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Overview of the technical results of the Northern Watch Project

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Abstract

This report constitutes a final deliverable of the Emerging Operational Domains—Arctic, or more familiarly, the Northern Watch (NW) project. The report provides a technical overview of the project, the objectives, and our progress toward meeting those objectives. The report describes the motivations, concepts, and history of the work effort. The sensors, the processors, and operation of the NW Surveillance System are also described. The capabilities of the system and its short falls are illustrated.

Overall, the NW project was quite successful and most of the short falls have arisen because the costs were beyond the reach of the project funding and; hence, had to be simulated or otherwise adapted to the realities of the situation. Although the project can be considered successful, considerably more work is required to bring an autonomous/remote-controlled multi-sensor surveillance system to practical reality. The report provides lists of accomplishments, risks/lessons learned, short falls, and future improvements to guide future efforts.

Significance for defence and security

The NW project and the results presented here are intended to inform on Capability Gap Identification for Arctic Surveillance. The NW project describes progress toward automated and eventually un-manned surveillance of remote sovereign territories. It illustrates current capabilities in systems and identifies areas where additional effort and research is required.

Résumé

Le présent rapport constitue un livrable final des domaines opérationnels émergents dans l'Arctique, mieux connus sous le nom de projet Surveillance du Nord. Il donne un aperu technique du projet, des objectifs et des progrès réalisés pour atteindre ces objectifs, en plus de décrire les motifs, les concepts et l'historique du travail. Les capteurs, les processeurs et le fonctionnement du système de surveillance du Nord y sont également décrits. Les capacités et les lacunes du système sont illustrées.

Dans l'ensemble, le projet Surveillance du Nord a été assez bien réussi et la plupart des lacunes sont apparues en raison des cots excédentaires pour le financer. Par conséquent, il a fallu le stimuler ou l'adapter à la situation réelle. Bien que le projet soit considéré comme un succès, il reste encore beaucoup à faire pour ramener un système de surveillance multicapteurs autonome ou télécommandé à la réalité pragmatique. Le rapport fournit une liste des réalisations, des risques, des leons retenues, des lacunes et des améliorations éventuelles afin d'orienter les efforts à venir.

Importance pour la défense et la sécurité

Le projet Surveillance du Nord et les résultats présentés visent à fournir des renseignements sur la détermination des écarts de capacités pour la surveillance de l'Arctique. Le projet décrit les progrès réalisés afin d'obtenir une surveillance automatisée et, en définitive, télécommandée des territoires souverains éloignés. Il illustre les capacités actuelles des systèmes et cerne les domaines qui exigent une recherche et des efforts additionnels.

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1 Introduction and background

Defence Research and Development Canada (DRDC) has been working on a demonstration project of Arctic surveillance for the past eight years. This project was originally called the Northern Watch Technology Demonstration Project, or NW for short. Recently, the name of the project changed to reflect program changes and it is now called 'Emerging Operational Domains—Arctic'. For simplicity we will use NW to refer to the project in this report.

Initially, the project was defined by a steering committee and subsequently approved by DRDC senior management and Canadian Armed Forces (CAF) clients. The initial plan for the project was to demonstrate surveillance capabilities for short intervals of time each year at an Arctic choke-point for traffic transiting through the Queen Elizabeth Islands. This demonstration plan allowed for the build-a-little-test-a-little concept as our capabilities evolved over time. The desired demonstrations evolved as time progressed, but so also did the difficulties, staffing, and budgets. The end result has been largely successful, but there have been some short falls in the objectives.

1.1 Project objectives

The objectives of the NW project also evolved during the lifetime of the project. The final set of objectives, paraphrased from the latest project documentation are [9]:

1. Develop and demonstrate a capability to conduct up to 365 days, 24/7 persistent local area surveillance of air, maritime surface, and sub-surface objects in the Canadian Arctic.
2. Develop and demonstrate concepts of integration, resource management, and employment of sensor systems at an uninhabited site.
3. Develop and demonstrate a capability to operate sensor systems remotely.
4. Develop the underwater array technology required to be deployed in the Arctic environment and be monitored remotely.
5. Develop the capability (within DRDC) to conduct scientific research in an Arctic environment.
6. Inform Capability Gap Identification for Arctic surveillance.

1.2 Motivation

Motivation for the NW project is readily apparent from science publications on Arctic climate conditions, news reports, and the need for the CAF to exercise surveillance over a portion of the Arctic for defence, safety, and security.

Many scientific publications have appeared in press that point to a change in the climate that may be in response to mankind's use of fossil fuels and the release of pollutants that serve to alter the thermal balance on a global scale. Whatever the actual cause of climate change, it is clear that ice conditions in the Arctic as a whole are changing. Both the Arctic Ocean and the channels of the archipelago are experiencing a reduction in the thickness, areal coverage, and duration of total ice cover. An often quoted example of this reduction in Ice Extent is provided by the US National Snow and Ice Data Center [1]. Figure 1 shows the decrease of ice extent in the Arctic Ocean over the period 1978–2015 during the month of November [1]. Similarly, Figure 2 shows the reduction in ice thickness as derived from satellite observations over the period 2004–2008 [2].

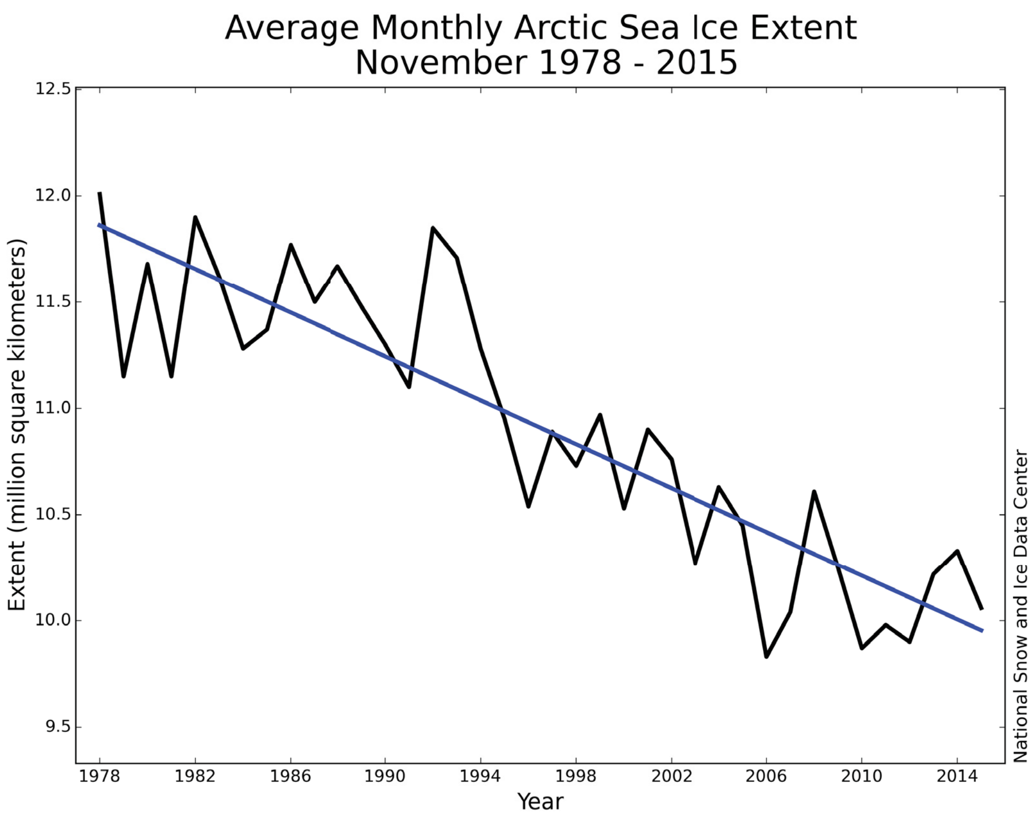

Figure 1: *Ice extent in millions of square kilometres versus time in years. National Snow and Ice Data Center [1].*

There is no doubt that total ice volume in the Arctic is reducing. With this reduction in ice comes the opportunity for the transit of vessels where this was previously dangerous, difficult, or practically impossible. Although the ice coverage of the Arctic is reducing, we can expect winter-time ice cover for many more years, but summer-time conditions are likely to change more quickly. During our own field experiments

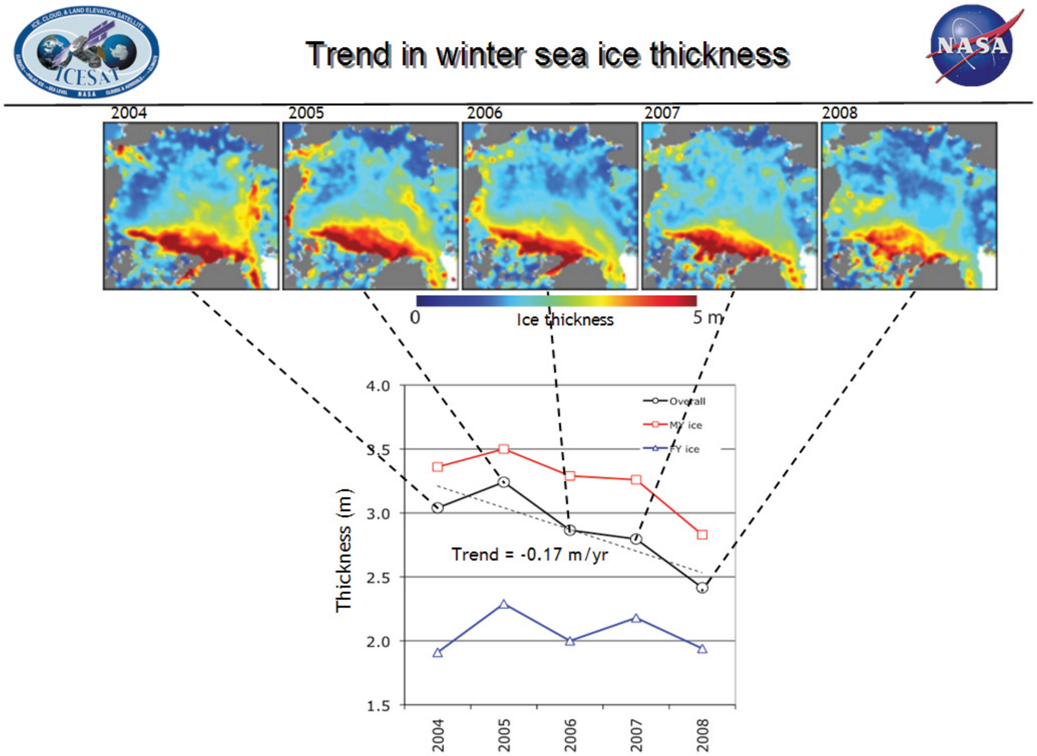

Figure 2: *Map showing the reduction in ice thickness in the Arctic Ocean over a five-year period 2004–2008 [2].*

we have seen changes in the vehicle traffic in the archipelago. Where once there was the odd eco-tour, due to reduced ice in summer there are now regularly scheduled trips by numerous cruise ships, growing numbers of adventure sailors, and industrial vessels such as fishing boats and oil and gas investigations.

With greater levels of human activity comes an increased requirement for surveillance by the CAF to ensure that conditions of safety, security, and sovereignty are maintained. Multiple news media reports have included events such as the grounding of the cruise ship MV Clipper [10], foreign poachers on Ellesmere Island [11], and the Nordic Orion bulk carrier transiting the northwest passage enroute to Finland [12].

In the summer of 2015 between the dates of August 10 and September 11, we observed nine cruise ships (some with multiple trips), two large yachts, six adventure sailors, two cargo ships, one fishing vessel, and one Canadian Coast Guard vessel. In addition, the Canadian Naval ships MONCTON and SHAWINIGAN were operating in the area. During that same interval we detected one unknown vessel, which may or may not have been the MONCTON, transiting through the area. It is these unknown vessels that are of greatest interest and are a strong motivation for chokepoint surveillance.

Our desire is to detect, track, and classify these surface and sub-surface vessels in order to determine their origin and intent, to ensure safety, and to enforce Canadian laws and regulations as applicable.

1.3 Surveillance concept

The Arctic Archipelago is comprised of the islands north of mainland Canada and to the west of Greenland. The surveillance concept that has been considered in Northern Watch is the monitoring of key maritime chokepoints in the waterways of the Arctic Archipelago for surface and sub-surface objects (see Fig. 3). This is described as persistent, local-area surveillance—because 24/7 surveillance is being conducted in the local-area about a fixed location. As a secondary objective, it is also possible to conduct air surveillance of the local airspace surrounding the chokepoint surveillance site.

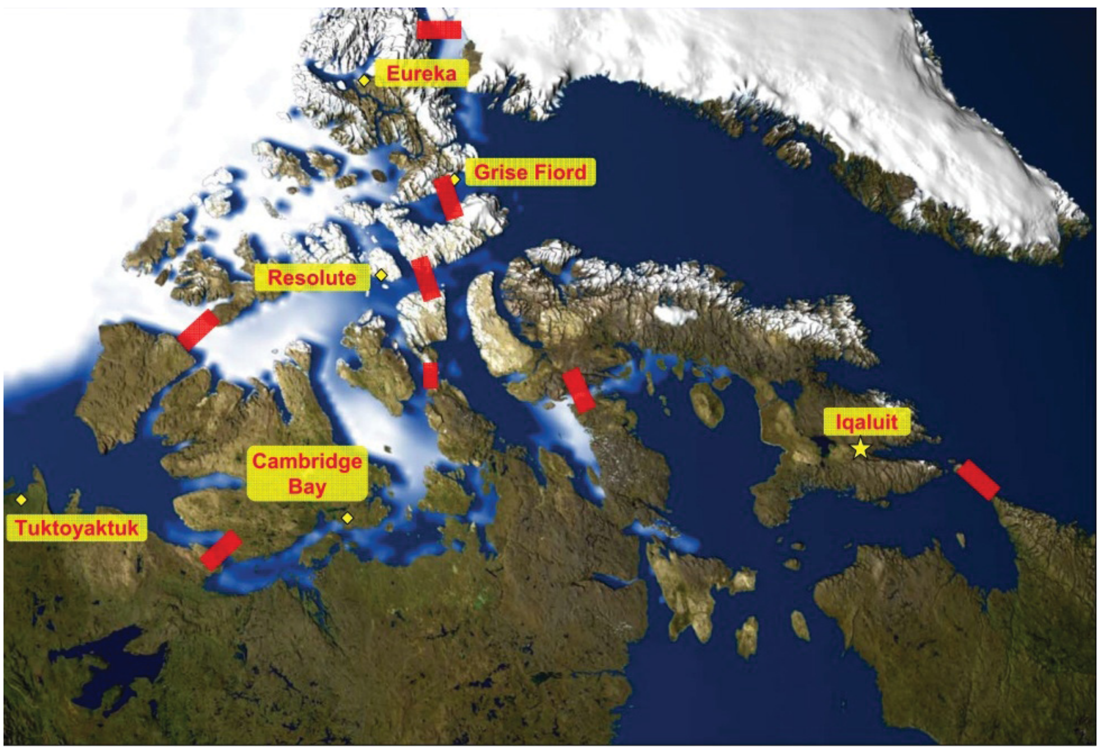

Figure 3: *Potential Arctic chokepoints. The site of interest for Northern Watch is just to the east (right) of Resolute. [3].*

Local-area surveillance complements the mobile, but more intermittent coverage provided by airborne or satellite-based wide-area surveillance assets, and can provide confirmation of information provided from self-reporting systems. With the use of bottom-mounted acoustic arrays, local-area surveillance provides a unique capability for monitoring the sub-surface domain.

1.4 History of the project

The NW project was first conceived of in 2006 and a working group was established to define the project scope and requirements. The concept derived from an enhanced interest in the Arctic that was apparent at the time.

In spring 2007, the project was approved and in July 2007 a project team visited Gascoyne Inlet, Devon Island, to assess it as a suitable location for the chokepoint demonstration. The decision was made to proceed with Gascoyne Inlet as the site of the experimental work.

In July-August 2008, the first field trial took place. This trial turned out to be very difficult. Weather conditions and very limited ship time prevented the deployment of the first underwater array prototypes and hampered all other activities as well. It also became apparent that working at the southern edge of the high cliffs overlooking the strait was problematic. A lot was learned, including practical matters of living in the Arctic such as the need for better accommodations, supply, transportation, and communications.

Following the summer 2008 field trial the NW project was halted. There were many concerns about the outcome of the project, safety, and even the project goals were questioned. The underwater (UW) sensors team was eventually given permission to continue development and to attempt to deploy the acoustic array prototypes.

In summer of 2009 the project resumed in a limited fashion allowing the UW sensor effort to continue alone [13]. The first task of this trial was to test the cable and repeaters deployed in 2008 to determine if they were still operable. The tests were a success. The cable and repeaters were functional after the year long stay on the sea floor. This time, the arrays were successfully deployed, but they began to fail within hours of deployment. A week or two of limited data were collected with the failing arrays before they were finally shut-off completely. The arrays provided a number of useful detections and did demonstrate the underwater sensor concept, but the failure of both arrays and the back-up array indicated a major problem.

One array and both telemetry cables from the 2009 deployment remained in the water until summer 2011, when they were recovered. Prior to recovery we tested the repeaters through the cables and found that both cables were fully functional.

Following the 2009 trial, work was conducted on what came to be known as the Habitat [14]. The Habitat was intended to be an unmanned shelter for the sensors and computers and be the source of persistent operating energy. Unfortunately, the cost of the Habitat and its fuel for a year-long operational period was deemed to be too great for the NW project to support. A decision was made in 2011 to stop work on the Habitat before it was constructed.

The next three years involved major project changes and eventually full project activities were restored in 2012. All aspects of the project had continued to evolve during the three to four years of review, but many sensors received only minor funding support during that interval. The UW sensors were completely redesigned and the electronic system was enhanced during this interval.

In the summer of 2012 a major field trial was conducted at Gascoyne Inlet [15, 4]. All above-water sensors were tested, including Automatic Identification System (AIS), navigation radar, radar intercept, electro-optical/infrared camera system, Automated Dependent SurveillanceBroadcast (ADS-B), and meteorological systems. A large amount of data was collected in support of the assessment of above-water sensor performance based both on controlled surface runs conducted by CFAV QUEST and on vessels and aircraft of opportunity that transited through the surveillance coverage area. The UW arrays were not deployed and cabled to shore during this field trial. A prototype of the new array design was to be temporarily deployed and powered from a large buoy. Unfortunately, we were never able to make the array operate due to a failure in the supporting buoy system. After five days, we recovered the array that had been deployed on the sea floor without the long telemetry cables to the camp. During the recovery we ran into major problems holding position with the ship. At the last moment the array receiver snagged on the side of the recovery vessel and the array cable parted under the strain. All components were recovered and after rejoining the cable wires, the array operated correctly. After recovery of the support buoy, the fault was located. The array on the sea floor had never received power from the buoy and so had never been turned on. We never managed to prove the acoustic operation of the array in this trial; however, we did deploy, leave in place at depth, and during recovery drag the array over 500 m along the sea floor. In the final moments of recovery we subjected the array to extreme forces that tore it apart. Aside from the cable break, the array was completely undamaged proving we had built a hardened system. In this trial DRDC Starfish Sensor Cubes [16, 17, 18, 19] were employed to gather ambient noise and acoustic propagation data. A large quantity of oceanographic information was collected to support analysis of all sensor system results.

In addition to improvements in the sensors and the project plan, a major upgrade of the field camp on Devon Island was completed. The camp changed from the ruins of the original 1980's camp, to a larger, modern, safe, and comfortable field site. The Gascoyne Inlet Camp (GIC) is something of a showpiece for Arctic Operations. It has served a role in several CAF trials and hopefully will continue to be employed by the CAF, DRDC, and other research groups for years to come.

Efforts were also expended on the Processing and Display System (PDS) for the underwater arrays. The PDS is based on the DRDC System Test Bed [20], which has been previously used to support demonstrations of active and passive sonars in field trials and on operational trials.

A second major programming effort was conducted to create the Northern Watch Surveillance System (NWSS) server through a contract with MacDonald Dettwiler and Associates (MDA) [21, 6]. The NWSS server integrates the data feeds from the above water sensors and the underwater arrays via the PDS. The NWSS server helps create the local area picture using detections and tracks created from the sensor systems.

In late 2013 and early 2014, the UW Sensor System (UWSS) underwent a major test to prove its ability to survive at depth in the sea. A single UWSS array was deployed at CFMETR on Vancouver Island, BC, at a depth of about 160 m for a period of seven months [22]. The array was operated remotely from DRDC in Dartmouth, Nova Scotia during this interval. The array operated flawlessly for the entire period. At the end of the test, the array was recovered, inspected, and required only minor additional improvements before being ready for re-use. It should be noted that the array used for this extended trial was the one that had been previously ripped apart in the 2012 field trial. The main array cable was simply mechanically and electrically joined and the joint water-proofed by potting the joint in resin.

In early 2015, the entire NW system was deployed at CFMETR for a period of approximately five weeks [23]. Two UW arrays, the above-water sensors, and the remote NWSS server were installed. A satellite link with DRDC Atlantic's Southern Control Centre (DSCC) operator station consisting of a second NWSS server was established. The entire system was tested and all aspects of remote control, target detection, track generation, data transfer and dissemination were demonstrated. At the completion of the trial all equipment were recovered, examined and made ready for the final demonstration trial.

The final demonstration trial was conducted from late July through to mid-September at the GIC on Devon Island [24]. A remote operator station was set up at the DRDC Atlantic Dockyard Laboratory. The entire system was demonstrated end-to-end under cooperative tests with HMCS SHAWINIGAN and system operations against targets of opportunity. Demonstration of the system was provided to interested parties and the entire trial was deemed a success.

1.5 Report organization

The following sections provide a summary overview of the technical progress accomplished under the NW project. The following section provides an overview of the Northern Watch Surveillance System (NWSS) system concept and the experimental location in the Arctic. The third section describes the Arctic Surveillance Demonstration System (ASDS), which is the Arctic chokepoint surveillance equipment that was remotely operated from a southern location. This section describes the sensors, their installation, operation, signal processing and data handling. In particular, it describes the two main processors; the PDS which handles the UW array data and the NWSS server, which combines the sensor detections and helps to build a local area picture. The fourth section describes the 2015 Northern Demonstration Trial, the targets, and the results. The fifth section describes the technical accomplishments of the project, the main lessons learned in the conduct of the project and provides a discussion of the system capabilities and short falls. Finally, the document ends with a conclusions section that summarizes the results and makes recommendations for future effort.

2 System concept overview

The system concept for Northern Watch is based on unmanned, remotely controlled and monitored local-area surveillance systems that could be deployed at one or more maritime chokepoints at locations in the Canadian Arctic Archipelago [25]. The Northern Watch system concept is illustrated in Figure 4. Northern Watch has demonstrated a single local-area surveillance system, termed the Arctic Surveillance Demonstration System (ASDS). The ASDS was installed at Gascoyne Inlet, on Devon Island, Nunavut, and it monitored a recognized maritime chokepoint on Barrow Strait.

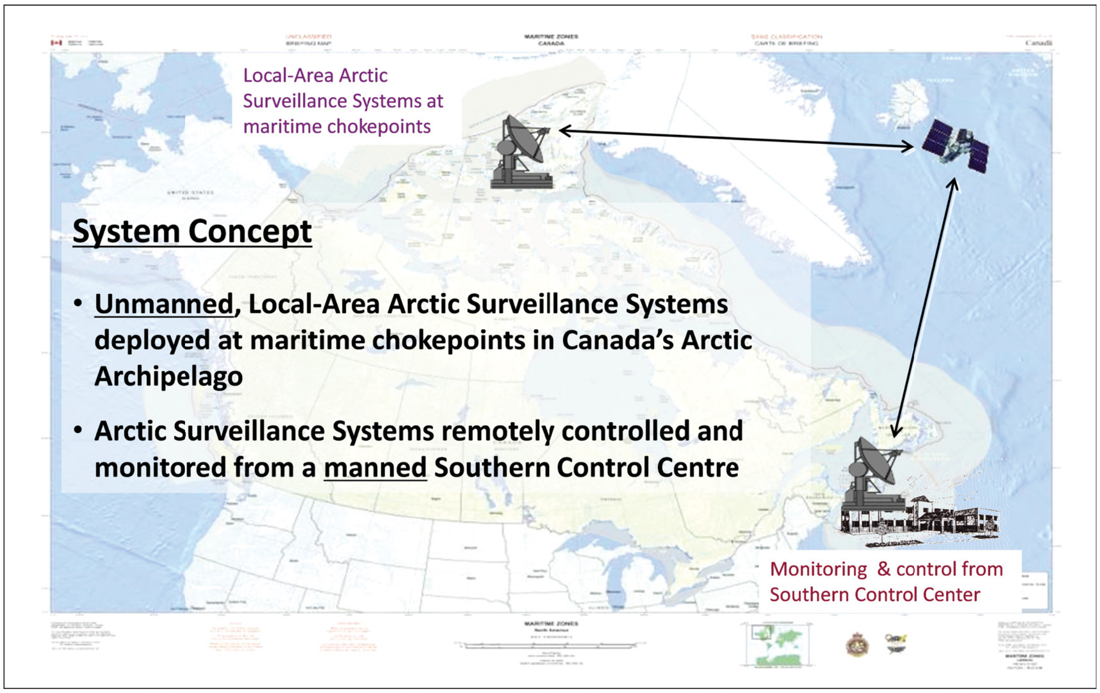

Figure 4: *Northern Watch system concept for unmanned, remotely monitored and controlled, local-area Arctic surveillance.*

The ASDS was operated over a satellite communication channel from a DRDC Southern Control Centre (DSCC) located at CFB Halifax. Surveillance information for each detected platform along with environmental reports for the local operating area were compiled from the integration of data from multiple above-water and underwater sensors and self-reporting systems. These reports could be disseminated, in near real-time, to clients such as the RJOC and MSOC. Sensors and self-reporting systems integrated with the ASDS included X-band radar, underwater acoustic arrays, Automatic Identification System (AIS), Automatic Dependent Surveillance-Broadcast (ADS-B), and a meteorological system. A radar intercept receiver and an EO/IR camera system were originally included in Northern Watch, and were trialed at Gascoyne Inlet in summer 2012. However, these systems were later removed from the project and thus were not integrated into the demonstration system.

2.1 The northern experimental site

Gascoyne Inlet, Devon Island, was chosen as the experimental site because of its proximity to a centrally located Arctic Archipelago choke-point and because the area had been previously used to study methods for bringing UW cables ashore without damage from the grinding action of ice. These studies had drilled a pipe-lined hole from high ground through the bedrock to a point underwater where the lower end emerged at a depth and location that was unlikely to result in direct contact with grounded ice near the shore. Our plan was to make use of this drilled hole so that the cables for the underwater sensors could be left in the water indefinitely.

Figure 5 is a map showing the location of Gascoyne Inlet, which is not often labelled on maps.

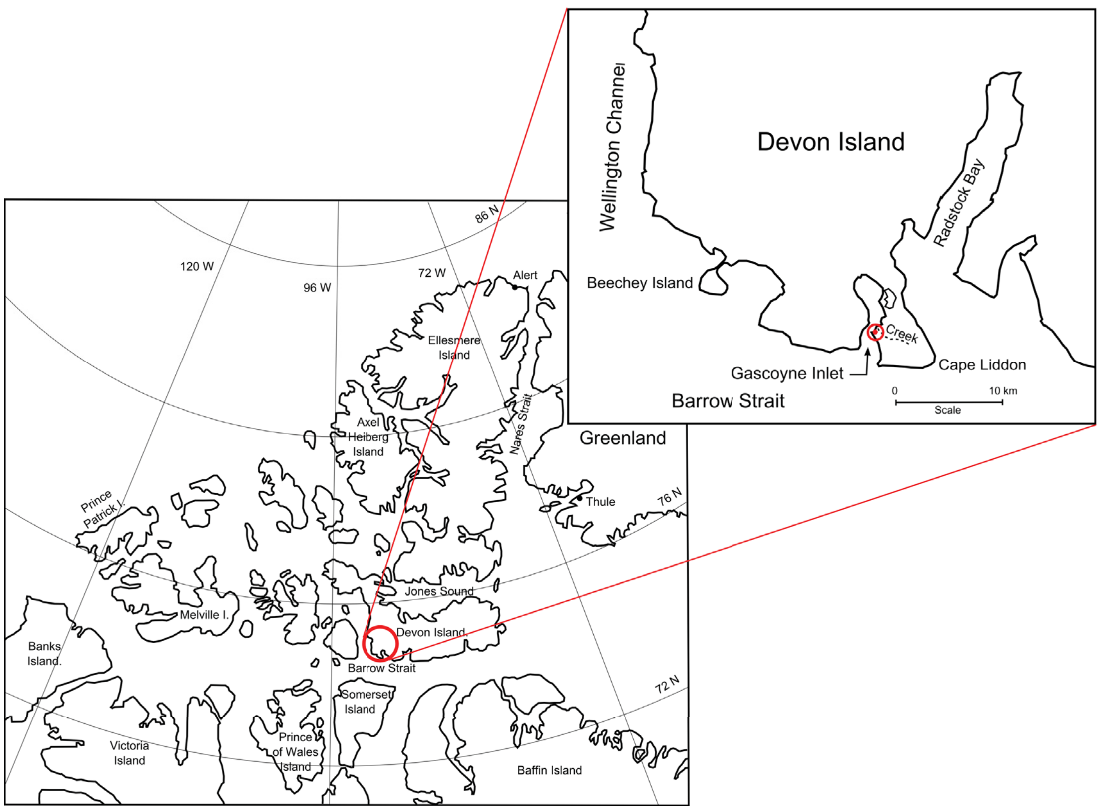

Figure 5: *The Queen Elizabeth Islands showing the location of Gascoyne Inlet (insert) and the field camp (red bullseye).*

The Gascoyne Inlet Camp (GIC) has been built just to the north of a small bay that is located immediately behind a point, informally called Walrus Point. A ridge gradually slopes upward from the point toward the north edge of the 150-m high mesa-like plateau south of the camp. This is clearly shown in Fig. 6. The plateau slopes upward toward the southern edge where substantial cliffs (>300 m) fall to Barrow Strait below.

Figure 6: *Gascoyne Inlet Camp is shown in the foreground. Walrus Point is to the south and the high mesa-like plateau to the east. A second high mesa is located just to the west of Gascoyne Inlet.*

The small bay beside Walrus Point provides a highly sheltered location for cables to approach the shore. Unfortunately, because of the ridge and mesa to the south of the camp and another high mesa to the southwest, there is no direct view of Barrow Strait from GIC. The camp is located at the best position for logistical reasons, but its location and the shape of Gascoyne Inlet limit the field of view for the above-water sensors. As a result, the above-water sensors were located at a site on the ridge at 55 m elevation.

GIC is the largest scientific field camp in the Arctic. A gravel airstrip is located to the northeast of the camp on a raised beach. This gravel strip allows twin otter aircraft to land with people and supplies. A basic road, about 1.5-km long, was graded to ease transport between the camp and the airstrip. Figure 7 shows the camp as it appeared in August 2015 as viewed from the north side of the ridge extending from Walrus Point. The satellite dish for the link to the southern control station appears to the right-hand edge of the picture. The building nearest this satellite dish is the Science Hut. This is where the dry-end processing hardware was located for the demonstration trial. To the left of the Science Hut and down the slope to the beach a strip of lighter coloured gravel is visible. This strip marks where the cables from the underwater sensors were buried after emergence from the drilled hole. The cover for the drilled hole is just visible where the first gravel strip and a second lighter strip intersect. The second strip is where the DFO Real-Time Arctic Ocean Observatory [26] cables were buried. Their dry-end hardware is located in the hut to the left edge of the camp, closest to the second lighter gravel strip in the photo.

Figure 7: *A detailed view of Gascoyne Inlet Camp during the NW Demonstration field trial August 2015.*

3 The Arctic surveillance demonstration system

In this section we describe each of the sensor systems—divided between the underwater and above-water systems. We describe the processing systems and how all of the sub-systems interconnect, particularly those in the Arctic and those located in the south.

A high-level block diagram that summarizes the components making up the Northern Watch Surveillance System, is provided in Figure 8. Each of the sub-systems in this figure are described in detail in the following sub-sections of this report.

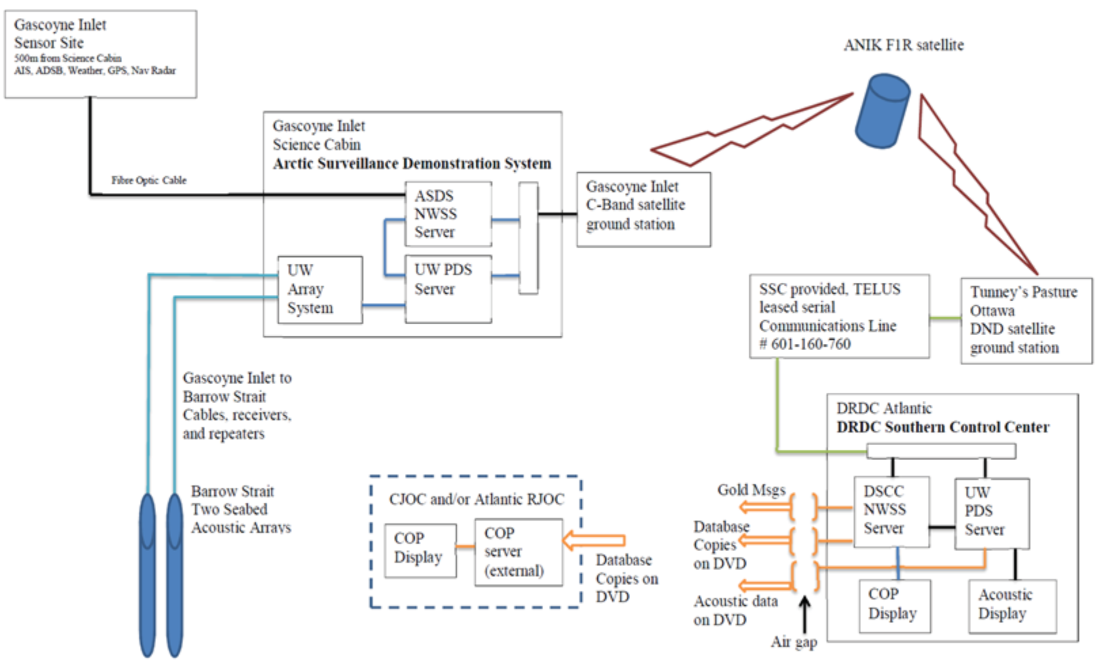

Figure 8: *High-level block diagram of the NW Surveillance System (NWSS).*

3.1 The underwater sensor system

One of the objectives of the NW project was to develop an UW acoustic array capable of being remotely monitored and operated that would be suitable for surveillance tasks. The project put a lot of effort into the development of such an acoustic system and has succeeded.

At first glance it might seem that this objective is not difficult. After all there are many examples of acoustic surveillance systems operated by defence organizations over a long period time. The difficulties arise with the constraints that are applied to the acoustic system. These constraints include:

1. the array must be robust and be able to operate continuously for several years,

2. the array must operate with very low power requirements,
3. the array should be easy to deploy,
4. the array should be relatively low-cost,
5. the array should not be limited by self-noise as it must potentially operate in some of the quietest marine environments,
6. the array must have excellent low-frequency performance, and
7. the array must be reconfigurable in design so that it can be optimized for the conditions and requirements of different UW environments.

DRDC – Atlantic Research Centre has been working on a promising array technology for a number of years. This array technology was developed under the Rapidly Deployable Systems (RDS) Technology Demonstration Program [27]. A number of subsequent projects have added to the technology's capabilities and it was decided to pursue this technology to meet the requirements of the NW project. For convenience, we will refer to the RDS array technology as RDSAT.

3.1.1 UW system components

Here we describe the components of the UW sensor system (UWSS). Figure 9 is a block diagram of the UWSS components. The system employs two seabed deployed horizontal line arrays (HLA) that can each provide an estimate of an acoustic source bearing. These HLA are separated by a number of kilometres so that cross-fixing based on the acoustic bearings can be used to estimate the location of the acoustic source.

Each of the UW arrays covers an aperture of 119 m ($\sim$150 m total length) and has 48 digital hydrophones working at low-frequency in the band from approximately 5–700 Hz. The hydrophones are distributed into three inter-laced, equi-spaced modules that provide 24 or 25 hydrophones in each of three sub-bandwidths. These modules provide a maximum array gain of about 14 dB under ideal noise and deployment conditions. Connections to the digital hydrophones are distributed across four isolated data pairs in the system bus to provide gradual degradation in the event of water leakage. The RDSAT provides many other useful features, such as, calibrated and matched hydrophones, health monitoring, accurate intra- and inter-array sampling synchronization, extremely low-power operation, and rapid recovery from overload conditions. The result is a robust low-frequency array with high quality acoustic data. Information concerning the development of the RDSAT can be found in references [27, 28]. Additional details related to the NW array design can be found in references [29, 30, 31].

Copper telemetry cables supply the arrays with operating power and a series of drivers and repeaters (REP) ensure reliable data transfer. The telemetry cables were chosen to be 10 km and 11 km in length. These lengths allowed for a reasonable array separation and deployment of the HLAs along the northern edge of Barrow Strait. It should be noted that custom copper-fibre cables could be easily used with the arrays and eliminate the need for the repeaters. Custom cables were not employed in NW due to the initial costs involved.

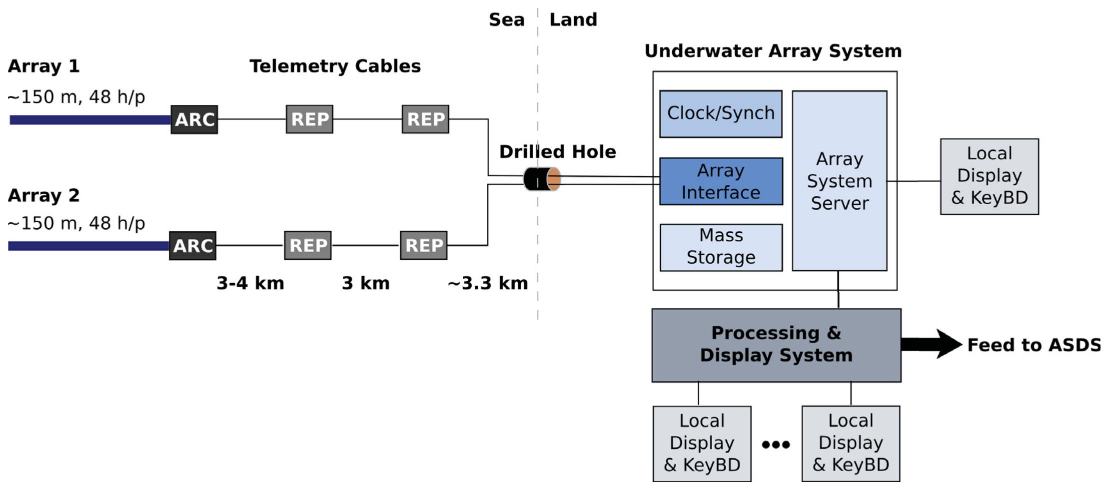

Figure 9: *Block diagram of the UW sensor system components. The UWSS has two arrays connected to a processing system on shore via copper telemetry cables. The hydrophones in each array are locally controlled by the Array-Receiver-Controller (ARC). Two repeaters (REP) are required for each array due to the use of copper telemetry cables. The array system server (DCU) provides complete system control and data handling with the aid of the clock synchronizer, array interface, and mass storage.*

A processing system is located on shore in the GIC. The UW array system is directly controlled and data from the arrays are stored by the array system server otherwise known as the DCU (digital control unit). The arrays are accurately synchronized by GPS pulse-per-second signals, so that data from the two separated arrays can be coherently processed if desired.

The DCU sends data to the Processing and Display System (PDS), which is the acoustic analysis system. The PDS provides local sonar operators a suite of standard sonar displays and carries out standard processes on the acoustic data, the results of which are sent south to another PDS at the remote operator station.

In addition, the PDS attempts to make automatic detections of signal sources and estimate the acoustic source locations. The detections and location results are sent to the NWSS server whose job it is to integrate the UW contacts with those from the above-water sensors.

3.1.2 Component locations

The UW array system processors were located in a wooden building, called the Science Hut, that was constructed on the site. Refer to Fig. 7 in order to identify the Science Hut in the GIC.

The two HLAs are located near the northern edge of Barrow Strait as shown in Fig. 10. The western array had originally been planned for deployment near the green circle marked ‘AMAR LOCATION’; however, in 2012 a large iceberg created the gouges shown in the inset side scan image. To avoid these gouges we moved the array south and east of the initial location.

In the 2015 demonstration trial the western UW array ended up approximately 1 km further east than planned. The latitude of the array was as planned. The western array was dragged during deployment for an estimated 450 m. This unintentional dragging was risky, but resulted in a very good, straight, array deployment. Being experienced with the first array deployment we tried to avoid dragging the eastern array. Unfortunately, we were over cautious and the eastern array was not well laid down. It has a significantly clumped and non-linear deployment. The eastern array ended up approximately 250 m to the northeast with respect to the planned location.

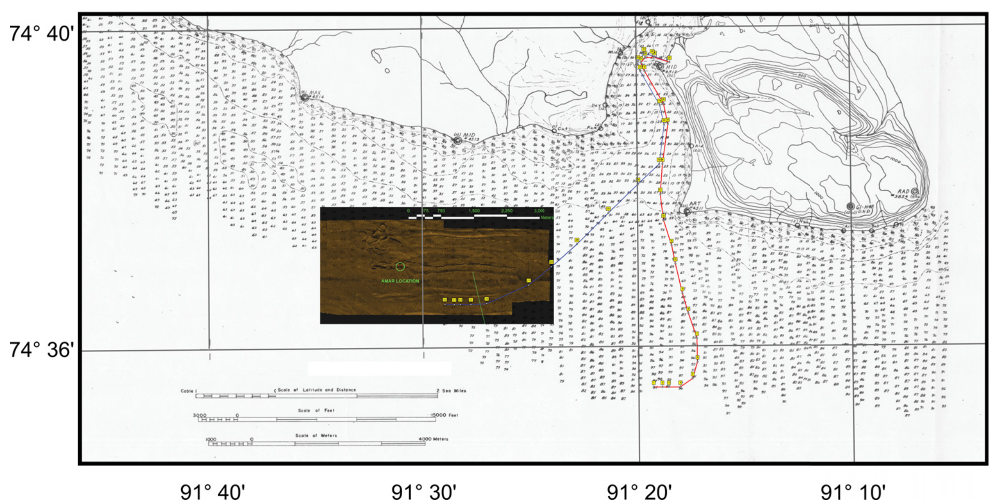

Figure 10: *Map showing the planned telemetry cable paths and the HLA locations at the southern end of the cables. Insert shows the available bottom side scan information showing bottom gouging from the large iceberg that transited in late summer 2012. A long-term acoustic recorder (AMAR) was lost when the iceberg transited.*

3.1.3 Deployment and recovery

Throughout the entire NW project, deployment and recovery of the HLAs has been an on-going concern. When the project began we attempted to build an extremely low-cost and light-weight array that could be deployed in water up to 200 m deep without resorting to mechanical deployment assistance. This need for easy deployment was very important because we did not have access to the types of vessels that could deploy the arrays accurately in a remote location. The cost of vessel transit to the Arctic was too much for the project and therefore the deployment had to be as simple as possible.

In the early days of the project we had available, for a limited interval, the Canadian Coast Guard Ship Terry Fox. This very capable ship has good manoeuvering capability, but because we were hand deploying the arrays and cables it was felt that we could not safely control the deployment and match the range of possible ship motions.

For this reason we initially (in 2008) tried to deploy the arrays and cables from a landing craft (LCM) with a lowerable front ramp while we worked in the cargo area surrounded by 6–7 foot high sides. This scheme worked, but was difficult because of cramped space and an almost complete lack of visibility of our surroundings.

The weather, which at the best of times was poor, complicated matters. Our initial deployment plan involved our laying the telemetry cable from shore towards the southern end where we would temporarily buoy the cable at the surface. This temporary surface expression would be a junction box to which the two arrays would connect. Once the junction box was deployed and held at the surface we would then proceed to deploy each array. Each array in turn would then be connected to the junction box at the end of the main cable. Once both arrays were connected, we would then lower the junction box to the sea floor and deployment would be complete.

Unfortunately, in the time it took to lay the main cable, the weather degraded to the point where there was no hope of deploying an array. We were forced to attach buoys to the cable and head back to shelter.

Overnight the wind increased and blew from the south. This wind direction caused ice floes to cross the strait and impact with our buoyed cable. The morning after our cable deployment the Terry Fox was surrounded by ice and the buoys on the cable were gone. We attempted to under-run the telemetry cable from shore to recover the free end of the cable. Unfortunately, while under-running worked, the weather was too severe to carry through with the idea. We returned to shore and ended up waiting 11 days for the weather to improve. During this interval very little gainful work was accomplished, the plane could not fly with people or supplies, and the Terry Fox departed after waiting as long as possible.

The net result was that we were unable to deploy the arrays in 2008. Instead, just the telemetry cable and repeaters were deployed and left on the sea floor.

We returned to GIC in 2009 with a new deployment scheme for the light-weight arrays. Working with the Coast Guard we developed a plan to use a 40-foot long dumb barge pushed or pulled by a smaller, but more easily controlled powered barge known as an SP barge. Figure 11 shows the 2008-deployed telemetry cable being recovered with the aid of a large diameter reeler attached to the deck of the dumb barge.

Prior to recovery of the 2008 telemetry cable we tested the cable and the repeaters. The system worked perfectly thus we had a good demonstration of system survival after a 12-month deployment. The cable and repeaters were carefully checked after recovery to determine what corrosion and wear were exhibited.

Figure 11: *A large dumb barge being pushed by the highly manoeuvrable SP barge while recovering the telemetry cable laid in 2008.*

The weather in 2009 was generally much better than in 2008 and the recovery of the cable was easily accomplished. The next task was to deploy the arrays.

This time around the arrays were deployed on separate telemetry cables so that there would be no delays in getting the arrays safely on the sea floor once a weather window opened. Also, we began the critical array deployment as the first action and deployed the cable toward the shore. There were many concerns about running out of cable before reaching the shore, but in fact this was easily managed by ensuring the run followed the prescribed route and by checking the amount of cable fed at multiple points along the deployment. The amount of cable was controlled by simply increasing or decreasing the drag, which was supplied manually by workers during the deployment. Working in this manner we were able to pick the best moments for the array lay down and if the weather decayed as the deployment progressed we were at least heading into shore and into the lee of the cliffs thus providing the best chance of completing a deployment without incident.

Figure 12 shows the dumb barge loaded with the light-weight array and the reels holding the telemetry cable. The entire process was handled by hand without the need for powered winches. Another innovation for the deployment was the use of the Wireless Array Gateways (WAG). The WAGs were attached to the side of the telemetry cable reels and powered with the aid of two small rechargeable batteries. With the WAGs we were able to activate the array and analyze its data during the deployment. One of the WAGs is shown on the side of a telemetry cable reel in Fig. 13.

Figure 12: *The dumb barge loaded in preparation for the deployment of an array in summer 2009. The light-weight arrays were deployed entirely by hand. No powered winches or reels were required.*

The WAGs were extremely useful in the array deployments. By monitoring the acoustic signals, the current draw, and the data frame synchronization we were able to ensure that the array was functional and whether components were being dragged or strained. In particular, we saw a synchronization issue arise while dragging an array to straighten it. It appeared that this synch issue coincided with an increase in the pull and appears that it was an indication of high strain on some components. By stopping the drag immediately we saw synchronization return and prevented damage to the arrays. In the end, the array current draw proved itself to be a sensitive indica-

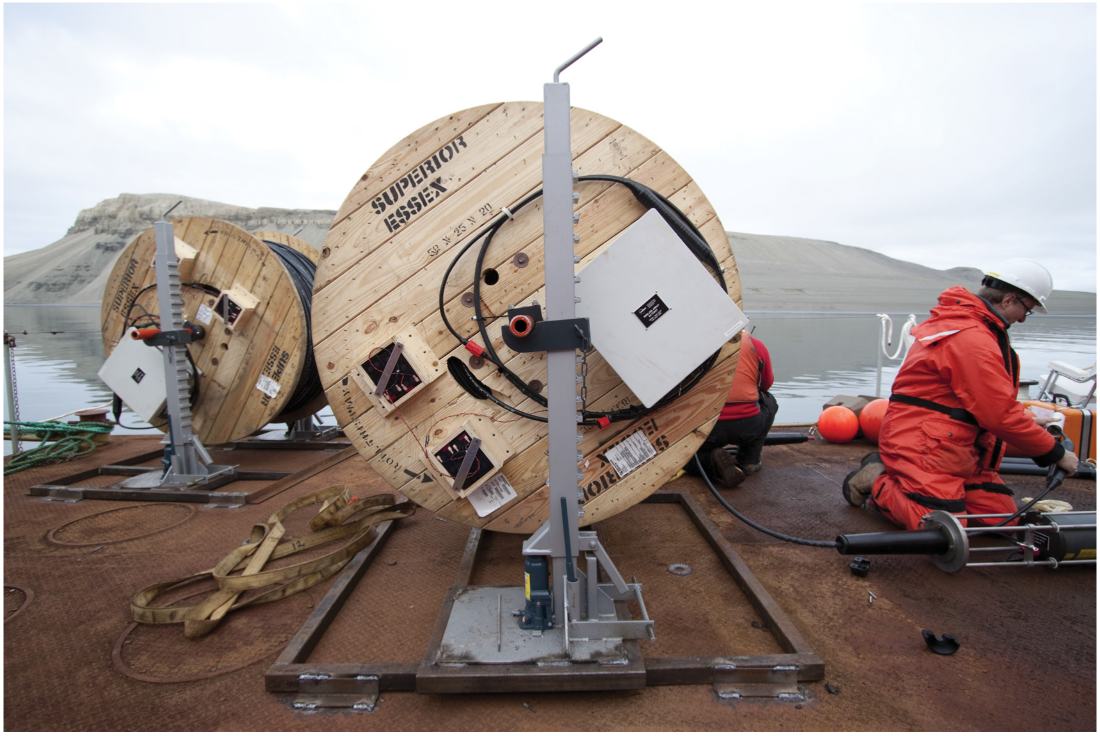

Figure 13: *A wireless array gateway is shown attached to the side of a telemetry cable reel. Two small gel cell batteries are used to power the array through the cable while deployment is on-going.*

tor of a water leak in an array. A change in the current draw of just a few milliamps was our first indication that there was an issue with one array.

The 2009 deployments were in fact very successful. We were able to lay two of the three light-weight arrays and the telemetry cables quite accurately. The third array deployment, replacing Array 1 which failed soon after deployment, did not go as well as the first two deployments. The reason for this was that our monitoring computers lost power and crashed in the middle of the deployment. Without feedback on the lay-down and boat motion, the array was deployed too quickly and as a result the array was not fully extended. The reason for this was that although the barge continued in the desired direction it failed to make as much headway against wind and current as we thought. The array deployment team felt the pull of the cable and believed that all was well, but in fact the pull was largely from drag due to a current we had entered. Instrumented feedback is extremely important for these deployments.

One additional mechanical aid was important for the deployment and recovery operations and in particular for system repairs. This equipment is known as the ”Mule”. The Mule shown in Fig. 14 is a very simple, electrically driven, friction winch. This slowly moving winch pulls on the cable by forcing it between two car tires. Even when under load, one person can pull up or push down on the cable to control friction. The Mule was an essential tool for under-running the cable when making repairs, such as when one array failed.

Figure 14: *A friction winch formed by mounting two car tires side-by-side is known as the 'Mule'. The Mule is elevated slightly to assist with keeping the cable deeply embedded between the tires to ensure a steady pull. Lines are sometimes tied over the cable to control the cable position.*

Unfortunately, the arrays deployed in 2009 failed prematurely after deployment. The problem was a slow ingress of water, which gradually crippled the arrays. This catastrophic failure was largely caused by an incompatibility between plastic components and the resin used in the array construction and poor design and construction practices [32].

The remaining sea bed array and the two telemetry cables with repeaters that were deployed in 2009 were eventually recovered using the dumb barge and reeler in the summer of 2011. Prior to recovery, the cable and repeaters were tested and found to be fully functional after their 2-year long deployment.

The array failures in 2009 led to the construction of more substantial arrays and the abandonment of the all-plastic light-weight array concept. The new array design cost significantly more and was much heavier than the previous all-plastic arrays. Deployment by hand was no longer an option, so the Under Water Array Handling

System (UWAHS) was constructed on an iso-pad, which allowed the UWAHS to be employed on a CF MCDV.

Figure 15 shows the UWAHS in use on board HMCS SHAWINIGAN during summer 2015. UWAHS has a deployment/recovery chute at one end. This chute is well rounded and provides minimal opportunity to catch array components and repeaters as they are recovered. UWAHS also has two powered winches. One winch, which is physically small, is located in front of a larger winch mounted at the opposite end of the iso-pad from the chute. The middle section of the pad is where the deployment team works.

Figure 15: *An iso-pad based deployment/recovery aid known as the UWAHS was developed to assist in deployments of the heavier arrays from CF vessels.*

The small winch is used to wind or unwind a steel cable that runs from the array anchor, alongside the hydrophones and cable, and then along 200-m of the telemetry cable. We added the steel cable to take the added strains of deployment or recovery that could be caused by limitations in the winch speed or sudden motions of the ship, which was not purpose built for such controlled deployments. The array is equipped with clips at each hydrophone that securely attach to the steel cable as it is being deployed. Stoppers on the steel cable prevent the clips from moving on the steel cable and ensure the array does not slide down the cable during deployment.

Once the steel cable is on the sea floor, the larger winch then deploys a short section (1 km) of telemetry cable. The larger winch is faster and more able to adjust to ship speed changes, but it cannot pull as hard as the small winch. Once the first kilometer of telemetry cable is in place, the forces on the cable are relatively benign and we once again resort to hand-driven reels for the remainder of the telemetry cable.

The UWAHS was successful in several tests and in the actual final demonstration trial deployments. In use we discovered that the larger winch was adequate for deployment of the steel cable and the better one to use as it was more able to keep up with the ship's motion. Ideally, we would have bought a single capable winch for the UWAHS rather than use winches we had on hand, but this was beyond the available project budget at the time.

Ideally we also need more instrumentation to measure cable run and tension in real-time as well as sensors in the array to aid in deployment. An integrated deployment/recovery software aid would be beneficial to ensure that the arrays are properly laid down without excessive dragging or without fully extending the arrays. Working manually on the ship during deployment with calculators, GPS, and computerized maps is error prone and too slow to ensure success. Spending effort and money on the deployment gear, sensors, and monitoring equipment is an important lesson learned.

To summarize, a large diameter winch/reeler compatible with the array bending radius and with highly variable rotation speed to adjust to the ship's motions is an essential tool for deployment and recovery. The use of the smooth chute is another essential tool which cannot be over-looked. Investment is needed to produce the properly sized and shaped chute to avoid snags which have been shown to lead to catastrophic events. A motorized friction winch is an essential tool for maintenance and array/repeater recovery. The use of the WAGs provides real-time array operation during deployment or recovery and provides essential feedback to the team for avoiding damage. Additional, deployment sensors for cable tension and scope are also absolutely essential as is the development of real-time software to monitor ship position, cable tension, etc. Risk of array damage during deployment and of poor lay-down could be greatly reduced by improved aids and sensors.

3.1.4 Array localization

Once an array has been deployed on the sea floor, the deployment team can produce an estimate of the array's absolute geographic position. The position of the array is needed as part of the solution for the location of acoustic signal sources. The lay-down estimated position is often relatively poor. Depending on water depth it is often only accurate to approximately 50 to 100 m in absolute geographical location. In addition, the lay down position does not estimate how straight or how well extended the array is.

In order for acoustic signal processing methods to work properly we require accurate estimates of the three-dimensional relative location of each hydrophone in an array. The locations must also be accurate. In general, a rule-of-thumb requires that the hydrophone positions each be known to an accuracy better than $\lambda/10$, where λ is the wavelength of the highest frequency of interest. In our case the arrays operate to approximately 700 Hz. The nominal speed of sound in seawater is 1500 m/s, which implies that we must know the hydrophone positions with a relative accuracy of approximately 20 cm.

This level of accuracy is difficult to achieve by any surveying technique. Fortunately, an acoustic method has been developed to allow hydrophone locations to be accurately determined. The technique is known as Array Element Localization (AEL) [33, 34]. The method for AEL employed for NW involves making impulsive acoustic signals at a number of locations around the deployed array. In this case, we lower incandescent light bulbs on a thin steel cable to a desired depth and then drop a messenger (weight) down the steel line. The messenger rapidly falls down the line and strikes an anvil, which delivers a sharp blow to a light bulb held in the device. The impact causes the light bulb to implode under the hydrostatic pressure. This implosion results in a loud ”pop” that contains sufficient low-frequency energy to be easily detected on each hydrophone of the array.

By measuring the pop arrival time differences on each hydrophone for a number of light bulb implosions at a variety of locations near the array it is possible to estimate the location of each hydrophone. By globally optimizing the solution for hydrophone locations and supplying estimates of light bulb locations, water depth, the initial hydrophone position estimates, mean sound-speed of the water column, and the uncertainties of each of these quantities, we can obtain accurate estimates of the hydrophone locations.

In most cases, where the array has been laid relatively straight, we can immediately use the hydrophone locations obtained in this manner for acoustic signal processing tasks. Sometimes, further processing is needed to create a virtual array. This is only necessary when the original lay-down has resulted in a jumbled or badly non-linear deployment. Further development is needed to handle these cases.

3.2 The above-water sensors

Above-water sensors were installed at the BIRDSEYE surveillance site (our name for the sensor site on the ridge extending eastward from Walrus Point), located at 55 m elevation on the hillside overlooking Barrow Strait. The setup used for the final demonstration trial in summer 2015 is shown in Fig. 16. The sensors were powered locally with a portable diesel generator. Communications back to the ASDS NWSS server, installed in the GIC Science Hut, was achieved using a fibre optic cable.

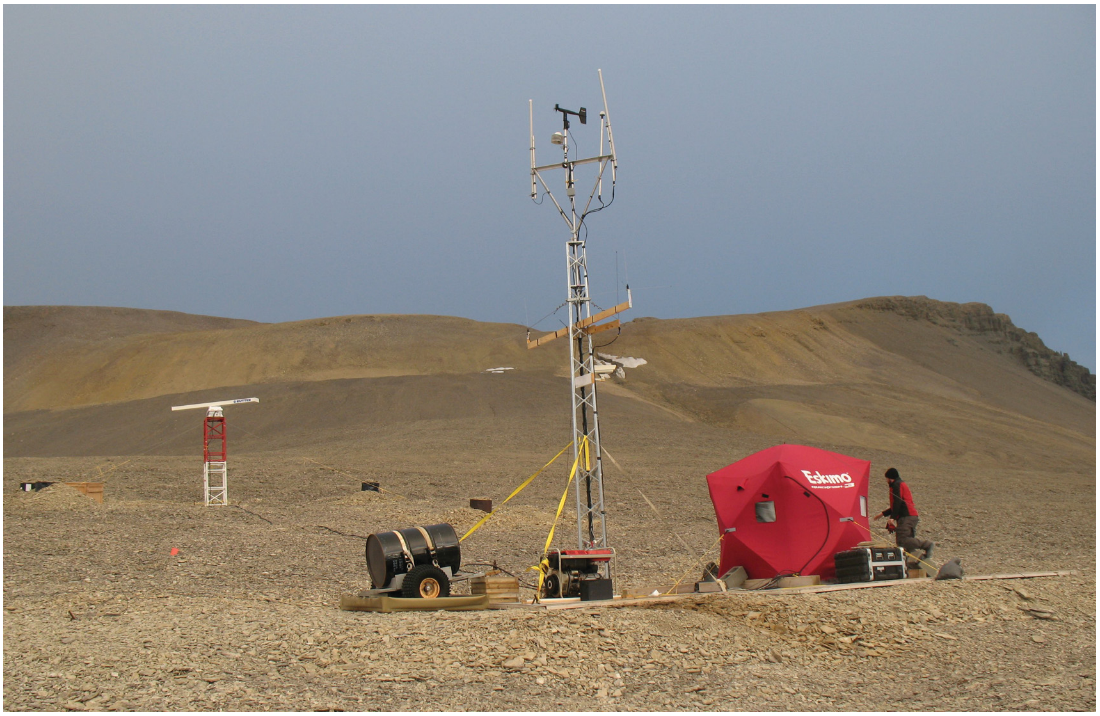

Figure 16: *Above-water sensors installed at the BIRDSEYE surveillance site in summer 2015. A small tent was used to provide protection from the elements for sensor receivers, the hardware for networking, and power regulation. Antennas, meteorological sensors, and the camera were installed on the mast shown next to the tent. The radar's mast is visible in the background.*

Above-water sensors and self-reporting systems integrated with the ASDS included: Rutter 100S6 X-band radar; Comar SLR300N Automatic Identification System (AIS) receiver; Kinetic Avionics SBS-3 Mode-S Automatic Dependent Surveillance - Broadcast (ADS-B) receiver; Texas Weather Instruments WPS-N meteorological system; and a StarDot-Tech NetCam-XL camera. AIS and ADS-B are self-reporting systems for ships and aircraft, respectively; ships equipped with AIS or aircraft equipped with ADS-B will broadcast their position and identifying information, which can be collected by AIS or ADS-B receivers. The camera has a 3M pixel resolution, with fixed view and focus, and was designed to supplement the meteorological system with imagery of local environmental conditions at Barrow Strait. Each of the installed above-water sensor systems were COTS. Some additions were made to the software installed on the Rutter radar computer to facilitate interfacing to the NWSS server.

A radar intercept receiver and an EO/IR (electro-optical/infra-red) camera system were originally included as NW sensors, but were not integrated into the demonstration system. The Advanced Wideband Adaptive Intra-pulse Receiver (AWAIR) radar intercept receiver, developed by DRDC – Ottawa Research Centre, provides detection, bearings-only tracking, and classification/identification of maritime platforms, based the detection of RF (radio-frequency) emissions from X- and S-band radars. The Canadian Night and Day Imaging Surveillance System (CANDISS), developed by Obzerv Inc. for DRDC – Valcartier Research Centre, includes visible light and IR cameras, a laser rangefinder, and an active laser illuminator. These sensors were tested on-site at Gascoyne Inlet in the summer 2012. Examples of data collected by each sensor are provided in Figures 17 and 18. Further details regarding the performance of the CANDISS and AWAIR systems during the 2012 Trial is provided in references [15, 4].

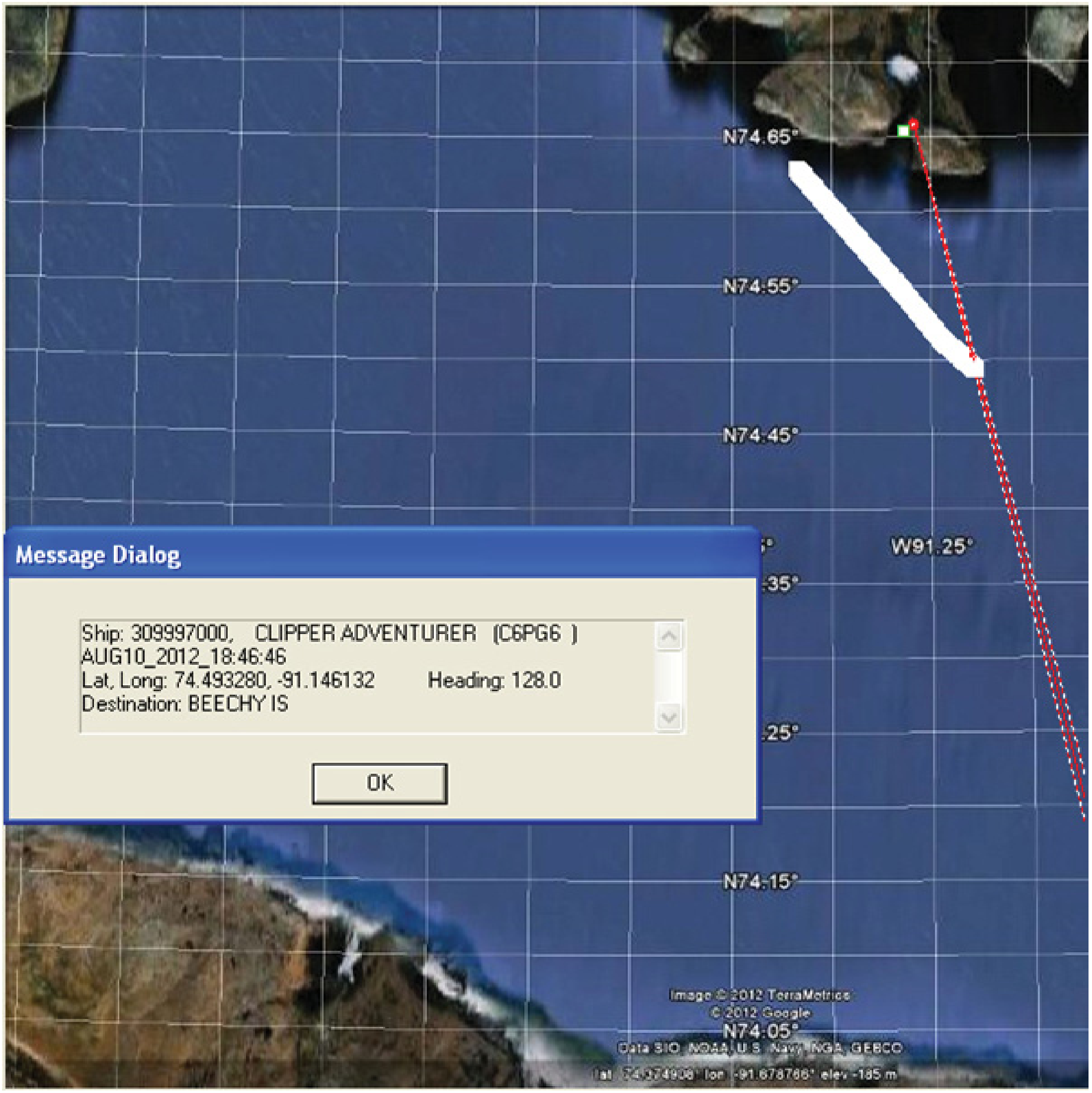

Figure 17: *Detection (red bearing line) of cruise ship CLIPPER ADVENTURER by AWAIR. The vessel track (in white) and identification information (message dialog) are from AIS [4]. The unclassified release of information that combines vessel identity with geo-temporal location (in this case, ship's position together with Maritime Mobile Service Identity (MMSI) number and ship name) is consistent with the guidelines provided in reference [5].*

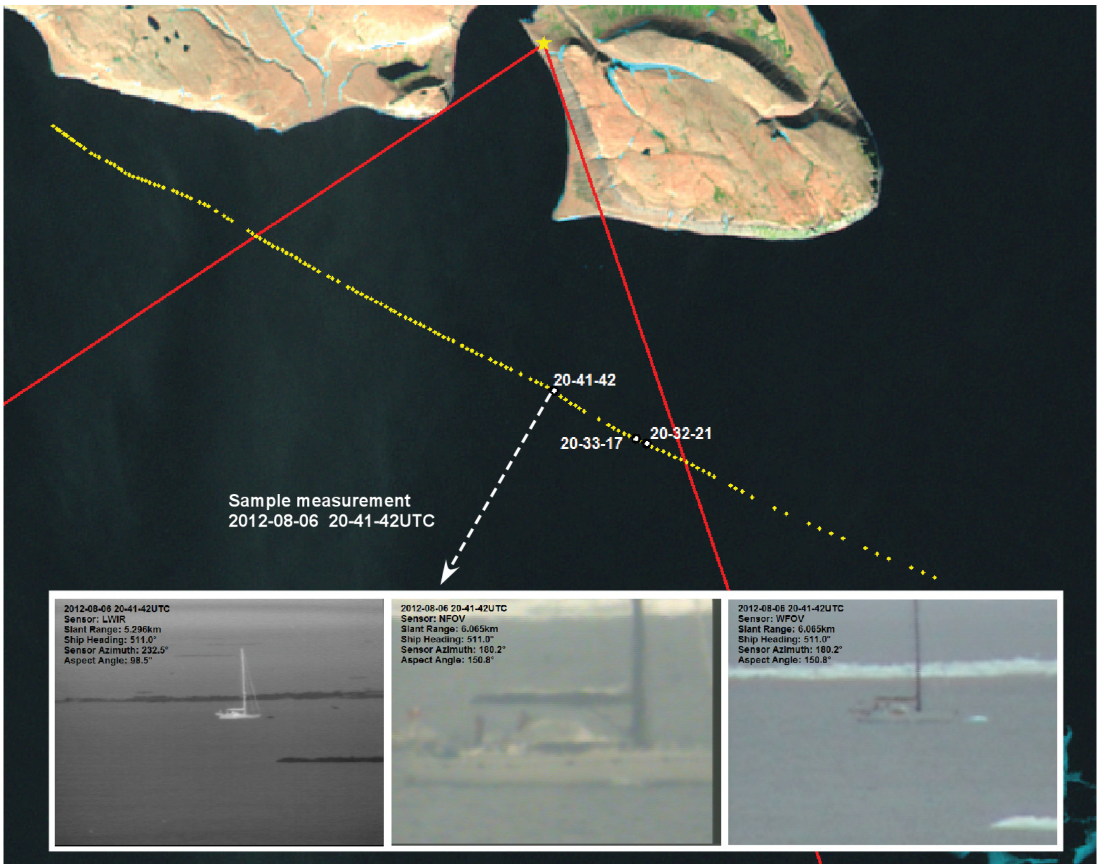

Figure 18: *Imagery from CANDISS EO/IR system's (left-to-right): IR camera; narrow-field-of-view visible light camera; and wide-field-of-view visible light camera, obtained during the transit of the sailboat KATHARSIS II, at a range of 6.1 km. The AIS track for KATHARSIS II is shown as yellow dots; the red lines indicate the visual field of view limits from the Northern Watch above-water surveillance site (yellow star) [4].*

3.3 The Northern Watch surveillance system processing and display systems

This section describes the main processing components of the ASDS and DRDC Southern Control Centre (DSCC). The NWSS Server is the main integrator of sensor detections. The Processing and Display System (PDS) processes the UW array data, generates all of the sonar displays, and provides derived content to the NWSS server.

3.3.1 The PDS and NWSS server functionality

The NWSS and PDS servers are the core data processing components of the surveillance system. The NWSS servers were developed under contract by MDA and provide for the production of the local-area surveillance picture and for the monitoring and control of the above-water sensors. The PDS servers provide for acoustic data processing and for the monitoring and control of the underwater arrays. The PDS system is based on DRDC Atlantic's System Test Bed (STB) and was developed in-house.

NWSS and PDS servers are installed at both the ASDS (remote northern location) and southern DSCC. The interconnection of these components is illustrated in Fig. 8. PDS and NWSS servers installed in the ASDS provide interfaces to the UWSS and above-water sensors, respectively. The system concept is that the NWSS and PDS servers located in the ASDS run unattended and can be monitored and controlled from the DSCC. During trials these servers were operated from both the ASDS and from the DSCC.

3.3.2 The PDS

The UWSS processing and display system (PDS) was developed using the DRDC System Toolbox (STB) [20]. The STB is a collection of software components that provide data management, data processing, data interface, and data visualization functionality. The STB supports a flexible, scalable, and extensible architecture that readily supports component reuse. The STB maximizes generic functionality by limiting component functionality. Many STB components provide generic functionality that can be reused for many types of applications. Other components provide application specific functionality. The STB supports distributed multi-processor and multi-platform processing across local area networks and wide area networks.

The PDS application leveraged existing generic STB components to implement most of the required functionality. New components were developed to support the UWSS arrays. These components included an UWSS array data format encoder, an UWSS array data format decoder, and a generic XY beamformer component. The functionality of several existing generic components were extended to improve existing functionality. Like previous STB application developments, the enhancements to the

STB during the development of the PDS application have strengthened the maturity of the STB and broadened the functionality of the STB. Existing and future STB applications will benefit from these enhancements.

Both PDS systems consist of a processor and two large monitors. The remote system, in the ASDS, processes and displays real-time array data. The remote PDS sends all track data, line of bearing data, and meteorological data across the satellite link to the DRDC Southern Control Centre; however, the satellite bandwidth is too limited to stream real-time raw array data to the DSCC. The remote PDS sends a limited subset of real-time processed acoustic data across the satellite link to the control system. This data includes broadband and narrow-band data at the longer time averages and coarser frequency resolutions. These data provide an operator with a summary acoustic display.

Both PDS systems, north and south, can process and display recorded data. The operator has the ability to request selected intervals of raw acoustic data (*e.g., 5–10 minutes of recorded data files*) if a more detailed analysis is required. A 5-minute file of recorded data took approximately 40 minutes to send across the satellite link used in the 2015 Arctic Demonstration Trial.

The PDS systems provide the following functionality:

- interface to the ASDS to send line of bearing data and cross fix data, and receive AIS data and meteorology data;
- interface to the DSCC to send feature data, track data, meteorological data, acoustic data, and receive control data to and from the DSCC PDS. The remote PDS provides a web services interface to support web pages and web requests for image files and acoustic data files;
- interface to the UWSS to receive array acoustic data and array non-acoustic data, and to send control data to the arrays;
- acoustic data processing including audio analysis, channel analysis, beamforming analysis, broadband analysis, demon analysis, narrow-band analysis, and select various spectral and temporal resolutions;
- signal detection and signal localization in broadband, demon, and narrow-band acoustic data;
- acoustic range prediction including visualization, propagation path, transmission loss, and signal loss estimation;
- acoustic data auralization;

- acoustic data visualization including normalized and un-normalized channel spectral displays and tools, broadband bearing power displays and tools, demon bearing spectral power displays and tools, and narrow-band bearing spectral power displays and tools;
- tactical visualization including nautical chart overlays and tools, bottom bathymetric overlays and tools, acoustic range prediction overlays and tools, track overlays and tools, line of bearing overlays and tools;
- web publishing including periodic screen grabs and track summaries,
- data recording and data replay; and
- management of the acoustic data sub-net bandwidth utilization.

Examples of PDS displays are presented in the following figures. Figure 19 shows an example of the operator desktop. Figure 20 shows an example of a narrow-band bearing spectral power display with a detected signal overlay. Figure 21 shows the broadband bearing power displays of the two arrays for an opening range surface vessel. Figure 22 shows the chart display with line of bearing and track overlays enabled. The intersection of the line of bearings provides a localization estimate which corresponds closely to the AIS reported position of the passing vessel.

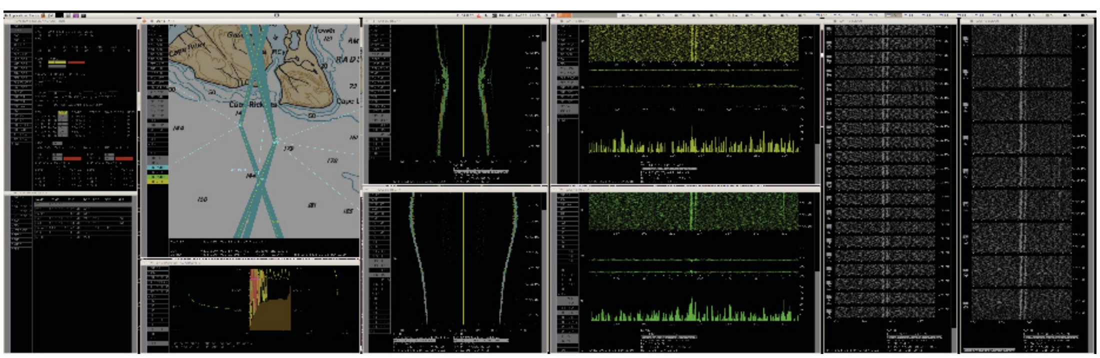

Figure 19: *This figure shows the typical desktop configuration for the two UWSS arrays spread over two displays. Starting at top-left is the status and UWSS command window, below that is the log window. Moving to the right we find a tactical map and an acoustic model prediction window. Further right comes the broadband bearing displays, then the composite lofargrams, and finally two beam lofargram displays at different settings.*

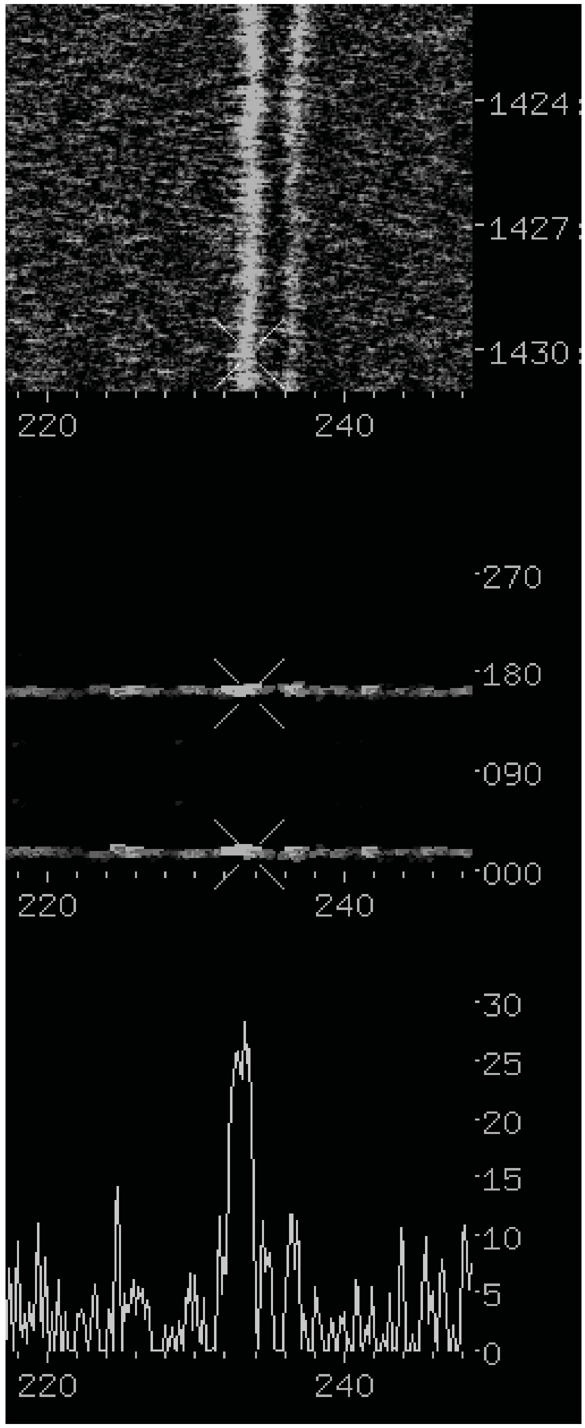

Figure 20: *This figure shows a portion of the narrow-band lofargram display at top, with bearing display centre, and sprectral display at bottom. The cross-hairs indicate a target detection.*

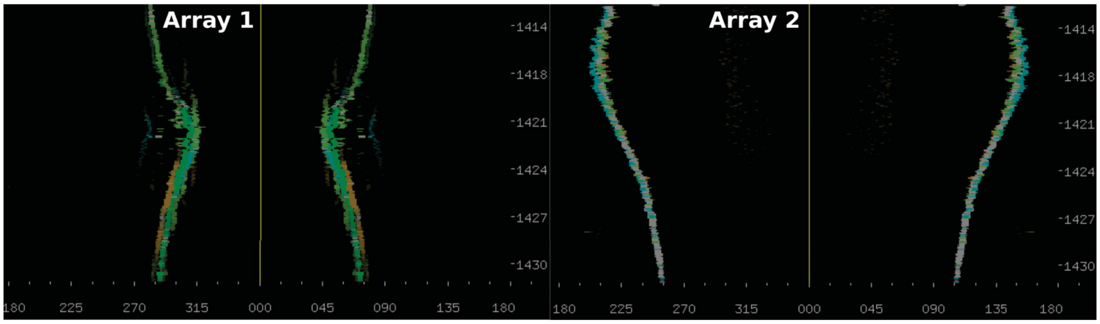

Figure 21: *Broadband bearing displays (array 1 left and array 2 right) for a vessel moving away from the arrays.*

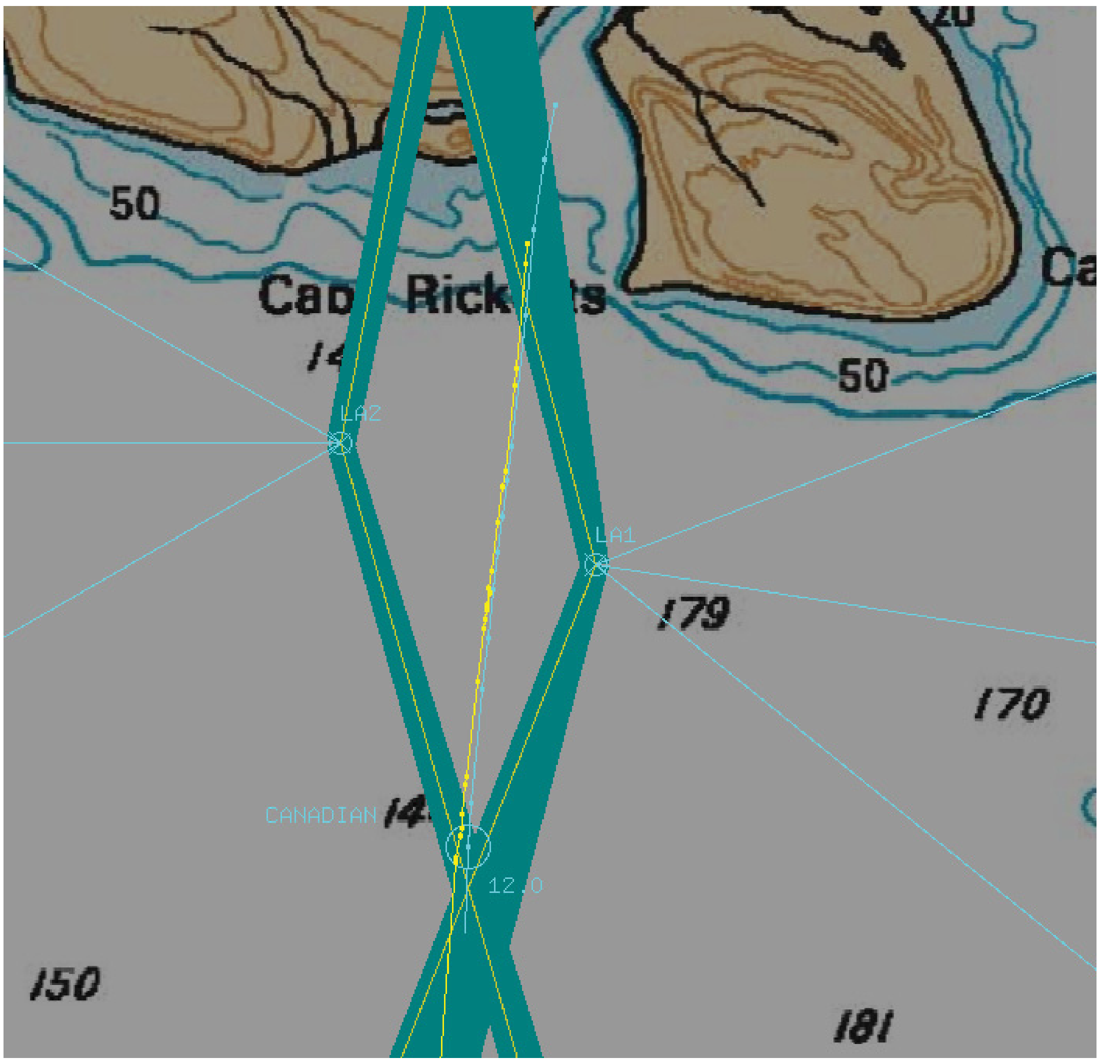

Figure 22: *Chart display with the bearing (blue-green) and track (light-blue and yellow) overlays enabled. A vessel heading south is accurately localized by the bearing intersection.*

3.3.3 The NWSS server

The NWSS servers, developed by MDA Halifax, are implemented using a modular, distributed, service-oriented software architecture, termed the Sensor Integration Framework (SIF), which is built on top of OMG standard Data Distribution Service (DDS) for Real-Time Systems. This architecture enables the decoupling of software components, one benefit of which is that no individual software service acts as a single point of failure for the system. The Sensor Integration Framework provides the routing of messages between services, the management of system power on/restart and graceful shutdown, system configuration, and, the handling of system errors and alerts. Layered on top of the SIF are a set of Sensor Integration Services, for sensor adapters, data management, track management, sensor control, display, network management, and data dissemination. The NWSS software architecture is depicted in Figure 23 and is described in greater detail in [6].

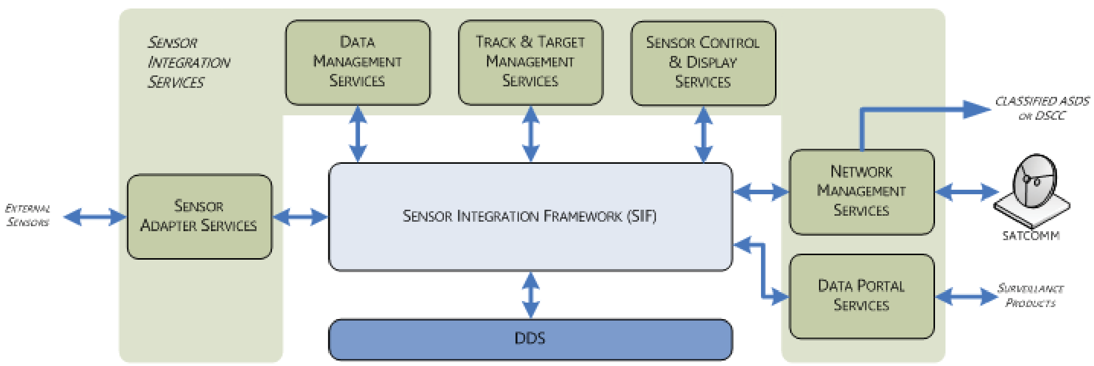

Figure 23: *Software architecture for NWSS servers [6].*

The key functions provided by the NWSS server include:

- Interfaces to above-water sensors systems (NWSS installed at ASDS);
- Management of data transmissions between the ASDS and DSCC;
- A contact track database;
- Tools to support compilation of a local-area surveillance picture;
- Operator displays. The NWSS server has two primary displays—a local-area COP (surveillance picture) and a status display. The status display also includes sub-windows for display of meteorological and meteorological camera data. The status display also provides ‘tabs’ for access to individual sensor web pages;
- Time management using GPS-synchronized Network Time Protocol (NTP) servers installed in both the ASDS and DSCC;

- Remote monitoring and control of above-water sensors, and other NWSS system components (such as, NTP server, router, etc.); and
- Data dissemination to external clients.

These functions are described in greater detail in Section 4.2.

The NWSS was designed and implemented to support multi-level security, with separate servers on separate classified and unclassified networks, and with a data diode for low-to-high classification data transfers. However this capability was not demonstrated as all trials were conducted at the unclassified level.

3.4 The sensor habitat

One of the objectives of the project was to demonstrate year-round operation of the NWSS. In order to do this, a special enclosure is required to protect the computers and other instrumentation from the cold and the effects of wind, rain, and icing. The enclosure also has to supply the communications and a significant amount of energy to continue operations for such a long period.

Effort was conducted within the project to plan for a year-long operating period. In order to carry out such a demonstration, plans were made to build a habitat for the sensors. A contract Statement of Work (SOW) was developed to build the habitat. Unfortunately, the cost of building the habitat, transporting it and the fuel to the northern site, and operating the system was beyond the NW project resources. The habitat concept was shelved and the full year of operation was never demonstrated. The SOW for the contract was re-worked and turned into a DRDC publication [14] in order to capture the requirements and possible solution to the extended operation requirement.

4 The 2015 northern demonstration trial

This section describes the activities that were conducted as part of the final northern demonstration in summer of 2015. A description of the cooperating vessels and the vessels of opportunity is provided along with information on the relevant environmental conditions in which the ASDS was functioning. The performance of the underwater and above-water sensors is illustrated and many results for the integration of sensor detections, bandwidth usage, picture compilation, information dissemination, and system remote control are provided.

4.1 Demonstration of local-area chokepoint surveillance

Local-area maritime chokepoint surveillance was demonstrated using:

- HMCS SHAWINIGAN and MONCTON who were acting in support of the trial;
- vessels of opportunity transiting within the surveillance area during the time period the system was active;
- Three sub-surface EMATT target launches on 2 September at 1451 UTC and 8 September at 1928 and 2033 UTC.

In addition, local-area surveillance of air traffic was demonstrated, to a limited extent, using data received from ADS-B.

4.1.1 Vessels of opportunity

During the one month time period when the NW system was operational, a total of 21 identified vessels of opportunity and one unknown were detected in the surveillance coverage area. A summary of vessel transits in or through the surveillance area is provided in Tables 1 and 2. Each entry in the table includes the date, vessel name (derived from AIS), sensors that detected the vessel, and any additional comments. In many cases vessels were not tracked continuously, they exited and re-entered the surveillance area in a single day, or they loitered within the surveillance area for an extended time period. This is illustrated in Figure 24. The cruise ship LE SOLEAL is first detected by AIS when entering the mouth of Radstock Bay at 12:21 UTC on 1 September (location A in Figure 24). She loiters in Radstock Bay from 1300–1700 UTC (location B). Contact is lost briefly, at 17:31 (location C) and regained at 17:38. LE SOLEAL transits from east to west just off the coast, passing across the mouth of Gascoyne Inlet, until contact is lost at 18:39 (location D). There is a brief detection in Erebus and Terror Bay at 18:59. LE SOLEAL is re-detected by AIS entering the surveillance area at 23:45 (location E) transiting south-east across Barrow Strait. Last contact on AIS (location F) is received at 01:54 UTC, 2 September.

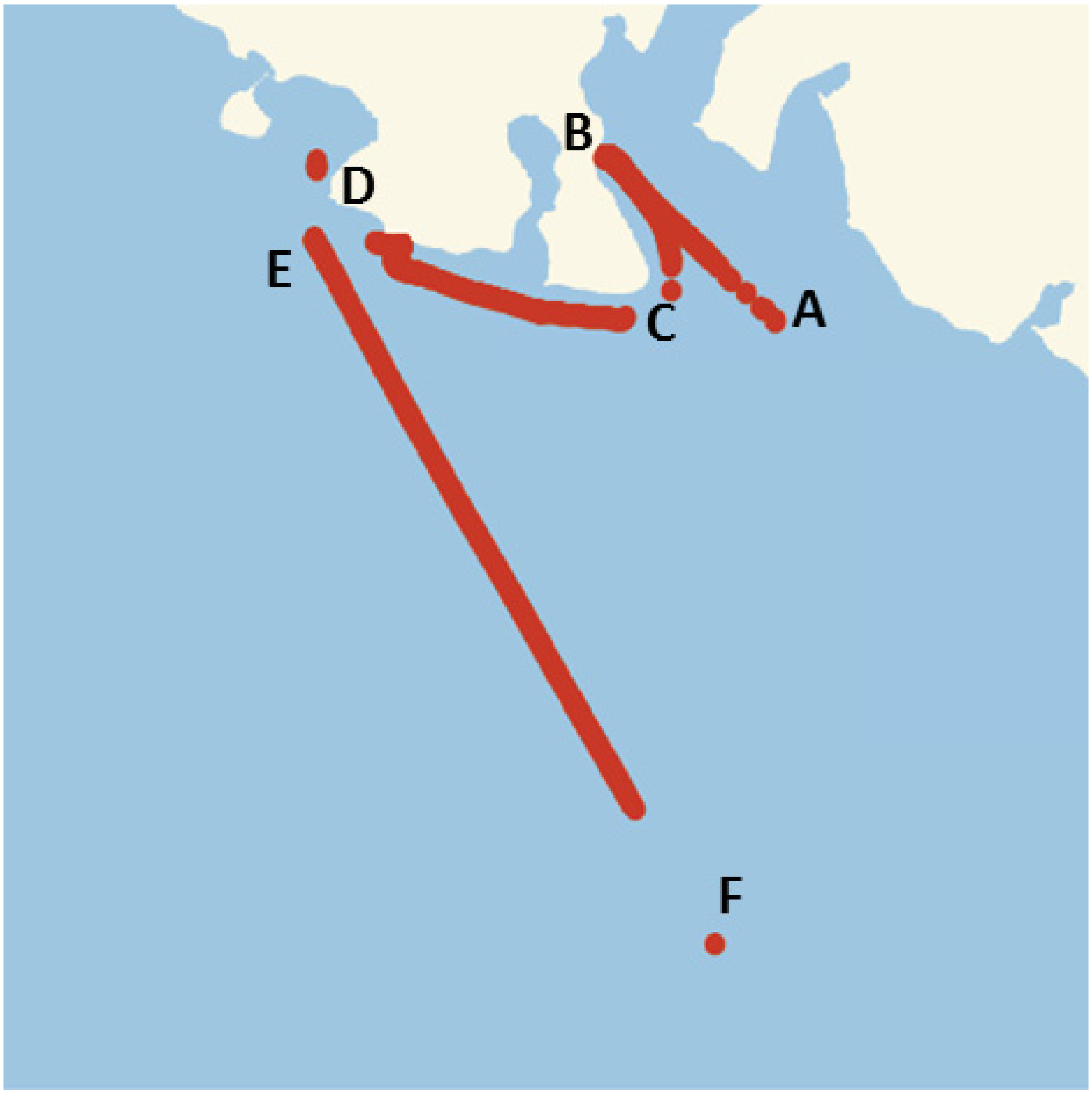

Figure 24: *AIS track for cruise ship LE SOLEAL recorded on 1 Sept 2016.*

Table 1: *Transits by vessels of opportunity through the Northern Watch surveillance area in August.*

Date	*Vessel Name*	*Detected by Sensors*	*Comments*
10 Aug	OCEAN ENDEAVOUR	AIS, radar	
11 Aug	SALTY	AIS (Class B), radar	
11 Aug	SNOW DRAGON	AIS (Class B), radar	
14 Aug	AMUNDSEN	AIS	
17 Aug	HANSEATIC	AIS, radar	
18 Aug	AKADEMIC VAVILOV	AIS, radar	Until 01:20 UTC, 19 Aug
20 Aug	AKADEMIC IOFFE	AIS, radar	
23 Aug	UNKNOWN	radar	02:06–02:27, UWSS2 begins ops.
23 Aug	UNKNOWN	UWSS	Target to the west. Possibly SHAWINIGAN based on satellite AIS
23 Aug	HAWK	AIS (Class B), UWSS	
25 Aug	NTL. GEO. EXPLORER	AIS, UWSS	
25 Aug	UNKNOWN	UWSS	Possibly icebreaker DES GROSEILLIERS or cargo ship CAMILLA DESGAGNES based on satellite AIS.
26 Aug	NTL. GEO. EXPLORER	AIS, radar, UWSS	UWSS1 deployed.
26 Aug	SEA EXPLORER	AIS, radar, UWSS	
28 Aug	SEA EXPLORER	AIS, radar, UWSS	Until 00:27 UTC, 29 Aug
28 Aug	SEA ADVENTURER	AIS, radar, UWSS	Until 01:41 UTC, 29 Aug
28 Aug	AKADEMIC IOFFE	AIS, radar, UWSS	
29 Aug	AKADEMIC IOFFE	AIS, radar	UWSS lots of signals?
29 Aug	LE BOREAL	AIS, radar, UWSS	
30 Aug	OCEAN ENDEAVOUR	AIS, radar, UWSS	
30 Aug	WAVE	AIS (Class B), UWSS	
31 Aug	LATITUDE	AIS, radar[1], UWSS	
31 Aug	T/T LATITUDE	AIS (Class B)	Towed by LATITUDE
31 Aug	OCEAN ENDEAVOUR	AIS, radar[1], UWSS	
31 Aug	WAVE	AIS, radar[1], UWSS	

[1]Detected by radar, but radar interface was off-line.

Table 2: *Vessel transits during September.*

Date	*Vessel Name*	*Detected by Sensors*	*Comments*
1 Sept	KIVIUQ I	AIS (Class B), UWSS	
1 Sept	LE SOLEAL	AIS, radar[2], UWSS	Until 01:54 UTC 2 Sept
1 Sept	LS AXE07	AIS (Class B)	Co-located with LE SOLEAL
1 Sept	LATITUDE	AIS	
1 Sept	T/T LATITUDE	AIS (Class B)	
1 Sept	WAVE	WAVE (Class B)	Moving east from Radstock
2 Sept	LATITUDE	AIS, UWSS	
2 Sept	T/T LATITUDE	AIS (Class B)	
2 Sept	UNKNOWN	UWSS	Possibly tanker ALSTERSTERN based on satellite AIS
3 Sept	LATITUDE	AIS, UWSS	
3 Sept	T/T LATITUDE	AIS (Class B)	
3 Sept	MITIQ	AIS, UWSS	
6 Sept	CAMILLA DESGAGNES	AIS, radar	
6 Sept	UNKNOWN	UWSS	Possibly cargo ship CAMILLA DESGAGNES based on satellite AIS
8 Sept	EQUANIMITY	AIS, UWSS	
8 Sept	UNKNOWN	UWSS	Not noted in log. Found on data playback.
9 Sept	EQUANIMITY	AIS, radar	
9 Sept	OCEAN ENDEAVOUR	UWSS	
9 Sept	SEA ADVENTURER	UWSS	
11 Sept	OCEAN ENDEAVOUR	AIS, radar	
11 Sept	UNKNOWN	UWSS	Strong signals to southwest. Satellite AIS provides no clues. SEA ADVENTURER was to the west.
11 Sept	SEA ADVENTURER	AIS, radar[2], UWSS	Shut-down.

[2]Detected by radar, but radar interface was off-line.

As noted in Tables 1 and 2, AIS data received from adventure sailors and small craft were of the lower-power class B variety. Two vessels, the yacht LATITUDE and the cruise ship LE SOLEAL, appear to have deployed AIS-equipped small craft. The pleasure craft T/T LATITUDE was observed on camera being towed behind LATITUDE as she transited across the mouth of Gascoyne Inlet (see Figure 25). The LS AXE07 was detected in the immediate vicinity of LE SOLEAL during a time period when the cruise ship was at rest, close to shore in Radstock Bay, and is assumed to be a small craft being used for sightseeing purposes.

To date only a partial analysis has been conducted of the detection of vessels of opportunity by UWSS; however, the UWSS detected all of the vessels listed in the table, except for the smaller vessels, detected on AIS, but not independently powered (*i.e.*, they were likely being towed, but still transmitting AIS signals) when in an area covered by the arrays. The UWSS also detected seven acoustic sources that could not be directly associated with local AIS tracks. Likely, these unknown signal sources are associated with the vessels seen by the local AIS at other nearby times and on the wider coverage of the satellite based AIS.

Figure 25: *Yacht LATITUDE transiting across the mouth of Gascoyne Inlet, 31 August 2016. LATITUDE is towing a small craft (assumed to be T/T LATITUDE).*

4.1.2 The underwater sensor performance

The underwater sensor is more complicated in operation than the above water sensors such as the AIS or radar, both of which generally give simple track information. Passive sonar systems are sensitive detectors of acoustic energy and they can provide bearing estimates to sources of acoustic energy, but they generally do not provide reliable estimates of acoustic source range. Using several acoustic sensors simultaneously receiving the same acoustic signal, it is possible to estimate the bearing of the source from each receiver and if the receivers are sufficiently well separated, the source location can be estimated from the crossing of the bearing fixes. This cross-fix localization is the primary tool used for acoustic source localization in NW.

The NW arrays are certainly capable devices and were operating effectively. During the trial we routinely detected broadband acoustic noise that was attributed to ships operating near Baffin Island approximately 240 km distant. Sensitivity to acoustic signals is both a strength and a weakness. The weakness arises from the fact that signals are detected from a variety of natural and man-made sources. At any time there are usually several dynamic signals from a number of sources that can complicate the acoustic signal detection and the association of the acoustic signals both in discrete intervals of time (detections are often not continuous) for a single acoustic receiver and between two or more acoustic receivers. To further increase difficulty, acoustic signals cover a range of frequencies and the same signal received on two different receivers may not be at the same frequency due to Doppler Shift effects.

Another factor complicating the acoustic sensing is that the signals from a single acoustic source can travel to the receiver over a number of paths underwater. The arrival of acoustic energy on different paths generally gives rise to uncertainty in the bearings to the acoustic source. In the NW situation, there are three main reasons for bearing uncertainty: up-slope acoustic refraction, three-dimensional effects of the local bathymetry, and steeper angle ray paths.

Up-slope refraction can be significant when an acoustic signal propagates in shallow water in a direction that is not perpendicular to the slope. As the signal propagates, it interacts with both the bottom and surface of the water. The surface can be considered to be a horizontal plane, but the slope of the bottom can be large enough to cause the reflected signals to be deflected (refracted) out of the arrival signal plane. The result is that the acoustic energy follows a curved path over the sloped sea floor. The effect of the refraction is cumulative and substantial changes in the apparent direction of signal travel can occur. In NW, the receiving arrays are located on the northern edge of the strait and many signals reaching them must travel over a sloping sea floor. The result is an uncertainty in the true bearing to the acoustic source. The receivers can only measure the apparent bearing of the acoustic energy right at the receiver. They do not know how the energy travelled from the source to the receiver, nor what refractive effects might have occurred along the route.

Three-dimensional propagation effects are a generalization of the refraction effect described above. In the NW case, the receivers were located relatively close to the shoreline, which was irregular in shape. The seafloor between the arrays and the shore has a complex bathymetry. The result is that acoustic signals travelling toward the shore refract and reflect multiple times. So much so, that on more than one occasion we observed particular signals from vessels transiting past the receivers to suddenly jump in apparent bearing. Typically, we observed a signal on a bearing that correlated with the position of a vessel from the AIS or radar. Suddenly, the signal on that bearing would disappear and reappear on a greatly different bearing that initially made no sense given the source location. This type of signal change has been attributed to a strong three-dimensional propagation effect where the dominant path switches from the obvious direct line to a more complex refracted/reflected path.

The third cause of bearing uncertainty, may actually be the most dominant cause of error. This cause of bearing uncertainty is largely due to human interpretation. The NW acoustic receivers were horizontal line arrays (HLA). This type of array responds to acoustic arrivals with an axially symmetric response. What this means is that the response of the array is the same at all angles of rotation around the axis of the array of hydrophones as long as the angle of the acoustic arrival path with respect to the array axis remains constant. In other words, the response functions of the array are conic sections aligned with the axis of the receiving array. In the case of an HLA, people speak of 'beams' or the beam formed response function of the array. The narrowest beam of an HLA is at 90° to the array axis. It is common to call this the broadside beam, which is in fact disc shaped. The widest beams occur at 0° and 180° , these are called the end-fire beams. These beams are shaped like elongated tear drops with the broadest section pointing toward the ends of the array.

Acoustic signals travel through the three-dimensional underwater environment and reach the receiving array on one or more apparent pathways. These paths each generally correspond to one or more of the beam response functions of the receiver. At broadside the array response for a given sound pressure level signal would be the same for a source to the left, the right, or directly above the array (or for any position in between as well). For a source signal arriving between the broadside and end-fire directions, the beam response is cone-shaped. The HLA estimates the arrival direction from the maximum beam response. What the array actually provides is the beam angle between the array axis and the dominant acoustic path of arrival. The acoustic source beam angle is a function of the acoustic path vertical arrival angle and the horizontal bearing angle. Unfortunately, an HLA cannot directly determine either the vertical angle or the horizontal bearing of the acoustic arrival. Our difficulty arises from the fact that humans, and simple cross-fix localization algorithms, forget about the three-dimensional nature of the environment and simply consider a two-dimensional plan view of the source and receiver geometry. This results in the beam angle being interpreted directly as the horizontal bearing of the source with a two-valued (left-right) ambiguity. This interpretation of bearing is only true if the acoustic signal arrived horizontally at the receiver. Unfortunately, at shorter ranges and in a sloping sea floor environment this is not usually the case and the bearing estimate obtained by using the beam angle directly is biased. To illustrate that this bias can be large, we can draw on observations from our CFMETR tests where vessels that were clearly aligned in one of the receiving array end-fire directions were observed to appear in the beam 30° from the end-fire direction. In this case, the vertical arrival angle is close to 30°, while the bearing angle is actually zero. In this example, the direct use of the beam angle as the bearing angle results in a bias equal to the vertical arrival angle.

In order to better estimate the horizontal bearing angle, there are two approaches. First, we can include a vertical array with the horizontal array. The vertical array can directly estimate the vertical acoustic arrival angle, but not the bearing angle. Using the vertical and horizontal arrays together, a better estimate of the horizontal bearing angle can be produced. The second approach is to employ more complicated signal processing schemes on the HLA beam angle and its history as a vessel transits. Techniques such as matched field processing and environmentally adaptive processing can at the cost of significantly more computation result in less biased bearing and range estimates. Neither of these approaches were included in the NW project.

To summarize, acoustic source localization generally requires multiple receivers, which acquire simultaneous or near simultaneous measurements of common signals. The underwater systems are sensitive receivers and generally detect thousands of potential signals of interest in a short interval of time. These signals must be categorized on the basis of amplitude, frequency, dynamic, transient and persistence properties, and into natural, biological, and anthropogenic (man-made) classes. The signals on each array must then be associated in time as detections are often intermittent. This association can potentially change a sequence of transient signals into a weak persistent signal, which may raise its relative priority. The associated signals must then be prioritized and a sequence of localization estimates constructed that are turned into tracks (time histories of detections). These tracks are generally very noisy time and location estimates that require advanced filtering techniques (Kalman, particle cloud) to provide stable high-priority, accurate tracks. These tracks can then be fused with other tracks from independent sensors. This type of signal processing is extremely difficult. It is the subject of current research efforts and the performance of algorithms for autonomous operation can be sub-optimal.

The NW project originally planned to put effort into the development of autonomous algorithms to conduct many of these signal processing tasks; however, it was always intended that a human operator would be primarily responsible for the underwater sensor operations. Trained human operators can instinctively handle many of these advanced algorithmic tasks with ease. It is a short fall of the NW project that in the end almost no UWSS signal processing development was included and only the most basic detection and cross-fix algorithms were developed. The result is that the large number of underwater detections and dissociated tracks easily overwhelm the manual system track fusion approach provided by the NWSS.

Figure 36(a) presents an example where the PDS blindly reports all contacts to the NWSS. Many of the bearing lines shown in the image will have no association with the vessel to the south, but the NWSS operator does not have sufficient information to relate or discount the contacts. This issue can be ameliorated by the intervention of an acoustic operator who can select acoustic signals of highest interest for transfer to the NWSS. An example of the result when an operator selects a signal of interest is shown if Fig. 26. In this figure, the arrays are denoted by LA1 and LA2 and the blue circle with lines denotes the vessel's AIS fix information. In this example, both arrays have detected the vessel at a range of about 63 km (blue range rings are at 5 nm steps). Array bearing estimates are shown by the yellow lines and green bands, which denote an average direction. The western array (LA2) is laid very straight and has accurately estimated the bearing to the acoustic source. The eastern array (LA1) was crumpled in the deployment. The bearing estimate from this array is not as accurate, but it is not clear if the non-linear deployment or one of the bearing biases discussed previously is the cause of the bearing error. It is likely that estimate of the mean axis orientation of the array is in error by a few degrees as all detections seem to be biased westward of the actual bearing. Note also that the bearing lines are paired for each array. The bearings to the north represent the ambiguous horizontal bearing in the horizontal plane to which all HLA are subject (called the left-right ambiguity).

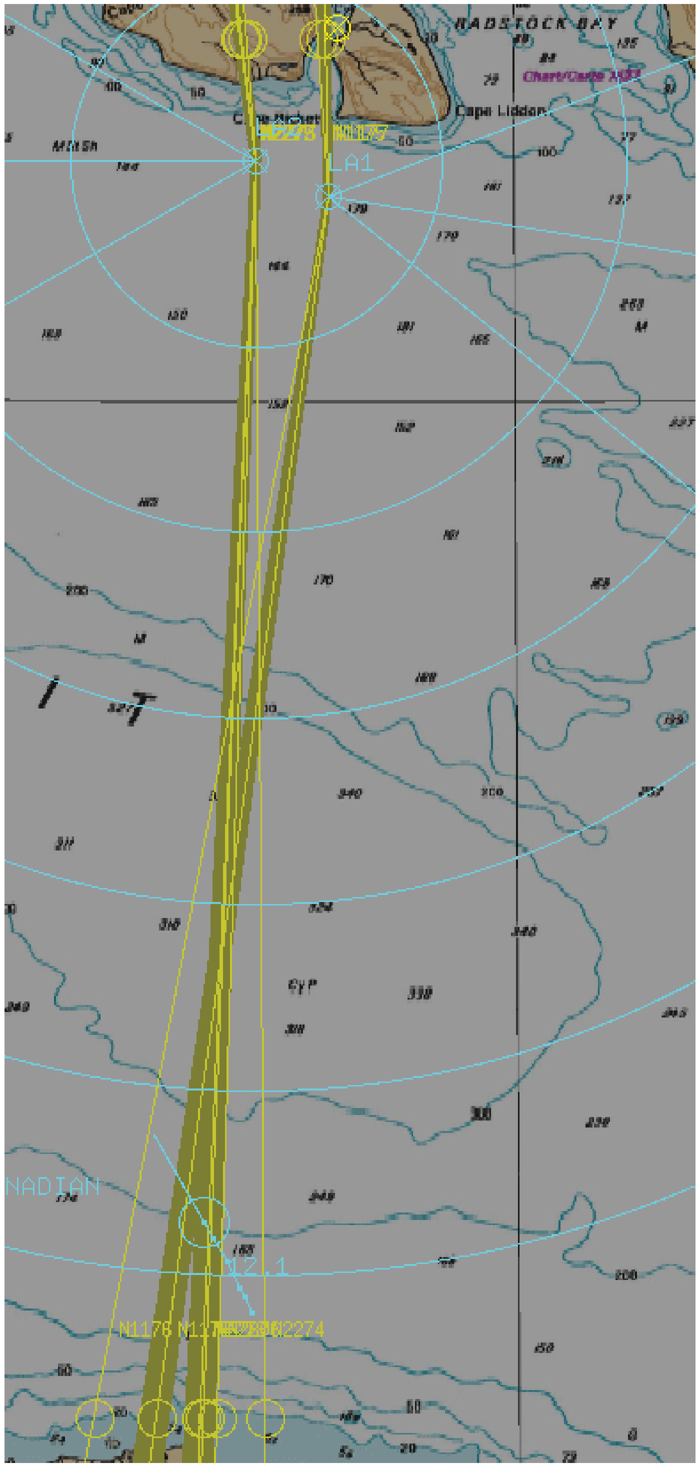

Figure 26: *Tactical display for one particular instant when the MCDV is almost completely to the far side of the strait. The acoustic operator has selected a signal of interest and auto-detection and bearing estimation is applied.*

In addition to the signal detection and processing issues already described there are two other factors that strongly influence the performance of the acoustic system. The first of these factors is the ambient noise. Acoustic signals are detected by the arrays in the presence of noise. The higher the noise level, the shorter the range at which a given strength acoustic signal can be detected. The second factor is due to the propagation of the signal from the source to the receiver. In given locations for the source and receiver, changes in the received signal can usually be attributed to changes in the water column sound-speed profile between the source and receiver. For the most part, the sound-speed profile changes are related to temperature changes. In the Arctic, there are some profound changes in the sound-speed profile during the year that are related to changes in temperature and the formation of ice-cover.

The NW project attempted to measure the change in sea floor ambient noise for a year-long period at one of the proposed array locations. Unfortunately, the project was not successful in this effort as the recording system was struck by a massive iceberg and lost. Summer time noise levels were recorded during two field trials at GIC. The results showed that the noise level is highly variable and correlates well with the recorded wind speed. In our band of interest ambient noise is well known to be correlated to wind noise, but surprisingly we found that the ambient noise level changes much more in Barrow Strait than it would in many other locations (especially the deep ocean) for a given wind speed change. The result is that acoustic sensing performance varies considerably as well. The location can be exceptionally quiet or exceptionally noisy.

Figure 27(a) shows a gram presentation of the noise from 10 Hz to 10000 Hz recorded by JASCO Scientific [7] near Resolute, NU. We expect the noise near Gascoyne Inlet to follow a similar pattern and level. In this figure, red represents a high noise level, while blue represents low noise conditions. Note that our field trials July–Sept are conducted in essentially the noisiest interval of the year. Figure 27(b) shows the band levels and percentiles for the 1-year period of noise measurement. In the summer trials we experienced the L5 and L95 levels from time-to-time. Ice cover forms in October and begins to break apart near the end of April. The interval from December through to June is significantly quieter than Aug–Sept. We can expect, on the basis of noise alone, that for this portion of the year, acoustic performance will be as good as the excellent performance we observed in the low-wind speed intervals during our field trials, but there is more to performance than just the noise.

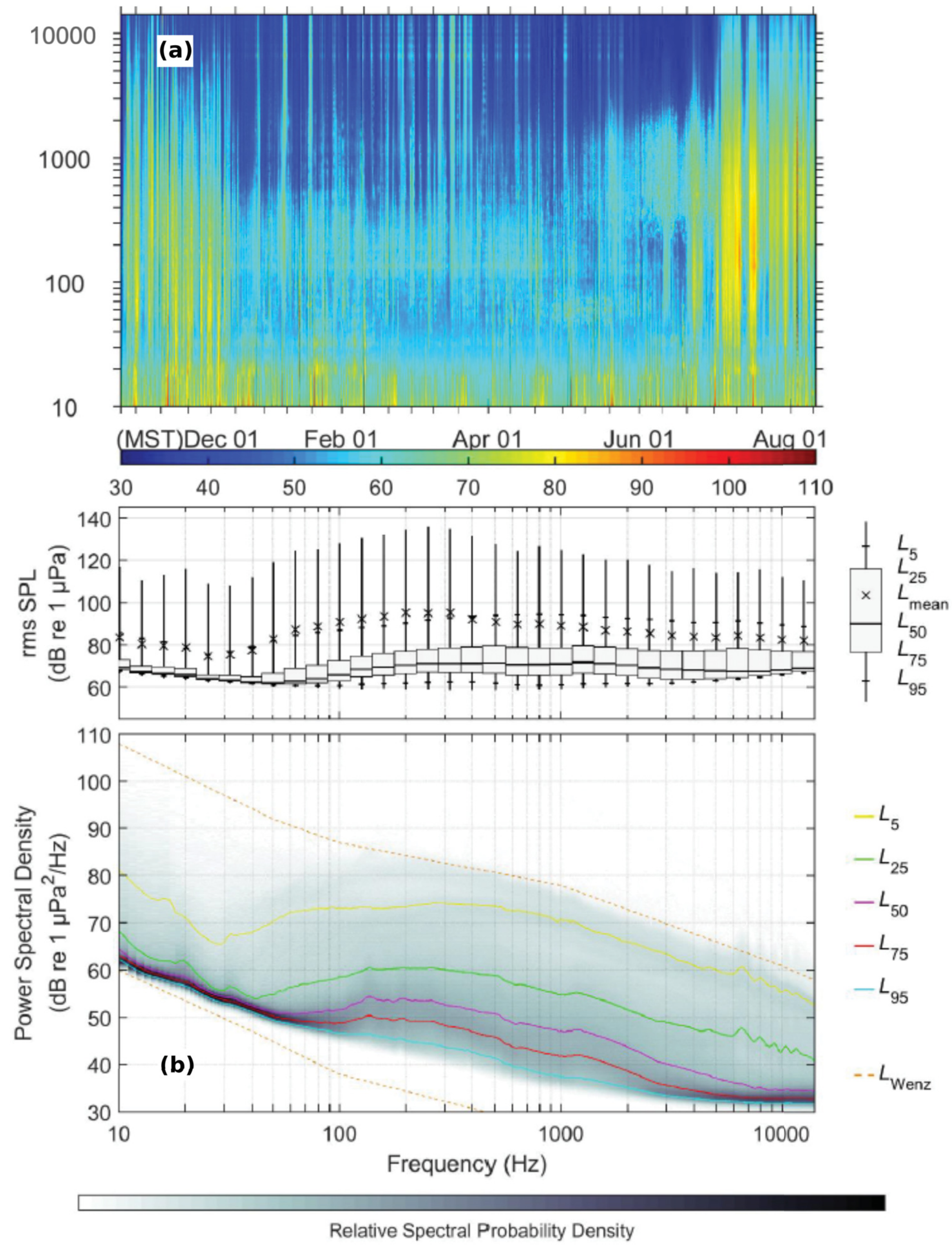

Figure 27: *(a) Year-long gram record of ambient noise near Resolute [7]. Summer time can be seen to be the noisiest period of the year, while December to June is relatively quiet. (b) Ambient noise spectra percentiles for the full year period. Noise levels are seen to range from very low to the Wenz upper limit. Funding for this data collection was provided to C. O'Neill by the Ocean Tracking Network (OTN, NETGP #375118-08), from Canadian Natural Sciences and Engineering Research Council (NSERC), and with additional support from the Canadian Foundation for Innovation (CFI, Project #13011).*

The NW project made a large number of sound-speed profile measurements in Barrow Strait in August 2012. A small number of sound-speed profiles were measured in Aug–Sept 2015. The sound-speed profile showed considerable variation across and along the strait, but some general features were observed that appear to be typical of the summer time conditions. Figure 28 shows one of the profiles collected in 2015 near the arrays. Note that there is a minimum sound speed near 75 m depth. This minimum sound-speed results in the formation of a sound channel. Sources and receivers located within or close to the axis of the channel will experience lower propagation loss than for situations where the source, receiver, or both are located shallower or deeper. While the depth and strength of the sound channel varies, this is a general feature. Also note that near the surface there is a second sound speed minimum. In this case covering the upper 20 m of the water column. Again, this is an often observed feature and it is reasonable to assume that this minimum will get lower as the air temperature declines. The near surface minimum results in a surface duct which tends to keep near surface noise partially trapped near the surface. Our measurements have shown that in summer time, propagation from a submerged source to either of the sea floor arrays is preferred over propagation from a source near the surface and this is a result of these two characteristic sound channels.

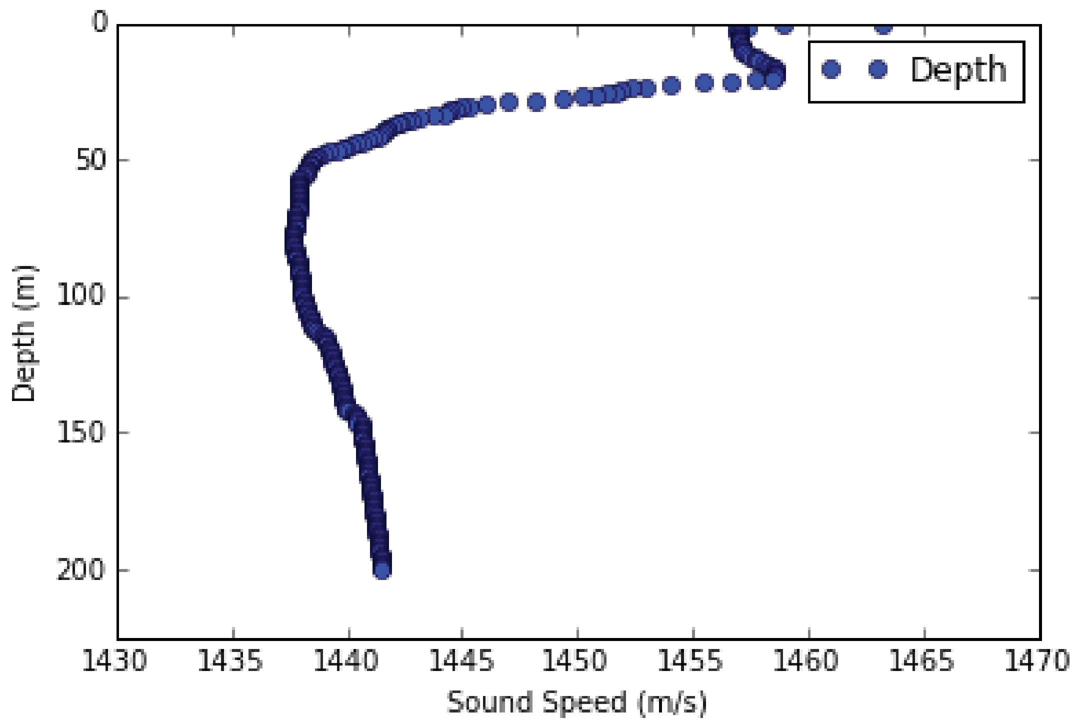

Figure 28: *An expendable bathythermograph profile measurement converted to sound speed just to the south of the arrays on 29 Aug 2015.*

The NW project was unable to make any environmental or acoustic propagation measurements in winter. For this reason, we must rely on published data and results of which there are few. We know that as the air and water cools, ice begins to form and the sound-speed profile becomes upward refracting. This means that the acoustic signals from all sound sources tend to propagate toward the surface. It would be easier to detect weak sounds near the surface than on the sea floor where our arrays are located. Another interesting factor arises from the fact that the sea ice is rough. The upward refraction ensures that the sound waves interact with the ice surface and they are scattered and absorbed. Only the lower frequencies with longer wavelengths tend to persist after multiple sound-ice interactions. In winter then, we can expect quieter conditions that will aid in detecting signals, but there will likely be a preference for the propagation of lower frequencies and losses in propagating to a bottom mounted receiver may be higher than they are in summer.

It is too early to definitively state the detection range performance of the NW arrays; however, a prediction of the performance has been created to illustrate the coverage area of the arrays for loud, moderate, and quiet acoustic sources. Figure 29 shows the estimated detection ranges for the three source levels (170, 150, and 130 dB//1μPa^2 @ 1 m). Part (a) of this figure shows coloured regions representing the detection range under the influence of median noise conditions during August. The source is considered to be a single 300 Hz tonal. The noise levels were taken from the JASCO Applied Sciences [7] and our own comparable noise measurements in August [16].

These detection range results are in good agreement with our observations. We routinely detected ship activity that according to space-based AIS data were 240-km or more distant and usually operating to the east of the Brodeur Peninsula. This result compares well with our prediction for the louder vessels. The MCDV, a moderately loud acoustic source, was detectable even when operating on the southern edge of the strait almost 70-km distant. The yellow prediction indicates that this coverage is possible. The detection range for the quiet source is surprisingly small. We did not have much opportunity to work with such low source levels, except for the dipped projector operations with 100 Hz. These signals were expected to be on the order of 145 dB and certainly they were detected to much greater range than that predicted for a quiet source. A detailed analysis is not yet complete, but the 100 Hz signals were detected to more than 25-km range, which is also in good agreement with the predictions in Fig 29(a).

Figure 29(b) shows a similar range prediction for the single 300 Hz tone, but this time the source is of necessity submerged due to the presence of an ice cover. The results shown in part (b) are speculative. Noise levels are taken from the JASCO results [7] and are the best available information. The transmission loss values are based on reported losses measured by others where the conditions were not always close enough to our conditions. Unfortunately, we do not have sufficient information to support more accurate predictions at this point in time. The winter time maximum range of detection works out to be similar to the summer time conditions. This is because while the noise levels generally drop, the losses at long range under the ice in winter were seen to be slightly higher in experiments. The range performance for moderate source levels is expected to drop, again this is largely due to the scattering and absorption under the ice layer, but there is some indication that the detection range for quiet sources may actually be larger than in summer. In this latter case there are fewer ice-layer interactions and the lower noise level is a benefit. All of these range predictions for winter are uncertain, but they are also pessimistic. In reality, the detection ranges could be substantially greater.

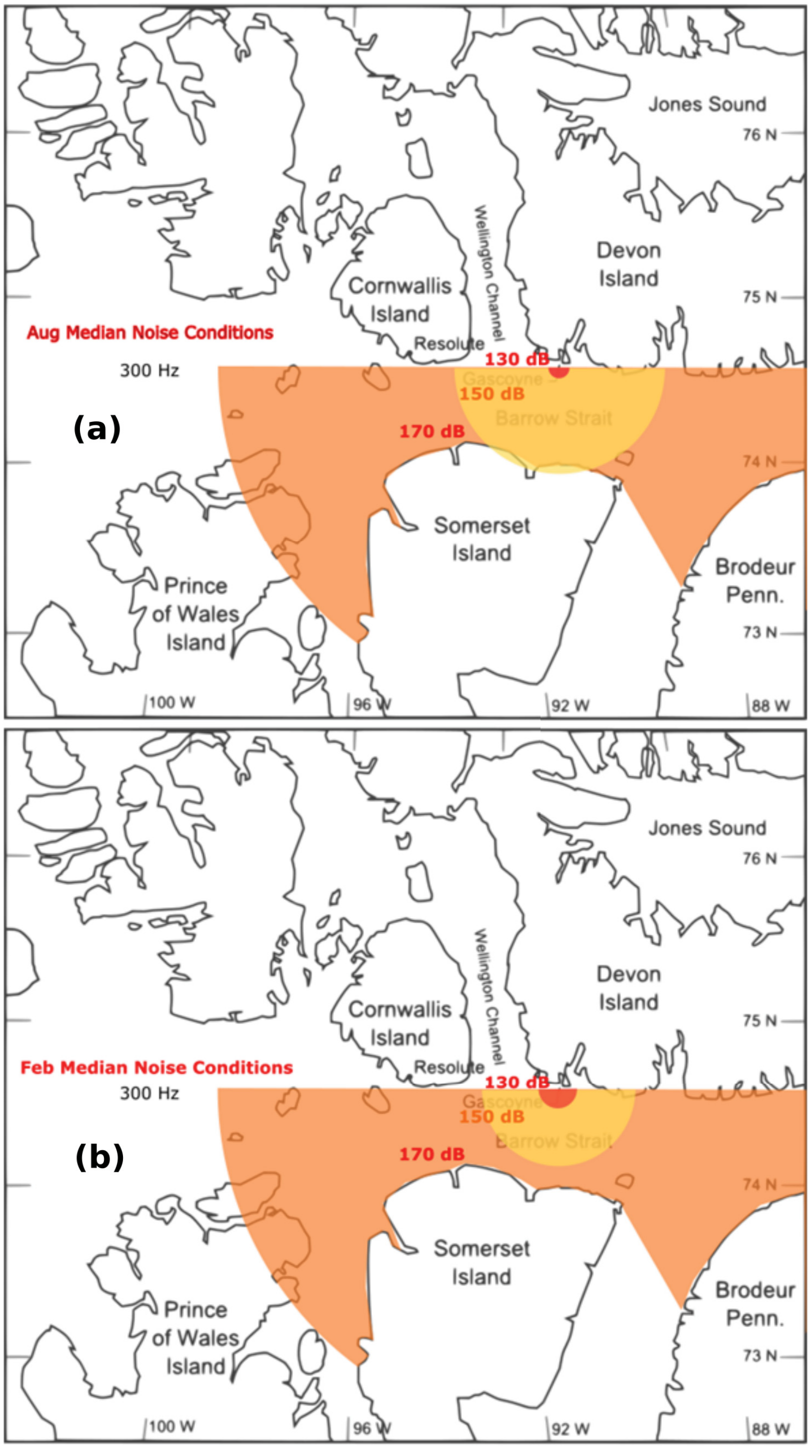

Figure 29: *Median range capability prediction for the NW underwater arrays working against a single 300 Hz tonal source. (a) Predicted and observed ranges for a surface vessel in summer time (AUG); (b) Loosely estimated ranges for winter conditions with ice cover and a submerged (60 m) source based on published loss estimates.*

4.1.3 The above water sensor performance

During the 2015 Capability Demonstration, AIS and radar were the two primary above-water sensors used for the surveillance of maritime surface traffic. AIS provides a capability to cooperatively track and identify vessels based on reception of their AIS transmissions (for vessels that are equipped with and operating AIS transmitters). Radar provides for non-cooperative detection and tracking of vessels.

The sensor coverage region for maritime surface traffic, using above-water sensors installed at the BIRDSEYE surveillance site, is illustrated in the plots of recorded AIS and radar tracks in Figure 30. These plots overlay all AIS and radar tracks recorded from 10 Aug–11 Sept. In comparing radar coverage against AIS, we observe that the radar coverage is more strongly constrained by the limited field of view from the BIRDSEYE surveillance site.

The maximum recorded AIS range was 83.3 km, while the maximum radar detection range was 39.6 km. These maximum ranges were obtained from the cargo ship CAMILLA DESGAGNES, on 6 September. Considering SHAWINIGAN, which conducted multiple runs as a cooperative target over the period from 2–9 September, the maximum range at which continuous radar tracks were maintained was 17.6 km; the minimum ranges at which intermittent radar tracks were observed varied between 12.1 and 16.3 km; and the maximum detected range was 26.9 km. Earlier in the project, DRDC Ottawa modeled the detection performance of the radar as a function of factors that included antenna height, target radar cross section, sea state and precipitation level. It was predicted that a larger vessel (having a radar cross section of 75 dBsm) would be detected at a range of 70 km (effectively across Barrow Strait) for an antenna installed at a 128 m elevation on Cape Liddon [35].

The detection, tracking, and identification performance of the AWAIR radar intercept and CANDISS EO/IR systems was demonstrated during the Summer 2012 trial at Gascoyne Inlet. For the X- and S-band radar installed on CFAV QUEST, the AWAIR system was able to provide coverage across Barrow Strait from a 55 m elevation. AWAIR produces bearings-only radar detections; as with the underwater arrays, location estimates can be produced by cross-fixing on bearings from multiple AWAIR systems.

Using the CANDISS EO/IR system, a recognizable ship's silhouette was produced at a range of 20 km for trials empoying CFAV QUEST as a target. Detailed images were producible at 10 km range. These results were obtained under best environmental and atmospheric conditions and performance was impacted by weather conditions such as fog, rain or snow (all of which were experienced in summer 2012). It is notable that because tourism-related vessel traffic (including cruise ships, yachts, and adventure sailors) tended to follow the north coast of Barrow Strait, the trial resulted in good opportunities for the shore-based collection of imagery.

The sensor coverage area for the detection, tracking, and identification of high-altitude commercial air traffic using ADS-B is illustrated in Figure 31. This data was collected during the Sensor Performance Trial conducted in August 2012[3]. A total of 77 fights by 59 aircraft were recorded over a period of 20 days. The maximum detected range using ADS-B was 424 km.

As demonstrated by data collected in 2102 for Twin Otter flights into and out of Gascoyne Inlet Camp and Transport Canada surveillance flights [25], the Rutter navigation radar is capable of detecting and tracking low-altitude local aircraft over flying the surveillance site. As well, the radar may have some capability to detect and track high-altitude commercial fights, based on experiments conducted in Ottawa [36]; however, this capability has not been confirmed during our Arctic field trials.

[3] ADS-B data collected during the 2015 Capability Demonstration was negatively impacted by damage to the ADS-B antenna that occurred early in the trial. The 2012 dataset is therefore more representative of ADS-B receiver performance.

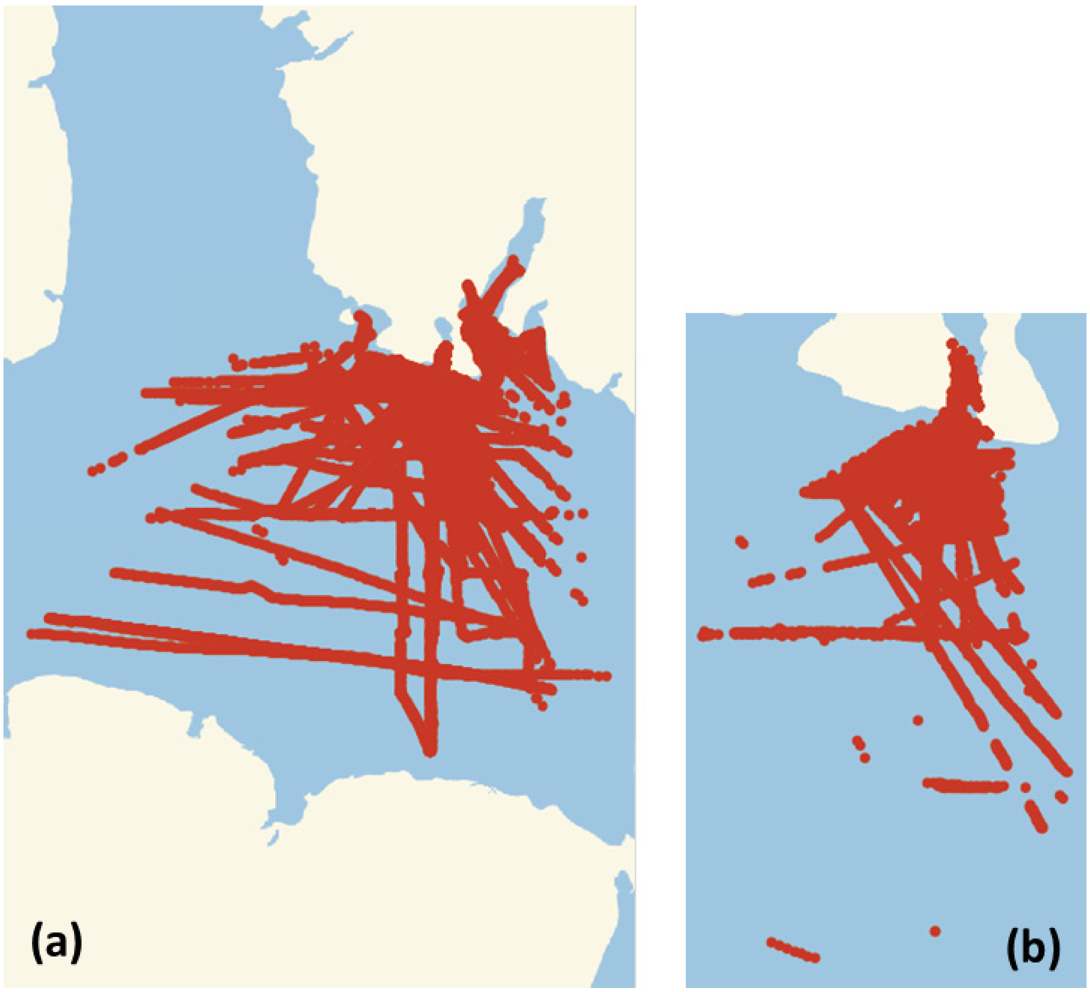

Figure 30: *Above-water sensor coverage for maritime surface traffic from the BIRD-SEYE surveillance site, 10 Aug–11 Sept, 2015. (a) Overlay of all recorded AIS tracks; (b) Overlay of all recorded radar tracks.*

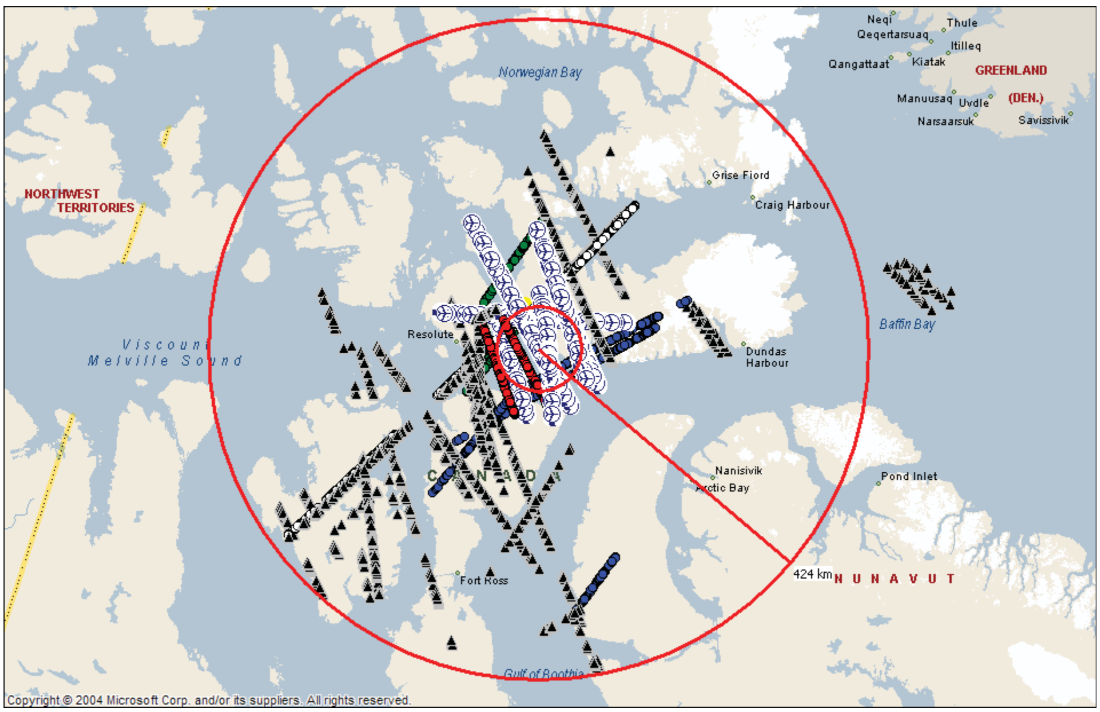

Figure 31: *Plot of all ADS-B data collected during the 2012 Sensor Performance Trial, August 2012. The outer red circle indicates the maximum observed range of 424 km and the inner red circle indicates the 50 km range inside which aircraft might be detected using the Rutter radar (from [8]).*

4.1.3.1 Comparison of local and satellite AIS

AIS data collected at the BIRDSEYE surveillance site over the time period from 10 Aug–11 Sept was compared against DRDC Atlantic's satellite AIS data feed (supplied by exactEARTH). With one exception, the small craft LS AXE07, an identical set of vessel transits within the local surveillance area was recorded by each source. LS AXE07, was detected in Radstock Bay, by local AIS only, during a two hour period on 1 September, and is assumed to have been launched from the cruise ship LE SOLEIL.

As expected, local AIS provides more continuous position updates than satellite AIS. In many cases local AIS simply confirms vessel positions that could be obtained by dead reckoning during gaps in satellite AIS coverage. Less frequently, local AIS adds new information to the vessel track that cannot be predicted based on dead reckoning. The latter case was observed in cases where gaps in satellite AIS were of long duration and the vessel was in the local area for an extended period of time. In the example, shown in Figure 32, for the small boat HAWK, local AIS provides additional data to fill a 33-hour gap between satellite AIS reports.

Conversely, satellite AIS was observed on occasion to supplement local AIS by providing updates while a vessel was transiting through a blind zone for the local AIS receiver. For example, many vessels were not continuously tracked by local AIS as they passed around Cape Liddon, on the way into or out of Radstock Bay.

4.1.3.2 Multi-sensor integration

Although automated picture compilation capabilities were not implemented in the NWSS, the benefits of employing these capabilities, such as reductions in the numbers of duplicate tracks and improved tracking continuity, were demonstrated during post-analysis. For example, the ability to maintain a single, continuous, track number on each detected contact was measured in an analysis of 34 separate vessel transits through the NW surveillance coverage area. Using radar data alone, at least one track number change was recorded in 24 of 34 events, with mean and maximum rates of track number change of 1.2 and 40 per hour. When radar data is automatically associated with AIS, track number changes occurred in only 2 of the 34 events, and mean and maximum rates of track number change were reduced to 6.6 X 10-3 and 0.13 per hour.

Radar, UWSS, and radar intercept are all capable of detecting vessels that do not self-report their position and/or identity (for example, by using AIS). By employing algorithms for automatic data association [37], it is possible to alert an operator to the possible presence of a non-reporting vessel. This was demonstrated as part of the analysis of the 2015 trial, using data from radar and AIS. Figure 33 (a) and (b) depict AIS and radar tracks collected on 23 August, 2016. Using algorithms developed for

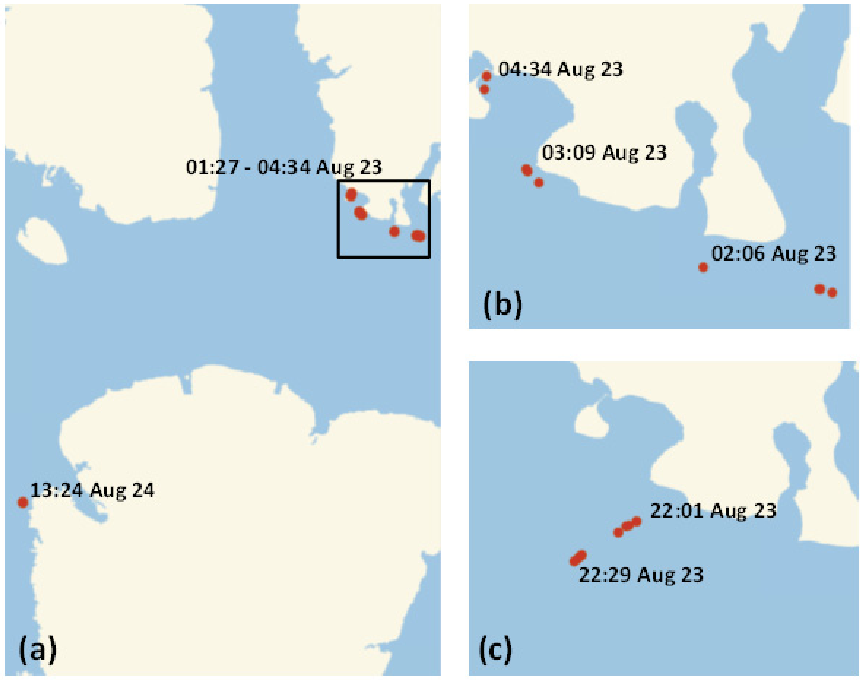

Figure 32: *Satellite and Local AIS data for small boat HAWK, 23–24 August. (a) HAWK is reported on satellite AIS travelling east to west along the south coast of Devon Island, in the vicinity of Gascoyne Inlet, from 01:27–04:34, 23 August. It then goes undetected for almost 33 hours, at which time a position report is received off the west coast of Somerset Island at 13:24, 24 August. (b) A zoomed-in view of the satellite AIS position reports received in the vicinity of Gascoyne Inlet (shown within the box in (a)). (c) Local AIS provides additional data for the time period 22:01–22:29, 23 August.*

automatic data association, it is possible to filter out those radar tracks which do not associate with AIS. The remaining radar tracks are shown in Figure 33(c). Ignoring short-lived tracks arising from clutter, there are two extended tracks, numbered 73 and 913, that are of interest as they may indicate possible unknown, non-reporting, vessels. Radar track 73 is almost certainly HMCS MONCTON, who was conducting a sidescan sonar survey of one of the array locations at that time and location. Based on satellite AIS, it is likely that track 913 originates from the small craft HAWK. The source of both of these tracks has yet to be verified.

4.1.3.3 Collection of meteorological data

In addition to surveillance data, the Northern Watch surveillance system also collected meteorological data that included wind speed and direction, temperature, barometric pressure, humidity, and solar irradiance. Meteorological data was transmitted to the Southern Control Centre on an hourly basis. The meteorological system also included

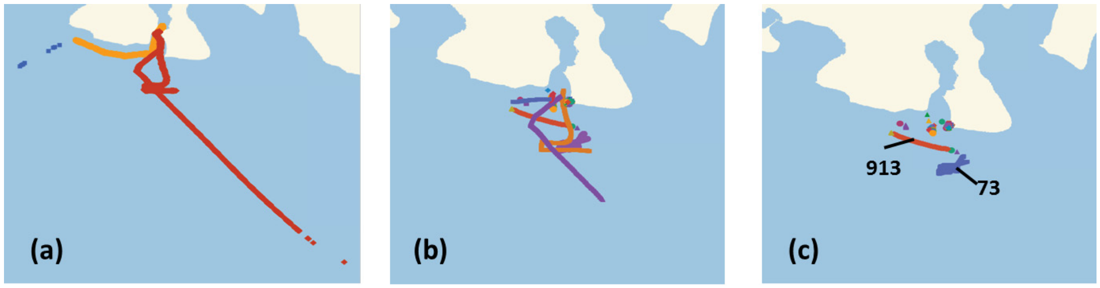

Figure 33: *Possible non self-reporting vessels, 23 August. (a) AIS tracks; (b) radar tracks; (c) radar track that cannot be associated with AIS. Radar tracks 913 and 73 are potential non self-reporting vessels.*

a low-resolution camera, pointed toward Barrow Strait, and used to enhance situational awareness of on-site visibility and general weather conditions. Camera images were transmitted south once every four hours. Sample meteorological data is depicted in Figure 34.

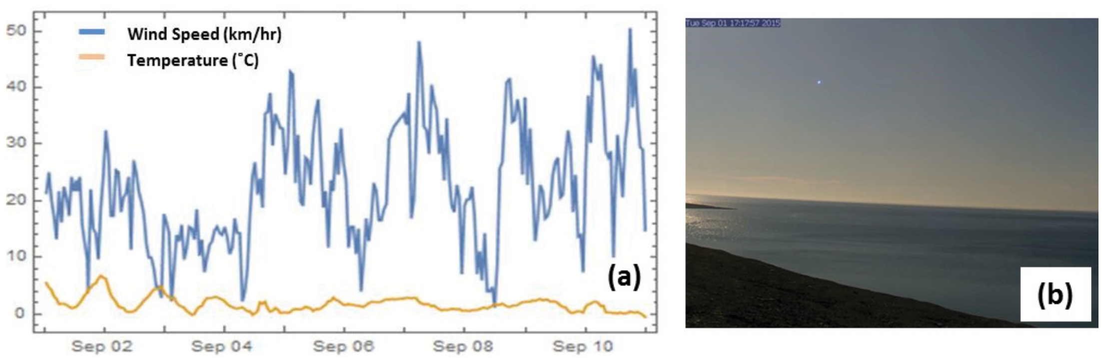

Figure 34: *Data collection from the meteorological system. (a) Wind speed and temperature data, 1–11 September; (b) Meteorological camera image, 1 September, 17:18 UTC.*

Meteorological data (primarily wind speed) was also used to support the real-time prediction of underwater acoustic array performance. A direct interface between the NWSS server and the PDS system was used to provide a meteorological data input to the PDS system's acoustic performance prediction module.

4.2 Demonstration of persistent, unattended, surveillance

Persistent surveillance of Barrow Strait was carried out from the manned Southern Control Centre, located at DRDC Atlantic Research Centre Dockyard Laboratory Atlantic, during the Capability Demonstration, from 10 August–11 September, 2015. Over that time period, the above-water sensors started data transmission on 10 August. Both underwater arrays were in operation by 26 August. After a period of calibration and testing to characterize array performance, the formal Capability Demonstration phase of the trial was conducted from 4–11 September.

Unmanned operation of the ASDS system at Gascoyne Inlet was emulated, with staff on hand to maintain power, provide system support, and conduct tests. For example, this meant that during array calibration hands-on testing of the arrays was conducted by staff at Gascoyne Inlet. However, during the Capability Demonstration the northern staff operated the ASDS system on a limited basis so as not to interfere with system operation from the Southern Control Centre[4]. The Southern Control Centre was manned from 3–6 hours per day, over the entire trial period, during normal working hours. Although longer-term (365 day) unmanned operation of the ASDS was not demonstrated, its possible future implementation has been supported by the design for an autonomous shelter and power generation system (or Habitat), as discussed in Section 3.4.

Key aspects of system operation that were demonstrated from the Southern Control Centre during the Capability Demonstration are discussed in the following subsections.

4.2.1 The Generation of a Local-Area Surveillance Picture

Many of the NWSS capabilities (operator tools, displays, database, data dissemination, etc.) are designed to support the compilation of a local-area surveillance picture. This picture contains the integrated information for all contacts transiting through the coverage area of the NW sensors. User tools for managing tracks are included as part of the NWSS local-area COP (Common Operating Picture) display, an example of which is shown in Figure 35.

One of the important aspects of the local-area surveillance picture generation is the creation and maintenance of system tracks. System tracks contain the integrated data from all sensors reporting on a detected contact. The maintenance of system tracks requires a data association process to determine that each of the sensor tracks comprising a system track originates from the same contact.

The NWSS system includes a basic set of operator tools for inspecting and manually associating (or disassociating) sensor tracks to form system tracks. For example, the operator can display the track histories of multiple sensor and/or system tracks as an aid to determining whether or not these are likely to correspond to the same contact. Then, using functions accessed from the local-area COP display, the operator can manually add or remove a sensor track from an existing system track. Execution of

[4] The system architecture permits certain ASDS functions, such as monitoring displays of processed acoustic data, to be performed by northern staff without affecting data transmissions to the Southern Control Centre.

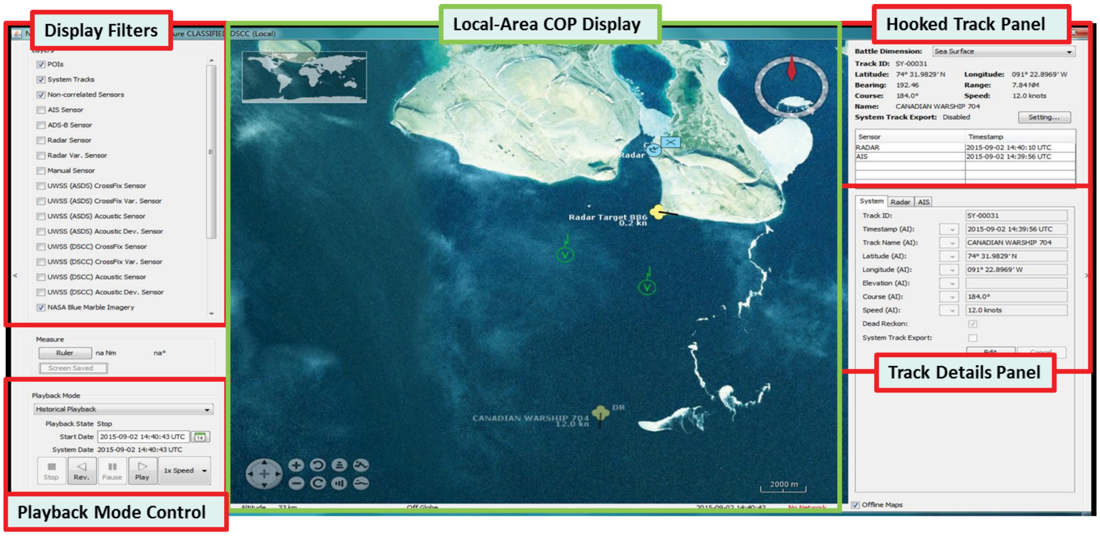

Figure 35: *NWSS local-area COP display. Detailed information about a track selected on the main situation display is provided in the Hooked Track and Track Details panels.*

the function results in the appropriate changes being made to sensor and system tracks in the track database. Subsequently, if the operator selects the system track on the COP, the data for each associated sensor track is displayed on the COPs Track Details panel.

Picture compilation can be performed in real-time or in a playback mode. The system includes a playback function that allows an operator to scroll backward and forward in time through the track database to manage previously recorded tracks. This supports the periodic manning concept for system operation described in reference [6]. Unfortunately, the system does not support raw data playback. Only the stored database records can be replayed.

The picture compilation process using manual tools is operator intensive and, as such, is only feasible for low track densities. Situations observed during trials where the manual process starts to break down include: i) the presence of many simultaneous acoustic bearing tracks originating from a single platform, or ii) the presence of highly-fragmented radar tracks, which tend to occur at the limits of the radar detection range. Examples of these situations are shown in Figure 36. The requirements for semi-automated and/or automated picture compilation capabilities are recognized, as discussed in reference [25].

Although automated picture compilation capabilities were not implemented in the NWSS, mature solutions for the automated integration of above-water sensor data have been demonstrated successfully in the lab using AIS and radar sensor data

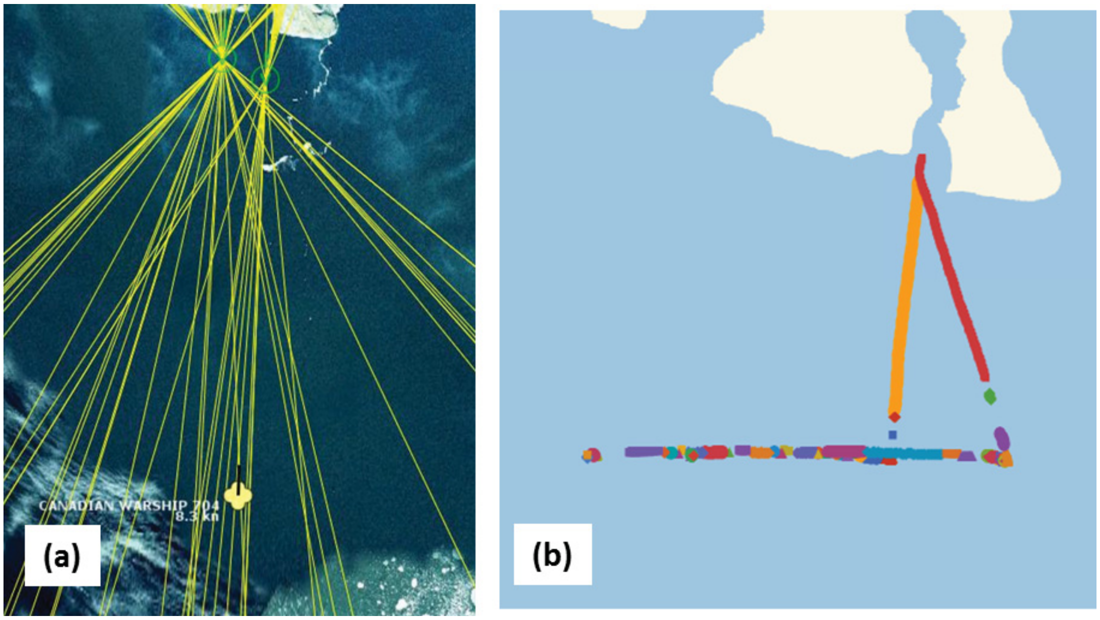

Figure 36: *Examples of situations that present difficulties for picture compilation using manual tools. (a) multiple acoustic bearings (shown as yellow lines) from both acoustic arrays—the AIS contact for HMCS SHAWINIGAN is visible at the bottom of the figure; (b) time history of 55 radar tracks corresponding to HMCS SHAWINIGAN over a 6.5-hour time period on 2 September.*

collected during the Arctic trials [38]. An example of the automatic association of AIS and radar is described in Section 4.1.1. Using automatic data association, radar tracks that associate with AIS are screened out, leaving those radar tracks that may represent a non-reporting vessel.

The automated integration of underwater sensor system data is a more difficult problem. At the present time, a very large number of acoustic detections and tracks are generated and there is no data association process running to collate the many different detections and tracks based on different frequencies and signal arrivals on multiple paths. Similar issues arise when there are multiple sources of acoustic noise, a common occurrence, and there is no association of the observed signals with the different sources. While potential solutions for the integration of above-water and underwater sensor data have been proposed and tested using synthetic data [39, 38], further research in this area is still required.

Until such time as mature solutions exist for the automated integration of underwater sensor system data, an operator will be required to manage acoustic tracks. This was demonstrated during the Arctic trial, with the provision of a PDS system in the DSCC in support of a southern acoustic operator. Acoustic bearing tracks selected by the acoustic operator were input to the NWSS. The NWSS system supported a dual mode of operation for the input of acoustic data from the PDS into the NWSS, with either: (a) the input of automatically initiated and managed UWSS tracks from the ASDS PDS into the ASDS NWSS; and (b) the input of operator-initiated and managed UWSS tracks from the DSCC PDS into the DSCC NWSS.

4.2.2 Dissemination of surveillance information products

Potential clients for information produced by Northern Watch include CJOC (Canadian Joint Operations Command), RJOC (Regional Joint Operations Centre), MSOC (Maritime Security Operations Centre), and for acoustic data, ADAC (Acoustic Data Analysis Centre).

The NW system supports the following mechanisms for the dissemination of surveillance information products to clients:

1. Generation of data messages. The NWSS system supports the generation of OTH-GOLD and XML-formatted output messages for (sensor & system) tracks and for meteorological data.

   An example of OTH-GOLD-formatted AIS sensor track data is shown below in Figure 37.

2. Generation of acoustic data products. The PDS produces several acoustic and non-acoustic image and data products that are available for distribution. Image products include acoustic source bearing and frequency images, and chart images with tactical overlays of acoustic, AIS, and radar contacts. The data products include the data files of the raw acoustic signals, AIS, radar data, and log files of acoustic and AIS contacts. All these products are available as files or through the PDS web service.

3. Installation of an NWSS terminal at a client site. During the Arctic trial the following procedure was used to test the dissemination of sensor track messages and acoustic data images to MSOC staff: (i) Data messages and acoustic images were generated using the NWSS and PDS systems in the DSCC and written to CD; (ii) the data on CD was air gap transferred to the DWAN (with appropriate scanning); and (iii) the data was e-mailed to MSOC staff.

   (a) The NWSS supports real-time access to the DSCC's NWSS COP from a remote computer running the COP application, assuming the provision of networked access from the remote site to the DSCC. This capability will provide the remote user with complete read-only access to all COP functions, including the generation of track data messages. Remote access to the NWSS COP over CFXnet was considered initially for the Arctic trial, but was dropped after it was decided to conduct the trial at the unclassified level.

(b) If networked access to the DSCC is not available, a stand-alone copy of the DSCC database and COP application running on a laptop can be provided to a remote client. This approach permits data replay using a snapshot of the track database and is being used in support of demonstrations to clients.

During the Arctic trial the following procedure was used to test the dissemination of sensor track messages and acoustic data images to MSOC staff: (i) Data messages and acoustic images were generated using the NWSS and PDS systems in the DSCC and written to CD; (ii) the data on CD was air gap transferred to the DWAN (with appropriate scanning); and (iii) the data was e-mailed to MSOC staff.

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CTC/00502/UNEQUATED-AKADEMIK IOFFE      ///MER//////30/////
/AI0000000502/UAUN   ///
AIS/273413400/8507731
RMKS/MMSI: 273413400 IMO: 8507731
DES/CROKER BAY          /OO/191500Z/AUG
XPOS/20104829Z6/AUG15/LL:743725.56N9-0912946.32W6/AIS
/294.0T/117.0M/18.0M/294.0T/12.3KTS////ACTFIX///
XPOS/20104729Z5/AUG15/LL:743721.18N3-0912903.06W0/AIS
/288.0T/117.0M/18.0M/289.0T/12.1KTS////ACTFIX///
```

Figure 37: *OTH-Gold formatted AIS sensor track message generated for the vessel AKADEMIK IOFFE, 20 August 2015.*

4.2.3 Communication and bandwidth management

Satellite communications (SATCOM) between the ASDS and DSCC were demonstrated during both CFMETR and Arctic trials, with a 256 kps link being utilized during the CFMETR trial and a 512 kbps link being utilized in the 2015 Arctic trial. During both trials the stability and availability of the SATCOM was excellent.

In order to manage the allocation of bandwidth between the NWSS and PDS systems, the surveillance system network architecture was structured to provide separate NWSS and PDS sub-networks for NWSS-to-NWSS and PDS-to-PDS communications between the ASDS and DSCC. Of the total 512 kbps satellite communications bandwidth, 128 kbps was allocated to NWSS-to-NWSS communications and the remaining 384 kbps was allocated to PDS-to-PDS communications. It was possible to change this bandwidth allocation under operator control by logging into the ASDS and DSCC network switches. The ability to automatically adjust the allocation in response to context-dependent bandwidth demands would be a useful extension to the current capability.

Both the NWSS and PDS systems were demonstrated to provide effective management of bandwidth. NWSS system bandwidth management was based on services provided by commercial Data Distribution Service (DDS) software. DDS was used to down-sample sensor data before transmission over SATCOM as well to cache data to manage data loss or interrupted communications. DDS time-based filtering (Time-Based-Filter Quality of Service policy [6]) enforces a minimum time separation between data samples. For example, AIS position reports, which have a native update rate of between 2 and 10 s (for vessels not at anchor or moored), are down-sampled to an update rate of 60 s. Time-based filtering can be applied independently for different sensors, message types, or even individual message IDs.

The bandwidth requirements for NWSS-to-NWSS transfers of sensor tracks, meteorological data and system status updates proved to be modest and were easily accommodated within the allocated 128 kbps bandwidth. This is illustrated in the two sample data captures of network traffic between the ASDS and DSCC NWSS systems that are presented in Figures 38 and 39. In the first sample, captured over a 5.5 hour time period during the CFMETR trial, on 4 Mar 2015, an average of 6.7 kbps was required for the transmission of AIS, ADS-B, meteorological, system status and, during the last 3.5 hours of the data capture, acoustic cross-fix data. It is noted that the volume of AIS and ADS-B traffic recorded at CFMETR was significantly higher than what is expected in the Arctic. For example, 66 vessels were reported at CFMETR over a 4 hour period on 4 Mar 2015 as compared against the maximum number of vessels detected by AIS over any 24 hour period during the Arctic Capability Demonstration, which was a total of 7 vessels. In the second sample, captured over a 2.75 hour time period during the final Capability Demonstration, an average of 5.3 kbps was required for the transmission of acoustic bearings, radar, meteorological and system status data. Figure 39 includes a breakdown of data by type, with the acoustic bearing data, at 3.1 kbps, being the largest consumer of bandwidth.

The PDS satellite channel was used by various system components to send and receive data. Bandwidth management became important when the data load was greater than the channel capacity. Many of the PDS services were unbounded in bandwidth usage and relied on the network infrastructure to manage the bandwidth usage. The network switches at both ends of the satellite channel were the primary bandwidth manager. If too much data was being sent, these switches would first queue the data to send later and then drop the data on a first-in-first-out basis if the queue be came full. The two commonly used protocols by the services were TCP and UDP. TCP is a synchronous protocol that is well behaved on limited bandwidth networks. The TCP

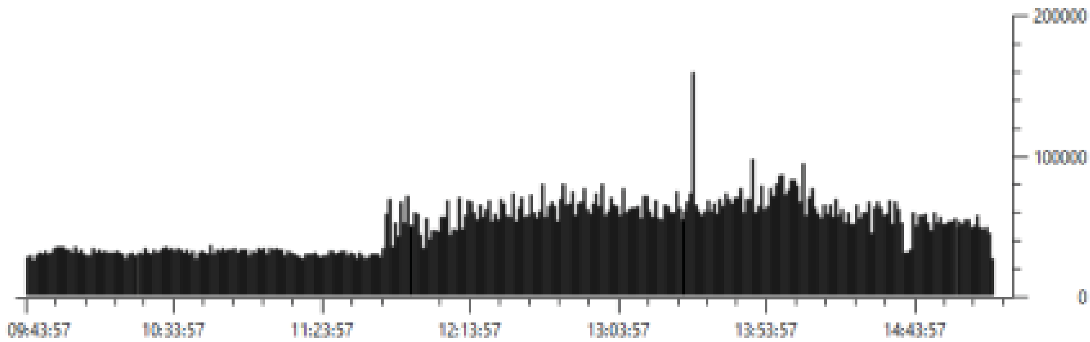

Figure 38: *Bar chart of DDS network traffic data volume transmitted from the NWSS ASDS, at CFMETR, to the NWSS DSCC, at DRDC Atlantic Research Centre, between 09:44 and 15:10 AST, 4 March 2015. Each bar represents a one minute time period; the y-axis scale is in bits/minute.*

sending service would not send more data if an acknowledgment for previously sent data was not received. This does not guarantee data delivery, but it does prevent data backup at the switch. UDP is an asynchronous send and forget protocol. Depending on bandwidth capacity, data sent by UDP could easily bog down the satellite channel.

The PDS also actively managed the allocated bandwidth. The PDS employed an information exchange service that queued out going data requests and streamed the data across the network at the allocated bandwidth. Each request had a priority and a life time. As each request is received, the service would insert the request into the queue based on the request priority. Periodically, the service would review the queue and remove requests that had been in the queue longer than their associated life time.

In general, the user decides on the PDS information that is required to be transferred to the DSCC in the south. This decision is made based on the available channel bandwidth and generally results in a subset of the northern PDS information being transmitted. Both NWSS and PDS systems support operator-initiated data transfers, which can be used to provide supplementary data in the case of a high-interest contact.

4.2.4 Remote monitoring and control

Remote monitoring and control of ASDS system components was demonstrated successfully from the DSCC in Halifax during the 2015 Trial using one or more of the following mechanisms:

1. NWSS status panel. The NWSS status panel provides status information, as well as alerts and alarms for most of the system components (other than the UWSS and PDS systems) installed at the ASDS and DSCC. The status panel provides:

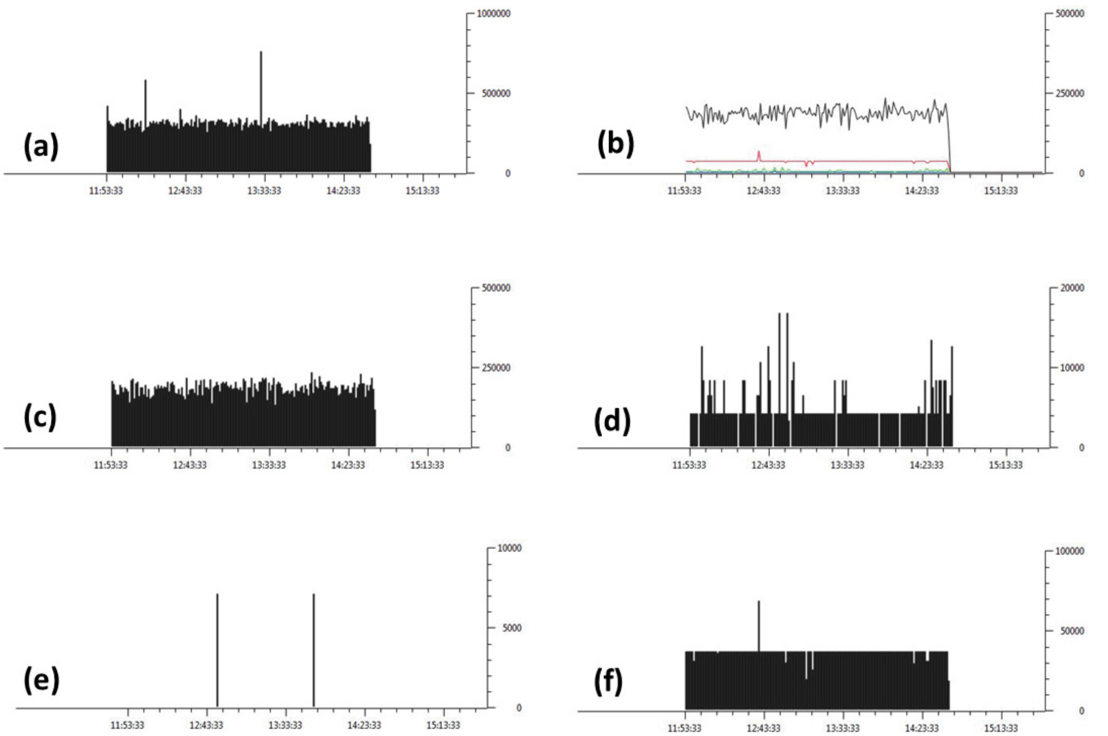

Figure 39: *Analysis of DDS network traffic transmitted from the NWSS ASDS, at Gascoyne Inlet, to the NWSS DSCC, at DRDC Atlantic Research Centre Dockyard Laboratory Atlantic, between 11:53 and 14:40 UTC, 10 September 2015. Data was captured and analyzed using the Wireshark tool. For bar charts, each bar represents a one minute time period; the y-axis scale is in bits/minute. (a) All DDS messages. (b) Decomposition of DDS network traffic by source type of: acoustic bearings (black); system status (red); radar (green); and meteorology (blue). (c) Acoustic bearing data messages. (d) Radar data messages. (e) Meteorological data messages. (f) System status messages.*

(a) Current and historical system status (current time, clock wander, system uptime, % CPU utilization, % disk space utilization) for NWSS servers installed at the ASDS and the DSCC;

(b) Current and historical status of sensor interfaces (on/off, time of last report) to the ASDS NWSS server;

(c) Current and historical logs of alerts and alarms logged by the ASDS and DSCC NWSS servers.

An image of the NWSS status panel, showing historical system status of servers and sensor interfaces, is provided in Figure 40.

2. PDS monitoring and control functions. The PDS provides user interfaces for:

status and control of PDS servers installed at the ASDS and DSCC, and status and control of the underwater arrays;

3. Web pages for networked sensors and system components. The majority of the third-party commercial sensors (AIS, ADS-B, meteorological, meteorological camera) and other system components (NTP servers, network switches) installed at the ASDS are network accessible and come configured with web pages for status and control. These web-pages can be accessed from the DSCC over the SATCOM.

4. Remote login. By default, all Unix servers (PDS and NWSS) installed at the ASDS support remote login. This capability was used extensively to conduct file transfers and system maintenance from the DSCC.

5. Remote desktop. System maintenance of Windows PCs installed at the ASDS was carried out from the DSCC using Windows Remote desktop. Remote access to the radar system user interface was achieved using the remote desktop application, UltraVNC. This permitted the remote monitoring of radar video as well as the control of radar operating parameters.

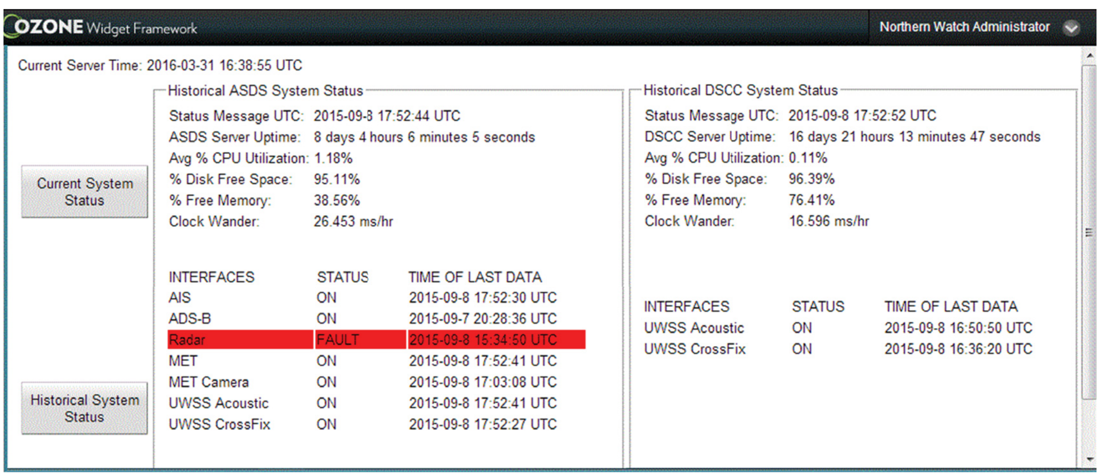

Figure 40: *The NWSS status panel displays status information for the NWSS servers installed in the ASDS and DSCC.*

While it was possible to demonstrate functional remote monitoring and control solutions using the methods outlined above, a more unified approach with a single user interface would be desirable for use in an operational system. As well, of the mechanisms listed above, the use of remote desktop for remote monitoring and control of the radar posed the biggest challenge given limited-bandwidth satellite communications. It was possible to change radar settings from the DSCC; however, long time delays for user interface operations made for a frustrating experience. One potential solution to this issue would be to dynamically re-allocate satellite bandwidth to the remote desktop application during the brief time periods when control of the radar is required.

5 Progress and lessons learned

This section of the report provides a brief summary of the accomplishments, short falls, areas and ideas for improvement, technical risks, and technical lessons learned.

Overall the NW project has been relatively successful. Of the six objectives for the project there has been demonstrable progress on each. Not all of the objectives were fully reached, but in almost all cases this was because it was necessary to scale back on the activities necessary to reach the objective due to limitations in the project budget.

5.1 Project accomplishments

The NW project accomplishments include:

1. Demonstration of a remotely operated Arctic surveillance system for a period of weeks;
2. Demonstration of concepts of integration for different sensor detections of a vessel;
3. Remote operation of the sensor system;
4. Management of limited resources, such as, communications channel bandwidth;
5. A reliable low-cost high-performance underwater sensor system with data processing and display;
6. Demonstrated deployment of an underwater array system from a CAF naval ship;
7. Collection of a large quantity of above and below water environmental data that can be used to aid in system performance prediction;
8. Improved Arctic scientific research capability within DRDC; and
9. Collection of information to support future Arctic surveillance concerns.

The project has demonstrated remote Arctic surveillance through limited duration field trials. The last trial in the summer of 2015 fully demonstrated a remotely operated surveillance capability. Unfortunately, the duration of the trial was a matter of weeks not the continuous 365 days, 24/7 persistent local area surveillance that was desired.

The integration of the different sensor detections and tracks was demonstrated, but required an operator to build the composite tracks. Laboratory grade algorithms were developed and tested for the integration of AIS and radar tracks, but these were not implemented within the NWSS. Integration of the underwater tracks was also demonstrated; however, an acoustic operator is required to preselect limited numbers of high priority signals. Without the acoustic operator, the large number of dissociated time-bearing measurements rapidly becomes unmanageable. Overall the integration of tracks from different sensor systems only partially fulfils the expected outcome. The underwater data, in particular, require significant pre-processing before being presented to the NWSS and even then the track data is expected to be difficult to integrate in a fully automatic fashion.

Remote operation of the NWSS was fully and successfully demonstrated. The only caveat here is that a variety of methods for communication with the system components was required. Further development effort is required to provide a single common status and control interface for all NWSS components. Such a development is not expected to be difficult.

Management of bandwidth was successfully demonstrated. The users predefined the available satellite bandwidth into two sub-networks. Network switches were the primary controllers of each of the sub-net bandwidths. The acoustic system was the most demanding component and additional queue based bandwidth control was demonstrated by the PDS.

NW and other projects have contributed to the development of the DRDC RDSAT arrays. The current array technology is versatile, robust, and significantly less expensive than other array systems that have been created or purchased in the past. The RDSAT system is capable of providing a high quality acoustic and/or heterogeneous sensing array with very good technical specifications.

Deployment of the arrays was demonstrated on several occasions using minimal specialized equipment. In the final demonstration trial, it was shown that a CAF Navy vessel was fully able to deploy arrays with no additional support.

The NW project included the collection of a significant quantity of supporting underwater environmental data for system performance prediction in Barrow Strait. Unfortunately, all of the data collected are for summer time conditions. No underwater data were collected in other seasons. In particular, direct transmission loss measurements under ice were not collected with the result that predictions for seasons other than summer is uncertain. Attempts were made to collect the required data, but they were not successful or had to be cancelled. An analysis of a one-year-long record of underwater ambient noise near Resolute was located and purchased [7]. This single record is a valuable contribution.

The NW project was quite successful at training a reasonable number of people for work in the Arctic. The project has helped increase the experience of our technical staff and expose them to operations on land and sea in the Arctic. There was limited cold weather experience generated, because most of the work was done in summer conditions; however, some camp maintenance and construction was carried out in the spring and this has helped build experience in harsh conditions.

Finally, the NW project has definitely increased our knowledge and experience with Arctic surveillance. We are currently far better positioned to advise on chokepoint surveillance at the completion of this project than we were at the beginning.

5.2 Project short falls and future improvements

Short falls in the project are somewhat hard to separate from future improvements in whatever projects might follow NW. Part of the reason for this is that the expectations of the project members and clients will vary and the details of implementation have never been fully laid out.

This section provides two lists: *Short Falls* and *Future Improvements*. The intention of both lists is to identify those areas where more work is required to produce an operational level system. In some of the listed items the additional work required is relatively small and straight-forward. For other items, the work can be difficult or expensive and may require a research effort.

5.2.1 Short falls

Long term operations The project operated the sensor system for two periods of several weeks. In reality we need to demonstrate long-term operations for a number of months. In order to do this, we need to develop, build, and test a sensor habitat. The project has provided a contract statement of work to do this and create a habitat suitable for one-year of unattended operation. The one-year period is fitting because fuel shipments to the Arctic are basically only possible on an annual basis. This is an expensive component, but not one of particularly high-risk. The problems are likely to arise dealing with equipment unreliability and issues of icing that might effect ventilation or sensor operation.

Totally unmanned operations Closely related to the 'Long Term Operations' element, this short fall considers the truly blind operation of the system and the physical state of the sensors and habitat. Although this has been partially accomplished during our testing phase there was some verbal and non-verbal communication taking place at some points in the testing. It is highly probable that a number of inspection cameras will be needed to provide the remote operator with information related to the state of vents, antennae conditions, and so forth. Devices such as these have not been included in our current system. In addition, the value of a true high-definition, telescopic, controlled camera will probably surface in these tests. This is a low-risk, but potentially high-effort work element that will need to identify the required *internal* system sensors and actuators that are necessary to maintain a complex remote system.

Integrated remote control interface The current NW system was capable of being fully remotely controlled; however, multiple system approaches were required. A single user at the southern station can control, re-boot, and configure the sensors and processors, but they are required to be a highly trained computer specialist. An operational system should be fully controllable through a common interface that reduces the need for a specially trained operator. This is a low-risk and relatively straight-forward development.

Environmental data The NW project collected a significant quantity of environmental data that is needed to assess system performance, but there were some missing elements that increased the risk to the project and made the system design uncertain. Each potential site of surveillance interest should have an environmental database constructed. This database needs to include terrain and bathymetry, high-resolution sea bottom maps, multi-year meteorological data, tides, above and below water ambient noise, seismic activity, above and below water thermal profiles, above and below water propagation speed profiles, light intensity, and marine and terrestrial flora and fauna, including human visitation. Where possible additional measurements of above and below water signal transmission loss and reverberation should also be collected for the common signal types. This data needs to be collected in all seasons of year and analyses conducted to provide the necessary statistical measures for assessment of common sensor performance. Much of this work is low-risk, but it requires on-going effort and expense. Such information has wide application beyond chokepoint surveillance.

Classified operations The current NWSS was designed for, but never tested in a classified mode of operation. Future applications of systems such as these may well enter into the classified information domain. Testing should be conducted to ensure proper system operations. In addition, direct connection to classified networks should be implemented. This element is low-risk technically, but can be difficult to implement and test with operational systems.

UW data pre-processing As described earlier, the UW arrays provide a significant amount of data and the development of the signal detection, association, and source localization and tracking algorithms is a complex problem. This is a research area and will require significant effort. Likely the best approach is to implement improved elements in a step-wise fashion, beginning with operator assists and eventually heading toward fully autonomous operations. This element should also consider abstract data analyses and approaches that are innovative and perhaps less directly related to human processes. Significant autonomy improvements can often be made by re-casting the problem to extract only the minimum information necessary for answering a specific problem.

Automatic track integration The NWSS relies on an operator to manually associate independent sensor contact tracks. Automatic algorithms for AIS and radar track association were developed, but were not implemented in the NWSS. The complex underwater sensors create additional problems for track association and considerably more effort is needed to automate their inclusion. This is a medium-risk, high effort element. Again, a step-wise approach is likely the best option. Improvements simply being uploaded as they are approved.

5.2.2 Future improvements

Minimize power consumption The current NWSS was created with only superficial attention to the overall power consumption. For example, the UWSS requires on the order of 700 W for the processors, telemetry, and arrays. Replacing the copper telemetry cables with fibre-optic cables and replacing the desktop computers with the latest high-end embedded processors could potentially reduce that power requirement to approximately 20 W. That represents a factor of 35 times energy saving for that sub-system. That single change could reduce the Habitat's fuel consumption by 3400 L/yr—a savings of 20 barrels of fuel per year (assuming 15 kW generator and 6 L/hr consumption)! Similar improvements are possible in other sub-systems as well. The NWSS could also be potentially hosted on newer embedded processors, the radar also could be more integrated, and most sensors could be operated at less than 100% duty-cycle. In winter, when there is ice cover, some sensors could be operated only at very low duty-cycles. Reducing total energy consumption can provide large cost savings in re-supply and man-power requirements.

Fibre-optic UW cables The UWSS currently employs copper cabling to supply power and data transfer. The actual NW arrays only require approximately 3 W each to operate, but the overhead of the cabling results in approximately 108 W of power being necessary. Ninety-four percent of this power can be saved by switching to custom fibre-optical cables. In addition, our tests with low-power fibre-optical interfaces indicate that we can easily increase the length of the cables to 75 km with roughly 1 W over-head. Extending the copper cables to such lengths would be prohibitive in cost and power consumption.

Optimized UW sensors As a result of our field tests in the NW trials, it is obvious that the UW sensors can be further optimized for the environment. Several options exist and they include smaller volumetric arrays that are easy to deploy and can directly estimate the vertical and horizontal signal arrival angles, larger

HLA with higher process gain, or combined HLA and vertical arrays. A system trade-off study is required. This study will need supporting data for noise and propagation losses in other seasons of the year.

Optimized UW sensor locations A preliminary study of array placement and orientation has been conducted and, ideally, with just two arrays we should place them near the opposite coastlines [40, 41]. It is also obvious that there would be benefits in deployment of the arrays in areas where the seafloor is not sloping. A further study of different array concepts and detection ranges should be done to support placement of various types of arrays.

Array deployment sensors Our experiences with the deployment of the NW arrays has led us to realize that it would be beneficial to include sensors in the arrays to specifically provide information for the deployment and the localization estimation. In particular, the incorporation of a number of strain sensors along the length of array could be very beneficial in understanding the deployment situation and the condition of the array on the sea floor. Multiple orientation and depth sensors would also be of considerable use for deployment and localization.

Array deployment software Real-time software analyzing the motion of the ship, data from the array being deployed, and information from the deployment system (cable strain and scope) would be an extremely beneficial aid during deployment. Incorporating maps and bottom-survey data along with GPS and ship's head and speed, combined with total acoustic power from each hydrophone, depth sensor information, orientation sensor information, and strain sensor measurements would allow the creation of an array location and shape estimate that could assist the users in deployment.

Instrumented deployment gear The NW UWAHS deployment gear provides no direct measurments and feedback to the deployment team. At a minimum two real-time measurements are required. These primary quantities are the cable scope and the cable strain. It would be useful to measure additional information, such as the differential GPS location of the UWAHS, ship's heading, ship speed, and a position estimate of a temporary noise maker attached at one or more locations along the array and cable.

High frequency UW sensors The current UWSS is a low-frequency detection system. It would be beneficial to have some high frequency capabilities in order to intercept forward-looking sonar and surface and bottom fathometer sonar pulses.

Additional sensor systems While the EO/IR and radar intercept systems were not integrated into the final surveillance system, each of these systems can contribute significantly to the local-area choke-point surveillance of maritime surface vessels, and should be considered for inclusion in any future development. The radar-intercept system can provide long-range detection, tracking, and identification, based on detected radar emissions. One or more of these receivers would be required as they are bearing only devices. The EO/IR system, while a shorter-range sensor and more affected by weather, is a primary sensor for classification and identification. Both of these sensors can contribute to the detection of non-reporting vessels and the verification of information from self-reporting sources, such as AIS. An atmospheric infrasound array and seismic detectors should also be considered as they will increase the aircraft and other asset detection capability. It is also recommended that wide-area information sources, such as satellite AIS, be included as inputs to the Southern Control Centre. These can be used to aid in the analysis of long-range detections (as was the case with the post-analysis of UWSS data) or potentially be used to provide automatic cueing of local-area surveillance sensors.

HF radio modem The NWSS was installed at a latitude where access to geostationary satellites is possible. If systems are required at higher latitudes they will have to rely on other means of communication. Polar orbit satellites are transitory in coverage and frequently provide an extremely limited bandwidth. It is unlikely that this situation will change in the near future; therefore, alternate means of communications should be investigated. One potential system of interest is the multi-channel HF radio modem. These radios make use of several 3 kHz bandwidth radio channels to increase the total data throughput. Such systems will likely not be able to match the bandwidth of 512 kbps used for the NW demonstration trial; thus, further data compression and bandwidth management tools will be required.

Raw data replay mode During the NW trials it was noted that the NWSS can only replay data already processed and stored in the database. This might be sufficient for the fully operational system, but it is a drawback for a developmental system. Without the ability to reprocess the raw data inputs, it is not possible to test new algorithms and improve results. For example, the underwater array locations were determined immediately following deployment, but were not available until the demonstration trial had begun and the system state was *frozen*. Since the system was processing using the planned nominal array/hydrophone position estimates and not the actual hydrophone locations, all the NWSS results from the UWSS are in error. This could easily be corrected by including a raw data replay mode.

Light weight UW arrays Due to the original difficulties with the all-plastic lightweight arrays, the NW project took a step backward in array construction toward more conventional structures. This included metal canisters and heavy protective shells at each hydrophone. The result is an excellent array, but the cost of the array has tripled and the weight of the array increased by a factor of ten times. In building the final NW arrays, the technology for building arrays was improved and the problem with water ingress essentially solved. Hydrophone structures and guards have also been subsequently improved by input from other projects. The result is that all-plastic, low-cost, light-weight arrays are now likely viable. Reducing the cost, size, and weight of the arrays has a major impact on the deployment difficulty and equipment acquisition.

Innovative sensor processing The NWSS is deeply rooted in conventional sonar processing and other signal analysis and presentation for a human operator. Replacing a human with an autonomous system is a difficult problem. There may be better solutions to the complex signal processing and analysis that are more tractable by asking a different type of question regarding what information is required to be determined by the sensor system outputs. For example, Heard and Pelavas [42] suggest that the UW processing could be made simpler, more autonomous, robust, and potentially requiring far less communication bandwidth by simply processing the detection of signals in different ways and subsequently clustering the detections. The types of clusters and the sequence of clustered detections can then be used to extract features concerning the source of the detection. Working in this way, the presence of an acoustic source, it's passage through the area, and estimates of the source location and speed can be made by relatively simple rule-based algorithms. The technique could identify the best interval of raw data or the conventional sonar images for transmission to the south. This technique is currently a concept only. It has not been developed or tested, but the authors believe that it may have considerable benefits and application to a number of sensors.

Low-data rate EM sea to shore signalling The NW system made use of a pre-drilled hole through the bedrock, that prevented the ice at the shoreline from tearing the UW cables apart. The hole began well above the high-tide and ice mark on land and emerged at depth beyond the range of the grounded sea ice. Such holes are expensive to create, but they do last a long time. In cases where UW sensors can be pre-processed and data rates are limited, it may be possible to transmit data at low rate through the bedrock using quasi-stationary electromagnetic fields [43].

5.3 Technical risks and lessons learned

This section deals with a number of risks and lessons learned that relate to the technical effort of development of equipment, field operations, and field trials of the system. There is a large overlap with the basic risks of logistics, transportation, weather, and supply. These particular risks are not addressed here, they have been listed by the Project Manager elsewhere.

5.3.1 Itemized risks & lessons learned

Icebergs Barrow Strait appears to be visited by icebergs and ice islands on occasion. Limited information from bottom maps indicate that there has been a long history of bottom scours from ice. Our understanding of the frequency, size of, and risk from icebergs has improved over the course of the project, but information is incomplete and the environment is changing. Predicting the likelihood of project-iceberg interaction is difficult. There were a couple of opportunities for catastrophic impact by icebergs during the NW project. In fact, we did lose a long-term ambient noise recorder following impact with an iceberg at 120 m depth.

Local area communications Communications within the local area and to ships in the vicinity was carried out with FRS (Family Radio Service) and Marine Band radios. Unfortunately, the comms were always difficult, especially to ships outside of the inlet due to the rugged terrain. There was never enough attention spent on setting up an adequate repeater on the nearby hills to facilitate local area communications. This was a significant risk and in the last demonstration trial, we would have had major issues if it wasn't for the fact that both the Camp and ship had satellite based Internet Email.

Environmental data This topic has been discussed in the Short Falls list; however, it was a risk and we need to ensure that we collect all available data early in future projects. We took a lot of risk in the array deployments in particular as we had and still have almost no detailed knowledge of the bottom. The impact on the cables could have been severe.

UW array deployment Although effort was spent was this topic, it was never considered a priority and the result is that even at the end of the project we could not guarantee a good array lay-down. It took a lot of negotiation to raise this topic to the point where effort and money was spent.

Stove-piped expertise Generally, the project kept the various components of the sensors and integration processing separate. This was a realized risk in that there was insufficient cross-area support and the barriers to collaboration only dissolved late in the project. Each sensor system was essentially isolated in development, sometimes by physical separation of the teams in different locations, but without sufficient feed-in to the development of the integration processing.

Contracting delays Activities, especially field trials, were often unconfirmed until just a day before hand. Sometimes this was related to the delay in contracts for services, transportation, and equipment. On more than one occasion plans were discarded or approvals came just in time.

Delayed financial approval Arctic work requires considerable application and planning in the year prior to a field activity. Since the fiscal year changed in April and trials occurred in August, the approval for funds were frequently just in time and usually only acceptable because we were given latitude by external organizations. This was a significant risk. Projects need to be assured of financial commitments from year-to-year in order to meet application and contracting deadlines.

Minimal pre-trial testing Due to the delays and long lead times, equipment often arrived too late for extensive testing and familiarization. A minimum two-year lead time is required for an Arctic Field trial involving new equipment built for the purpose. Where significant development and larger contracts are involved at least one additional year is required in the lead time.

Technical reassessment Some technical decisions should have been re-visited at intervals to see if they were still the best solution given our limitations. To illustrate, the UW array locations remained more or less fixed throughout the project due to cable limitations. Initially, the choice of cables and locations were a sound choice, but after experience and with time available, we should have investigated other options. In other areas we did make major changes, but more review should have occurred.

Sensor integration In retrospect, the goals of sensor integration and the procedures and techniques were not sufficiently well understood by all teams within the project. Sensor data integration was perhaps the most difficult component and it needed additional resources. There was insufficient understanding of what each sensor could provide and what it would require to associate information from the independent sensors. The nature of the sonar contacts and the difficulties of associating these contacts with other sensor results was a prime example. It was a learning experience.

Acoustic sources Due to rust-out of DRDC capabilities combined with uncertainty and limited access to ship support there was an on-going issue with generating UW sounds for testing and development. The project eventually put significant effort into the development of a towable acoustic source, but once it was functioning we were not able to use it due to limited ship availability. This was a major technical risk for the UW component of the project and will continue to be one for future projects.

Remote data collection Under current organization operating conditions establishing remote sensor systems, such as meteorological stations, that transmit data south is difficult. While we appear to have a working remote weather station with Iridium data transfer, we have never been able to receive the data from this system due to IT restrictions. The need for remotely monitored sensors and systems in the Arctic is going to increase. We need to find a way to make this work.

Long lead times A minimum of two years is required to start minor work in the Arctic. This is due to contracting times, advance application requirements, licensing, once per year shipping opportunities, and the Arctic climate. Any major activity requires at least an additional year.

Expense The cost of activities is a general risk already covered elsewhere by the Project Manager; however, the Arctic and remote operations puts extra demands on the project budget. The inability to visit a remote instrument, due to cost of travel and access limitations requires additional funding in the design and construction of that instrument. The risks of icebergs, storms, and animal intrusions all require that spares be acquired and plans be altered in a dynamic fashion often at the result of increased costs.

6 Conclusions and recommendations

The Emerging Operational Domains—Arctic Project, familiarly known as Northern Watch (NW) has now come to a largely successful conclusion. The project demonstrated the possibility of employing remotely operated, multi-sensor, surveillance systems at Arctic Chokepoints.

It was shown that it is possible to conduct surveillance for extended periods of time with these remotely controlled systems; however, one of our objectives of continuous 365-day, 24-hour, 7-day-a-week surveillance was not demonstrated. This short fall in the project objective was simply due to the cost of building, transporting, and installing the necessary power system, or habitat. The project developed a statement of work to cover the build of a habitat by a contractor [14]. The only remaining risk item for year-round operation is the assessment of performance in all seasons of the year. Again, largely due to costs, experimentation and testing was limited to summer-time conditions.

The project successfully managed surveillance system resources, such as, satellite bandwidth. Sensor detections and tracks were successfully integrated and the information used to build a local area Common Operating Picture. This particular objective may have fallen short in that track integration is an entirely manual process in the NWSS. Ideally, this process should be automated as an operator can be overwhelmed when there are many detections and tracks. Automatic track integration for AIS and radar tracks was demonstrated in the laboratory, but the algorithms were not implemented the NWSS. Additionally, the underwater sensor tracks are difficult to integrate and require the assistance of an acoustic analyst operator.

Remote control of the entire NWSS was fully and successfully demonstrated. The limitation on this component is that each computer, sensor, and device are independent in remote operation, and the operator must be highly skilled and knowledgeable. It is not expected to be a difficult task to simplify and make uniform the remote operation of all NWSS components.

The DRDC RDSAT underwater array technology [27] has been further developed by the NW project, other DRDC projects, and several international commercial sales to the point where it can produce robust, highly-capable underwater sensing systems at lower cost than most such systems. The array system is capable of working at any ocean depth and can be used for any array configuration large or small. The system can provide diagnostic information and will in the near future include subsidiary sensors to aid in deployment and localization of the array. The underwater arrays were coupled with the DRDC System Test Bed (STB) sonar processing capability [20]. The STB is an extensible system and as part of the NW effort it has the ability to create rudimentary tracks based on cross-fix localization estimates from two or more NW arrays. Advanced signal processing algorithms can be added in the future to further enhance the acoustic autonomy.

DRDC's in-house Arctic experience was significantly expanded by the activities of the NW project. Arctic experience had been continuously reducing due to the retirement of older staff members and NW provided training opportunities for a moderately sized group.

The NW project has refreshed our understanding of Arctic operations and built our technological experience. This report and others created during the project lifetime together with a series of briefings serve as a repository of information and guidance for future research and implementation.

6.1 Recommendations

Northern Watch has taken us well along the road to practical implementation of remote surveillance. It has also shown us where there remain areas requiring additional work. The following sub-section presents a list of recommended future actions.

6.1.1 List of recommendations for future work

Ambient noise A program of underwater and above water ambient noise measurements should be undertaken at the chokepoints, approaches, and ocean areas of interest. Conditions in the Arctic are changing and underwater noise in particular is expected to change. Electromagnetic noise may change as well, in part due to increased anthropogenic activities in the more accessible Arctic. Current day measurements and analyses for all seasons are needed to support prediction of acoustic and electromagnetic systems.

Sea floor surveys For cabled underwater systems detailed knowledge of the underwater terrain is required to plan cable routes and sensor locations. Accurate, detailed bathymetry is non-existent in most of the Arctic. High-resolution survey data suitable for cable route planning is rare. Areas should be prioritized and surveys conducted.

AIS networks AIS is an extremely useful tool in the Arctic. It relies on compliance, but it does provide valuable information. Local AIS has been shown to provide more detailed information and faster update rates than satellite based AIS. A network of AIS receivers should be established.

Environmental data In addition to ambient noise other data should be collected and analyzed for each area of interest. Meteorological data, light intensity, seismic, airborne sound, airborne and underwater propagation loss, tides, etc. As much information as possible should be collected and stored for easy access.

Signal processing More effort needs to be spent on basic and advanced signal processing. In particular, signal detection, association, localization, and tracking needs more support. Use of embedded processors for reduced power consumption and in-situ processing needs to be investigated. Many of the skills needed in these pursuits have been lost over time by DRDC staff.

Equipment development Due to the loss of CFAV QUEST, maritime operations in the Arctic have become increasingly expensive and difficult. We have had particular difficulties with acoustic projector systems and the availability of a ship to tow them. Traditional and innovative solutions, such as an AUV mounted projector should be developed to facilitate research in the Arctic. UAVs could similarly benefit above-water propagation and testing.

UW array deployment Instrumented arrays and deployment systems and software should be developed to facilitate a wide range of future activities.

In-ground EM signalling Quasi-static EM signaling should be investigated for application in moving low-rate data from the underwater to terrestrial domain without the need for a directionally-drilled hole through the bedrock.

Multi-channel HF radio Innovative solutions to limited satellite coverage in the Arctic should be investigated. HF radio is one possibility, high-bandwidth transient channels to nano-satellites is another.

Sensor location and type optimization studies A series of OR-like studies should be undertaken to investigate the optimal siting and type of sensors for all domains.

Power Systems Options for enduring power sytems and reducing system power consumption should be investigated.

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Annex A: List of Acronyms

Acronym	Meaning
ADAC	Acoustic Data Analysis Centre
ADS-B	Automated Dependent Surveillance—Broadcast
AEL	Array Element Localization
AIS	Automatic Identification System
AMAR	Autonomous Multichannel Acoustic Recorder
ARC	Array Receiver Controller
ASDS	Arctic Surveillance Demonstration System
ASW	Anti-Submarine Warfare
AUV	Autonomous Underwater Vehicle
AWAIR	Advanced Wide-band Adaptive Intra-Pulse Receiver
BC	British Columbia
CAF	Canadian Armed Forces
CANDISS	Canadian Night and Day Imaging Surveillance System
CD	Compact Disk
CF	Canadian Forces
CFAV	Canadian Forces Auxiliary Vessel
CFB	Canadian Forces Base
CFMETR	Canadian Forces Maritime Evaluation and Test Range
CFXNet	Canadian Forces Experimental Network
CJOC	Canadian Joint Operations Centre
COP	Common Operating Picture
COTS	Commercial Off the Shelf
CPU	Central Processing Unit
DCU	Digital Control Unit
DDS	Data Distribution Service
DFO	Department of Fisheries and Oceans
DRDC	Defence Research and Development Canada
DSCC	DRDC Southern Control Centre
EM	Electromagnetic
EMATT	Expendable Maritime ASW Training Target
EO/IR	Electro-optical/Infrared
FRS	Family Radio Service
GIC	Gascoyne Inlet Camp
GPS	Global Positioning System
HF	High Frequency
HLA	Horizontal Line Array
IR	Infrared
IT	Information Technology
LCM	Landing Craft Maritime

MCDV	Maritime Coastal Defence Vessel
MDA	MacDonald Dettwiler and Associates
MSOC	Maritime Security Operations Centre
MV	Motor Vessel
NTP	Network Time Protocol
NW	Northern Watch
NWSS	Northern Watch Surveillance System
OMG	Object Management Group
OTH	Over The Horizon
PDS	Processing and Display System
REP	Repeater
RDS	Rapidly Deployable Systems
RDSAT	Rapidly Deployable Systems Array Technology
RF	Radio Frequency
RJOC	Regional Joint Operations Center
SATCOM	Satellite Communications
SIF	Sensor Integration Framework
SOW	Statement Of Work
SP	Shore Patrol
STB	System Testbed
TCP	Transmission Control Protocol
UAV	Unmanned Air Vehicle
UDP	User Datagram Protocol
US	United States
UTC	Coordinated Universal Time
UW	Underwater
UWAHS	Underwater Array Handling System
UWSS	Underwater Sensor System
WAG	Wireless Array Gateway
XML	Extensible Markup Language

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This report constitutes a final deliverable of the Emerging Operational Domains—Arctic, or more familiarly, the Northern Watch (NW) project. The report provides a technical overview of the project, the objectives, and our progress toward meeting those objectives. The report describes the motivations, concepts, and history of the work effort. The sensors, the processors, and operation of the NW Surveillance System are also described. The capabilities of the system and its short falls are illustrated.

Overall, the NW project was quite successful and most of the short falls have arisen because the costs were beyond the reach of the project funding and; hence, had to be simulated or otherwise adapted to the realities of the situation. Although the project can be considered successful, considerably more work is required to bring an autonomous/remote-controlled multi-sensor surveillance system to practical reality. The report provides lists of accomplishments, risks/lessons learned, short falls, and future improvements to guide future efforts.

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submarines
submarine detection
hydrophones