that are not of interest or do not exist, such as surface wave action). One method to improve performance, as well as provide detection or observation of additional objects or behaviors, is to integrate surface sensors as an additional data source.

Surface sensors, such as visual or IR camera, could provide an additional opportunity to detect marine mammals at the surface. These detections can then be fused with the subsurface detections before passing to the integrated tracker. This could be beneficial as the weakest detection region for the SDSN system is often at the surface particularly when surface wave action is high. Much as the SDSN performance can be improved by fusing information from multiple SDSN nodes at different locations, performance may also be improved through integration with these additional surface sensors given that the objects of interest are known and expected to breach the surface.

7.4. Further SDSN Development

Beyond capturing specific marine mammal activity for signal processing tuning and improvement, as described earlier, there are a number of avenues for improving the SDSN system for MHK applications.

7.4.1. Long Term Deployment

This effort was successful in determination that the SDSN system can operate and provide a level of DLTC performance in a high-current MHK environment that is comparable to what has been demonstrated for more quiescent environments. However, the deployment was limited to less than a week and the location was changed from a direct installation on the MHK device where it would be directly in the tidal flow and in line with MHK device. A long term evaluation of the system in that context would be beneficial.

7.4.2. Long Term Data Acquisition

Collecting long-term ambient data is nearly as crucial as collecting actual marine mammal activity for algorithm development and parameter tuning. In most locations subsurface conditions that affect sonar performance change on time scales ranging from hours to seasonally. In addition, debris fields, schools of fish, and the marine mammal activity itself will vary.

7.4.3. General System Development

Based on the experience in this effort, a number of aspects of the SDSN system would likely benefit from further evaluation, design, and development for MHK applications.

For hardware/installation a primary consideration should be to reevaluate the integration and installation with the MHK device. Although the difficultly in installing in this environment was anticipated and a number of measures taken to mitigate the difficulty, further refinement to the installation to allow for a more modular installation (and replacement if needed for repair, etc.) and underwater mating or other solutions to simplify the process is likely necessary for future deployments.

Additional efforts could also include preparing the system software and network infrastructure to integrate other sensors and data as described in section 7.3. Although it may be unclear at this time which sensor path or paths may yield the biggest benefit in terms of overall system performance, it is clear that additional information can only aid in DTLC performance and/or system or operator decision making.

8. REFERENCES

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