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Employing Royal Canadian Air Force Sonobuoys for Passive Acoustic Monitoring of Whales

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The Royal Canadian Airforce (RCAF) is proud of its well-deserved reputation for environmental stewardship. With the advent of in-service low-frequency active sonar sources the RCAF is reviewing and updating policies and procedures to limit the potential impacts of active sonar on whales. During active sonar activities, passive sonar sonobuoys can be used to acoustically monitor for the presence of whales so that sonar operations can be shut down if an animal is too close to the active sonar source. Defence Research and Development Canada (DRDC) is assisting the RCAF to assess the effectiveness of in-service systems for marine mammal monitoring and mitigation. Case studies demonstrating the effectiveness of using sonobuoys for passive acoustic monitoring of marine mammals are presented using data collected in realistic scenarios.

1. INTRODUCTION

The Government of Canada has outlined a whole-of-government strategy to defend the health of Canada's marine environment; the Oceans Protection Plan[1] focuses on protecting marine species that are impacted by multiple anthropogenic threats, including anthropogenic noise. The Department of National Defence's (DND) major noise source is tactical active sonar used for anti-submarine warfare. Both Royal Canadian Navy (RCN) and Royal Canadian Air Force (RCAF) platforms can deploy active sonar: these include the hull-mounted sonar on the Halifax-class frigate, active sonobuoys dropped from the CP140 Aurora and CH148 Cyclone, and a dipping sonar used by the CH148 Cyclone. Active sonar use is often the only viable method of detecting a covert submerged target, and is thus critical to fulfilling DND's core mission to detect, deter and defend against threats to, or attacks on, Canada. In peacetime, sonar is used for readiness training, testing and evaluating systems, and developing new capabilities. Currently, there is no viable replacement for in-water training and testing in real environments with realistic scenarios. Thus, DND must carefully balance the potentially conflicting priorities of fielding a well-trained, combat-ready military, with observing its responsibility as an environmental steward and aligning with the goals of the Oceans Protection Plan.

DND has policies and procedures in place guiding the use of active sonar to mitigate its impact on marine mammals. The advent of in-service low-frequency active sonar sources and increased scientific insight about the impacts of active sonar initiated a review of the current approach to risk mitigation for active sonar usage, with the aim of updating policies and developing a broader understanding of the impacts of active sonar from a Canadian context. A review of the effects of "intense sounds" on marine mammals was recently conducted. This review was combined with an assessment of currently-in service RCAF sensors to propose actionable risk-mitigation strategies. This paper presents a brief summary of these findings as motivation for why the RCAF wants to assess the passive acoustic monitoring (PAM) capability of in-service sensors. The remainder of this paper focuses on two cases studies that demonstrate the effectiveness of using sonobuoys for PAM of marine mammals in realistic scenarios.

A. REVIEW OF EFFECTS OF ACTIVE SONAR ON MARINE MAMMALS AND RISK MANAGEMENT APPROACHES

Marine mammals rely on sound for many important life functions, such as communication and foraging. Sound is a natural phenomenon in all marine environments, and marine mammals have evolved in the presence of this natural soundscape. Anthropogenic activities, like active sonar, introduce additional sound into the marine environment. As such, active sonar has the potential to negatively impact marine mammals depending on:

- *Presence in an area where active sonar is being used*. Marine mammals must be in the ensonified area to be impacted. As a conservative estimate, the ensonified area can be equated to the zone of audibility as defined in Richardson et al.[2]. Understanding the site-specific propagation range of active sources is important to assess the overlap of the impact zone and marine mammal presence.
- *Characteristics of the sonar signal.* These characteristics include the frequency band, duration, and source level. In addition, the signal type can be important as some signals elicit a behavioural response at lower sound pressure level (SPL) values[4,3].
- *Hearing sensitivity.* Marine mammal species differ in their ability to hear sounds. This includes both absolute hearing sensitivity, as well as frequency band of hearing.
- *Proximity to the sonar source.* Marine mammals are more likely to avoid nearby sonar sources than more distant sources, even if the received SPL is similar. This is likely because a more proximate source is perceived as a greater threat[3].
- *Contextual factors.* Responses to active sonar exposure vary among individuals and populations. Contextual factors can include habituation stemming from prior exposure, and behavioural state at the time of exposure[4].

Current understanding of the impacts of exposure to anthropogenic noise – and sonar signals in particular – is insufficient for most species of concern. In part, this gap in knowledge is a result of large individual and species-specific variability in hearing sensitivity, as well as susceptibility to noise impacts in general. This variability, along with the fact that marine mammals are moving through complex sound fields, complicate assessments of impacts of sonar exposure.

To minimize the risk of harm during active sonar training and testing, DND employs a system of layered mitigations. These mitigations can be categorized in terms of strategic (plans-based and of long duration) and operational (employed immediately before and during active sonar use) mitigations. DND's primary strategic risk management strategy is avoidance; by conducting sonar training and exercises in areas where there is a low probability of encountering a marine mammal, the risks of adverse effects can be significantly reduced. During sonar operations additional mitigations are required to account for residual risks not addressed by the strategic mitigations. These include:

- *Mammal avoidance zones (MAZ)*: Sensor-specific MAZ were developed for in-service active sonars based on thresholds for causing temporary harm to marine mammal hearing[5].
- *Visual and passive acoustic monitoring:* Aircrews perform a visual search of the MAZ prior to commencing sonar transmissions assisted by electro-optical/infrared imagery, night vision, and passive acoustic monitoring, where practical.
- *Ramp up:* The active sonar systems capable of adjusting their source level increase the transmitted acoustic power over a series of attenuated steps prior to commencing full-power operations. The ramp up procedure can last between 2 and 30 minutes, depending on circumstance, and was motivated by the findings of von Benda-Beckmann et al.[6].
- *Shut-down procedures:* The MAZ is monitored by RCAF personnel who have been provided with marine species visual observation training. When a marine mammal is observed to enter within the MAZ, sonar operation ceases until the mammal is observed to have vacated the MAZ or the sonar source is relocated.

B. SONOBUOYS FOR PASSIVE ACOUSTIC MONITORING OF WHALES

The primary passive sonar sensors used by the RCAF's CP140 Aurora fixed-wing aircraft and CH148 Cyclone helicopters are DIrectional Frequency Analysis and Recording (DIFAR) sonobuoys (AN-SSQ 53D, 53F, and 53G). These DIFAR sonobuoys record three channels of data, such that the channels can be combined using trigonometric and phase relationships to produce both omnidirectional and directional acoustic data. The DIFAR acoustic signals are telemetered to an aircraft via a Radio Frequency (RF) uplink; these signals undergo real-time processing and analysis onboard the aircraft and are also recorded for post-flight analysis[7]. Calibration factors for both the omnidirectional and directional signals are known[7] and can be applied to the recordings to determine absolute sound pressure levels. The DIFAR sonobuoys used in the case studies in Sections 2 and 3 have a frequency band to a maximum frequency of approximately 2.5 kHz.

As in-service passive sonar sensors, DIFAR sonobuoys can be used as an operational mitigation measure for marine mammal monitoring (as described in Section 1.A); however, their recording bandwidth restricts the number of species that can be acoustically detected. All baleen whale species found in Canadian waters can be detected using DIFAR sonobuoys; whereas the calls/clicks of many odontocete species only partially overlap with – or completely fall outside – the recording bandwidth of the DIFAR sonobuoys. Using the sonobuoys in calibrated omnidirectional mode can increase the recording frequency bandwidth, with the tradeoff of losing directional information.

Employing sonobuoys for PAM of whales is complicated by the acoustic environment in which the whale vocalizations must be detected and the requirement to limit any additional workload for sonar operators. Automated detection, and ideally localization, of whale vocalizations in an acoustic environment cluttered with sonar transmissions is required to ensure that PAM is an effective operational mitigation measure. The first case study (Section 2) examines the ambient noise environment in which detections of whale vocalization must be made and the performance of automated detectors assessed in post-analysis using data from an active sonar exercise. The second case study (Section 3) presents results from using DIFAR sonobuoys for localization of endangered North Atlantic right whales in the Gulf of St. Lawrence.

2. CASE STUDY 1: PASSIVE ACOUSTIC MONITORING DURING AN ANTISUBMARINE WARFARE EXERCISE

A. BACKGROUND

CUTLASS FURY 2016 was an international antisubmarine warfare (ASW) exercise that took place from 13 to 21 Sep 2016. During this exercise there were active sonar transmissions from a variety of platforms,

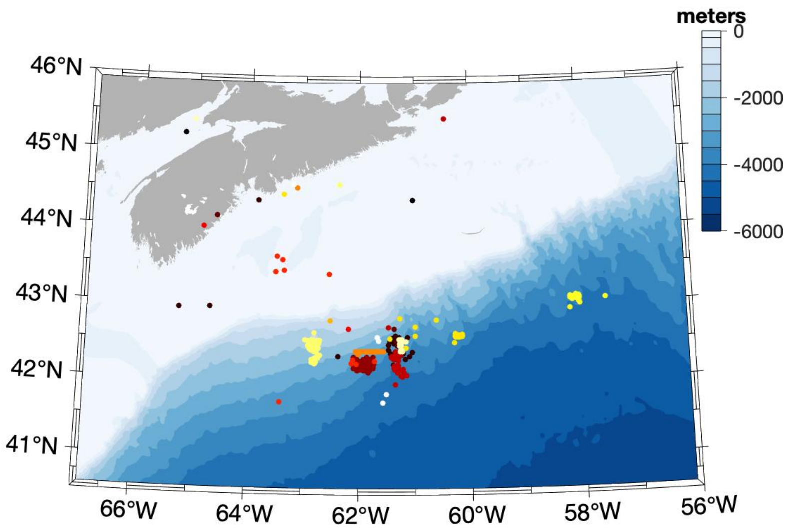

Figure 1. Drop locations of sonobuoys deployed between 13 to 21 Sep 2016. All sonobuoys deployed on the same sortie are represented by the same colour.

including hull-mounted sonar from naval ships, active sonar sonobuoys, and helicopter dipping sonars. The majority of sonar transmissions occurred off the continental shelf south of Nova Scotia.

Passive sonar recordings from 17 CP140 Aurora sorties were analyzed in post-processing to assess the performance of automated marine mammal detectors and classifiers in a realistic scenario. Locations of the sonobuoy deployments used in this analysis are shown in Figure 1. Recording durations for each sortie ranged between 0.5 and 4.5 hours, with 1 to 57 buoys used per sortie.

B. EXAMPLE ANALYSIS AND DISCUSSION

I. AMBIENT NOISE LEVELS IN THE PRESENCE OF ACTIVE SONAR

An important aspect of any detection problem is the noise environment. The first step in determining the ability to use automated PAM was to understand the noise environment. Specifically, we assessed the variability in noise levels as a function of frequency in a sonar-cluttered environment. Analysis time periods were selected to overlap with periods of active sonar transmissions from hull-mounted sonars and active sonobuoys. Some of the sonar transmissions were above the frequency bandwidth of the DIFAR sonobuoys.

The one-minute average decidecade SPLs were computed from the DIFAR recordings. Any data contaminated with radio static or interference on the sonobuoy channel was discarded. There was a total of 11299 minutes of acoustic recordings used in this analysis. The resulting SPL distribution is shown in Figure 2. Increased variability was noted in the lower frequency bins which may be explained by flow noise since the sonobuoys are free-drifting systems. The peak at 20 Hz is due to fin whale presence, and the peak at 63 Hz is associated with shipping. The median values of the 1250, 1600, and 2000 Hz bins are elevated by approximately 2.5 dB re 1 μPa^2, and the 90th percentile values by more than 15 dB re 1 μPa^2 as a result of sonar transmissions. Note that this does not represent the full impact of sonar transmissions on ambient noise levels, since there were also sonar transmission outside the bandwidth of these recordings.

Framing these results in terms of detection theory, the 10th and 90th percentile SPL values are used to assess the impact of sonar levels on minimum and maximum detection ranges, respectively. In the absence of sonar, one would expect the noise levels to be lower than those measured, consistent with the negative linear slope of the spectrum between 63 to 1000 Hz. The results in Figure 2 show only a small impact on the 10th percentile levels; thus, theoretical maximum detection distances were largely unaffected by the sonar transmissions. The ~3 dB re 1 μPa^2 change in median SPL indicates a 50% reduction in median detection range. The theoretical minimum detection ranges were greatly affected for signals with energy overlapping the sonar band, since there is a large change in the 90th percentile noise levels.

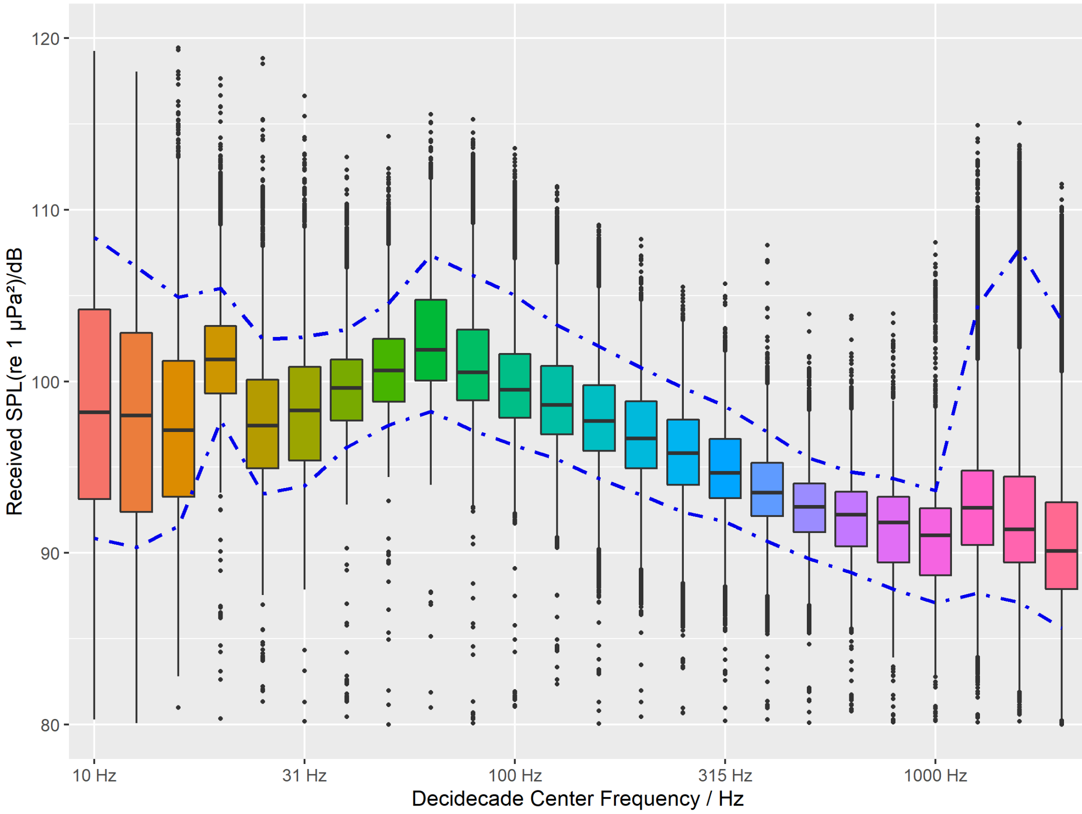

Figure 2 Distribution of 1-minute decidecade SPL recorded on sonobuoys during periods of active sonar transmissions. The median SPL is represented as the thick line in the box plots. The bottom and top of the boxes are the 25th and 75th percentiles, respectively. Dashed lines below and above the boxes are the 10th and 90th percentiles. Dots represent outlier values.

II. PERFORMANCE OF AUTOMATED DETECTORS IN A SONAR-CLUTTERED RECORDING ENVIRONMENT

An experienced marine mammal acoustic analyst manually annotated recordings from 66 of the 376 sonobuoy recordings in post-processing. Given time constraints, the analyst was unable to manually annotate all sonobuoys from each mission. Instead, the analyst focused on time periods with overlapping occurrence of both marine mammal vocalizations and sonar transmissions. These annotations were used as truth detections for determining the performance of automated detectors/classifiers.

The analyst noted the presence of blue, fin, pilot, and sperm whales. Given the frequency bandwidth of the recordings (i.e., $f < 2.5$ kHz), we did not expect to detect the presence of most odontocete species. Fin whales' 20 Hz pulse was the most common signal detected. The signal-to-noise (SNR) statistics of all annotated calls are summarized in Figure 3. Sperm whale clicks had the lowest SNR; the SNR of these clicks was at the limit of detectability for most automated detectors, and even for the experienced analyst.

JASCO Applied Sciences' click[8] and tonal[9,10] detectors were applied to sections of the data with 100% manual analysis (i.e., the analyst annotated every marine mammal vocalization). The click detector is based on zero-crossings in the acoustic time series and uses the features of these zero-crossings for classification[8]. The tonal detector identifies continuous contours of elevated energy and classifies them by comparing to templates of marine mammal signals[9,10]. Precision, P, and recall, R, were used to assess the detector performance. These complementary performance metrics are defined as,

$$P = \frac{TP}{TP + FP} \quad \text{and,} \tag{1}$$

$$R = \frac{TP}{TP + FN} \tag{2}$$

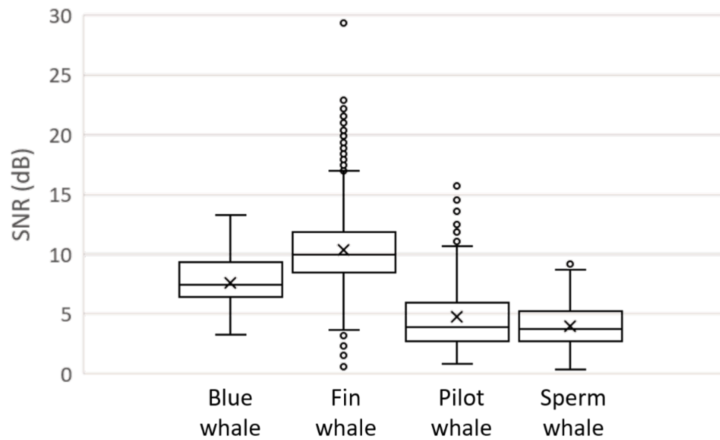

Figure 3. SNR of all calls annotated by an experienced analyst.

where *TP* is the number of true positives, *FP* is the number of false positives, and *FN* is the number of false negatives. Precision (sometimes referred to as positive predictive value) indicates the proportion of all detections that were true detections, and the recall (sometimes referred to as the true positive rate) indicates the proportion of all calls in the acoustic record that were correctly detected.

Precision-recall curves presented in Figure 4 summarize the performance of the automated fin and sperm whale detectors as a function of SNR. These results are based on performance per vocalization in segments of the acoustic record for which the analyst manually annotated all calls. The performance results were binned into ten SNR categories for each mission analyzed. Four missions were included in the fin whale analysis, and only one mission was included for the sperm whale analysis (due to the time-consuming nature of annotating all sperm whale clicks). Although blue and pilot whale vocalizations were annotated in these files, there were no automated detections because the SNR of these signals was too low and the calls were too distorted by propagation effects to trigger the automated detectors.

An ideal detector is characterized by $P = 1$ and $R = 1$. A good detector will have points on the precision-recall curve in the upper right region of the plot. The results in Figure 4 demonstrate that these detectors have better precision than recall. This is not surprising, given that the detectors were initially designed to ensure detection of species presence in 5–10 minute intervals without generating many false positives. The detectors were not designed to capture every call. That is, the detectors were designed to prioritize high precision, even at the sacrifice of recall.

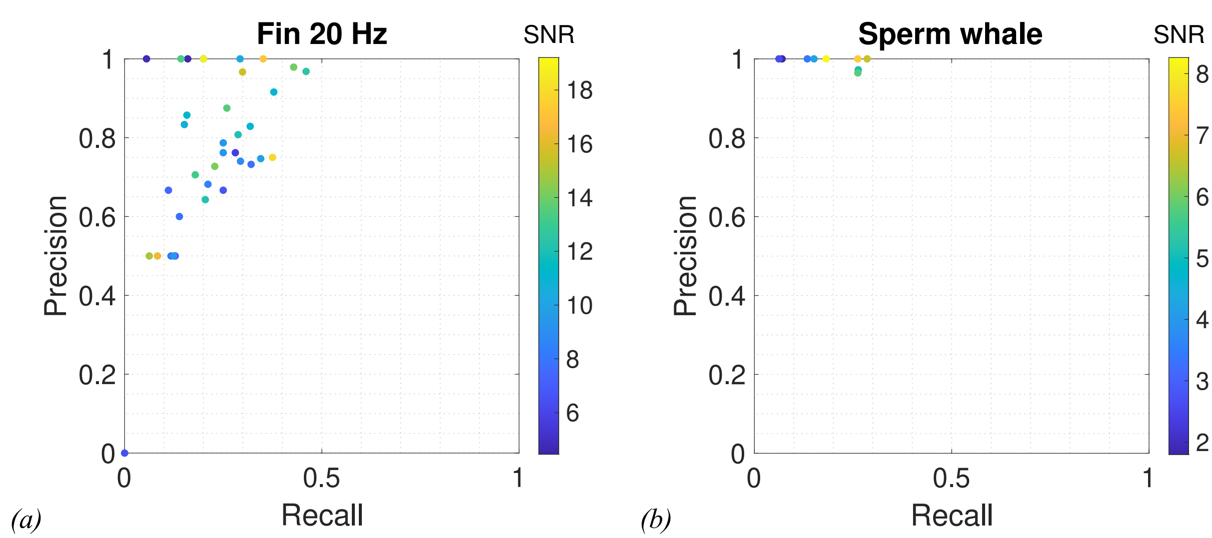

Figure 4. Performance of the automated (a) fin whale and (b) sperm whale detectors as a function of SNR.

The sperm whale precision-recall results (Figure 4b) indicate a relationship between detector performance and SNR; that is, although the precision is excellent across all SNR values, the recall rate increased with increasing SNR. This trend is not apparent for the fin whale detection results. In general, the precision was higher for high SNR calls than for low SNR calls for the fin whale detector (Figure 4b), although there were a few outliers.

Depending on the detection scenario, these detectors may be appropriate as currently implemented; however, higher recall values are required during pre-sonar activation PAM, particularly for less-vocal species. Future work is required to refine the detectors and select appropriate detection thresholds to increase the recall. Increased recall will likely result in lower precision and require a human analyst to manually verify detections.

3. CASE STUDY 2: NORTH ATLANTIC RIGHT WHALE DATA BLITZ

A. BACKGROUND

DND partnered with Dalhousie University, Transport Canada, Fisheries and Oceans Canada (DFO), and the National Oceanic and Atmospheric Administration (NOAA) to coordinate a data collection effort on the North Atlantic right whales (NARW) in the Gulf of St. Lawrence. NARW are listed as endangered in the Species at Risk Act[11], and there are many ongoing efforts to enhance conservation and management efforts for this species. A coordinated effort, like the one described here, is invaluable for collecting multi-modal data that can be used to better manage anthropogenic impacts on this species.

This two-day data blitz took place 30–31 July 2018. DIFAR sonobuoys were deployed and monitored by the RCAF to record passive acoustically for approximately 6 hours each day. A field of 32 sonobuoys was deployed each day, with approximately 8 km between drop locations. The sonobuoy deployment locations are shown in Figure 5. Dalhousie University deployed a Slocum glider to collect oceanographic information and conduct acoustic recording. The glider also performed real-time passive acoustic detection and classification using the digital acoustic monitoring (DMON) acoustic package[12]. Concurrent visual surveys were conducted by Transport Canada, DFO, and NOAA by boat and aircraft.

B. EXAMPLE ANALYSIS AND DISCUSSION

An experienced analyst reviewed the sonobuoy acoustic data and manually annotated all occurrences of NARW calls. The results presented in this paper focus on the acoustic data collected on 31 Jul 2018. A summary of the manually annotated calls is presented in Figure 6. In total, 1279 NARW calls were detected; of these, 375 were gunshot calls, 118 were mid-frequency tonals, 347 were screams, and 439 were upcalls. Gunshot and scream call types were most frequently detected on sonobuoys nearest the main cluster of visual sightings, whereas the upcall and mid-frequency tonal call types tended to be distributed at the south-west corner of the array.

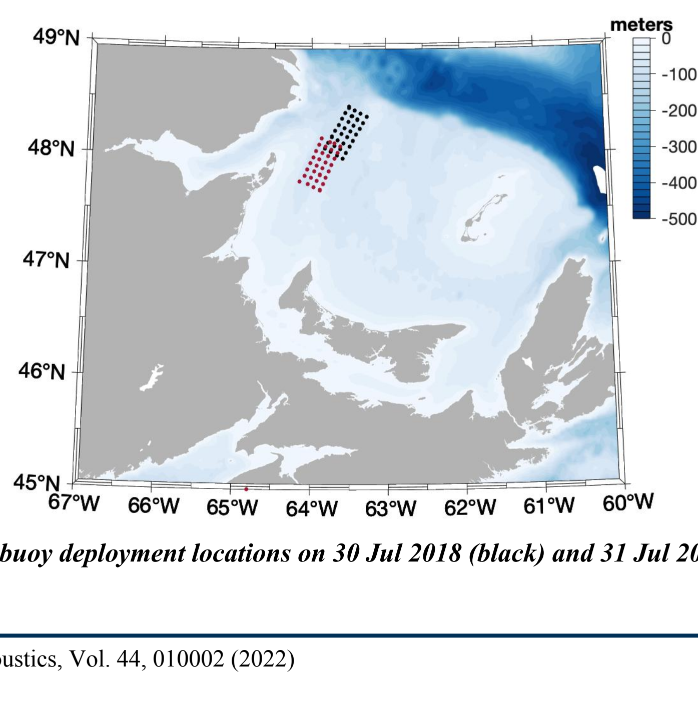

Figure 5. Sonobuoy deployment locations on 30 Jul 2018 (black) and 31 Jul 2018 (red).

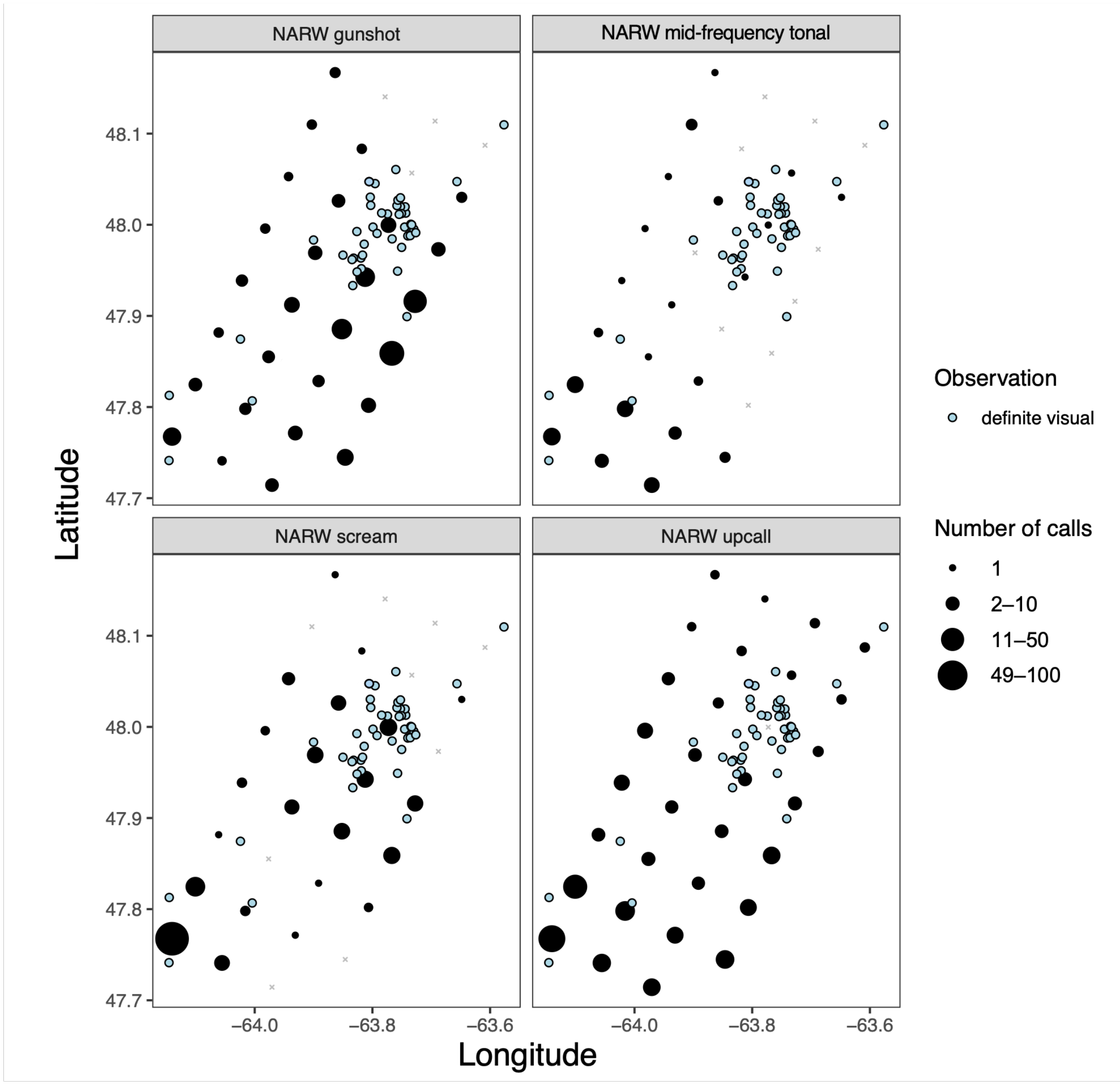

Figure 6. Spatial distribution of manually annotated NARW calls from each sonobuoy and visual observations (from boat and aircraft) on 31 July 2018.

I. LOCALIZATION OF NARWS

Localization estimates of NARW calls were determined using bearing estimates from the DIFAR sonobuoys[13,14] for the manually annotated calls. A localization estimate of a single whale call is made at the intersection point of two or more bearing estimates from sonobuoys that detected the same call. Each localization estimate has an inherent uncertainty due to e.g., compass accuracy, geometry of the sonobuoys, and uncertainty in sonobuoy position (the scale of position uncertainty is discussed in Section 3.B.ii). The uncertainty in a localization estimate is represented as a 2D area where bearing segments overlap (see Figure 7 for periods starting at 18:35 and 18:45).

In this analysis, bearing estimates were grouped into 5-minute temporal segments to show trends in calling behaviour with time. Examples of these results are shown in Figure 7. The bearing estimates have a precision of approximately ±5° and are represented as radial segments centered around the bearing estimate. The search area was divided into a grid; at each grid point the number of overlapping radial segments were counted. Regions with a large number of overlapping radial segments are indicative of a group of vocalizing whales (or possibly a very vocal individual whale).

The localization results in Figure 7 show some interesting patterns in calling behaviour. For example, the calling rate was not constant throughout the 35-minute period displayed, as there were some periods when few (periods starting at 18:25, 18:35, and 18:45) or no (period starting at 18:40) detections were made, whereas the

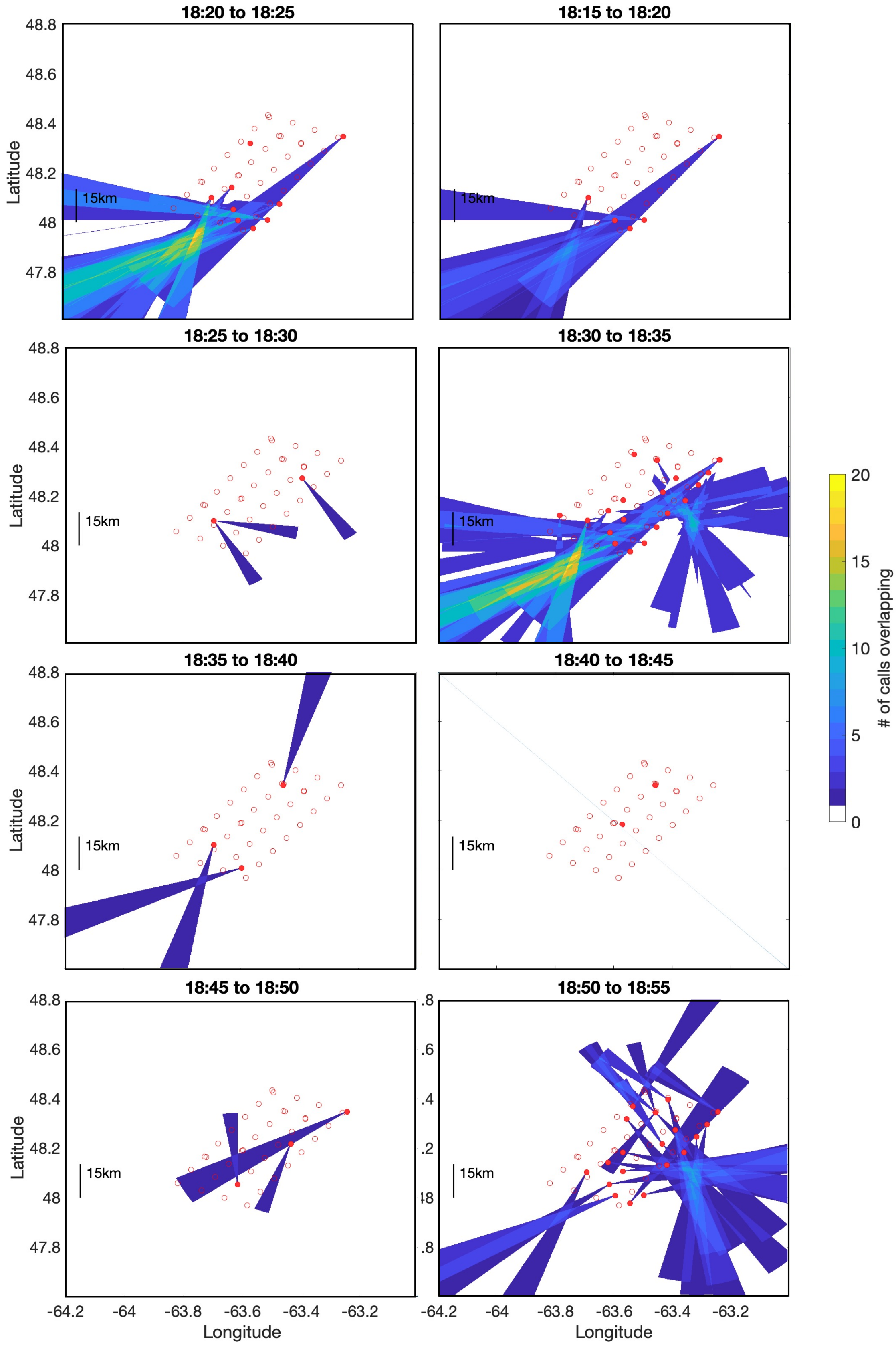

Figure 7. Localization estimates of NARW calls in 5-minute temporal segments. Bearing segments are displayed for each call based on a precision of ±5°. Circles represent sonobuoy deployment locations; filled circles indicate which sonobuoys contributed to the detection count.

other periods were characterized by higher calling rates. Localization results are indicative of at least two different groups of calling NARWs: one south of the array, and the other east of the array. Acoustic localizations to the south of the array were verified by nearby visual observations.

II. IMPACT OF SONOBUOY DRIFT ON LOCALIZATION PERFORMANCE

Unlike a moored hydrophone array, individual sonobuoys can drift freely such that the array becomes deformed over time. Figure 8 shows the GPS-derived locations of the sonobuoys over the approximately 6.5 hour period the sonobuoys were deployed on July 30. Local differences in drift were observed, with some of the sonobuoys drifting only short distances, and others drifting ~7 km. Not all sonobuoy types regularly update their positions via GPS; in these cases, aircrews localize non-GPS buoys by flying close overtop of each buoy to update position using RF. The position bias can then be accounted for with an updated position estimate however, this relies on the aircraft flying low over the water where they are unable to maintain a good RF link with all sonobuoys in the array, resulting in periods when no acoustic data is recorded. Thus, there is a trade-off with non-GPS buoys between having frequent position updates, but possibly generating gaps in the acoustic record for some of the sonobuoys. This section of the paper considers how localization performance may be affected by infrequent position updates to assess if it is necessary to use GPS-enabled buoys for regular position updates.

The probabilities of simultaneously detecting the same call on two, three, or four sonobuoys were determined using a parabolic equation propagation model to model transmission loss (TL) based on the sound speed profile measured by the glider during the experiment. Source levels (SL) for gunshots, mid-frequency tonals, upcalls, and screams of 183, 166, 153, and 149 dB re 1µPa @ 1m, respectively were obtained from the literature[15,16,17]. Source depths of 2.5, 5, and 10 m were modelled. Ambient noise estimates were calculated from the acoustic recordings. There were thus 12 different TL values determined for each grid point in the model region (combinations of 4 frequencies and 3 source depths). A signal excess of 10 dB was assumed to allow sufficient SNR for a good localization estimate. The probability of detection, P_d, is determined from

$$P_d = 1 - P_m \tag{2}$$

where P_m is the probability of missed detection. The value of P_m is determined by generating a distribution of RL = SL – TL (where RL is received level) and setting the detection threshold at the value of NL + SE (where NL is noise level and SE is signal excess). P_m is then determined by integrating the area of the RL distribution for values less than the detection threshold.

The probability of detection results in Figure 9 show that there is a high probability of detecting the same call on at least 2 sonobuoys anywhere within the sonobuoy field. This is good, because detection on at least two sonobuoys is necessary for a cross-fix localization estimate. Unsurprisingly, the probability of simultaneous detection decreases as more sonobuoys are included for detection. After the sonobuoys drifted and deformed

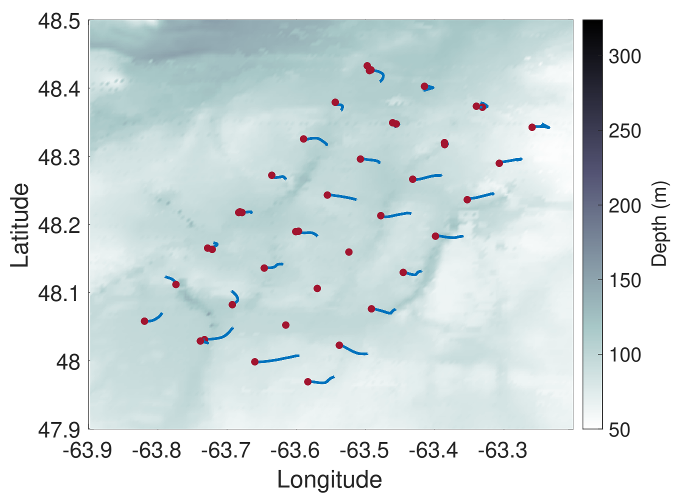

Figure 8. Sonobuoy GPS positions on Day 1, overlaid on a map of bathymetry. The red dots represent the deployment locations and the blue lines represent the GPS-derived drift tracks for approximately 6.5 hours.

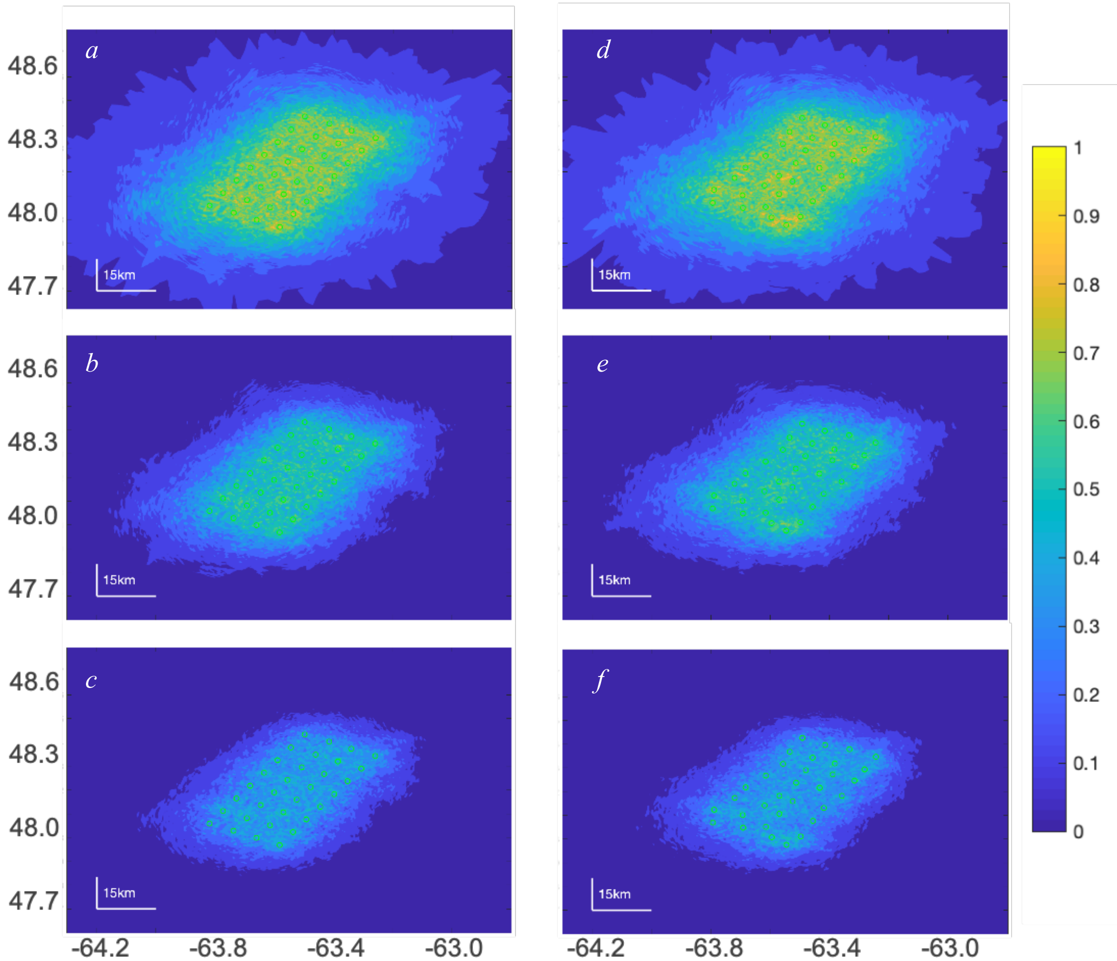

Figure 9 Probability that a NARW call will be simultaneously detected on two (a and d), three (b and e), or four (c and f) buoys simultaneously. The left column shows calculations based on the buoy drop locations, and the right column based on the final drift positions.

there were areas where the probability of detection increased, and other areas where it decreased. This was especially apparent as more sonobuoys contributed to the localization estimates. This non-uniform spatial distribution of the probability of detection as sonobuoys drift would be important to account for if this data is used for density estimation, for example. The deformation of the array may bias localization estimates if it is assumed that the sonobuoys remained at their drop location throughout the course of the data collection effort.

4. CONCLUSIONS

This paper presented DND's approach to active sonar impact management, based on current scientific understanding of the impacts of anthropogenic sound on marine mammals. The approach is a layered one, focused primarily on avoiding exposing marine mammals to active sonar. This starts at the planning phase by limiting active sonar training and testing events, when possible, to locations where marine mammals are least likely to be present. During such active sonar activities, passive sonobuoys can be used to acoustically monitor for the presence of whales, so that operations can be shut down if an animal enters the MAZ.

The two case studies presented in this paper demonstrate that acoustic data collected by sonobuoys can be useful for observing the impacts of anthropogenic noise on marine mammals and enhancing mitigation approaches. Sonobuoy data can be used to develop, refine, and validate automated detection, classification, and localization algorithms (e.g., sonobuoy data from an ASW exercise). We also demonstrated how DND can collaborate with other government departments, academia, and research organizations to collect high-quality multi-modal data to support marine mammal conservation and management efforts (e.g., NARW data blitz).

Further analysis of the CUTLASS FURY ASW exercise and 2018 Gulf of St. Lawrence datasets is planned as part of future work. CUTLASS FURY is an international ASW exercise that occurs biennially near Nova Scotia; it presents a perfect opportunity to test and refine marine mammal mitigation approaches and collect supporting data. In future, we plan to determine the baseline acoustic soundscape and marine mammal presence in order to assess differences from the baseline during and following an ASW exercise. Additionally, we plan on recommending broadband sonobuoys be used for PAM, and conducting coincident scientific data collection during an ASW exercise. Further work on the NARW Gulf of St. Lawrence 2018 data set will look at using localization estimates of high SNR calls to estimate source level. DND executed a new iteration of the 2018 NARW data blitz in August 2021. Ongoing development of automated detectors and classifiers is required to ensure that they can perform over a range of SNRs; for example, leveraging the directional information from the DIFAR sonobuoys will likely increase detector performance.

DND's forward-looking and comprehensive approach to active sonar impact management relies on continuing to deploy science expertise through Defence Research and Development Canada (DRDC), engaging industry partners, and forming new research collaborations. Readers interested in collaborating with DND on these efforts are encouraged to contact the authors.

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