2011 Beaufort Sea Active Acoustics Survey for Marine Mammal and Pelagic Fish Detection

Final Report

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2011 BEAUFORT SEA ACTIVE ACOUSTICS SURVEY FOR MARINE MAMMAL AND PELAGIC FISH DETECTION

Prepared for:

Beaufort Regional Environmental Assessment (BREA)
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2011 Beaufort Sea active acoustic survey for marine mammal and pelagic fish detection

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Abstract

As part of a large environmental research effort in the Canadian Arctic, a fisheries sonar (Simrad SX90) and a multi-frequency echosounder (Simrad EK60) mounted on the Canadian research icebreaker CCGS *Amundsen* were used to conduct a study on pelagic fish and marine mammal detection. The echosounder was continuously operated while adaptive and opportunistic sonar surveys were conducted from July 20th to August 10th in the St-Lawrence and eastern Canadian Arctic, and from August 27th to October 3rd in the Beaufort Sea. The fisheries component of this project was aimed at validating the hypothesis that arctic cod (*Boreogadus saida*) form schools near the surface during summer/fall. The acoustic surveys conducted in the Beaufort Sea area in 2011 suggest that, instead, age-0 fish form a scattered layer in the top 100 m of the water column, whereas larger fish (age 1+) form a distinct layer near the bottom, over the slope and in deep water areas. The main goals of the marine mammal component of this study were to assess the ability of the SX90 sonar to detect Arctic cetaceans and to develop acoustic recognition criteria for species identification. Acoustic detections were validated by trained Inuit and biologist Marine Wildlife Observers (MWOs). During all 367 hours of sonar operations, 126 cetaceans were visually sighted by MWOs, of which 60 (59 bowhead whales, *Balaena mysticetus*, and 1 minke whale, *Balaenoptera acrostrutoata*) were also detected by the sonar. Additional observations of pinnipeds were recorded both by MWOs and sonar operators. Most cetaceans were sighted outside the 2000 m maximum detection range of the sonar, but 92% of the whales sighted within 2000 m were acoustically detected. Target Strength (TS) of bowhead whales varied from -15 dB to 10 dB and TS of seals from -34 dB to -3 dB. Based on recognition criteria established during this study, echoes of two bowhead whales and one seal were identified without validation by MWOs. Although the SX90 sonar efficiently detected cetaceans at a range up to 2000 m, the detection range varied greatly with changes in the physical properties of the water column and real-time identification requires a number of technological improvements identified in this report.

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1. Introduction

1.1 Project overview

The ArcticNet active acoustic project in the southeastern Beaufort Sea and Amundsen Gulf was conducted in collaboration with Kongsberg Maritime AS, a leader in the research and development of sonars for fisheries and whale detection applications. The project was developed around two main research components: (1) fisheries research; and (2) marine mammal detection.

The general objectives of this project were:

Collect baseline data on fish, particularly arctic cod (*Boreogadus saida*), distribution and abundance during summer/fall in the southeastern Beaufort Sea and Amundsen Gulf using the SX90 fish finding sonar.

Assess the effectiveness of active acoustics in detecting and identifying marine mammals at a distance from the research platform.

The project was conducted from the Canadian research icebreaker CCGS *Amundsen* as part of its annual science expedition in the Canadian Arctic. The active bioacoustic survey was based on data collected with the newly installed Simrad SX90 fisheries sonar, in addition to the Simrad EK60 scientific echosounder (installed onboard the *Amundsen* since 2003).

1.2 Fisheries research component

Environmental changes and the recent interest in offshore hydrocarbon resources have heightened the need for data and an understanding of aquatic ecosystem components in the Beaufort Sea/Mackenzie Shelf/Amundsen Gulf region. Pelagic fish, predominantly arctic cod (*Boreogadus saida*), are an important component of the Beaufort Sea ecosystem allowing for the transfer of energy from plankton to apex predators such as seabirds and marine mammals (Craig et al. 1982). Despite having a central role in the ecosystem, little is known about the seasonal migrations and distribution patterns of arctic cod or other pelagic fish. Baseline data on fish species presence, distribution and abundance in the Canadian Beaufort Sea is identified as a major data gap for environmental and social impact assessments (Kavik Axys 2008; Arcticnet 2011) and is listed as one of the highest research priorities under the Beaufort Regional Environmental Assessment (BREA).

ArcticNet researchers have collected a significant amount of information on early life stages of arctic cod using mid-water trawls; however, adult arctic cod appear to easily avoid capture using this sampling method. Relative to conventional samplers, bioacoustics represents a promising avenue for obtaining non-invasive, direct and reliable observations of adult fish over a large area (Crawford and Jorgenson 1990; Benoit et al. 2010). Recent studies using the *Amundsen's* EK60 echosounder operating at multiple frequencies (38, 120 and 200 kHz) indicate that adult arctic cod form winter aggregations in the deep Atlantic layer and suggest that schools form in late April/early May, then migrate toward the upper layer of the water column (Benoit et al. 2010; Geoffroy et al. 2011). Welch et al. (1993) suggested that fish remain in the upper layer from summer until early December when they return to deeper waters. However, detecting arctic cod in the surface waters using echosounder-based techniques has proven challenging. Echosounders have a narrow beam and are blind in the first several meters of the water column (13.5 m for the *Amundsen*'s EK60 echosounder), limiting detection of fish schools in the upper layer (fig. 1). Thus, previous echosounder-based studies conducted in summer/fall may have underestimated arctic cod biomass by a factor up to ~25 fold relative to minimum consumption by seabirds and marine mammals estimated from stomach content (Welch et al. 1992).

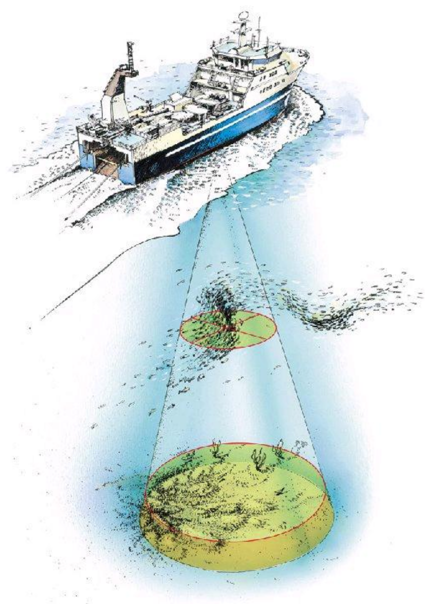

Figure 1. EK60 beam extent illustrating limited ability to detect fish in the surface layer.

Several studies have used a fisheries sonar to assess pelagic fish abundance (Rusby et al. 1973; Misund et al. 1995; Trevorrow 1997; 1998; 2001). In addition to the larger coverage relative to that of an echosounder, fisheries sonars allow detection of fish up to 1 m below the ocean surface and at distances of up to 2 km from the vessel (fig. 2), thereby reducing biases related to vessel interaction behaviour.

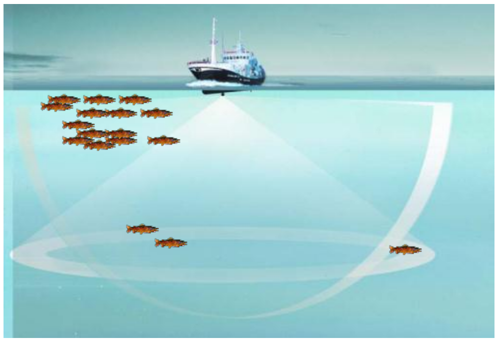

Figure 2. Schematic representation of the SX90 omni directional beam.

The detailed objectives of the fisheries research component are:

1. Detect pelagic fish (mainly arctic cod) schools in the surface layer and document their distribution, size and migration (including diel) patterns.
2. Combine data from the SX90 sonar and the EK60 echosounder to estimate school biomass using the mean Target Strength (TS_N) calculated from echosounder data.
3. Estimate arctic cod abundance at the ice-water interface.
4. Document the effectiveness of the SX90 sonar as a complementary bioacoustic device to study adult pelagic fish during the Arctic summer/fall.

1.3 Marine mammal detection component

Remote and environmentally sensitive areas of the Arctic offshore, such as the Canadian Beaufort Sea, are increasingly the focus of Oil and Gas Exploration and Production (E&P) activities. Over the past decade, the Oil and Gas industry has seen increased attention from stakeholders and regulators related to the environmental impact of offshore activities on marine mammals. These impacts are primarily related to sound associated with seismic exploration, construction activities (e.g. impact pile driving) and vessel operations. Regulations in most jurisdictions require monitoring for marine mammals during E&P activities and the use of mitigative measures to reduce potential impacts. Visual monitoring by Marine Wildlife Observers (MWOs) and the use of Passive Acoustic Monitoring (PAM) are the most common methods used. Visual observation by MWOs is limited or ineffective as a mitigative measure during periods of darkness or poor visibility, or during periods of heavy sea state. PAM is an evolving technology with limitations related to low-frequency baleen species (e.g. bowhead whales) and is only applicable to vocalizing animals, while towed PAM has water depth limitations.

Active acoustic technology, like the SX90 fish finding sonar could overcome the limitations of other monitoring tools and may prove useful as a mitigative tool during seismic operations. Sonars and echosounders are not limited by light, visibility or weather conditions and are not dependant on vocalization or surface presence of marine mammals for detection.

A number of studies have used sonars as a whale detection tool and to gather information on behaviour and feeding ecology (Au 1996; Bernasconi et al. 2007; Knudsen et al. 2007; Lucifredi and Stein 2007; Bernasconi et al. 2009; Brehmer et al. 2011; Vartdal 2011). The design of the 2011 survey is based on a previous study conducted in 2007 in three Norwegian fjords (Knudsen et al. 2007). This pilot study funded by the E&P Sound and Marine Life Joint Industry Program of the International Association of Oil and Gas Producers evaluated the effectiveness of two fisheries sonars (Kongsberg-Simrad SP90 and SH80) as active detectors of whales, specifically orca whales (*Orcinus orca*). MWOs were hired during the research to corroborate acoustic detections, and CTD (conductivity, temperature, depth) sensors were deployed for use in sound propagation and detection models. Knudsen et al. 2007 demonstrated that active acoustics using a fisheries sonar effectively detected orca whales at ranges exceeding 1000 m.

The main goal of the marine mammal detection component of this project is to evaluate the effectiveness of the fisheries sonar in detecting and identifying cetaceans at a distance from the vessel. Establishment of marine mammal identification criteria is critical to develop an efficient detection procedure. In addition to echo-track characteristics, Target Strength (TS) represents a key recognition criterion in bioacoustics (Parvin et al. 2007; Doksaeter et al. 2009). TS is commonly used to identify fish, but previous studies highlighted the fact that TS of marine mammals is generally poorly documented (e.g. Knudsen et al. 2007; Parvin et al. 2007). TS analysis were previously conducted on humpback whales (*Megaptera novaeangliae*; Love 1973; Miller and Potter 2001), northern right whales (*Eubalaena glacialis*; Miller and Potter 2001), fin whales (*Balaenoptera physalus*; Bernasconi et al. 2009), gray whales (*Eschrichtius robustus*; Lucifredi and Stein 2007), sperm whales (*Physeter macrocephalus*; Dunn 1969; Levenson 1974), orca whales (*Orcinus orca*; Knudsen et al. 2007), bottlenose dolphins (*Tursiops truncatus*; Au 1996), dusky dolphins (*Lagenorhynchus obscurus*; Bernasconi et al. 2011), and an unknown dolphin species (Selivanovsky and Ezersky 1996). To our knowledge, this study is the first one to document TS of bowhead whales, which, with gray whales and belugas, represent the main cetacean species living in the eastern Beaufort Sea.

The detailed objectives of the marine mammal detection component are:

1. Establish recognition criteria (echo-track characteristics and TS) for beluga, bowhead whales and other marine mammals detected by the SX90 sonar.
2. Determine the depth dependency of marine mammal TS and effect on target detection.
3. Determine detection ranges for belugas, bowhead whales and other marine mammals.
4. Study the effect of changes in temperature-salinity profiles on target detection.
5. Validate sonar detections with direct field observations by MWOs.

2. Material and methods

The active bioacoustic program was conducted from the CCGS *Amundsen* throughout the entire 2011 field season. The EK60 echosounder was operated from the beginning of leg 1 (July 18th) to the end of leg 3 (October 29th), while the SX90 sonar was operated on a dedicated and opportunistic basis during leg 1 (July 18th - August 11th) and legs 2b, 2c, and 3a (August 25th - October 4th). The sonar system was also successfully tested in the St-Lawrence River prior to departure, on July 2nd.

2.1 EK60 echosounder

The CCGS *Amundsen* is equipped with a Simrad EK60 two-frequency (38 and 120 kHz) splitbeam echosounder. The 7˚ beam width transducers are hull-mounted in oil-filled arctic wells protected by a 2.5-cm thick, acoustically transparent polycarbonate plate. The acoustic signal was recorded using the ER60 2.0.0 software. Ping interval varied following synchronization with the other scientific acoustic instruments on the ship (i.e. sub-bottom and multibeam echosounders, ADCP, SX90 sonar), and the pulse duration was set to 1024 µs. The standard sphere method (Foote et al. 1987) was used to calibrate the system prior to ship's departure from its home port of Quebec City, and after its return.

2.2 SX90 sonar

The key features of the Simrad SX90 long range, low frequency fish finding sonar are a choice of operational frequencies (range 20-30 kHz in steps of 1 kHz) and a theoretical horizontal detection range of 150-4500 meters. The cylindrical 256-elements transducer allows the omni-directional sonar beam to be tilted electronically from +10 to –60 degrees, to scan a large portion of the water column. When the omni beam is tilted, the total beam picture can be compared with folding an umbrella, which means that all beams in 360 degrees around the vessel have the same tilt angle (fig. 3a). In addition to seeing cetaceans or fish from above (horizontal transmission mode), it is also possible to see a target from the side, by using the vertical view transmission mode (fig. 3b). In this case, the beam covers a continuous vertical beam from 0 to -60 degrees in one transmission. This vertical slice, which is presented by a white line in the horizontal view of the sonar screen, can be selected manually to any bearing. The combination of the omni model and the vertical transmission mode provide an optimal visualization (fig. 3c). In addition to the omni picture, the vertical view is especially useful for visualizing the vertical distribution of a school of fish. In that way, it is not necessary to go over the target to see the distribution on the echosounder, which often results in a spreading of the school.

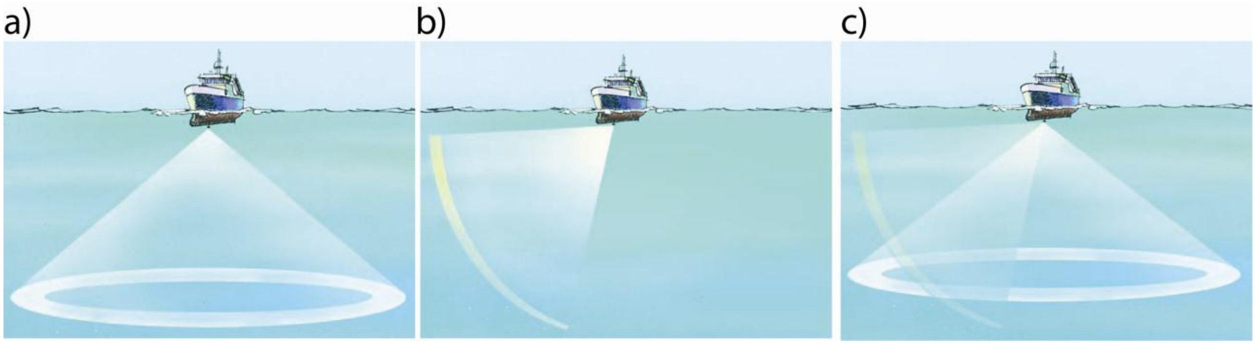

Figure 3. Schematic representation of (a) omni beam principle: the beam can be tilted from +10 up to -60 degrees down; (b) 60 degrees vertical slice; and (c) omni/vertical combination.

Target echoes are displayed on the sonar screen and speakers are connected to the system to listen for vocalizations in the 20-30 kHz frequency range (fig. 4). The sonar transducer is lowered 2.5 feet below the hull through a gate-valve. The source level at 26 kHz is 215.2 dB re 1 µPa at 1 m. During the 2011 survey, pulse form was set to FM Auto (Hyperbolic Frequency Modulated; 500 Hz bandwidth) and beam width to normal (table 1). TX power was set to a maximum of 0 dB re 1 µPa at 26 kHz. SX90 raw data were saved onto an external drive and print screens of interesting targets (fish schools and/or marine mammals) were recorded.

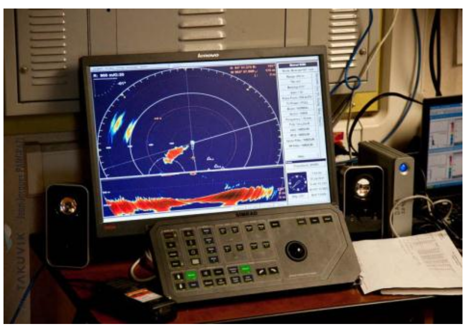

Figure 4. SX90 sonar interface onboard the CCGS Amundsen (photo: J.J. Pangrazzi)

Table 1. Beam width of vertical and horizontal transmission modes corresponding to Normal setting for operational frequencies ranging from 20 to 30 kHz.

Beam	Beam width
Horizontal transmission	360°
Horizontal reception	8.5°-13°
Vertical transmission	7°-10.5°
Vertical reception	7.4°-11.4°

2.3 Survey design and area

An adaptive survey approach was used in Cumberland Sound (eastern Canadian Arctic; fig. 5) and at five locations in the Beaufort Sea (fig. 6). Ship's track during surveys SA-01, SA-02, and SA-03 overlapped whale feeding areas previously identified by Fisheries and Oceans Canada, while survey SA-05 was conducted in an area where schools of arctic cod were likely to be encountered. Normal survey speed was 8 knots, but during good visibility conditions (≥5000 m), ship speed was increased to regular cruising speed (13-14 knots) to cover a larger area. When fish schools or cetaceans were encountered and/or detected with the SX90 sonar, the ship's course was modified to: (1) go over fish schools to record their backscatter with the EK60 and sample them with the Rectangular Mid-Water Trawl (RMT); or (2) follow cetaceans at a certain distance (>150 m, for a maximum of 10 minutes) to record their backscatter with the SX90 sonar over a wide range and at all operational frequencies (20-30 kHz) for TS analysis (see section 2.5.3). Starting during leg 2c, the multibeam echosounder and sub-bottom profiler were turned off while approaching whales. As soon as data acquisition was completed for all frequencies, the ship slowed down or changed its course to increase the distance with the whale, and the transect resumed. While increasing the range between the ship and marine mammals, the *in situ* maximum detection range was noted.

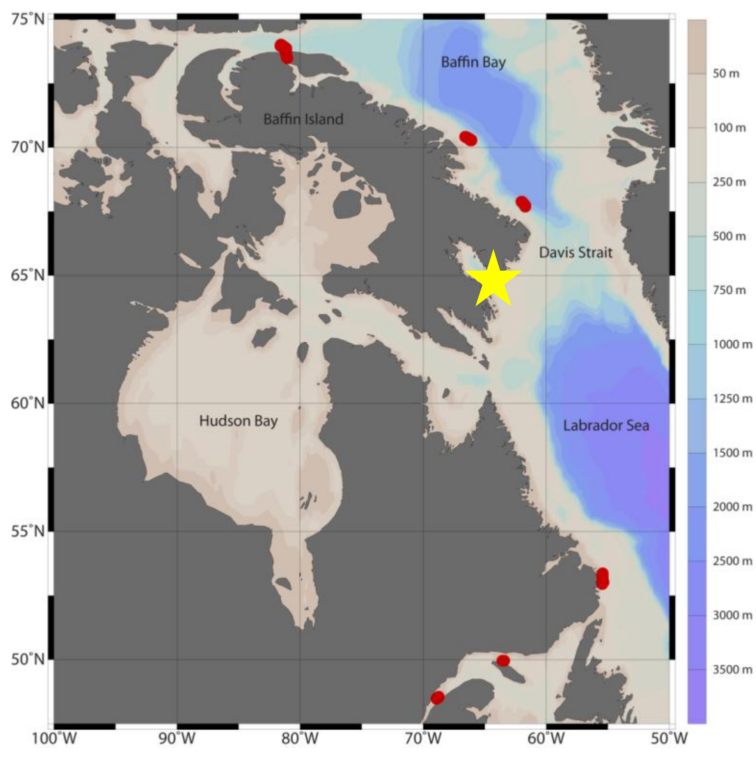

Figure 5. Areas where opportunistic (red line) and adaptive (Cumberland Sound; yellow star) surveys were conducted from July 20th to August 10th (leg 1) in the St-Lawrence and the eastern Canadian Arctic.

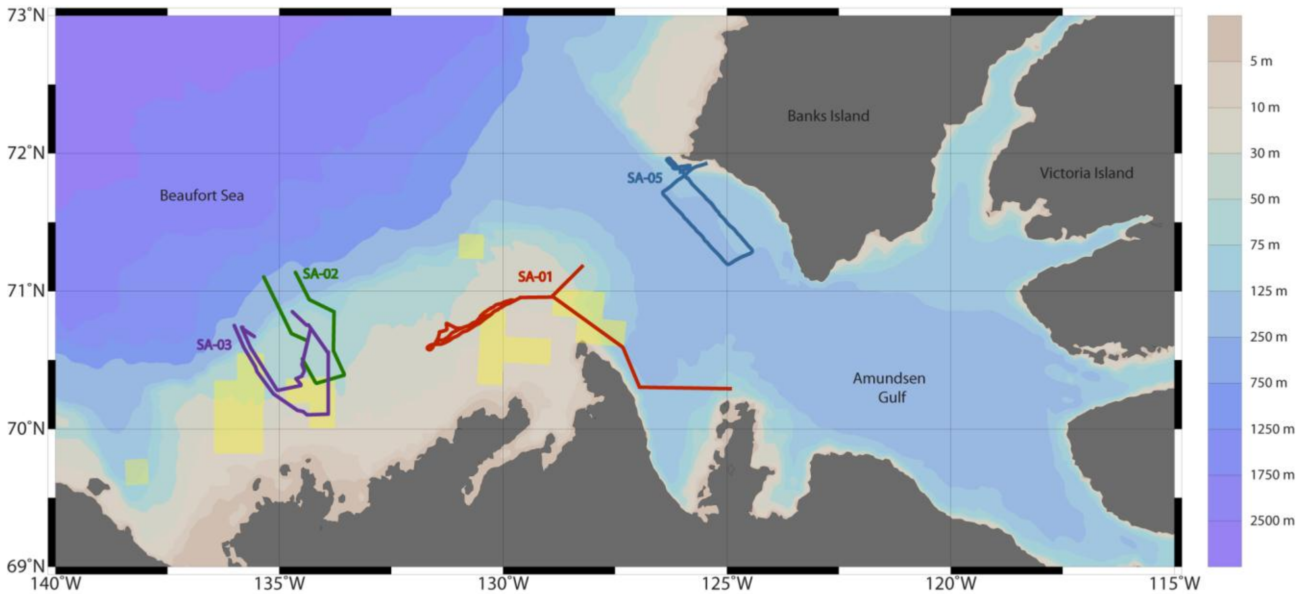

Figure 6. Map of the ship's track during adaptive surveys SA-01 (red), SA-02 (green), SA-03 (purple), and SA-05 (blue) conducted from September 1st to 29th. Yellow polygons indicate known whale feeding areas provided by Fisheries & Oceans Canada.

In addition to adaptive surveys, opportunistic surveys were conducted during transit and science operations (fig. 5 and 7). The ship was not deviated when targets were encountered during such surveys, but frequency of the SX90 sonar was changed on some occasions to measure TS variations. Several science operations were not compatible with the use of the SX90 sonar (e.g. high resolution bottom mapping, mooring operations) and the system was turned off during these activities.

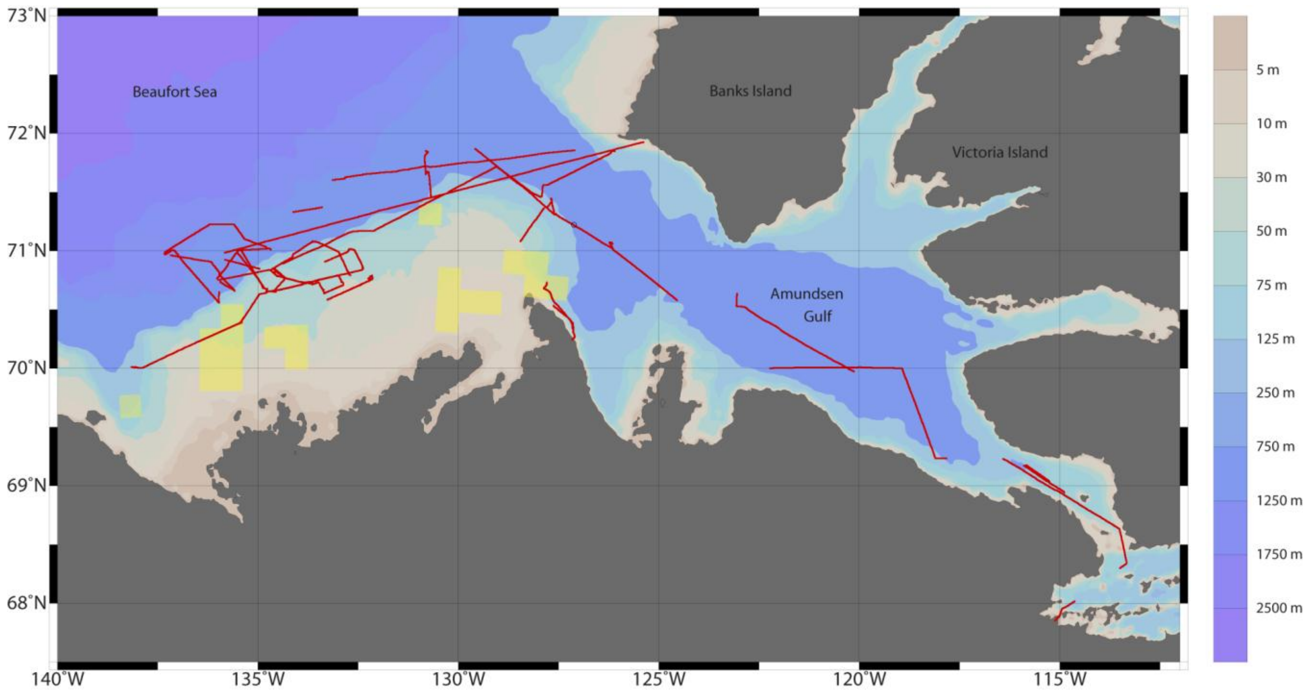

Figure 7. Map of the ship's track (red line) during opportunistic surveys conducted from August 27th to October 3rd in the Canadian Beaufort Sea. Yellow polygons indicate known whale feeding areas provided by Fisheries & Oceans Canada.

2.4 Collaboration with MWOs

Inuvialuit Marine Wildlife Observers (MWOs) were generally on duty during daylight hours of active opportunistic and adaptive acoustic surveys conducted throughout leg 2b, 2c and 3a. Their role was to visually detect and record sightings of wildlife. MWOs were provided with clear guidelines for all observation duties and communication procedures with the bridge and the SX90 operators. For all observations, MWOs logged the following information in a datasheet to be correlated with acoustic detections and used as an aid in the establishment of acoustic recognition criteria.

1. Time of sighting.
2. Bearing, travel direction, distance and location of marine mammals.
3. Species, certainty of identification, approximate size and appearance of marine mammals.
4. Number of individuals (including juveniles) observed and whether they resurfaced.
5. Behaviour of each individual (i.e. diving, blowing, feeding or any other activity).
6. Presence and shape of blows.
7. Picture file numbers (if available) and the position recorded on the operator's GPS.

There are discrepancies between counts of cetacean sightings reported in this study and in abundance estimates (Golder Associates 2012). For abundance estimates, all whales logged as re-sightings were systematically discarded. However, for this study they were included in the analysis (1) if re-sighting occurred more than 5 minutes after previous sighting; or (2) if re-sighting was clearly identified as a distinct target on the sonar screen. In addition, opportunistic sightings of marine mammals were not included in abundance estimates, but were included in this study. Acoustic detections of marine mammals were validated as single individuals when the range and bearing of one visual observation corresponded to the simultaneous position of one target on the sonar screen. Radios were used to communicate this information between the bridge and the acoustic acquisition room. It is important to note that as in other studies based on MWOs, sightings are subject to limitations originating from weather and observers experience.

2.4.1 Monitoring of marine mammal negative behaviours

Starting on leg 2c, it was asked that the MWOs report any negative behaviour observed to the SX90 operators while approaching marine mammals. Upon observation of avoidance behaviours, the ship's speed was reduced and its heading deviated from the target before resuming the original transect. For future surveys, it is suggested that MWOs be briefed with a clear negative behaviours monitoring protocol prior to departure and that their logging device be modified to log such observations (see point 5 of section 4.2 for further details).

It is important to note that the biological relevance of a behavioral response to noise exposure may depend in part on how long it persists. Many mammals perform vital functions on a diel cycle and a reaction lasting less than 24 h and not recurring on subsequent days is not regarded as particularly severe unless it could directly affect survival or reproduction (Southall 2007). Here, since the same target was followed for a very restricted period of time (< 10 minutes), the impacts of the adaptive survey are likely to be very limited.

2.5 Data analysis

Print screens of interesting features were recorded throughout the field season while all operations and observations were dutifully noted in a logbook. Both datasets were compiled with detailed MWO reports to confirm all detections of marine mammals by the SX90 sonar. Print screens were also used to determine the echo-track characteristics of different marine mammal species and individuals. Recorded EK60 raw data were replayed and processed using Echoview® 5.1. to estimate fish biomass and TS. As no software allowing a direct analysis of the SX90 sonar data was available and print screens were not recorded for every single ping, a Matlab routine was developed to visualize each ping of interest in radial (fig. 8a) and surface (fig. 8b) plots.

At each science station, a CTD-rosette system (Seabird Electronics SBE-911 plus®) was deployed from the CCGS *Amundsen* to record temperature and salinity from 10 m above the bottom to the surface. In addition, a portable YSI CastAway® CTD was deployed from 80 m to the surface prior to and at the end of each adaptive survey. Temperature-salinity profiles were used to determine the coefficients of absorption (α) and speed of sound (c) used in acoustic calculations (Francois and Garrison 1982). The closest cast in time was selected to calibrate acoustic profiles.

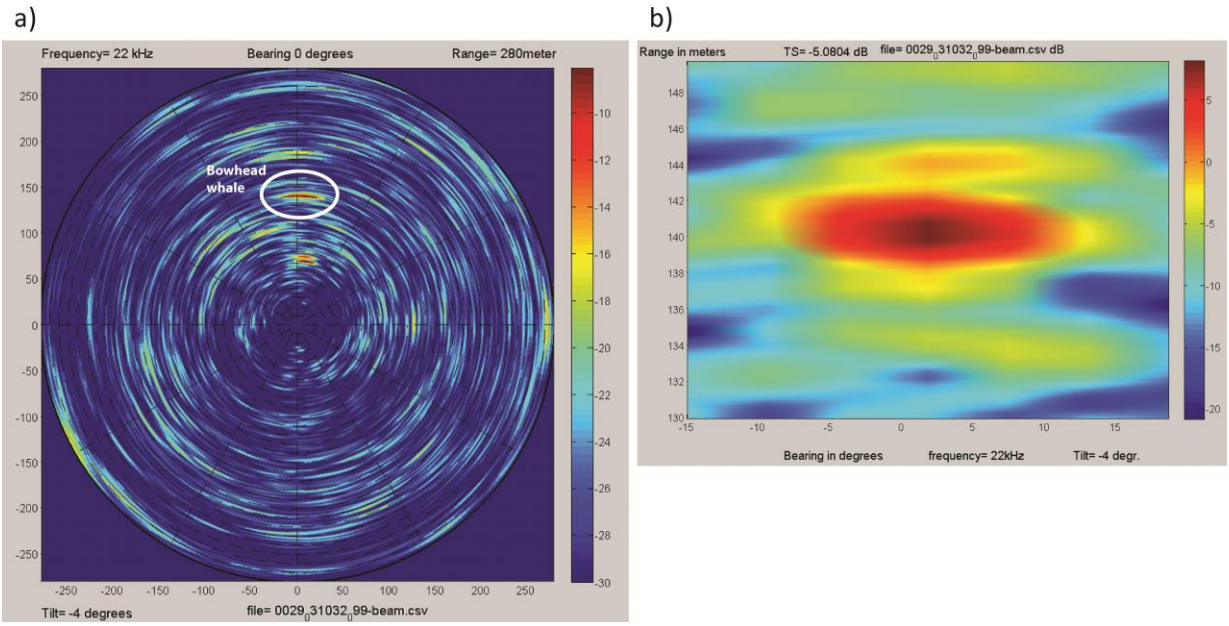

Figure 8. Examples of a bowhead whale in (a) a radial plot, and (b) a surface plot generated from SX90 sonar data and using Matlab.

2.5.1 Determination of the SX90 sonar theoretical detection range

Based on CTD casts conducted during legs 2b-3a, the Lybin software developed by the Norwegian Navy and Norwegian Defense Research Establishment was used to model ray tracing, propagation losses, probability of detection, and maximum detection range for each cast (Knudsen et al. 2007). Sonar and environmental parameters used for simulations are found in figure 9. Note that the frequency was set to 26 kHz, tilt angle to -2º, ship noise to 57 dB re 1μPa (measured at sea on July 20^{th} 2011, see annex 8.1), wind speed to 5 m/s (or 10 knots, a realistic value in this area during fall), and detection threshold to -5 dB re 1μPa. On September 1^{st}, a custom 50x50 cm tri-plane target reflector (fig. 10) was deployed hanging by a rope below a floating buoy to compare the theoretical maximum detection range (calculated with the Lybin software) near the surface with the *in situ* conditions, following the procedure detailed by Knudsen et al. (2007). At 15 m, the reflector was just above the thermocline (determined from a CTD cast conducted prior to the calibration). Once the reflector was deployed, the ship turned around the target at a speed of 2 knots while the radius was slowly increased to determine the maximum detection range. Once the maximum range was reached, the ship slowly (2 knots) came back toward the target before recovering the corner reflector and the buoy.

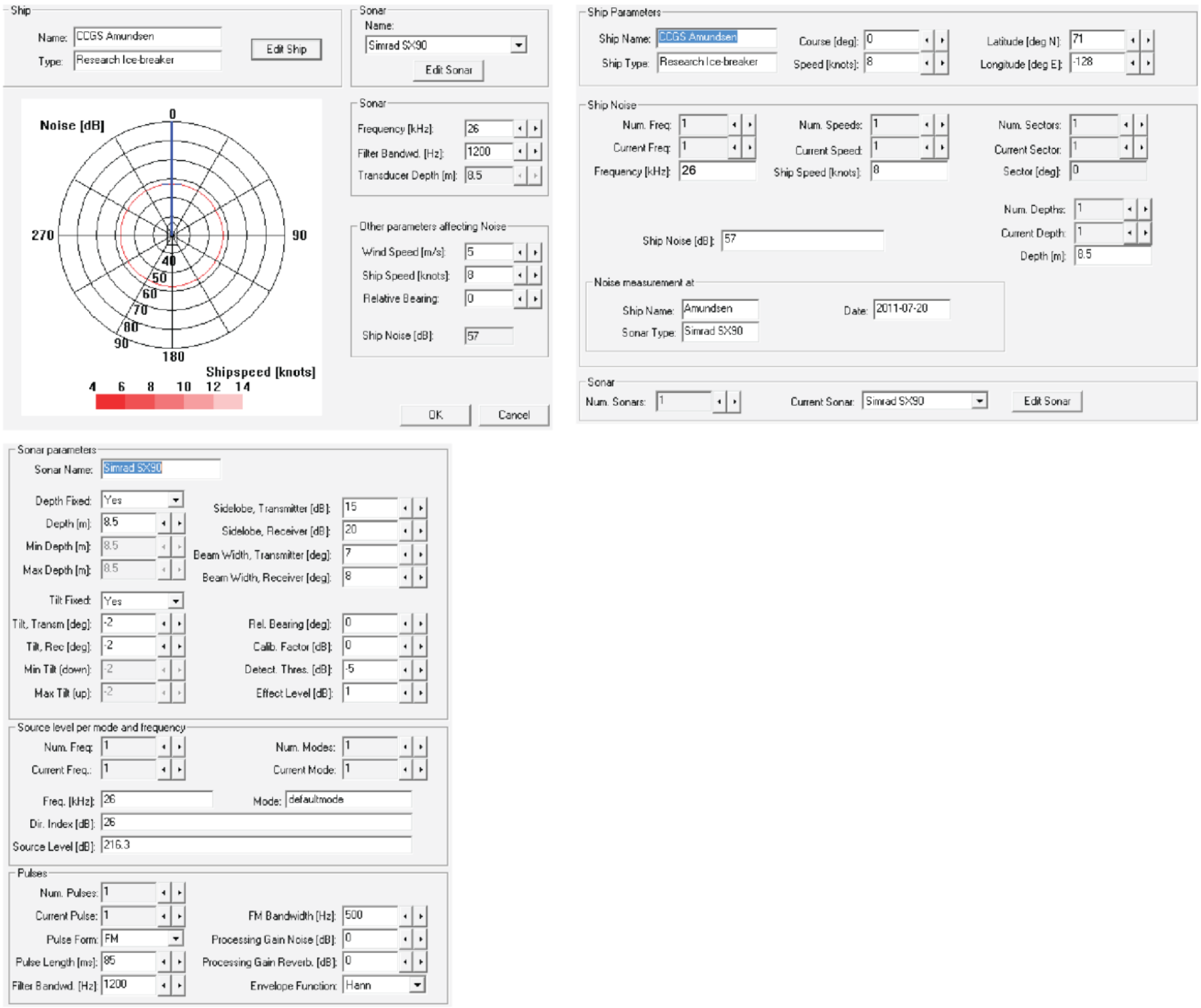

Figure 9. Parameters used for the simulation of ray tracing, propagation losses and probability of detection with the Norwegian Lybin software.

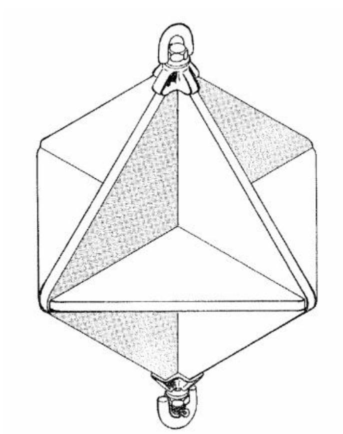

Figure 10. Triplane target reflector (50x50 cm) with a TS of -15 dB re 1μPa at 25 kHz (from Knudsen et al. 2007).

2.5.2 Fish TS analysis

Target Strength (TS) is a key quantity in the acoustic assessment of fish abundance (Foote 1987) and can be related to fish length for a given species (Cordue et al. 2001). A TS analysis was conducted on a representative sub-sample (September 7th-22nd, 2011) of the EK60 echosounder dataset using Echoview® 5.1 single-echo detection (SED) algorithm for split-beam echosounders (method 2) to isolate single targets and calculate TS. Analysis cells were set to 3 m deep for a period of 1 minute, and a -65 dB threshold was used to exclude zooplankton from the analysis (Geoffroy et al. 2011).

A first TS analysis was conducted on targets in the first 100 m and a second analysis was conducted from 100 m to the ocean floor. TS frequency distributions of top and bottom layers were compared to document size segregation.

2.5.3 Marine mammal TS analysis

Knudsen et al. 2007 stated that high priority should be given to investigate the Target Strength (TS) of whales. Few studies have been published on the TS of marine mammals; however, it is of general agreement that theories and models developed for fisheries acoustics equally apply to marine mammal backscattering and that species, size, orientation and depth all contribute to influence the resulting TS of marine mammals (Love 1973; Lucifredi and Stein 2006; Bernasconi et al. 2009; Doksaeter et al. 2009). TS varies significantly with length and angle of incidence (Horne and Clay 1998), emphasizing the importance of conducting *in situ* TS measurements on many pings and for as many individuals as possible.

For this study, a method was developed to calculate the TS of marine mammals from SX90 sonar raw data. The TS of bowhead whales (*Balaena mysticetus*), minke whales (*Balaenoptera acrostrutoata*), ringed seals (*Phoca hispida*), and bearded seals (*Erignathus barbatus*) was calculated. For each marine mammal, a minimum of five pings per frequency at which the animal was detected were selected and for each of these pings the maximum TS was calculated. On some occasions, the frequency was changed too quickly by the operators, and less than five pings were recorded; in such cases, all available pings were selected for the analysis. For each individual, TS was thereafter averaged at each frequency to obtain a TS-frequency relationship.

The TS analysis was conducted using Matlab and the maximum TS for each ping was calculated using the sonar equation (eq.1):

$$TS = EL + 2TL - \Delta TS \quad \text{(eq. 1)}$$

$$2TL = \text{spreading losses} + \text{absorption losses} = 40 \log R + 2\alpha R \quad \text{(eq. 2)}$$

$$\Delta TS = SL - \text{correction factor} \quad \text{(eq. 3)}$$

Where EL is the Echo Level measured at the transceiver due to a target, TL are the two-way transmission losses (eq. 2), R is the range, α the absorption coefficient, and SL the source level.

ΔTS (eq. 3) is a constant that was calculated from a calibration at each operational frequency using a 63 mm Cu sphere deployed from the side of the ship in three different positions:

1. At the bow, approximately 13.5 m below the sea surface, to obtain a 10° tilt angle from the transducer.
2. On port and starboard sides (in front of the transducer) approximately 11 m below the sea surface.

The constant ΔTS represents the difference between the *in situ* and theoretical TS values of the sphere at each frequency (table 2). For the three positions, the raw signal of the sphere (*in situ* TS) was recorded at all 11 frequencies (20-30 kHz) and averaged over 10 pings (for a total of 30 pings per frequency). The resulting *in situ* TS values were subtracted from the theoretical TS of the sphere (fig. 11).

Table 2. TS correction factors (ΔTS in dB re 1 μPa) and standard deviation (σ in dB re 1 μPa) for each frequency of the Simrad SX90 sonar onboard the CCGS Amundsen. Values were calculated with the beam mode set to Normal.

Frequency (kHz)	**ΔTS (dB)**	**σ (dB)**
20	-8.6	1.7
21	-11.1	0.8
22	-13.2	0.3
23	-15.0	1.9
24	-16.3	1.0
25	-17.0	0.7
26	-17.5	0.4
27	-17.3	1.7
28	-16.8	1.6
29	-15.5	0.4
30	-14.2	0.1

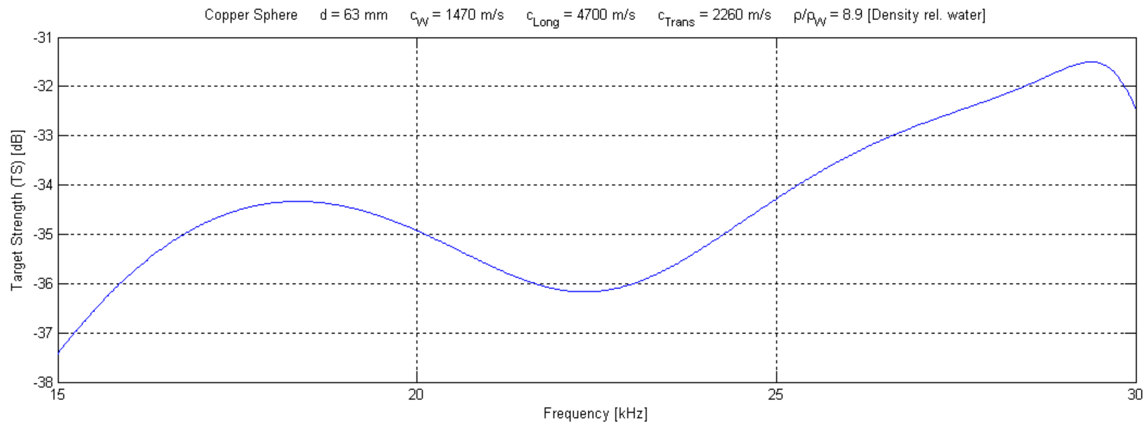

Figure 11. Frequency response of the 63 mm calibration sphere from 15 to 30 kHz.

3. Results

A total of 109 hours were dedicated to adaptive acoustic surveys (table 3), most of which were conducted during daytime (84%) to allow target validation by MWOs. In addition, the sonar was operated 258 hours on an opportunistic basis (table 4). Throughout the 2011 field season, MWOs and the SX90 sonar were simultaneously monitoring during 170 hours. Bathymetric areas surveyed include the continental shelf (bottom depth ranging from 0 to 100 m), continental slope (bottom depth ranging from 100 to 350 m) and deep water (bottom depth > 350 m). Note that bathymetric areas are based on industry standards.

Table 3. Detailed summary of the adaptive acoustic surveys conducted in 2011 onboard the CCGS Amundsen. Note that survey SA-4 was merged with survey SA-1. N/A indicates that no CTD cast was conducted to verify the existence of an acoustic channel.

Survey	Date	Total survey time (hours)			Simultaneous MWO observations (hours)	Distance (NM)				Bottom depth (m)		Ship speed (knots)	Weather	# of CTD casts	Presence of an acoustic channel
		Daytime	Night time*	TOTAL		Continental shelf	Continental slope	Deep water	TOTAL	Min	Max				
SA-1	September 20-21 and September 28-29	25	0	25	20	198	68	0	266	30	220	8-13	On September 20-21 : Very good visibility (5000 m); winds up to 27 knots and wave caps from 16h00 to 21h30 On September 28-29: Excellent visibility (>8 000 m); light winds	4	Yes on September 20-21, no on September 28-29
SA-2	September 12-13	17	4	21	15	167	15	11	193	27	657	8-14	Excellent visibility (>8000 m); moderate winds (up to 21 knots)	2	Yes at the beginning and at the end of the survey
SA-3	September 8-9	13	5	18	12	94	13	20	127	37	777	8	Poor visibility due to the presence of fog; light winds	2	Yes over the slope, no over the shelf
SA-5	September 1	15	6	21	0	26	121	33	180	20	412	8	Very good visibility (5000 m); strong winds (up to 25 knots)	2	No
Cumberland Sound	July 25-26	22	2	24	0	0	49	54	103	117	741	5-8	Poor visibility due to the presence of fog; light winds	0	N/A
Total for adaptive surveys		**92**	**17**	**109**	**47**	**485**	**266**	**118**	**869**	**20**	**777**	**5-14**			

*Based on civil twilight

Table 4. Summary of the opportunistic acoustic surveys conducted in 2011 onboard the CCGS Amundsen.

Date	Survey Area	Total survey time (hours)	Simultaneous MWO observations (hours)
July 20 - August 10	Eastern Canadian Arctic	53	0
August 27 - October 3	Canadian Beaufort Sea	205	123
Total for opportunistic surveys		**258**	**123**

3.1 Theoretical detection range and ray tracing of the SX90 sonar

The maximum detection range of the SX90 sonar is a function of the temperature-salinity profile of the water column. If CTD data from an area are available prior to a sonar survey, maximum detection ranges can be modelled using the Norwegian software Lybin. A total of 78 CTD casts were conducted in the Beaufort Sea from August 27th to October 3rd (annex 8.2). A relatively warm (~5°C) surface mixed layer generally extended from the surface to a depth varying from 15 m to 60 m. For 46 of these casts (59%), a thick surface mixed layer was present above a strongly stratified pycnocline. Such conditions led to the formation of an acoustic channel (Knudsen et al., 2007) where the sound wave was refracted between the surface and the strong density gradient of the pycnocline. Sound spreading in this channel tends to be cylindrical rather than spherical. As interactions between spherical and cylindrical spreading losses are complicated to predict (Shapiro et al. 2009), the spherical spreading losses model (i.e. 40logR) was used for TS analysis. For this reason, marine mammals had to be approached at a close range (usually less than 300 m) to collect backscattering data from outside the acoustic channel, since transmission losses and TS were overestimated in the channel (see example in fig. 12). The portion of the sound not entrapped in this channel, where spreading losses can be assumed spherical, is here referred to as the "normal" beam (fig. 13a). In the absence of an acoustic channel (41% of the CTD casts; annex 8.2), the totality of the sound follows the "normal" beam spreading pattern (fig. 13b) and the sonar detection range is much lower. The theoretical maximum detection range, based on simulations conducted with the Lybin software, was 5000 m (for an average of 1911 m) at 10 m depth when the acoustic channel was present and 1400 m (for an average of 703 m) when it was absent. The overall average simulated detection range was 1415 m (table 5 and annex 8.2).

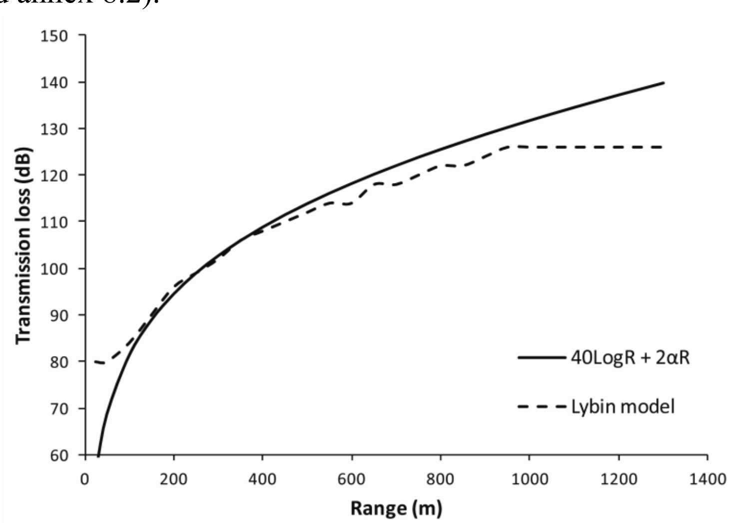

Figure 12. Example of transmission losses used for TS calculations (solid line) compared with transmission losses computed with the Lybin software (dashed line) based on a representative CTD cast conducted on September 28th in the Canadian Beaufort Sea. In this case, an acoustic channel was present and TS calculations under-estimated losses at a range <100 m, were accurate from 100-350 m, and over-estimated losses at a range >350 m.

It is important to note that Lybin simulations compute the theoretical detection range under ideal circumstances, which are rarely found *in situ*. For instance, the maximum theoretical detection range (5000 m; annex 8.2) is much higher than the maximum distance at which a marine mammal was detected with the SX90 sonar (2000 m; see section 3.3). This difference between the theoretical and *in situ* maximum detection ranges is similar to previous estimations for a fin whale (*in situ* maximum detection range of 1250 m relative to a theoretical detection range of 4900 m; Parvin et al. 2007). Hines et al. (1997) reported that spreading losses are extremely sensitive to the sound speed profile. CTD casts being conducted only prior to and at the end of each survey, water properties must be uniform throughout transects for the modeled beam pattern to be accurate for the entire survey, which was never the case. For instance, transects frequently intersected the continental slope, starting on the shelf and ending in the deep water, with all the variations in water conditions that such a transition implies. On the other hand, the triplane target reflector calibration proved accurate when compared to the theoretical value calculated with the Lybin software. The theoretical maximum detection range of 400 m, based on a CTD cast conducted immediately prior to calibration, suggested that no acoustic channel was present and corresponded with the *in situ* detection range.

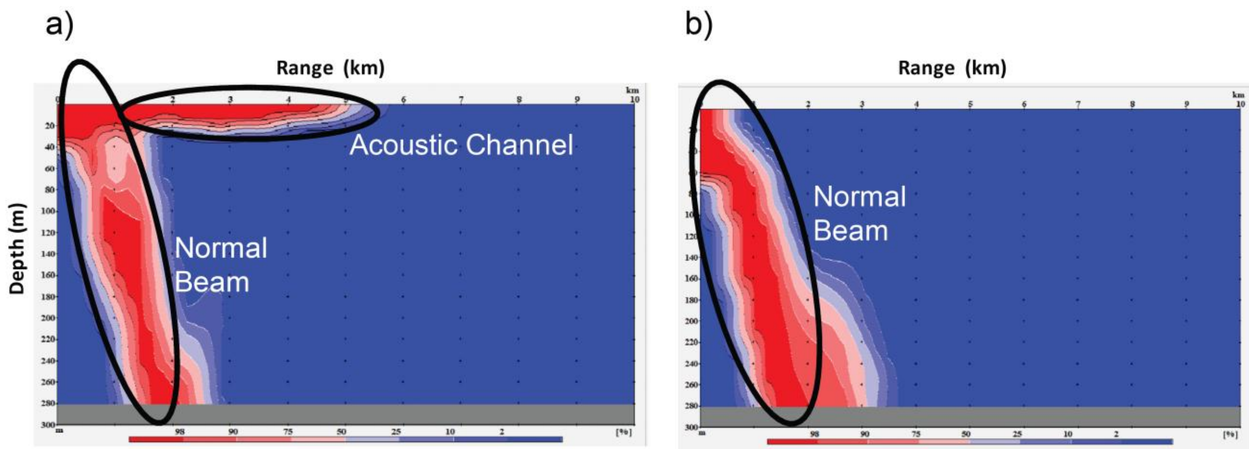

Figure 13. Examples of the sound beam pattern and probability of detection of a target (%, color scale) by the SX90 sonar computed with the Lybin software in (a) the presence, and (b) the absence of an acoustic channel based on the temperature-salinity profile.

Table 5. Theoretical average detection ranges based on simulations computed with the Lybin software for 78 CTD casts conducted in the Canadian Beaufort Sea from August 27th to October 3rd.

Average detection range in the presence of an acoustic channel (n = 46)	Average detection range in the absence of an acoustic channel (n = 32)	Overall average detection range (n = 78)
1911 m	703 m	1415 m

In the "normal" beam, ray bending occurred due to temperature stratification (warmer at the surface), misleading the operator's judgment about the vertical position of targets detected in the water column (Simmonds and MacLennan 2005). What was visualized on the sonar screen as a target close to the surface could, in fact, have been located at greater depth (fig. 14). The influence of water stratification on ray bending was greater when the SX90 sonar was oriented horizontally, and diminished as the tilt angle increased toward a downward position.

In shallow areas, ray bending generally caused the acoustic wave to be quickly deflected before being reflected by the bottom, generating annular noise on the sonar screen. Annular noise was usually present at bottom depths shallower than 200 m, and the portion of the horizontal view filled with noise started ~300 m from the ship when the tilt angle was low. For instance, in an area where bottom depth was 50 m, the portion of the horizontal view between 300 m and 550 m from the ship was filled with noise and it was impossible to detect fish or marine mammals located within this range (fig. 15). The portion of the horizontal view filled with annular noise was more important when the tilt angle was increased. The maximum detection range corresponded to the lower limit of the annular noise when the acoustic channel was absent, but when it was present targets were detected beyond it. As all bowhead whales were detected over the continental shelf (bottom depth <100 m), they were approached at a close range to be detected inside the annular noise (fig. 15).

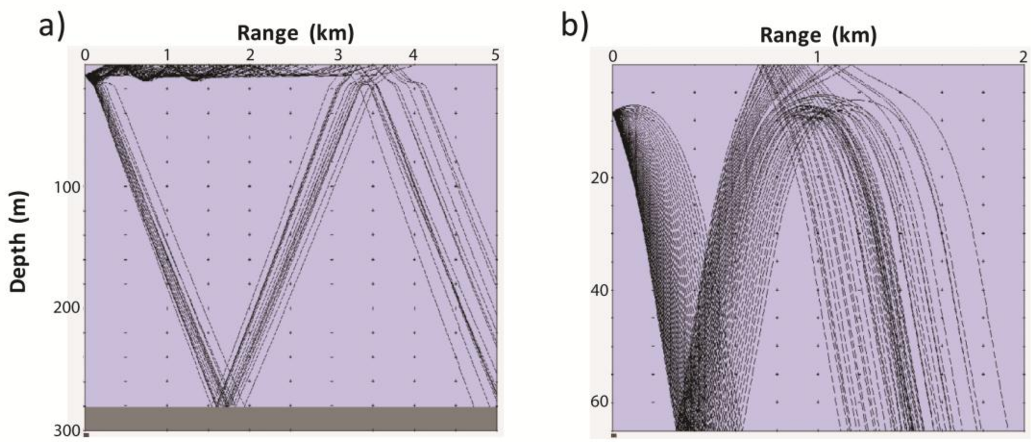

Figure 14. Examples of ray trace simulations computed with the Lybin software for CTD casts conducted in the Canadian Beaufort Sea in (a) the presence and (b) the absence of an acoustic channel. Note the downward bending, typical for the area during summer/fall. Bottom depth was 300 m and 65 m, respectively.

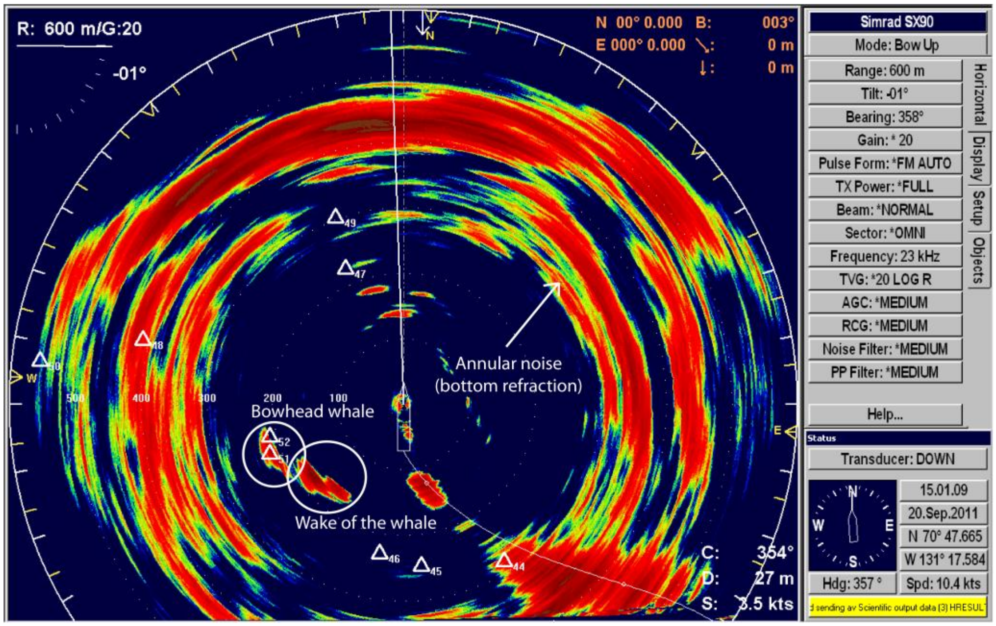

Figure 15. Example of annular noise created by bottom refraction and of a bowhead whale detected in the "normal" beam. Bottom depth was 50 m.

3.2 Fisheries research component

3.2.1 Detection of pelagic fish schools with the SX90 sonar in the St-Lawrence River and in Cumberland Sound

On July 20th, the SX90 sonar was deployed and tested for approximately one hour in the St-Lawrence River, in front of Grandes-Bergeronnes (48.14˚N 69.20˚W). This area is known as an upwelling site with high productivity and an important fish biomass (Marchand et al. 1999). Six schools of pelagic fish, most likely formed of capelin (*Mallotus villosus;* personal communications from Yvan Simard and Louis Fortier), were detected near the surface on the horizontal and vertical views of the SX90 sonar during these trials (fig. 16).

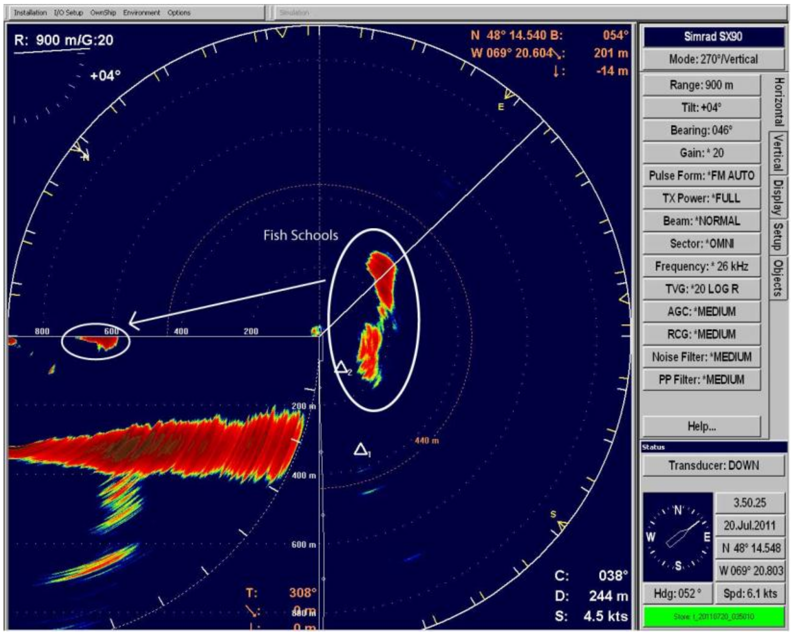

Figure 16. Example of a fish school detected in the St-Lawrence River on July 20th.

Six additional schools of pelagic fish were detected near the surface during the Cumberland Sound adaptive survey (fig. 5) conducted on July 25th and 26th. One of these schools was targeted to be sampled with the RMT net for echo-validation. Unfortunately, as the net entered the school, the tension on the slings suddenly increased before the nicopress fittings yielded, and the net was lost. A joint survey was also conducted for eight hours during the Cumberland Sound adaptive survey. The Nunavut Government's research trawler *Nuliajuk* (fig. 17) was following the CCGS *Amundsen* in an attempt to sample the schools observed on the sonar screen. Coordinating both ships using radios proved to be complicated, and the *Nuliajuk* had difficulty maintaining his trawl near the surface; thus, no fish were collected during this survey.

Figure 17. Nunavut Government's research trawler vessel Nuliajuk (photo: J.J. Pangrazzi).

In Cumberland Sound, a 2-m x 150-m free drifting trammel net was deployed at the surface (0-2 m) for a 24 hours period to collect fish samples from schools observed near the surface on the sonar screen. No fish were caught, possibly due to the introduction of a depth bias from ray bending (see section 3.1), and the net should rather have been deployed at ~15 m depth.

3.2.2 Detection of pelagic fish layers with the EK60 echosounder

In 2011 in the Canadian Beaufort Sea, an almost continuous layer of pelagic fish was observed with the EK60 echosounder in the top 100 m of the water column, along with an occasional layer near the bottom (fig. 18). An analysis was conducted on a sub-sample representative of the acoustic data (September 7th to September 22nd), resulting in a mean integrated fish biomass of 1.84 x 10^{-2} ±8.19 x 10^{-5} kg m^{-2} (Robert et al. 2011). A Diel Vertical Migration (DVM) pattern was observed in the top layer, contrarily to the bottom layer (Robert et al. 2011). Fifteen ichthyoplankton net deployments, consisting of two 6-m long, 1-m^2 mouth aperture carrying side by side 500- and 750-µm mesh, square-conical nets (fig. 19), were conducted in the surface layer throughout the same period. In addition to *Boreogadus saida*, which dominated the juvenile fish assemblage, sand lance *Ammodytes* sp. and Arctic shanny *Stichaeus* sp. were also found at most stations and certainly contributed to the backscatter signal. Fish standard length ranged from 13 to 42 mm, for an average of 26.35 mm (Robert et al. 2011). Three RMT net deployments (fig. 20) were also conducted in the surface layer, but no adult fish were caught, suggesting that this layer was only formed by juvenile fish (age-0). Unfortunately, it was impossible to sample the bottom layer because the CCGS *Amundsen* is not equipped with bottom trawling devices; future surveys should tackle this issue (see point 1 of section 4.2).

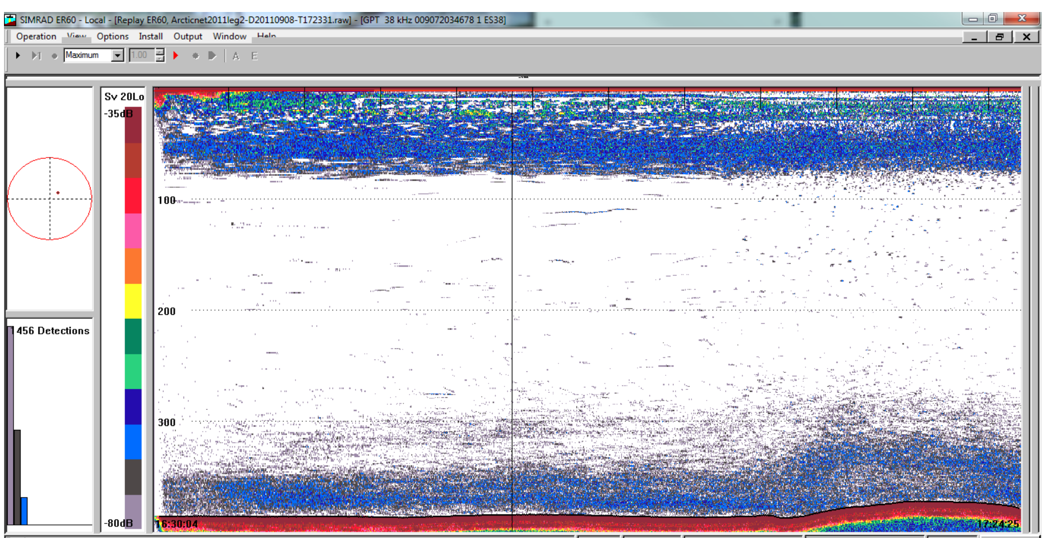

Figure 18. Example of a 1-hour EK60 echogram (Sv minimum threshold = -80 dB) in the Canadian Beaufort Sea in September 2011. Two distinct layers of pelagic fish can be observed, in the top 100 m and at 350 m near the bottom.

Figure 19. Ichthyoplankton nets deployed from the CCGS Amundsen.

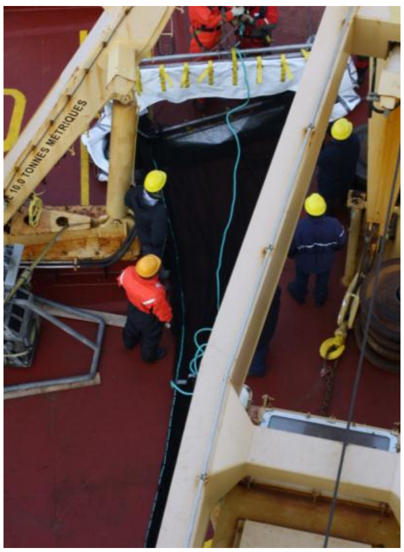

Figure 20. Rectangular Mid-Water Trawl (RMT) before deployment from the CCGS Amundsen.

A TS analysis was conducted separately on the surface and on the bottom layers of fish observed from September 7th to September 22nd. In the surface layer, TS ranged from -65.0 dB to -30.0 dB re 1 m^2 (all values related to TS will be abbreviated as "dB" subsequently), with a mean Target Strength (TS_N) of -51.0 dB (fig. 21a). In the bottom layer, TS ranged from -65.0 dB to -18.2 dB, for a TS_N of -41.7 dB (fig. 21b). TS of fish in the top layer presented a single mode distribution, and TS of those in the bottom layer presented a distinct single mode distribution, suggesting that one different size class was present in each layer (fig. 21). Moreover, as TS_N is proportional to length, it can be concluded that the pelagic fish forming the top layer (0-100 m) are smaller than those forming the bottom layer (>100 m). As it is known from net sampling that age-0 fish formed the top layer, one can assume that age 1+ fish form the bottom layer. Similar size segregation was previously reported by Parker Stetter et al. (2011) in the U.S. Beaufort Sea for the same time of year.

Applying the TS to length relationship used by Crawford and Jorgenson (1993) (eq. 4) for arctic cod to the TS_N values calculated here results in an average length of 9.9 cm for the fish forming the top layer and 26.4 cm for those forming the bottom layer. With an average fish length of 2.6

cm (Robert et al. 2011) obtained from net samples in the surface layer, these values, at least in the surface layer, are clearly overestimated. The presence of other fish species in this layer could contribute to this error, since equation 4 is specific to arctic cod. Other species are probably present in the bottom layer as well and average length values are only an indication and should not be considered exact. However, the difference in TS_N clearly shows a size segregation between the fish near the surface and those at depth >100 m.

$$TS_N = 21.8 \log(L_T) - 72.7 \quad \text{(eq. 4)}$$

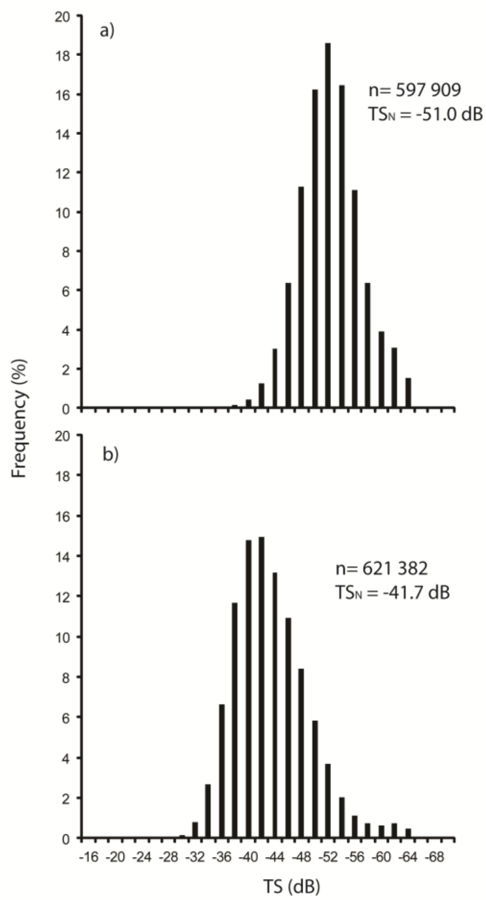

Figure 21. Frequency distribution of the Target Strength (TS in dB re 1m^2) of individual fish in the Canadian Beaufort sea from September 7th to September 22nd for (a) the surface layer (0-100 m), and (b) the bottom layer (>100 m). TS weaker than -65 dB were excluded from the analysis.

3.3 Marine mammal detection component

3.3.1 Detection of marine mammals with the SX90 sonar and validation by MWOs

Table 6 summarizes all 82 MWO-validated marine mammal detections by the SX90 sonar and 164 observations made by MWOs while table 7 details all sonar detections. Cetaceans were always observed over the continental shelf, in bathymetric areas ranging from 20 to 80 m (fig.

22). Mate et al. (2000) previously reported that bowhead whales spend 87% of their time at depths <100 m during summer in the Canadian Beaufort Sea. However, it is important to note that all bathymetric areas were not surveyed with the same effort during the 2011 survey (table 3). With the exception of one seal that was first detected by the SX90 sonar operators, marine mammals were always detected by MWOs first while still outside the sonar detection range, and appeared on the sonar screen as the target was approached. Once the sonar detected cetaceans or pinnipeds, it was possible to continuously track the animal even as it dove below the surface (but not at great depths), which was impossible for the MWOs. The use of a fisheries sonar to track whales periodically re-surfacing was previously reported by Vartdal (2011).

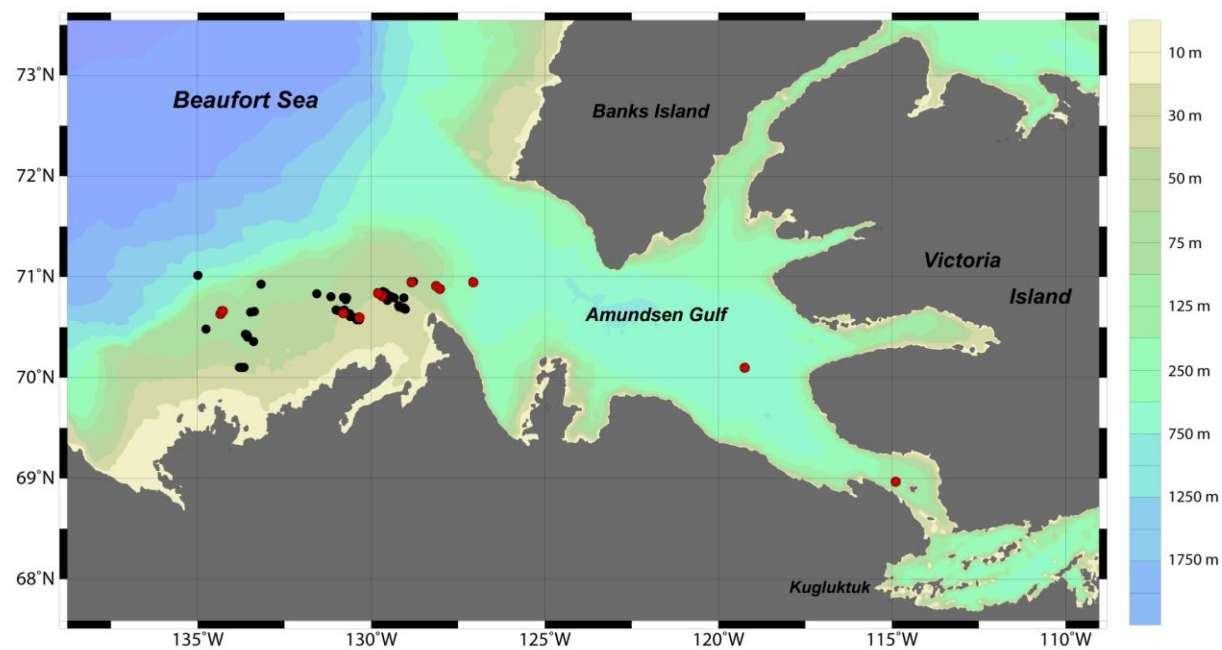

Figure 22. Location of 59 bowhead whales (black dots) and 15 seals (red dots) detected with the SX90 sonar from August 27th to October 3rd, 2011. All detections were validated by MWOs.

Table 6. Summary of MWO-validated marine mammal detections by the SX90 and of MWO sightings throughout the 2011 active acoustic survey. N/A indicates periods of time when MWOs were not present and "-" indicates that none were observed. Note that harp seals, humpback and minke whales were all sighted in eastern Canadian Arctic and were validated by marine biologists rather than Inuvialuit MWOs.

Survey	Bowhead whales		Beluga whales		Humpback whales		Minke whales		Ringed seals		Bearded seals		Harp seals		Unknown seals	
	SX90 detections	MWO observations	SX90 detections	MWO observations	SX90 detections	MWO observations	SX90 detections	MWO observations	SX90 detections	MWO observations	SX90 detections	MWO observations	SX90 detections	MWO observations	SX90 detections	MWO observations
SA-1	47	82	-	4	-	-	-	-	6	6	2	2	-	-	-	-
SA-2	6	17	-	-	-	-	-	-	5	6	-	-	-	-	-	-
SA-3	-	-	-	-	-	-	-	-	-	7	-	-	-	-	-	4
SA-5	-	N/A	-	N/A	-	N/A	-	N/A	-	N/A	-	N/A	-	N/A	-	N/A
Cumberland Sound	-	N/A	-	N/A	-	N/A	-	N/A	-	N/A	-	N/A	-	N/A	-	N/A
Opportunistic	6	20	-	-	-	2	1	1	2	3	-	-	7	7	-	3
TOTAL	**59**	**119**	**0**	**4**	**0**	**2**	**1**	**1**	**13**	**22**	**2**	**2**	**7**	**7**	**0**	**7**

Out of the 126 cetaceans sighted by MWOs or marine biologists while the sonar was operating, 48% were also detected with the SX90 sonar (table 6). For the 38 seals sighted, this ratio reaches 58%. The main reason explaining the higher detection by MWOs is that they usually sighted whales at distances between 2000 m and 5000 m, whereas the *in situ* maximum detection range of the sonar was 2000 m (table 7). If only considering the 64 whales sighted by MWOs at a distance < 2000 m from August 27th to October 3rd, 59 were also detected with the SX90 sonar, increasing the whale detection ratio to 92%. Moreover, during adaptive surveys whales were often observed in scattered groups at distances >2000 m, from which one individual was selected to be approached for detection by the SX90 and TS calculations, while the others remained out of the sonar detection range. In addition, these groups were occasionally detected in areas considered hazardous to navigation (e.g. pingo-like features), which prevented the ship to approach them. Some individuals dove shortly after being sighted by MWOs while outside of the sonar detection range and did not re-surface, preventing acoustic detection. Finally, marine mammals observed by MWOs at a range filled with annular noise could not be distinguished on-screen. Noise created by waves and the ship also prevented some ringed seals sighted by MWOs to be distinguished on the sonar screen.

Forty-six bowhead whales were only detected in the acoustic channel, seven in the “normal” beam, and six over a large range covering both acoustic areas (table 7). Except for one ringed seal, all other marine mammal species were only detected in the “normal” beam. Avoidance behaviours (change in swimming direction) were observed on two occasions upon which the ship’s speed was reduced and its heading deviated from the target before resuming the original transect. The SX90 sonar maximum detection range for cetaceans varied from 155 to 2000 m, for an average of 1044 m. It varied from 80 to 525 m for seals, with an average of 193 m (table 7). Note that the maximum detection range of animals detected in the “normal” beam corresponded to the lower limit of the area filled with annular noise. As the limit was generally ~300 m (see section 3.1), this distance was defined as the transition between the “normal” beam and the acoustic channel.

Table 7. Details of all marine mammals detected with the SX90 sonar and validated by MWOs. Maximum detection ranges starting with “ > ” indicate that the animal could have been detected beyond the display range of the sonar. TS are included for each frequency at which the animal was detected in the “normal” beam and/or the acoustic channel. A note “the echo is not clear” indicates that the echo was detected on the sonar screen, but was not clear enough to conduct a TS analysis. N/A indicates that no data are available.

Date	Time (UTC)	Latitude (° North)	Longitude (° East)	Species	# of ind.	Maximum detection range (m)	Mean detection range (m)	Avoidance behaviour	TS in normal beam (dB)	TS in acoustic channel (dB)	Note
2011-07-21	00:22	50.005	296.259	Minke whale	1	155	135	No	26 kHz = -19.0	N/A	
2011-07-22	10:36	53.003	305.421	Harp seal	7	130	124	No	26 kHz = -18.0	N/A	
2011-08-28	19:00	70.928	226.840	Bowhead whale	1	2000	1367	No	N/A	26 kHz = -7.5	
2011-09-10	19:19	70.658	226.642	Bowhead whale	1	1300	Normal beam = 226 Acoustic channel = 597	No	23 kHz = 3.4 26 kHz = -1.9	23 kHz = 3.9	
2011-09-12	20:04	70.660	225.719	Ringed seal	4	140	113	No	28 kHz = -17.3 29 kHz = -14.0	N/A	
2011-09-12	20:10	70.660	225.708	Ringed seal	1	140	129	No	29 kHz = -10.3	N/A	
2011-09-13	03:12	70.360	226.625	Bowhead whale	1	175	174	No	20 kHz = -1.5 21 kHz = -2.1 22 kHz = -1.4 23 kHz = 2.3 24 kHz = -5.4 25 kHz = -6.5 26 kHz = -6.7 27 kHz = -8.2 28 kHz = -8.2 29 kHz = -10.1	N/A	
2011-09-13	03:45	70.400	226.447	Bowhead whale	1	1200	885	No	N/A	26 kHz = 1.0	
2011-09-13	03:51	70.421	226.418	Bowhead whale	1	1100	638	No	N/A	20 kHz = 3.8 21 kHz = 5.3 22 kHz = 6.5 23 kHz = 3.9	
2011-09-13	03:59	70.434	226.381	Bowhead whale	1	280	214	Slight change in direction	20 kHz = 0.3 21 kHz = -0.8 22 kHz = -0.6 23 kHz = -1.9 24 kHz = -0.1 25 kHz = 1.5 26 kHz = -1.3	N/A	
2011-09-13	14:25	70.106	226.210	Bowhead whale	1	800	633	No	N/A	22 kHz = -14.4	
2011-09-13	14:37	70.106	226.319	Bowhead whale	1	600	566	No	N/A	22 kHz = -9.4	
2011-09-17	17:35	70.804	228.842	Bowhead whale	1	1050	851	No	N/A	20 kHz = -0.1 21 kHz = 2.5 22 kHz = 3.1 23 kHz = 3.0 24 kHz = 3.1 25 kHz = 3.0 26 kHz = 2.5 27 kHz = 2.7 28 kHz = 3.2 29 kHz = 4.5 30 kHz = 5.2	
2011-09-17	18:13	70.837	228.436	Bowhead whale	1	600	538	No	N/A	21 kHz = 0.3 22 kHz = 2.8	
2011-09-19	01:54	70.485	225.243	Bowhead whale	1	440	397	No	N/A	20 kHz = 8.3 22 kHz = 5.7 23 kHz = 4.1 24 kHz = 3.7 25 kHz = 3.0 26 kHz = 2.2 27 kHz = 2.7 28 kHz = 3.2 29 kHz = 3.8 30 kHz = 5.8	
2011-09-19	03:25	70.654	226.545	Bowhead whale	1	1050	1035	No	N/A	23 kHz = -4.3	

Date	Time (UTC)	Latitude (° North)	Longitude (° East)	Species	# of ind.	Maximum detection range (m)	Mean detection range (m)	Avoidance behaviour	TS in normal beam (dB)	TS in acoustic channel (dB)	Note
2011-09-20	14:55	70.779	229.268	Bowhead whale	1	450	438	No	N/A	20 kHz = 10.1	
2011-09-20	14:56	70.784	229.272	Bowhead whale	1	> 810	Normal beam = 222 Acoustic channel = 720	No	25 kHz = -2.7 26 kHz = -3.8 27 kHz = -3.4 28 kHz = -5.0 29 kHz = -3.5 30 kHz = -4.7	20 kHz = 5.1 21 kHz = 4.7	
2011-09-20	14:58	70.776	229.280	Bowhead whale	1	> 1000	Normal beam = 216 Acoustic channel = 596	No	20 kHz = -11.7 21 kHz = -4.4 22 kHz = -0.6 23 kHz = -3.7 24 kHz = -3.7	21 kHz = 6.5 22 kHz = 6.7 23 kHz = 4.7 24 kHz = 3.0 25 kHz = 2.0 26 kHz = 2.0 27 kHz = 2.2 28 kHz = 3.2 29 kHz = 4.5 30 kHz = 5.5	
2011-09-20	14:58	70.776	229.280	Bowhead whale	1	> 1025	Normal beam = 205 Acoustic channel = 640	No	21 kHz = -2.5 22 kHz = -0.9 23 kHz = -4.3 24 kHz = -4.9	21 kHz = 5.5 22 kHz = 5.2 23 kHz = 4.3 24 kHz = 3.2 25 kHz = 1.6 26 kHz = 0.8 27 kHz = -1.3 28 kHz = -1.1 29 kHz = -1.3 30 kHz = -0.3	
2011-09-20	15:00	70.793	229.287	Bowhead whale	1	290	217	No	20 kHz = -2.8 21 kHz = -0.5 22 kHz = 2.0 23 kHz = -0.1 24 kHz = 2.1 25 kHz = 2.6 26 kHz = 0.8 27 kHz = 0.1	N/A	
2011-09-20	15:00	70.793	229.287	Bowhead whale	1	218	192	No	25 kHz = -6.7 26 kHz = -4.7 27 kHz = -3.3 28 kHz = -2.1 29 kHz = -2.7 30 kHz = -12.4	N/A	
2011-09-20	15:03	70.798	229.281	Bowhead whale	1	1250	955	No	N/A	23 kHz = 4.4	
2011-09-20	15:10	70.797	229.215	Bowhead whale	1	1390	1152	No	N/A	23 kHz = -11.1 24 kHz = -1.4 26 kHz = 0.0 27 kHz = -1.2 29 kHz = -2.6 30 kHz = -3.7	
2011-09-20	15:34	70.793	230.945	Bowhead whale	1	> 950	844	No	N/A	23 kHz = -0.5	
2011-09-20	16:03	70.795	230.663	Bowhead whale	1	1200	943	No	N/A	25 kHz= 2.3	
2011-09-20	16:16	70.799	230.576	Bowhead whale	1	> 600	405	No	N/A	21 kHz = 6.2	
2011-09-20	16:27	70.817	230.493	Bowhead whale	1	530	514	No	N/A	21 kHz = 4.9	
2011-09-20	16:35	70.831	230.435	Bowhead whale	1	830	774	No	N/A	21 kHz = 5.4	
2011-09-20	16:37	70.834	230.420	Bowhead whale	1	770	740	No	N/A	21 kHz = 4.4	Very briefly detected
2011-09-20	16:39	70.840	230.407	Bowhead whale	1	> 1200	N/A	No	N/A	N/A	The echo is not clear
2011-09-20	16:41	70.843	230.399	Bowhead whale	1	900	806	No	N/A	21 kHz = 7.2	
2011-09-20	16:42	70.846	230.395	Bowhead whale	1	1100	1092	No	N/A	21 kHz = 6.6	

Date	Time (UTC)	Latitude (° North)	Longitude (° East)	Species	# of ind.	Maximum detection range (m)	Mean detection range (m)	Avoidance behaviour	TS in normal beam (dB)	TS in acoustic channel (dB)	Note
2011-09-20	16:49	70.856	230.348	Bowhead whale	1	450	Normal beam = 217 Acoustic channel = 330	No	20 kHz = 0.8 21 kHz = 3.2 22 kHz = -0.3 23 kHz = 0.2 24 kHz = -0.9 25 kHz = -2.2 26 kHz = 0.4 27 kHz = 1.0 28 kHz = -2.4 29 kHz = -5.7 30 kHz = -4.6	21 kHz = 5.3	
2011-09-21	21:10	68.969	245.124	Ringed seal	1	300	N/A	No	N/A	N/A	The echo is not clear
2011-09-25	20:49	70.095	240.773	Ringed seal	1	525	493	No	N/A	26 kHz = -11.1	
2011-09-28	17:11	70.953	231.165	Ringed seal	1	152	144	No	27 kHz = -11.9	N/A	
2011-09-28	17:20	70.953	231.217	Ringed seal	1	168	149	No	28 kHz = -11.2	N/A	
2011-09-28	19:41	70.884	231.990	Bearded seal	1	136	106	No	24 kHz = -16.7 26 kHz = -19.4 28 kHz = -23.5 29 kHz = -20.4 30 kHz = -22.1	N/A	
2011-09-28	20:18	70.844	230.196	Bearded seal	1	210	144	No	23 kHz = -17.1 24 kHz = -10.2 25 kHz = -12.8 26 kHz = -11.6 27 kHz = -13.0 28 kHz = -9.5 29 kHz = -14.9 30 kHz = -18.7	N/A	
2011-09-28	20:39	70.816	230.303	Ringed seal	1	105	87	No	24 kHz = -29.2 25 kHz = -24.2 26 kHz = -24.3 27 kHz = -31.3 28 kHz = -29.3 29 kHz = -34.1 30 kHz = -30.6	N/A	
2011-09-28	20:44	70.808	230.333	Ringed seal	1	210	167	No	23 kHz = -4.3 24 kHz = -6.2 25 kHz = -6.1 26 kHz = -6.4 27 kHz = -7.6 28 kHz = -6.8 29 kHz = -7.6 30 kHz = -4.7	N/A	
2011-09-28	20:45	70.807	230.339	Ringed seal	1	80	72	No	28 kHz = -27.2	N/A	
2011-09-28	20:56	70.779	230.442	Bowhead whale	1	1600	1003	No	N/A	20 kHz = 1.4 21 kHz = 1.6 22 kHz = 5.3 23 kHz = 1.8 24 kHz = 2.5 25 kHz = -1.3 26 kHz = -1.9 27 kHz = -2.1 28 kHz = -5.1 29 kHz = -2.0 30 kHz = 4.8	
2011-09-28	20:57	70.779	230.442	Bowhead whale	1	1600	1227	No	N/A	20 kHz = 5.9 21 kHz = 8.0 22 kHz = -3.5 23 kHz = -6.7	
2011-09-28	21:01	70.769	230.480	Bowhead whale	1	1500	733	No	N/A	20 kHz = 7.3 21 kHz = 9.0 22 kHz = 6.8 23 kHz = 5.0 24 kHz = 3.7 25 kHz = 3.0 26 kHz = 2.5 27 kHz = 2.7 28 kHz = 2.9 29 kHz = 4.5 30 kHz = 5.2	
2011-09-28	21:55	70.712	230.786	Bowhead whale	1	850	845	No	N/A	22 kHz = 4.0	

Date	Time (UTC)	Latitude (° North)	Longitude (° East)	Species	# of ind.	Maximum detection range (m)	Mean detection range (m)	Avoidance behaviour	TS in normal beam (dB)	TS in acoustic channel (dB)	Note
2011-09-28	21:59	70.707	230.812	Bowhead whale	1	740	716	No	N/A	22 kHz = 4.4	
2011-09-28	22:01	70.704	230.830	Bowhead whale	1	1000	835	No	N/A	21 kHz = 6.7 22 kHz = 5.2 23 kHz = 3.6	
2011-09-28	22:02	70.704	230.830	Bowhead whale	1	900	683	No	N/A	22 kHz = 6.3 23 kHz = 5.0	
2011-09-28	22:04	70.701	230.851	Bowhead whale	1	700	548	No	N/A	21 kHz = 3.8 22 kHz = 4.7	
2011-09-28	22:11	70.698	230.899	Bowhead whale	1	1150	818	No	N/A	21 kHz = 7.1 22 kHz = 2.8 23 kHz = 3.5 24 kHz = 2.5 25 kHz = 1.5 26 kHz = -0.4 27 kHz = -2.4	
2011-09-28	22:12	70.696	230.906	Bowhead whale	1	1250	934	No	N/A	21 kHz = 1.4 22 kHz = 1.8 23 kHz = 1.8 24 kHz = 0.7 25 kHz = 1.6 27 kHz = 1.4 28 kHz = 2.0 29 kHz = -0.7 30 kHz = 1.5	
2011-09-28	22:13	70.696	230.906	Bowhead whale	1	> 1400	970	No	N/A	27 kHz = 2.7 28 kHz = 2.4 29 kHz = 2.3 30 kHz = 3.2	
2011-09-28	22:14	70.693	230.923	Bowhead whale	1	2000	984	No	N/A	21 kHz = 5.7 22 kHz = 5.8 23 kHz = 2.1 24 kHz = -3.2 25 kHz = -5.2 26 kHz = -6.4	
2011-09-28	22:15	70.692	230.929	Bowhead whale	1	1400	1230	No	N/A	26 kHz = -7.4	
2011-09-28	22:17	70.690	230.937	Bowhead whale	1	1900	1658	No	N/A	21 kHz = -5.5 22 kHz = -4.6 23 kHz = -6.3	
2011-09-28	22:18	70.688	230.945	Bowhead whale	1	2000	1937	No	N/A	20 kHz = -7.5 21 kHz = -7.3 22 kHz = -2.4 23 kHz = -3.1	
2011-09-28	22:25	70.679	230.983	Bowhead whale	1	180	171	No	21 kHz = -4.6 22 kHz = -3.8 23 kHz = -3.3	N/A	
2011-09-28	22:28	70.673	229.008	Bowhead whale	1	1500	1004	No	N/A	20 kHz = 6.2 21 kHz = 6.6 22 kHz = 6.0 23 kHz = 4.3 24 kHz = 3.5 25 kHz = 2.5 26 kHz = 2.4 27 kHz = 2.7 28 kHz = 3.2 29 kHz = 4.5 30 kHz = 1.9	
2011-09-28	22:35	70.664	229.058	Bowhead whale	1	1800	1558	No	N/A	24 kHz = -3.9 25 kHz = -0.7 26 kHz = -3.9 27 kHz = -0.9	
2011-09-28	23:15	70.606	229.399	Bowhead whale	1	1095	1054	No	N/A	26 kHz = 2.0 27 kHz = 2.6	
2011-09-28	23:19	70.606	229.437	Bowhead whale	1	1300	N/A	No	N/A	N/A	The echo is not clear
2011-09-28	23:42	70.602	229.651	Bowhead whale	1	1500	1352	No	N/A	26 kHz = -1.9	

Date	Time (UTC)	Latitude (° North)	Longitude (° East)	Species	# of ind.	Maximum detection range (m)	Mean detection range (m)	Avoidance behaviour	TS in normal beam (dB)	TS in acoustic channel (dB)	Note
2011-09-28	23:43	70.601	229.660	Ringed seal	1	220	170	No	20 kHz = -7.4 21 kHz = -8.1 22 kHz = -16.2 23 kHz = -8.2 24 kHz = -9.2 25 kHz = -9.9 26 kHz = -13.9 27 kHz = -2.8 28 kHz = -13.5 29 kHz = -8.4 30 kHz = -11.1	N/A	
2011-09-28	23:46	70.598	229.677	Bowhead whale	1	1650	1134	No	N/A	20 kHz = 0.9 21 kHz = 0.9 22 kHz = 1.0 23 kHz = 2.9 24 kHz = 3.7 26 kHz = -0.7 27 kHz = 2.5 30 kHz = 0.0	
2011-09-29	00:00	70.573	229.660	Bowhead whale	1	850	746	No	N/A	24 kHz = 3.5	
2011-09-29	00:03	70.572	229.639	Bowhead whale	2	204	173	Change in direction	24 kHz = -12.6 30 kHz = -15.0	N/A	Two males fighting
2011-09-29	00:10	70.572	229.605	Bowhead whale	1	1100	912	No	N/A	20 kHz = 4.3 21 kHz = 7.2 22 kHz = 5.5 23 kHz = 4.9 24 kHz = 3.3	
2011-09-29	00:42	70.638	229.387	Bowhead whale	1	1800	1100	No	N/A	20 kHz = 8.7 21 kHz = 5.0 22 kHz = 5.0 23 kHz = 2.3 24 kHz = 3.7 25 kHz = 2.1 26 kHz = 2.2 27 kHz = 1.6 28 kHz = 1.7 29 kHz = -1.2 30 kHz = -5.1	
2011-09-29	00:48	70.635	229.354	Bowhead whale	1	1550	1442	No	N/A	20 kHz = -2.5 21 kHz = 0.3 22 kHz = -5.2 23 kHz = -3.8	
2011-09-29	01:33	70.675	229.245	Bowhead whale	1	1100	Normal beam = 211 Acoustic channel = 698	No	21 kHz = -0.4 22 kHz = 0.8 23 kHz = 1.4 24 kHz = -1.8 25 kHz = -4.1 26 kHz = -8.3 27 kHz = -6.4 28 kHz = -4.3 29 kHz = -6.3	20 kHz = 5.7 21 kHz = 7.9 22 kHz = 6.6 23 kHz = 4.4 24 kHz = 3.7 25 kHz = 1.5 26 kHz = 2.0 27 kHz = 2.7 28 kHz = 2.9 29 kHz = 2.7 30 kHz = 1.5	

3.3.2 Echo-track characteristics of marine mammals

When detected in the acoustic channel with the SX90 sonar, bowhead whales presented a characteristic signal consisting of repeated, strong, curved echoes (fig. 23a). The echoes originated from wakes created when the whale was swimming or blowing under the surface, or from the whale itself. It proved difficult to distinguish the whale from its wake, especially at a far range when the distance between the whale and the ship could not be determined with accuracy by MWOs. The wake and the whale presented a similar acoustic signature, preventing a differentiation based on TS. The air contained in the whales' lungs was likely responsible for the backscattering signal (Au 1996). Echoes from the wake probably originated from air bubbles, either from the bowhead whale blowing underwater before surfacing, or from air bubbles generated from swimming in close proximity to the surface (Selivanovsky and Ezersky, 1996). No echoes from vocalizations were observed on-screen, most likely because bowhead whales use frequencies lower than the SX90 sonar frequency range (Blackwell et al. 2007). As a general rule, the whale was assumed to be the last echo along the wake track (i.e. if the whale was swimming away from the ship, the whale echo was the farthest away from the ship). This rule also holds in the “normal” beam, where the whale was more easily distinguishable from its wake (fig. 15 and 23b).

Ringed seals and bearded seals were generally detected in the “normal” beam during acoustic surveys (table 7). They were observed as groups or single individuals swimming in proximity to the ship as it sailed along its pre-defined transect. Since they were approaching the ship on their own, they were often detected at a close range (<150 m). Except for one occasion when a ringed seal was detected in the acoustic channel at 525 m, their echoes were generally too weak to be detected at ranges exceeding 200 m. Blubber and lungs were most likely responsible for the seal echoes, which were very different from those of bowhead whales. Echoes originating from seals did not exhibit the repeated, curved echoes typical of a whale, but rather appeared as an isolated, rounded and slightly curved acoustic signal (fig. 23 c and d). In the presence of drifting ice, seal echoes were easily mistaken with floating pieces of ice. Detection of seals was facilitated when the sonar was emitting at frequencies >23 kHz (table 7).

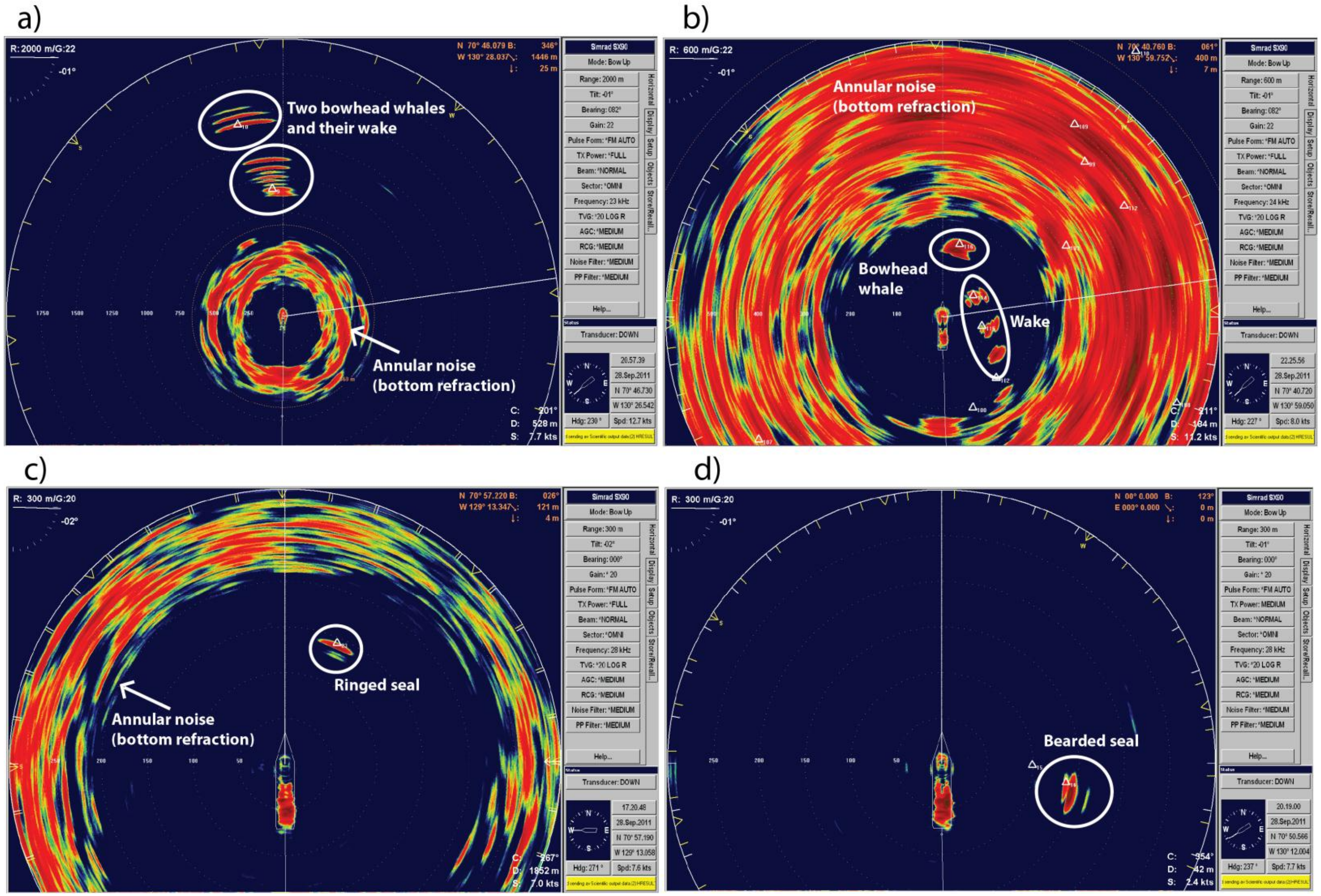

Figure 23. Echo-track characteristics of (a) two bowhead whales and their wake detected in the acoustic channel at a range ~1500 m; (b) a bowhead whale and its wake detected in the "normal" beam at a range ~175 m; (c) a ringed seal detected in the "normal" beam at a range ~150 m; and (d) a bearded seal detected in the "normal" beam at a range ~150 m. Annular noise due to bottom refraction is present in panels (a-c), but not in panel (d), most likely because water stratification did not result in ray bending.

3.3.3 Acoustic signature of marine mammals

The Target Strength (TS) of 50 bowhead whales detected in the acoustic channel (range > 300 m) varied from a minimum of -14.4 dB at 22 kHz to a maximum of 10.1 dB at 20 kHz (fig. 24a). TS of 13 bowhead whales detected in the “normal” beam ranged from -15.0 dB at 30 kHz to 3.7 dB at 24 kHz (fig. 24b). TS values were higher in the acoustic channel relative to the “normal” beam (fig. 24c), as transmission losses are overestimated in the channel (fig. 12).

The TS of all bowhead whales was averaged (TS_N) for each frequency and the resulting plot represents the acoustic signature of the species (fig. 24c). In the acoustic channel, TS_N was higher (5.6 dB) at 20 kHz and decreased gradually until it reached a minimum at 26 kHz (0.4 dB). From 26 kHz, TS_N increased with frequency to reach 3.0 dB at 30 kHz. In the “normal” beam, the average TS increased with frequency until a maximum was reached (0.9 dB) at 23 kHz, and then decreased to reach a minimum of -7.1 dB at 30 kHz. Au (1996) also observed a decrease in TS with increasing frequency (from 23 to 45 kHz) for measurements made on an Atlantic bottlenose dolphin under controlled conditions.

A minke whale was detected in the “normal” beam, at 26 kHz, with the SX90 sonar on July 21st. The corresponding TS was -19.0 dB (table 7), which suggests that minke whales have a lower TS than bowhead whales. However, as only one minke whale was detected this result may not be representative.

TS was generally lower for pinnipeds than for bowhead whales and was comprised within a similar range for all three seal species detected. TS of ringed seals ranged from -34.1 dB at 29 kHz to -2.8 dB at 27 kHz, and TS of bearded seals ranged from -23.5 dB to -9.5 dB at 28 kHz (fig. 25a). A group of 7 harp seals was detected at 26 kHz with the SX90 sonar on July 22nd. It was difficult to distinguish one individual from the others and a TS analysis was conducted on the herd as a whole, resulting in a TS of -18.0 dB (table 7). As pinnipeds were all detected in the “normal” beam except for one, the difference between detections in the “normal” beam and the acoustic channel was not investigated. No trend was observed in the TS_N-Frequency relationship of pinnipeds and intervals of confidence were large (fig. 25b) due to the limited amount of data available at each frequency ($0 \leq N \leq 6$).

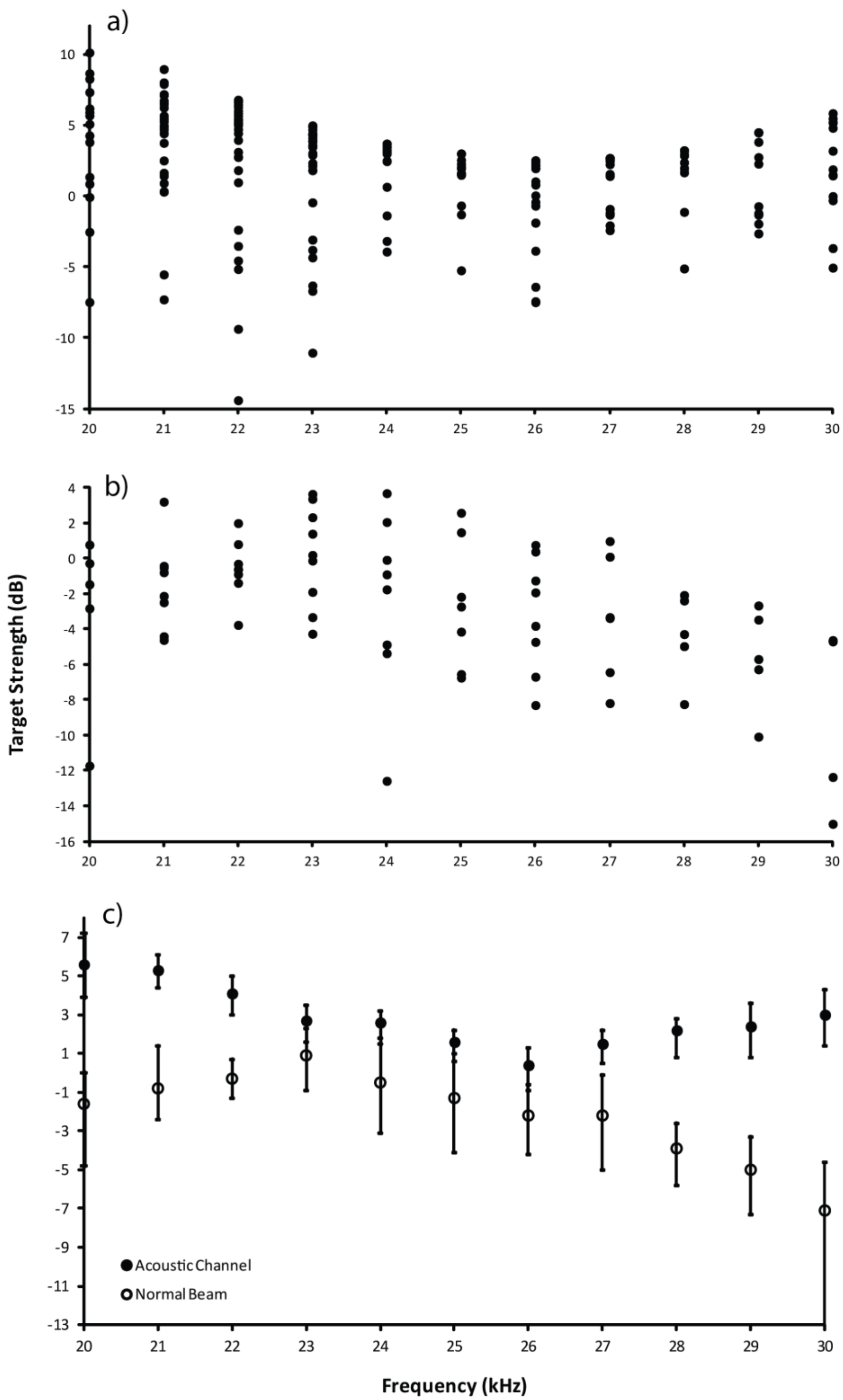

Figure 24. Target Strength (TS) as a function of frequency of the SX90 sonar for (a) 50 bowhead whales detected in the acoustic channel (range >300 m), and (b) 13 bowhead whales detected in the "normal" beam (range <300 m). (c) Mean Target Strength (TS_N) as a function of frequency in the acoustic channel (solid line) and the "normal" beam (dashed line) with confidence intervals.

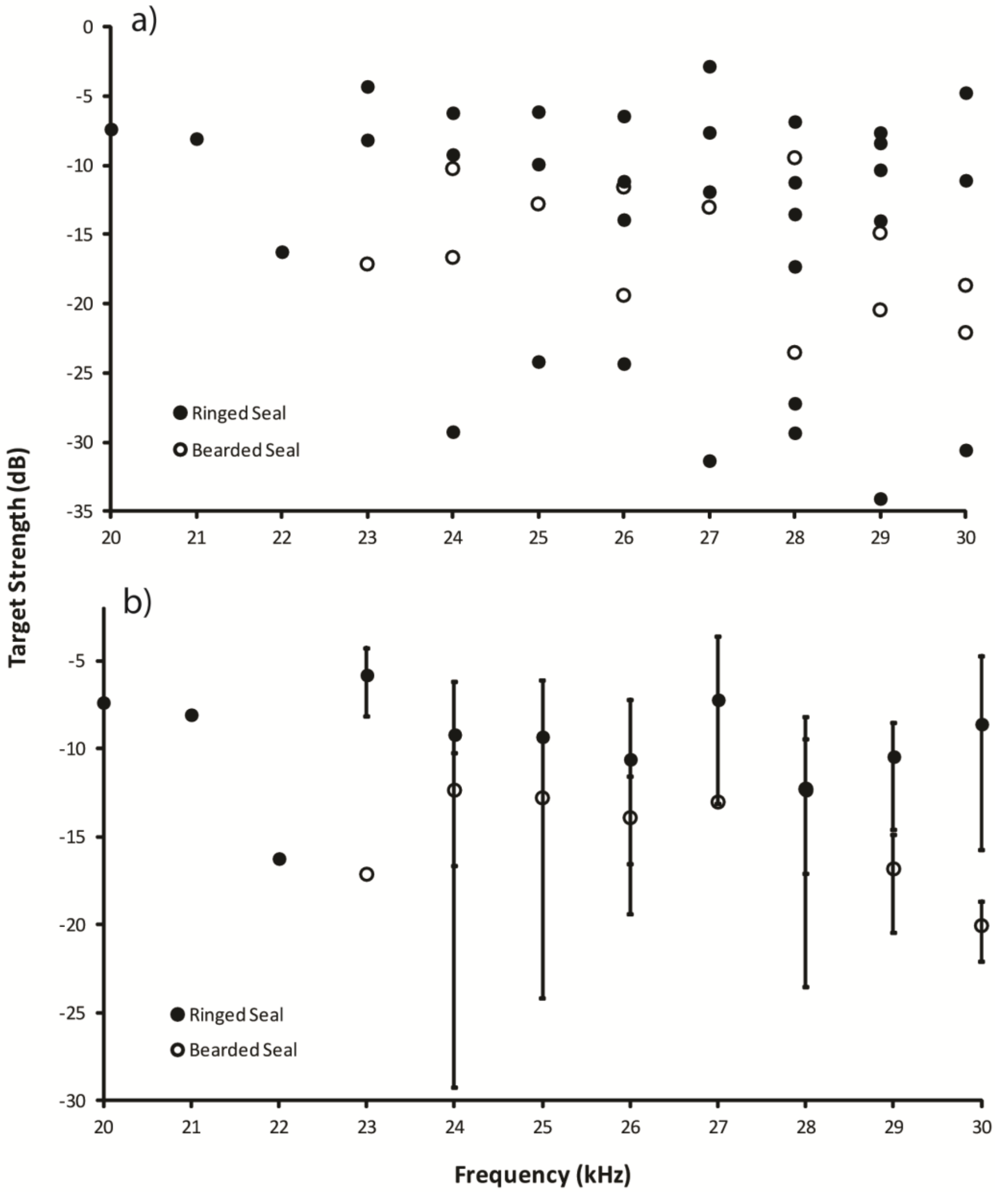

Figure 25. (a) Target Strength (TS) as a function of frequency of the SX90 sonar for 12 ringed seals (solid line), and 2 bearded seals (dashed line). (b) Mean Target Strength (TS_N) as a function of frequency for ringed seals (solid line) and bearded seal (dashed line) with confidence intervals. No confidence interval means that only one TS value was available for a given frequency (N = 1).

A strong correlation exists between TS and target distance from the ship due to the inaccuracy of the sound propagation model (40logR+2αR) used for TS calculations, which is exact only under ideal conditions (see section 3.1). This correlation is greater below 150 m (where most seals were detected) and diminishes as the range increases. This TS-range dependency explains much of the variability observed between individuals, and may also explain the decrease in TS with increasing frequency observed in the "normal" beam, which differs from the increase in TS observed in the acoustic channel (fig. 24c). Indeed, data were usually acquired at 26 kHz while transiting, from 26 kHz to 20 kHz while approaching a whale, and at higher frequencies (27-30 kHz) closer to the animal. For this reason, it is difficult to eliminate any bias created by the range dependency of TS in the present study, which likely impacts the frequency response of TS measurements. Despite TS overestimation in the acoustic channel, the range dependency is less important and TS values remain stable over a longer range in the channel than in the "normal" beam.

Air bubbles around marine mammals may also contribute to bias TS measurements since distinction between the animal and its wake was not always possible. However, the large sample size (especially for bowhead whales) on which a TS analysis was conducted diminishes the impact of biases on the results and TS ranges obtained for bowhead whales and seals represent preliminary thresholds that could be used as recognition criteria for future acoustic studies.

3.3.4 Incident angle dependency of Target Strength

The direction of bowhead whales was determined from the wake track and used to estimate the angle of incidence relative to the acoustic beam. A TS-angle of incidence relationship was calculated for five bowhead whales detected at different angles. Whales were all pooled because each whale was only detected at a narrow range of angles of incidence, which could explain the low coefficient of determination (r^2=0.25). However, the low p-value ($p<0.001$) clearly demonstrates a positive relationship between the angle of incidence and the TS for bowhead whales (fig. 26). Overall, the broadside position presented the highest TS and tail/head on position the lowest TS, as previously documented for gray whales (Lucifredi and Stein 2006), humpback whales (Love 1973), and bottlenose dolphins (Au 1996). Bowhead whales were usually closer to the ship when presenting a broadside position, potentially introducing a bias due to the previously discussed TS-range correlation and this relationship should be validated during future surveys.

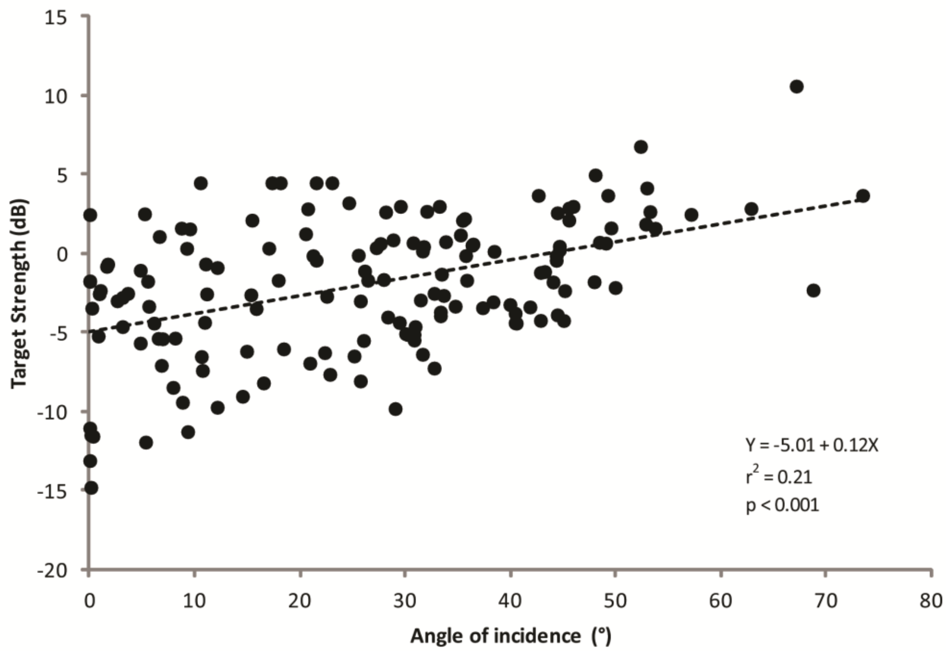

Figure 26. Target Strength (TS) as a function of the angle of incidence (relative to the acoustic beam) for five bowhead whales detected in the Beaufort Sea in September 2011. 0° is tail or head on; 90° is broadside.

3.3.5 Non-validated marine mammal detections

On three occasions, a persistent echo presenting echo-track characteristics very similar to those of marine mammals was observed on the SX90 sonar screen without being validated by MWOs. A TS analysis averaged over three to five pings for each of these echoes indicates that two of them could have been bowhead whales and one an unidentified seal (table 8). These detections were not validated due to the presence of fog (September 5th), because MWOs were off duty (September 28th), and possibly because one of the whales remained just below the surface (September 13th). As these echoes cannot be validated, they were not included in section 3.3.1.

Table 8. Details of non-validated marine mammals detected by the SX90 sonar. Maximum detection ranges starting with " > " indicate that the animal could have been detected beyond the display range of the sonar. TS are included for each frequency at which the animal was detected in the "normal" beam and/or the acoustic channel. N/A indicates that no values are available.

Date	Time (UTC)	Latitude (°North)	Longitude (° East)	Species	# of ind.	TS in normal beam	TS in acoustic channel	Maximum detection range (m)	Mean detection range (m)	Avoidance behaviour	Note
2011-09-05	16:45	71,015883	225,00225	Bowhead whale	1	N/A	26 kHz = 0.5	> 900	715	No	Presence of fog
2011-09-13	14:39	70,10455	226,33293	Bowhead whale	1	N/A	22 kHz = -4.5	> 600	556	No	
2011-09-28	19:21	70,90845	231,88212	Unidentified seal	1	28 kHz = -28.1	N/A	120	86	No	No MWO on duty

3.4 Iceberg detections

In addition to marine mammals and fish, two icebergs were detected with the SX90 sonar in the eastern Canadian Arctic. One tabular iceberg was detected on July 22nd offshore the Labrador coast (53.0°N 54.6°W; fig. 27a), and a portion of the Peterman tabular iceberg was approached with the CCGS *Amundsen* in Lancaster Sound (74.0°N, 81.6°W; fig. 27b) on July 30th. It was possible to detect the iceberg at a range up to 1450 m on July 30th. The vertical view was used to estimate the submerged depth of the icebergs to ~50 m on July 22nd and ~100 m on July 30th. A confirmation of the latter was obtained from the Ocean Mapping Group (University of New Brunswick) who mapped the contour of the iceberg with a multibeam echosounder installed on a barge and estimated a maximum depth of 104 m.

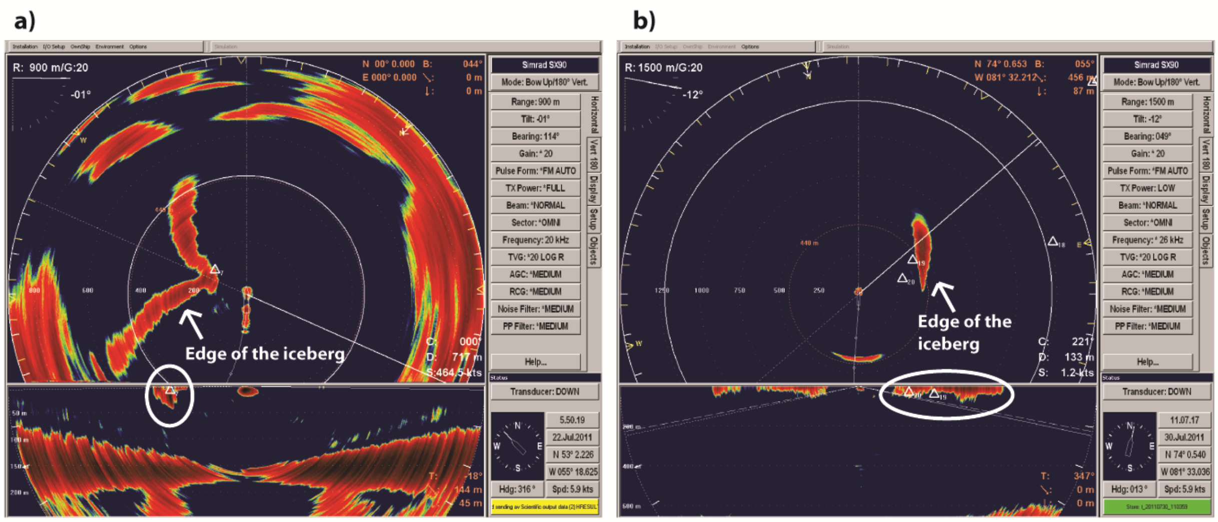

Figure 27. Detection of the edge of an iceberg with the SX90 sonar on (a) July 22nd offshore the Labrador coast; and (b) July 30th in Lancaster Sound. The vertical view window is superimposed on the horizontal view.

4. Recommendations for future acoustic surveys

4.1 SX90 hardware and software improvements

1. The SX90 DataLogger software records each ping of the horizontal transmission, but none of the vertical transmission. Recording of the vertical transmission mode data would greatly increase the possibilities for post-analysis and should be added to the software. Moreover, the size of the vertical view window might be large enough to detect slow moving fish schools, but not fast swimming marine mammals. We suggest the use of a two-screen interface: one for the horizontal view and the second for the vertical view. A two-screen interface would also prevent hiding a section of the horizontal view when using the vertical transmission mode (fig. 27).

2. As ranges of TS for different marine mammals are now known, the next step is to implement real-time TS calculations within the SX90 software interface. This would allow direct differentiation of marine mammals from noise and identification to the order or suborder (i.e. cetaceans or pinnipeds) and, eventually, to the species. For instance, clicking on a target on the screen could return its TS value to be compared with known TS ranges of whales and seals. In addition, the software should automatically calculate the sound of speed (c), coefficients of absorption (α), and transmission losses based on the most recent temperature-salinity profile and using the Lybin algorithm for losses.

3. Vocalizations within the 20 to 30 kHz frequency range (e.g. from orca whales) can be heard and visualized with the SX90 sonar (Knudsen et al. 2007). However, bowhead whales vocalize at lower frequencies (<400 Hz; Blackwell et al. 2007) and vocalizations were not observed nor heard during the present study. The possibility of increasing the passive frequency range of the sonar to cover the vocalization frequencies of several species should be investigated.

4. The annular noise created by bottom refraction in shallow areas greatly diminishes the detection range in the absence of a sound channel and creates noise on a wide range. Filtering techniques should be improved to reduce noise resulting from bottom refraction.

5. Onboard the CCGS *Amundsen*, the SX90 is operated from the acquisition room, which complicates communications between the SX90 operators and MWOs or the bridge. Echo-validation of marine mammal detections through radio communications can create a bias on the interpretation of what is displayed on the sonar screen relative to what is seen from the bridge, especially for whales swimming rapidly. We strongly recommend to move the SX90 interface from the acquisition room to the bridge, or to install a duplicate interface that would allow operation of the SX90 from the bridge when needed.

6. A gate-valve is installed onboard the CCGS *Amundsen* for the deployment of the SX90 transducer. The gate-valve is operated (i.e. opened or closed) from the moon-pool room by Coast Guard officers, but the transducer is deployed and retrieved by SX90 operators from the acquisition room. Normally, a limit switch prevents any transducer deployment while the gate-valve is closed, as well as the closing of the gate-valve while the transducer is deployed. In addition to the limit switch, lights indicating whether the gate-valve is open or closed should be installed near the SX90 interface to prevent any confusion.

4.2 Survey design recommendations

1. High priority should be put toward the detection and sampling of adult pelagic fish (mainly arctic cod) during summer/fall in the Canadian Beaufort Sea. Joint surveys are planned with Fisheries and Oceans Canada (DFO) to sample pelagic fish using a trawling vessel. Part of the sampling should focus on the bottom layer formed of larger fish (fig. 18) occurring over the continental slope and deep water areas (bottom depth ranging from 200 to 400 m). Operation of the SX90 sonar near the Marginal Ice Zone (MIZ) should also be planned for future acoustic surveys as these areas are known to be highly productive due to wind-induced upwellings (Smith et al. 1985; Pickart et al. 2011). It is assumed that arctic cod school in the MIZ areas to benefit from higher prey concentrations and this hypothesis could be verified using the SX90 sonar.

2. A more extensive calibration, consisting of TS measurements of a known target (i.e. the corner reflector; fig. 10) at several distances (50-2000 m range using a 50 m increment), should be conducted at all operational frequencies to better understand TS variations relative to range and frequency. Measurements should also be conducted at several depths to understand the depth dependency of TS.

3. For future acoustic surveys, efforts should be made to collect acoustic data of marine mammals at different depths to understand the pressure effect on the acoustic signature. During the 2011 survey, it was not possible to evaluate the depth dependency of marine mammal TS since data from the vertical transmission mode were not recorded and all acoustic detections occurred near the surface, where validation by MWOs was possible. As previously mentioned, recording vertical data, increasing the size of the vertical view window, and conducting an extensive calibration using the corner reflector would help documenting TS and echo-track characteristics of marine mammals detected at several depths. It is thought that an inverse relationship exists between TS and depth due to the air contraction in the lungs occurring as the pressure increases (Knudsen et al. 2007).

4. Only one group of belugas (four individuals) was sighted by MWOs (at 900 m) during the 2011 active acoustic survey, which was not detected by the SX90 sonar (table 6). These individuals could have avoided detection for one of the following reasons: (1) they stayed within 2000 m for a very limited amount of time; (2) the detection range was <900 m at this moment; or (3) they dove at great depths before being detected. Belugas represent an important proportion of the cetaceans living in the Canadian Beaufort Sea, with a population estimated to ~20 000 individuals in 1992 (Harwood et al. 1996), and it is primordial to establish recognition criteria for this species during future acoustic surveys. The highest concentrations of belugas occur in Kugmallit Bay, near Tuktuyaktuk (up to 1.137 beluga/km^2; Harwood et al. 1996; MWOS, personal communication). Future acoustic

surveys should partly focus on this area to collect information on echo-track characteristics and TS of belugas.

5. A more exhaustive protocol should be developed to monitor negative behaviours of marine mammals, and MWOs' logging devices should be modified to log such behaviours based on table 9. While approaching marine mammals during adaptive surveys, reporting of the response scores corresponding to the observed behaviour would allow the SX90 operators to immediately mention the appropriate measures to the officer in charge. As a precautionary approach, when sighting a group of marine mammals, the most severe response (higher response score) by any individual observed within the group should be used to make a decision on the corrective measures to be taken. According to Southall et al. (2007), behaviours corresponding to a response score between 1 and 3 (table 9) are relatively minor and/or brief. If one or more of them is observed, the ship should maintain its actual distance from the target and stop approaching while data acquisition continues. Behaviours with a response score between 4 and 6 are more likely to affect foraging, reproduction, or survival. Upon observation of one of these, the sonar power should immediately be decreased to low and the ship's heading deviated away from the target before the original transect resumes. Finally, behaviours with a higher response score (7-9) are considered likely to affect vital activities. In the unlikely event that such behaviours are observed, the adaptive survey should immediately stop and the sonar be powered off while cruising away from the targets. Once the avoidance and/or aggressive behaviour ends and the ship is further than 3000 m from the individual, the transect should resume as a systematic survey.

Table 9. Severity scale for ranking observed behavioral responses of free-ranging marine mammals to anthropogenic sound during SX90 adaptive surveys (adapted from Southall et al. 2007).

Response score	Corresponding behaviours (Free-ranging subjects)
0	- No observable response
1	- Brief orientation response (investigation/visual orientation)
2	- Moderate or multiple orientation behaviours
3	- Prolonged orientation behaviour - Minor changes in locomotion speed, direction, and/or dive profile but no avoidance of sound source
4	- Moderate changes in locomotion speed, direction, and/or dive profile but no avoidance of sound source - Brief, minor shift in group distribution
5	- Extensive or prolonged changes in locomotion speed, direction, and/or dive profile but no avoidance of sound source - Moderate shift in group distribution - Change in inter-animal distance and/or group size (aggregation or separation)
6	- Minor or moderate individual and/or group avoidance of sound source - Brief or minor separation of females and dependent offspring

	- Aggressive behaviour related to noise exposure (e.g., tail/flipper slapping, fluke display, jaw clapping/gnashing teeth, abrupt directed movement, bubble clouds) - Visible startle response
7	- Extensive or prolonged aggressive behaviour - Moderate separation of females and dependent offspring - Severe and/or sustained avoidance of sound source
8	- Obvious aversion and/or progressive sensitization - Prolonged or significant separation of females and dependent offspring
9	- Outright panic, flight, stampede, attack of conspecifics, or stranding events

5. Summary and conclusions

5.1 Fisheries research component

The detection of 12 schools of fish near the surface in the St-Lawrence River and during the Cumberland Sound Survey proved the effectiveness of the SX90 sonar as a complementary bioacoustic device to study adult pelagic fish. However, apart from the Cumberland Sound area, no schools of adult fish were detected in the Canadian Arctic. This prevented the achievement of some of the initial objectives of the fisheries research component, mainly the biomass estimation of arctic cod schools. On the other hand, it suggests that unlike the initial hypothesis, adult arctic cod do not school near the surface in the survey area in September. However, they possibly school in coastal shallow waters (<25m) and in the MIZ region as these areas were not surveyed.

Data collected with the EK60 echosounder showed that rather than forming schools, pelagic fish segregated in scattered aggregations in the Canadian Beaufort Sea. On several occasions, a layer (>100 m) of large fish (TS_N = -41.7 dB) was observed near the bottom in bathymetric areas ranging from 200 to 400 m. Due to equipment constraints, the bottom layer was not sampled and future surveys should focus on fish assemblage and length distribution within this layer. A distinct and almost continuous layer of smaller fish (age-0 arctic cod, arctic shanny and sand lance; TS_N = -51.0 dB) was observed in the first 100 m of the water column. As the SX90 sonar uses frequencies allowing detection of adult fish schools, but not smaller fish, the echosounder remains more efficient to detect layers of age-0 fish near the surface. Thus, the SX90 sonar cannot solve the biomass underestimation issue of arctic cod in areas where the species do not school.

5.2 Marine mammal detection component

Except for detection of belugas and determination of depth dependency, all initial objectives related to marine mammal detection were achieved. Fifty-nine bowhead whales, 1 minke whale, 13 ringed seals, 2 bearded seals, and 7 harp seals were detected with the SX90 sonar. All detections were validated by MWOs and a TS analysis was conducted on 59 whales and 21 seals that returned a clear echo. This survey was a success in establishing recognition criteria for bowhead whales, ringed and bearded seals. For all three species, the echo-track characteristics and acoustic signatures based on TS_N at all frequencies (20-30 kHz) and for different ranges were documented. Using these criteria, three signals that were not validated by MWOs were identified as two bowhead whales and one seal. TS of the minke whale was -19.0 dB at 26 kHz, TS of bowhead whales ranged from -15.0 dB to 10.1 dB, and TS of seals ranged from -34.1 dB to -2.8 dB. Results for bowhead whales are in good agreement with values reported for other cetacean species. For instance, TS values ranged from -4 dB to 7 dB at 20 kHz for a humpback whale located at a 20-78 m range (Love 1973), and from 3 dB to 11 dB at 23 kHz for a gray whale located at a 408-607 m range (Lucifredi and Stein, 2007). Miller and Potter (2001) reported a maximum TS of 4 dB for a humpback whale and -1 dB for a northern right whale at a close range (< 90 m; frequency of 86 kHz).

Bowhead whales were detected at a range up to 2000 m by the SX90 sonar, but the maximum detection range was lower in the absence of an acoustic channel. If temperature-salinity profiles are available for a survey area, maximum detection ranges can be modelled with the Norwegian software Lybin. As CTD water properties are rarely uniform throughout transects, CTD casts must be conducted as often as possible during acoustic surveys to estimate changes in detection ranges. Despite the high variability of the detection range due to changes in physical properties of the water column, the average maximum range at which whales were detected was greater than 1000 m. Since 92% of all bowhead whales sighted by MWOs at a range within 2000 m were detected by the SX90, we conclude that once the recommendations of section 4.1 are implemented, the sonar will represent an efficient complementary tool to MWOs for detection of marine mammals. Although MWOs sighted bowhead whales at a distance up to 5000 m, the SX90 sonar proved useful to detect marine mammals during low visibility conditions (e.g. fog) and to track them below the surface after being sighted.

Even with a second screen for the vertical view and a recording mode for the vertical data, it would be difficult to detect fast swimming marine mammals at depth. Knudsen et al. (2007) detected orca whales at 100 m and 200 m depth, but these individuals were stationary and dove for foraging in the same area for several minutes. On the other hand, a transiting whale would cross the vertical slice too rapidly to be detected and the horizontal view therefore represents the only option to detect such individuals. During summer in the Canadian Beaufort Sea, bowhead whales surface once every 2-5 minutes on average, spend 8-21% of their time at the surface and 60% at depth ≤16 m (Dorsey et al. 1989; Krutzikowsky and Mate 2000). Heide-Jørgensen et al. (1998) report that belugas in the Canadian Archipelago spend on average 40% of their time at the surface (<5 m) and dive for 7-8 minutes. On average, gray whales spend 17% of their time at the surface and dive for ~2 minutes (Stelle et al. 2008). Thus, in the Canadian Beaufort Sea any cetacean spending a few minutes at a distance <2000 m from the ship has a high probability of being detected on the horizontal view (tilted 1 or 2 degrees below the surface).

Bowhead whales and belugas tend to avoid industrial activity, seismic vessels and dredges at distance ≤ 10 km and sometimes more (Richardson et al. 1985; Ljungblad et al. 1988; Erbe and Farmer 2000). However, they were observed within 1 km of drillship or dredges on some occasions (Richardson et al. 1985). The noise levels prevailing at 1 km from seismic operations might have an impact on marine mammals (Southall et al. 2007; Richardson et al. 1990) and this study demonstrates that the combination of MWOs and use of a SX90 sonar is efficient to detect and track marine mammals at such distances. The applicability of the sonar technology to a fixed platform still needs to be investigated.

5.3 General conclusions

To our knowledge, with a total of 367 hours of SX90 sonar operations, this study represents the largest active acoustic survey simultaneously monitoring pelagic fish and marine mammals. The SX90 sonar uses a robust interface and the whole system proved to be simple to use with practice. The two operators were at ease to operate the system after a two-day training session at the Kongsberg factory in Horten (Norway), and improved their skills for data analysis and interpretation of the echoes within two weeks under the supervision of Kongsberg operators. Results from the 2011 active acoustic survey are promising and suggest that the SX90 sonar is an effective tool to detect both marine mammals and schools of fish.

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8. Appendices

Appendix 8.1 Results from the SX90 sonar passive noise test conducted in the St-Lawrence River on July 20th, 2011.

Table 10. Passive noise (dB re 1 μPa) measured around the ship. Tests were conducted at 26 kHz.

Ship speed (knots)	Bearing					
	-120°	-60°	0°	+60°	+120°	+180°
0	64	60	54	62	60	70
2	64	68	58	66	64	73
4	66	70	54	66	60	70
6	67	65	57	66	63	74
8	70	65	57	65	66	77
10	70	68	62	67	67	77
12	68	64	62	64	65	72

Table 11. Passive noise (dB re 1 μPa) measured at stable speed, during acceleration, and during deceleration of the ship. Bearing is 0° for all measurements and tests were conducted at 26 kHz. "-" indicates that no data are available.

Ship speed (knots)	Noise at stable speed	Noise during acceleration	Noise during deceleration
0	54	57	-
2	58	58	-
4	54	57	-
6	57	60	-
8	57	70	49
10	62	61	52
12	62	-	53

Appendix 8.2 Details of simulated detection ranges

Table 12. Simulated detection ranges at 10 m depth based on CTD casts conducted in the Canadian Beaufort Sea from August 27th to October 3rd. Calculations were made with the Norwegian Lybin software.

CTD cast	Date	CTD model	Acoustic channel	Detection range (probability of detection >90%) at 10 m depth (± 100 m)
1	11-08-28	CTD/Rosette	Present	1000
2	11-08-28	CTD/Rosette	Absent	900
3	11-08-28	CTD/Rosette	Absent	400
4	11-08-29	CTD/Rosette	Absent	200
5	11-08-30	CTD/Rosette	Present	2900
6	11-08-30	CTD/Rosette	Absent	600
7	11-09-01	YSI CastAway CTD	Absent	300
8	11-09-03	CTD/Rosette	Present	1100
9	11-09-03	CTD/Rosette	Present	3100
10	11-09-04	CTD/Rosette	Present	1500
11	11-09-04	CTD/Rosette	Absent	500
12	11-09-05	CTD/Rosette	Present	900
13	11-09-05	CTD/Rosette	Present	1300
14	11-09-05	CTD/Rosette	Absent	900
15	11-09-06	CTD/Rosette	Present	3900
16	11-09-08	YSI CastAway CTD	Present	2400
17	11-09-09	YSI CastAway CTD	Absent	500
18	11-09-09	CTD/Rosette	Absent	300
19	11-09-10	YSI CastAway CTD	Absent	500
20	11-09-10	CTD/Rosette	Absent	600
21	11-09-10	CTD/Rosette	Absent	1400
22	11-09-10	CTD/Rosette	Present	1600
23	11-09-11	CTD/Rosette	Present	1300
24	11-09-11	CTD/Rosette	Present	2100
25	11-09-12	CTD/Rosette	Present	2900
26	11-09-12	YSI CastAway CTD	Present	1300
27	11-09-12	CTD/Rosette	Absent	300
28	11-09-13	YSI CastAway CTD	Present	2000
29	11-09-13	CTD/Rosette	Present	2800
30	11-09-14	CTD/Rosette	Absent	700
31	11-09-14	CTD/Rosette	Present	800
32	11-09-15	CTD/Rosette	Absent	700
33	11-09-15	CTD/Rosette	Absent	700
34	11-09-15	CTD/Rosette	Present	5000
35	11-09-16	CTD/Rosette	Present	1600
36	11-09-17	CTD/Rosette	Present	2300
37	11-09-17	CTD/Rosette	Present	800
38	11-09-17	CTD/Rosette	Present	1500
39	11-09-18	CTD/Rosette	Present	1000
40	11-09-19	CTD/Rosette	Present	2900
41	11-09-20	YSI CastAway CTD	Present	1700

42	11-09-26	CTD/Rosette	Present	2300
43	11-09-26	CTD/Rosette	Present	1300
44	11-09-26	CTD/Rosette	Present	3500
45	11-09-26	CTD/Rosette	Present	2500
46	11-09-26	CTD/Rosette	Absent	1100
47	11-09-27	CTD/Rosette	Absent	1000
48	11-09-27	CTD/Rosette	Absent	800
49	11-09-27	CTD/Rosette	Absent	1100
50	11-09-27	CTD/Rosette	Absent	800
51	11-09-27	CTD/Rosette	Present	1200
52	11-09-27	CTD/Rosette	Present	1000
53	11-09-27	CTD/Rosette	Absent	1000
54	11-09-27	CTD/Rosette	Present	1900
55	11-09-28	YSI CastAway CTD	Absent	1000
56	11-09-28	CTD/Rosette	Present	2100
57	11-09-28	CTD/Rosette	Present	2000
58	11-09-28	CTD/Rosette	Present	900
59	11-09-28	CTD/Rosette	Present	2000
60	11-09-28	CTD/Rosette	Absent	600
61	11-09-28	CTD/Rosette	Absent	1000
62	11-09-29	YSI CastAway CTD	Absent	900
63	11-09-29	CTD/Rosette	Absent	600
64	11-09-29	CTD/Rosette	Absent	400
65	11-09-30	CTD/Rosette	Absent	500
66	11-09-30	CTD/Rosette	Present	1500
67	11-09-30	CTD/Rosette	Absent	700
68	11-09-30	CTD/Rosette	Present	800
69	11-09-30	CTD/Rosette	Present	700
70	11-10-01	CTD/Rosette	Present	2900
71	11-10-01	CTD/Rosette	Present	1700
72	11-10-01	CTD/Rosette	Present	1600
73	11-10-01	CTD/Rosette	Present	1700
74	11-10-01	CTD/Rosette	Present	2500
75	11-10-02	CTD/Rosette	Absent	1000
76	11-10-02	CTD/Rosette	Present	2300
77	11-10-02	CTD/Rosette	Present	1800
78	11-10-03	CTD/Rosette	Absent	500