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Original Article

Target strengths and echotraces of whales and seals in the Canadian Beaufort Sea

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Active acoustics as a tool to detect and avoid Arctic marine mammals was assessed in the Canadian Beaufort Sea. The target strengths and shape of the echoes of whales and seals were characterized using a bi-frequency (38 and 120 kHz) split-beam scientific echosounder in winter 2003/2004 and a scientific scanning sonar (20–30 kHz) in summer 2011. The echosounder detected 452 signals of diving ringed seals and the sonar detected 59 bowhead whales, 13 ringed seals, and 2 bearded seals. Target strengths of diving ringed seals tracked by the echosounder ranged from −56 to −12 dB re: 1 m^2 and did not vary with the depth of the animal. Target strengths of animals tracked by the sonar varied from −15 to 10 dB for bowhead whales and from −37 to −3 dB for seals. Marine mammals presented higher target strength values near broadside than near tail- or head-on. The sonar detected whales at a distance up to 2000 m and their echoes were discriminated from that of seals. This study suggests that active acoustic technology can be used as a complementary tool for marine mammal surveys in the Arctic.

Keywords: active acoustics, Arctic, bearded seals, bowhead whales, echosounder, marine mammals, ringed seals, sonar, target strength.

Introduction

Marine mammal surveys are typically based on visual observations and/or passive acoustic monitoring (PAM). Darkness, poor visibility, and heavy seas often limit visual observations, whereas PAM is limited to vocalizing animals (Weir and Dolman, 2007). These limitations have fuelled a growing interest in the use of active acoustics to detect marine mammals. The active acoustic echoes of whales are recognizable thanks to the size and motion of the target (e.g. Lucifredi and Stein, 2007; Brehmer *et al.*, 2012). The echotraces (i.e. sequences of contiguous marks from successive transmissions on an echogram; Simmonds and MacLennan, 2005) can also be used to distinguish smaller marine mammals, such as seals and dolphins, from pelagic fish (Doksaeter *et al.*, 2009; Benoit *et al.*, 2010; Bernasconi *et al.*, 2011). Since observations by sonars and echosounders are independent of light, visibility, and vocalizations, active acoustics may prove useful as a complementary tool to detect marine mammals (Pyć *et al.*, 2015).

In addition to echotraces, target strength (*TS* in dB re: 1 m^2; the echo energy from a single target) is commonly used to discriminate large animals from smaller organisms and to estimate size, as *TS* is proportional to length in animals of similar morphology (e.g. Foote, 1987; Guillard *et al.*, 2004). Echotraces, *TS*, and variations in backscatter signals with distance, depth, and angle of incidence must be documented to identify marine mammals by active acoustics (Doksaeter *et al.*, 2009). To date, these recognition criteria have been established for at least eight species of whales and dolphins (Levenson, 1974; Miller and Potter, 2001; Benoit-Bird and Au, 2003; Benoit-Bird *et al.*, 2004; Au *et al.*, 2007; Lucifredi and Stein, 2007; Xu *et al.*, 2012; Bernasconi *et al.*, 2013a). In particular, *TS* has been documented for species inhabiting or transiting through the Atlantic (e.g. Love, 1973; Levenson, 1974; Miller and Potter, 2001) and Pacific basins (Benoit-Bird and Au, 2003; Lucifredi and Stein, 2007).

In the present study, we assess the value of active acoustics in detecting marine mammals in Arctic waters. Recognition criteria (i.e. echotrace characteristics and *TS*) are developed to distinguish bowhead whales *Balaena mysticetus* from ringed seals *Pusa hispida* and bearded seals *Erignathus barbatus* using a scientific scanning sonar (Simrad SX90). Variations in the recognition criteria with distance and angle of incidence are documented. The *TS* of diving ringed seals tracked with a scientific echosounder (Simrad EK60) are also analysed to assess variations in *TS* with depth.

Material and methods

Study area and survey design

As part of the Canadian Arctic Shelf Exchange Study (CASES), the research icebreaker CCGS *Amundsen* was immobilized in stable landfast ice in the southeastern Beaufort Sea from 12 December 2003 to 1 June 2004 (Figure 1). A downward-looking Simrad EK60 38 and 120 kHz split-beam scientific echosounder (hereafter referred to as the echosounder) was hull-mounted and operated continuously during this period (see Benoit *et al.*, 2010, for details on the methodology). Ping interval was set at 2 or 3 s, pulse length at 1.024 ms, and power to 2 kW at 38 kHz and 500 W at 120 kHz. The echosounder was calibrated following the standard sphere method before departure (Foote *et al.*, 1987). Four hundred and fifty-two echoes from ringed seals diving down to 220 m below the ship were detected with the echosounder and analysed to assess variations in *TS* with depth.

To investigate further the applicability of using active acoustics to detect Arctic marine mammals *in situ*, the CCGS *Amundsen* was fitted with a scientific Simrad SX90 scanning sonar (hereafter referred to as the sonar). Dedicated sonar surveys were conducted in September 2011 in the Beaufort Sea (Figure 1). In addition to the dedicated surveys, the sonar was deployed to detect marine mammals on an opportunistic basis during transit in the Beaufort Sea. Overall, sonar surveys in 2011 covered a total of 1418 km over bottom depth areas ranging from 20 to more than 1000 m. During dedicated surveys, a team of up to four trained Inuvialuit Marine Wildlife Observers (MWOs) took 4-h shifts on the bridge (16 m above sea level), identifying and enumerating marine mammals and estimating distance from the ship with binoculars (Kinzey *et al.*, 2000). When MWOs could see farther than 5000 m, ship speed was 24–25 km h^{-1} (13–14 kn). When visibility was <5000 m, ship speed was reduced to 15 km h^{-1} (8 kn). The ship course was modified to approach and track marine mammals sighted by MWOs or detected by the sonar so as to establish detection distances and record backscatters at different frequencies. When detecting a target, the sonar frequency was changed by 1 kHz increment at 5–15 s intervals over the 20–30 kHz spectrum to allow *TS* measurements over several pings at each frequency. Once this cycle completed, the ship veered away from the target and maximum detection range was noted as distance from the animal increased. Swimming and/or diving animals often exited the acoustic beam before the frequency cycle was completed.

Mitigation measures

Active acoustics can affect the behaviour of cetaceans and pinnipeds and high received levels, varying between species and sound sources, can result in temporary or permanent hearing losses and auditory injuries (Richardson *et al.*, 1995; Southall *et al.*, 2007). During sonar surveys, MWOs monitored the behaviour of marine mammals and reported any negative behavioural reaction, for instance, shifts in group distribution or changes in locomotion, speed, direction, or dive profile, to the sonar operator using the severity scale of Southall *et al.* (2007). Negative behavioural responses commanded an immediate reduction in the power of the emission to low (i.e. a reduction of 12 dB) and a deviation of the vessel away from the target. A minimum distance of 150 m was kept between the ship and whales at all times. As soon as data acquisition was completed or the target disappeared from the screen, the ship slowed down or changed course to increase the distance to the animal before resuming transect. Whales were not approached for more than 10 min. This active acoustics research project was reviewed by the Environmental Impact Screening Committee (EISC) for the Inuvialuit Settlement Region (www.screeningcommittee.ca) under

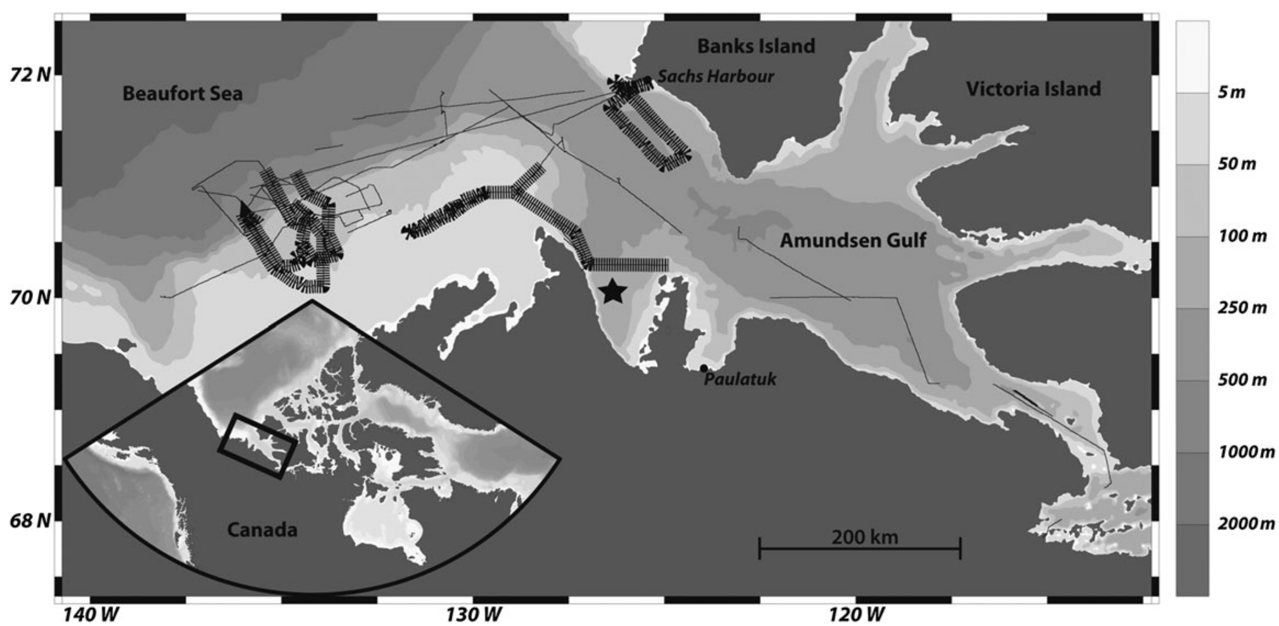

Figure 1. Map of the overwintering location in 2003/2004 (black star) and of the ship's track during dedicated surveys (wide dashed lines) and opportunistic surveys (thin black lines) conducted from 27 August to 3 October 2011. Note that the projection of the map in the insert is pseudocylindrical.

Table 1. Nominal specifications of the sonar pulse emission when beam width is set to normal.

Frequency (kHz)	20	21	22	23	24	25	26	27	28	20	30
Vertical beam width (°)	10.9	10.6	10.1	10.1	9.5	9.3	8.9	8.6	8.4	7.8	7.7
Source level (dB re: 1 μPa at 1 m)	209.5	211.1	212.3	213.2	213.9	214.8	215.2	215.4	214.7	214.2	214.1

proposal numbers 06/03-10 (2003/2004) and 04/11-03 (2011). Following the reviews, the scientific research licences 13888N (2003/2004) and 14917R (2011) were issued by the Aurora Research Institute in accordance with the Northwest Territories Scientists Act.

Characteristics and calibration of the sonar

The transducer of the sonar is lowered 76 cm below the hull through a gate-valve. Two different transmission modes provide different two-dimensional on-screen representations of the acoustic backscatter. In the horizontal omnidirectional mode, the acoustic signals of the 256 elements of the transducer are processed by the transceiver and the digital beamforming provides a 360° (radar-like) instantaneous horizontal coverage around the ship (Bernasconi *et al*., 2013a). After beamforming, the 360° are divided into 64 beam sectors with a width varying from 8 to 11° depending on frequency (Table 1). By tilting the beams towards the seabed, they form a horizontal cone slicing diagonally through the water column (e.g. Brehmer *et al*., 2012; Bernasconi *et al*., 2013a; Pyć *et al*., 2015). This omnidirectional horizontal mode is used to detect fish schools or marine mammals around the ship at ranges up to several kilometres. In the second, vertical transmission mode, the acoustic beams form a narrow 180° vertical fan pointing to the seabed. The operator selects the azimuthal direction of the beam, for example, to cut across a target detected in the omnidirectional horizontal mode. The system can alternate between both modes, providing simultaneous horizontal and vertical views of the target in separate screen windows (details in Pyć *et al*., 2015). Echoes from fish schools were discriminated from those of marine mammal by looking at the vertical extent of the signal using the vertical transmission mode.

The sonar operates from 20 to 30 kHz in increments of 1 kHz. During the study, pulse form was set to FM Auto (hyperbolic frequency modulated; 500 Hz bandwidth) to limit noise and reverberation (Brehmer *et al*., 2012). Beam width was set to normal, resulting in source level varying from 209.5 to a maximum of 215.4 dB re: 1 μPa rms SPL depending on the frequency (Table 1). The transmission power was set to full emission (i.e. 0 dB re: 1 μPa at 26 kHz), and pulse duration varied from 4 ms at a detection range of 150–72 ms at a detection range of 2000 m. The ping rate varied with bottom depth, as the sonar was synchronized with the Simrad EK60 and with sub-bottom and multibeam echosounders. The display was generally set to "Bow up", the horizontal range to 2000 m, and the tilt angle to −2° below the surface to detect marine mammals that could be sighted by MWOs for echo-validation. The sonar raw data were continuously saved onto an external hard-drive and print screens of marine mammal detections were recorded.

To help distinguish targets near the surface, the reverberation controlled gain (RCG) of the sonar operation software automatically filters nearly constant signals such as surface reverberation, but can also delete echoes from small animals near the surface when set too strong (Brehmer *et al*., 2006). The RCG individually regulates receiver gain for each of the 64 receiving beams of the transducer. In addition, a ping-to-ping filter algorithm compares the echoes from one ping with that of the next ping to further suppress noise. When an echo is present at the first ping but disappears at the next, the algorithm interprets it as noise and removes it from the display. The RCG and the ping-to-ping filters were generally set to "medium", but were increased to "strong" under abnormally noisy conditions. The automatic gain control (AGC) was set to "medium". Note that the RCG, the ping-to-ping filter, and the AGC were not applied on raw data recordings, which were used to calculate *TS*.

Table 2. Threshold values set for the EchoView® single-echo-detection algorithm to filter out single echoes for *TS* calculations of ringed seal signals recorded with the echosounder.

Single target detection parameters	Values
Minimum *TS* threshold (dB)	−60 to −42
Pulse length determination level (dB)	6
Minimum normalized pulse length	0.1
Maximum normalized pulse length	5
Maximum beam compensation (dB)	12–20
Maximum standard deviation of minor-axis angles (alongship; °)	2
Maximum standard deviation of major-axis angles (athwartship; °)	2

The sonar was calibrated under Beaufort 0 sea-state before the survey, while the ship was anchored. The *TS* of a 63 mm calibration copper sphere (Foote, 1982) deployed perpendicularly to the acoustic beam tilted at 10° below the surface was measured at three different positions: at the bow and then successively on port and starboard. For each position and each of the 11 frequencies in the range 20–30 kHz, the raw signal of the sphere (*in situ TS*) was linearly averaged over 10 pings (for a total of 30 pings per frequency) and thereafter transformed in dB. The theoretical *TS* of the sphere at each frequency in function of the sound speed was subtracted from *in situ* measurements to obtain the gain correction (GC; Bernasconi *et al*., 2013a) at each frequency.

Environmental data

A CTD-rosette system (Seabird Electronics SBE-911 plus®) was deployed daily in 2003/2004 and at 78 stations in the 2011 survey area to record temperature and salinity from 10 m above the bottom to the surface. In addition, a portable YSI CastAway® CTD was cast down to 80 m before and at the end of each dedicated survey in 2011. Based on temperature and salinity profiles, the coefficients of absorption (α; François and Garrison, 1982) and sound speed (c; Mackenzie, 1981) were calculated to determine (i) the time-varied-gain; and (ii) the range of the target.

Data analysis

Detections with the echosounder

The 452 ringed seal acoustic signals recorded with the echosounder at 38 and 120 kHz over winter 2003–2004 were processed using Echoview® 5.2 single-echo detection (SED; Higginbottom *et al*., 2008) algorithm for split-beam echosounders to calculate distinct

TS (Table 2). Parameter values were selected with a conservative trial and error approach to allow *TS* analysis on targets as large as seals. A *TS* threshold was used to discriminate seal signals from fish and noise (Table 2). Minimum *TS* and maximum beam compensation were usually set to −42 and 12 dB, respectively, but for some signals were changed down to −60 dB (*TS*) or up to 20 dB (beam compensation) to increase the number of detections. The 67 signals presenting a noise-free acoustic track over a depth interval >55 m were selected to test the hypothesis of a decrease in *TS* with depth due to lung compression (e.g. Au, 1996; Doksaeter *et al.*, 2009). To test for a dependence of *TS* on angle of incidence, a separate subsample of 18 seal echoes for which the V-shaped dive was entirely visible was analysed to compare *TS* distributions during descent, ascent, and when the seals were turning at the bottom of the dive and presented a broadside position in the echosounder beam.

Detections with the sonar

In daytime under good visibility, marine mammals were detected first by MWOs, enabling the sonar operators to assign echoes to individual targets. Echotraces characteristic of marine mammals that persisted over 3 pings or more and were not validated by MWO observations were not included in the analysis but were compiled separately.

Bowhead whales and the wakes they produced when breathing and/or swimming formed series of successive similar-shaped echoes on the sonar screen (Figure 2a and b). If the whale was swimming towards (away from) the ship, the nearest (farthest) echo of the series was assumed to be the whale. When detected by an echosounder, bubbles released by a target can quench the echo and preclude reliable *TS* measurements (Doksaeter *et al.*, 2009). In contrast to an echosounder, the sonar allowed *TS* determination for both the animals and their wakes. The angle between the line created by the wakes (i.e. the swimming direction of the whale) and a straight line from the ship to the whale represented our best estimate of the angle of incidence at which the target was insonified in the acoustic beam (Figure 2a). The relationship between *TS* and angle of incidence was established for six bowhead whales detected at different angles that presented long wake signals (≥4 simultaneous echoes). The data from these whale tracks were pooled as each whale was only detected over a narrow range of angles of incidence.

For each marine mammal recorded by the sonar, radial and surface plots of pings of interest were produced with a MATLAB© script during post-survey analyses. The script was used to calculate *TS* for all validated signals that could easily be distinguished from the ambient noise. Following Lucifredi and Stein (2007), for each marine mammal detected up to five pings per frequency were selected and linearly averaged to determine its *TS* at each frequency. For each ping, the maximum *TS* was calculated using the sonar equation (e.g. Bernasconi *et al.*, 2013a, b):

$$TS = \mathrm{EL} - \mathrm{SL} + \mathrm{TVG} + \mathrm{GC},$$

where EL is the received dB level at the transceiver due to the single target, SL the source level of the sonar, TVG the time-varied-gain (that is, the attenuation of the acoustic signal with distance from

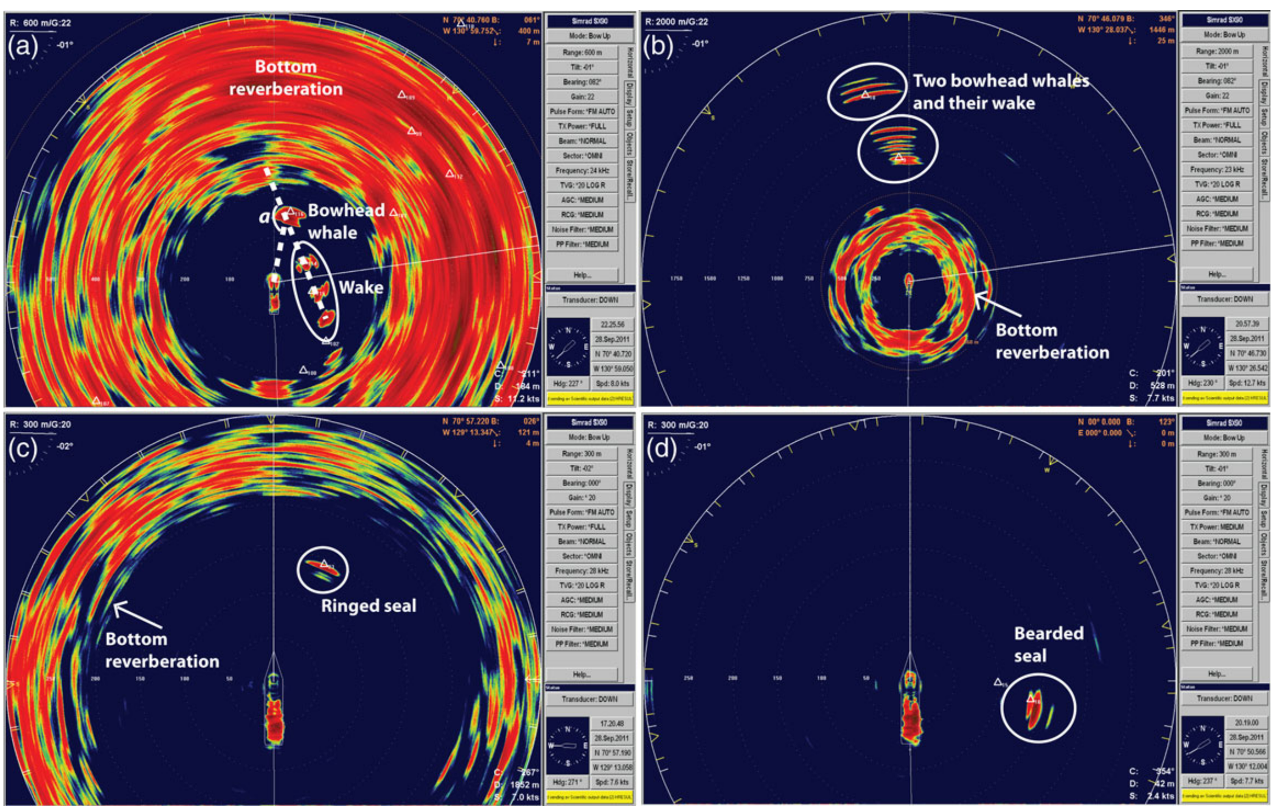

Figure 2. Echotraces of (a) a bowhead whale and its wake detected at a range of 175 m, the angle of incidence (α) at which the whale was detected is indicated by two dashed lines; (b) two bowhead whales and their wakes detected in the surface acoustic duct at a range of 1500 m; (c) a ringed seal detected at a range of 150 m; and (d) a bearded seal detected at a range of 150 m. Noise created by bottom reverberation is present in (a)–(c).

the source to the target at range R), and GC the gain correction measured during the calibration.

TVG in the main ray propagation path was calculated from the closest temperature and salinity profile using the software Lybin 4.0 developed by the Norwegian Defence Research Establishment. However, profiles used to calculate TVG were decoupled in time and space from target detections because CTD casts were only conducted before or after the surveys. In Arctic seas, an acoustic duct that reduces sound attenuation appears below the surface when the surface mixed layer is deep enough to allow reverberation of the acoustic signal at the pycnocline (Sutton *et al.*, 1993). TVG within the main ray propagation path varied similarly from one cast to the other, but slight local changes in surface temperature and salinity resulted in the appearance or disappearance of the acoustic duct. An acoustic duct could have been present during the CTD cast and absent during detections or *vice versa,* thus creating a bias in Lybin calculations outside the main ray propagation path. The standard spherical model of attenuation ($TVG = 40\log_{10} R + 2\alpha R$) was closer to Lybin calculations than other models (e.g. $20\log_{10}R$ or $30\log_{10}R$) and was therefore used to calculate TVG outside the main ray propagation path.

Results

Echotraces of marine mammals detected by the sonar

The sonar detected 59 bowhead whales, 13 ringed seals and 2 bearded seals in 2011, all of which were validated by MWOs. Bowhead whales detected by the sonar invariably appeared on the screen as a series of separate echoes (Figure 2a and b). Echoes forming a series persisted over several pings, with new echoes appearing at one end of the series and echoes disappearing at the other end. Correlating visual observations by the MWOs (bearing and distance from the ship) with the position of the echoes on the screen enabled us to confirm which echo in the series corresponded to the whale sighting. This actual whale echo was invariably located at one end of the series, usually ahead of the ship. Bowhead whales detected at close range (<300 m) typically presented echoes separated by a distance of 55–115 m (average = 81 m; s.d. = 25 m), with a thickness to width ratio of ~0.8 (Figure 2a). Bowhead whales detected at greater range, up to 2000 m in the acoustic duct, presented a characteristic signal consisting of up to seven strong, closely distributed elongated echoes (Figure 2b). The distance from the centre of one of these echo to the centre of the next varied from 35 to 70 m (average = 51 m; s.d. = 11 m). The thickness to width ratio of the elongated whale echoes in the acoustic duct was ~0.1 (Figure 2b).

Seals were usually detected by the sonar when immobile or when swimming slowly at the surface close to the ship as it progressed along predefined survey lines. Seals typically moved towards the ship and detection often occurred within 150 m. Except for one ringed seal detected at 525 m, seal echoes were generally too weak to be detected at ranges exceeding 200 m. By comparison to the multiple round echoes of whales detected at a given range, the singular trace of seals was smaller and flatter (thickness to width ratio of ~0.25; Figure 2c and d). Detection of seals was clearer at frequencies >23 kHz.

Target strengths of marine mammals detected by the sonar

Out of the 15 seals and 59 bowhead whales detected by the sonar, 14 seals and 57 whales had an echo clear enough to allow *TS* calculations (i.e. no noise from bottom or surface reverberation). Of the latter, 52 were detected from a near tail-on aspect only (180 ± 45°); three were detected from tail-on to near broadside; and two at an indeterminate incidence angle (Supplementary material S1). Bowhead whales presented *TS* as strong as 10.6 dB when detected near broadside (90 ± 45°), with the signal diminishing as the angle of incidence tended towards a tail-on position (Figure 3a).

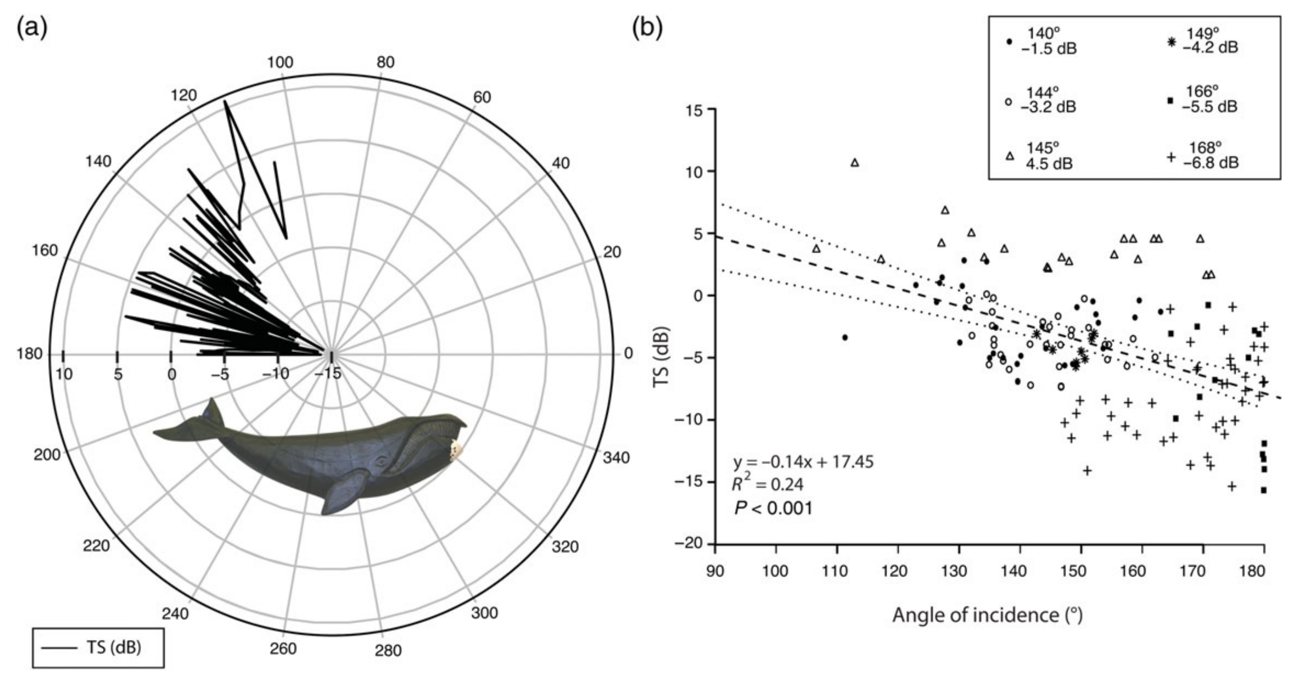

Figure 3. *TS* as a function of the angle of incidence (relative to the acoustic beam) for six bowhead whales. (a) Polar plot where 0° is head-on, 180° is tail-on, and 90° is broadside. (b) Corresponding regression (dashed line) and 95% CI (dotted lines) when all detections of the six bowhead whales are pooled together. Each individual is identified by a different symbol. Average *TS* and angle of detection for each individual are indicated in the inset.

TS varied from one individual to the other, but a linear regression between *TS* and the angle of detection for the six bowhead whales detected over the widest range of angles (from 107 to 180°) demonstrated a significant trend ($p < 0.001$; Figure 3b). The regression predicts a *TS* of −8 dB when detected tail-on to +5 dB when detected near broadside aspect.

TS of bowhead whales at all frequencies varied from −14.8 to 10.1 dB (average = 2.4 dB; Bootstrap 95% CI = −7.5 to 5.7 dB; Supplementary material S1). The *TS* linearly averaged over all bowhead whales detected at a near tail-on aspect varied significantly with frequency (Kruskal–Wallis test; $p = 0.001$), declining from a maximum of 4.8 dB at 21 kHz to a minimum of −0.2 dB at 26 kHz and increasing again to 2.0 dB at 30 kHz (Figure 4). The *TS* of the wakes were similar to that of the whale that produced them (Wilcoxon signed-rank test; $p > 0.05$). For a bowhead whale detected at a given frequency in both the acoustic duct and the main ray propagation path, the difference between mean *TS* in the acoustic duct and the main ray propagation path was always <3 dB.

Seals detected with the sonar presented lower *TS* than bowhead whales (Wilcoxon signed-rank test; $p < 0.001$) and their aspect during detection could not be measured as they often turned rapidly and did not produce wake echoes that would have allowed calculation of an angle of incidence. Values for individual ringed seals and bearded seals at all frequencies overlapped within a range from −36.7 to −2.9 dB (average = − 10.2 dB; Bootstrap 95% CI = − 15.7 to −6.4 dB; Supplementary material S1). *TS* of bearded seals were not statistically different from those of ringed seals (Wilcoxon signed-rank test; $p = 0.13$). Linearly averaged *TS* for seals varied from −20.8 dB at 30 kHz to −6.0 dB at 23 kHz and no significant dependence on frequency was found (Kruskal–Wallis test; $p = 0.87$; Figure 5). Confidence intervals on the average *TS* were wide due to the small sample size.

Target strengths of diving ringed seals detected by the echosounder

Each of the 452 ringed seal echoes detected by the echosounder during winter of 2003/2004 formed a partial or complete V-shaped acoustic signal in the echogram (Supplementary material S2). Their *TS* ranged from −48.0 to −12.2 dB at 38 kHz (average = − 35.1 dB; Bootstrap 95% CI = −38.6 to −28.9 dB) and from −55.6 to −16.1 dB at 120 kHz (average = − 38.2 dB; Bootstrap 95% CI = −42.1 to −32.3 dB). *TS* linearly averaged for each frequency was −35.1 dB at 38 kHz and −38.2 dB at 120 kHz. The *TS* analysis conducted on 67 seal dives that covered a depth interval >55 m showed no significant relationship between *TS* and depth during the descent or ascent of a given individual (linear regression with the individual set as a random variable; $p = 0.15$). Average *TS* of 18 seals for which the entire dive were clearly visible was significantly lower during the descent, when detected tail-on, then during the ascent, when detected head-on (Wilcoxon signed-rank test; $p < 0.001$; Figure 6a and b). Average *TS* was higher at the bottom of the V-shaped time-depth trajectories, most likely when the animals turned around to return towards the surface and presented a broader aspect (Wilcoxon signed-rank test; $p < 0.001$; Figure 6c).

Non-validated marine mammal echoes

On three occasions, a persistent echo presenting the characteristics of a marine mammal was observed on the sonar, while the MWOs were off-duty or during low visibility conditions preventing validation. Based on echotraces and *TS* averaged over three to five pings, two of the three echoes likely originated from bowhead whales with *TS* of 0.5 and −4.5 dB and one from an unidentified seal with a *TS* of −27 dB.

Discussion

Active acoustic recognition criteria for Arctic marine mammals

A review of the literature yielded eight species of marine mammals for which active acoustic recognition criteria have been measured (Table 3). The present study adds bowhead whales, ringed seals, and bearded seals to the list. As most bowhead whales were only detected over a narrow range of angles of incidence, the variation of *TS* with the aspect of detection could only be measured for six individuals. Nonetheless, our observations suggest that the *TS* of bowhead whales (Figure 3) and seals (Figure 6) increased as the angle of incidence decreased towards the broadside position. Except for the northern right whales detected by Miller and Potter (2001) and the orca whales detected by Xu *et al.* (2012), which had a *TS* slightly higher at near tail-on, all other studies have reported stronger *TS* in marine mammals detected near broadside than head-on or tail-on (Table 4 and Figure 7).

As reported for fish (e.g. Foote, 1987; Guillard *et al.*, 2004), the *TS* of marine mammal species increased with length (Figure 7). A linear relationship was statistically significant ($p < 0.05$) for three of the four categories of aspects considered, but not for head-on ($p = 0.10$; Figure 7). Body length explained from 33 to 63% of the variation in *TS* between species, depending on the aspect of detection.

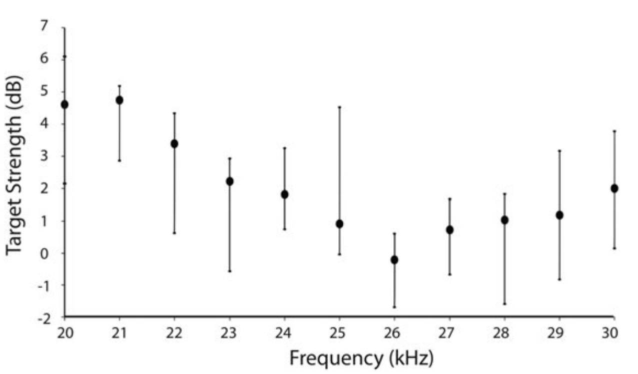

Figure 4. Mean *TS* for all bowhead whales vs. operational frequencies of the sonar with bootstrap 95% confidence intervals.

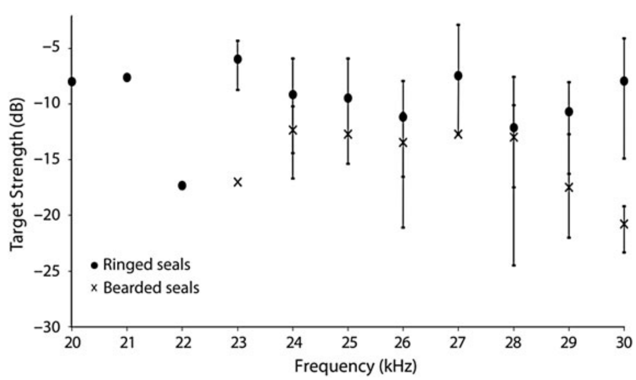

Figure 5. Mean *TS* for all seals vs. operational frequencies of the sonar with bootstrap 95% confidence intervals. No confidence interval means that only one seal was detected at a given frequency ($n = 1$).

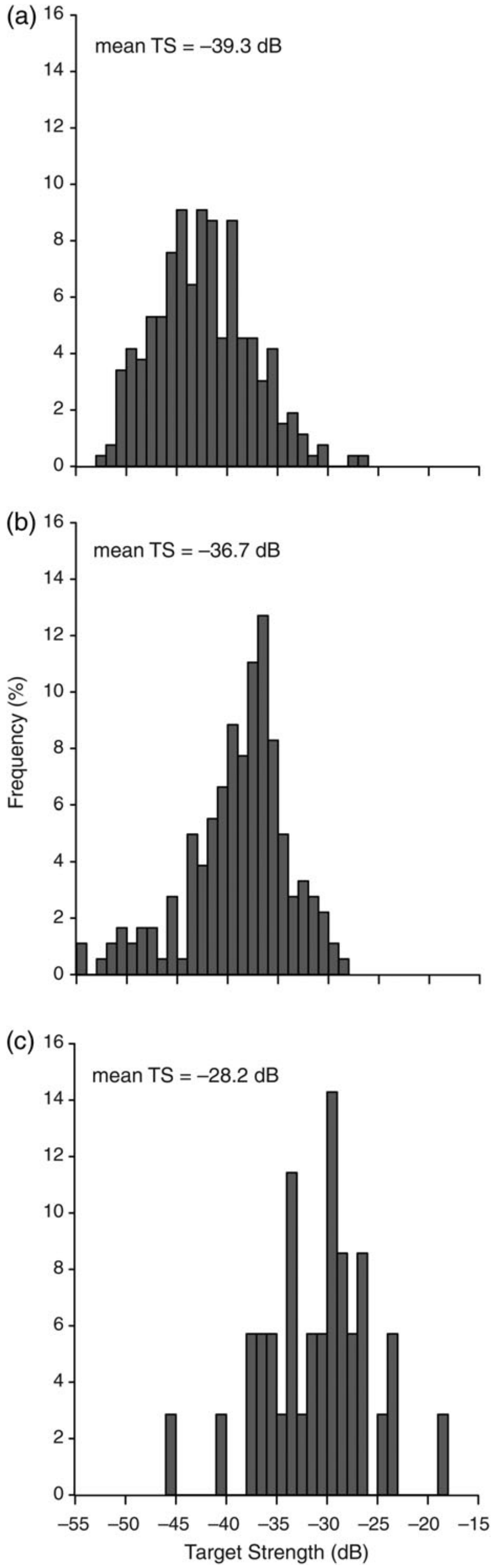

Figure 6. Histograms of all single echo detections of 18 diving ringed seals at 38 kHz (a) during their descent; (b) during their ascent; and (c) at the bottom of the V-shaped time-depth trajectories, when turning to return towards the surface. Data were recorded with the echosounder during winter of 2003 – 2004.

Two main clusters were found: a first group of relatively small (<3 m) animals, including dolphins and seals, and a second group comprising large whales (>12 m). The medium-sized (~8 m) orca whale fell between these two groups. Within the two clusters, *TS* overlapped considerably among species, limiting the power of active acoustics to assign a species to a given echo (Figure 7). In the Beaufort Sea, for example, the frequent bowhead whale (13–20 m; Schell *et al.*, 1989; Reeves *et al.*, 2002) and the infrequent grey whale (12–15 m; Reeves *et al.*, 2002; Lucifredi and Stein, 2007) overlap both in length and *TS* (Figure 7), making it unlikely to discriminate the two by active acoustics. Similarly, the different species of seals could not be distinguished based on *TS* or echotraces. However, the recognition criteria (*TS* and echotraces) provided here can easily differentiate seal echoes from those of large whales.

At 2.2–3.6 m in length, the Pacific walrus *Odobenus rosmarus divergens*, occasionally present in the area, would unlikely be differentiated from seals by active acoustics. Given their intermediate length and swimming/breathing pattern, beluga whales *Delphinapterus leucas* (3–5 m), frequent in the Beaufort Sea but not detected in the present study, would likely be differentiable from seals and larger whales based on the combination of their *TS* and echotraces.

The echotraces of bowhead whales detected by the sonar and their variations with range are consistent with previous observations for large whales. At a range <350 m, the signal from a fin whale consisted in a series of rounded (large thickness to width ratio) echoes (Bernasconi *et al.*, 2013a), similar to our observations. Orca whales detected in an acoustic duct at ranges up to 1500 m presented multiple elongated echoes (Knudsen *et al.*, 2007), alike to our observations for bowhead whales in similar conditions. The propagation of eigenrays in the acoustic duct can result in multiple echoes of the same whale, because the different set of echoes would arrive at different times (Smith *et al.*, 1992). This situation is unlikely to be the cause of the repeated signals observed here as the distance between reflections of the signal in the acoustic duct modelled with Lybin varied from 200 to 1500 m (MG, unpublished data), while the distance between whale and wake echoes in the duct was within 70 m. Moreover, wake echoes were also observed for bowhead whales detected at a closer distance, outside the acoustic duct (Figure 2a).

In previous studies, the observed repeated wakes were interpreted as echoes from bubbles produced when swimming near the surface (fluke print) or by blowing before surfacing (Selivanovsky and Ezersky, 1996; Knudsen *et al.*, 2007; Bernasconi *et al.*, 2013a). In the present study, visual observations enabled us to identify clearly the echo in a series that corresponded to the surfacing whale. As in the studies above, we interpret the several stationary echoes appearing in succession behind the moving whale as air expulsed during previous blows and/or as fluke prints, with the echo furthest from the whale disappearing first as bubbles raised to the surface.

In contrast to large whales, seals tended to remain stationary at the surface or to approach the ship slowly, without producing wakes. Thus, in addition to the *TS* differences, the presence or absence of wakes is a useful criterion to discriminate seals and whales near the surface with sonars. Finally, echoes from whales were clear at all operational frequencies (20–30 kHz), while seals were more easily detected at frequencies >23 kHz, a difference that may help discriminate the two groups. Knudsen *et al.* (2007) also used on-screen visualization of orca whale vocalizations as an additional recognition criterion with a similar scanning sonar.

Table 3. Details of marine mammal detections with active acoustic instruments from literature and this study.

Species	# of ind.	Max. detection range (m)	Area	Instrument	Min. frequency (kHz)	Max. frequency (kHz)	Studies
Humpback whales (*Megaptera novaeangliae*)	4	78	Bermuda	Side-mounted echosounder	10	20	Love (1973)
Humpback whale (*Megaptera novaeangliae*)	1	–	Stellwagon Bank	Forward-looking sonar	–	86.25	Miller and Potter (2001)
Humpback whale (*Megaptera novaeangliae*)	1	240	–	Simrad SH80 and SX90 fisheries sonar and EK60 echosounder	18	200	Bernasconi *et al.* (2013b)
Fin whales (*Balaenoptera physalus*)	3	∼400	Norwegian Sea	Simrad SH80 fisheries sonar	–	110	Bernasconi *et al.* (2013a)
Northern right whales (*Eubalaena glacialis*)	3	84	Cape Cod Bay	Forward-looking sonar	−12.4	−1.4	Miller and Potter (2001)
Grey whale (*Eschrichtius robustus*)	1	>1000	Coast of California	Upward-looking directional sonar	21	25	Lucifredi and Stein (2007)
Sei whale (*Balaenoptera borealis*)	6 or 7	∼300	Seychelles	SP90 omnidirectional sonar	–	26	Brehmer *et al.* (2012)
Sperm whale (*Physeter macrocephalus*)	1	2740	South of Bermuda	Explosives and hydrophone	–	1	Dunn (1969)
Sperm whales (*Physeter macrocephalus*)	5	3153	Coast of Nova Scotia	Sonobuoy array	0.25	16	Levenson (1974)
Orca whales (*Orcinus orca*)	Several	1500	Coast of Norway	Simrad SP90 and SH80 fisheries sonars	20	122	Knudsen *et al.* (2007)
Orca whales (*Orcinus orca*)	3	250	Coast of Washington State	BioSonics DT-X echosounder	–	200	Xu *et al.* (2012)
Orca whales (*Orcinus orca*)	>12	>100	Lofoten, Norway	SeaBat 6012 multibeam sonar	–	455	Nøttestad and Axelsen (1999)
Dusky dolphins (*Lagenorhynchus obscurus*)	54	–	Coast of Angola	Simrad EK500 echosounder	–	38	Bernasconi *et al.* (2011)
Dusky dolphins (*Lagenorhynchus obscurus*)	–	–	New Zealand	Fishfinder NCC 5300 echosounder	–	200	Benoit-Bird *et al.* (2004)
Spinner dolphins (*Stenella longirostris*)	–	–	Hawaiian islands	Fishfinder NCC 5300 echosounder	–	200	Benoit-Bird and Au (2003)
Unknown dolphin species	6	450	–	Fisheries sonar	20	140	Selivanovsky and Ezersky (1996)
Bowhead whales (*Balaena mysticetus*)	59	2000	Canadian Beaufort Sea	Simrad SX90 sonar	20	30	This study
Bearded seals (*Erignathus barbatus*)	2	210	Canadian Beaufort Sea	Simrad SX90 sonar	20	30	This study
Ringed seals (*Pusa hispida*)	13	525	Canadian Beaufort Sea	Simrad SX90 sonar	20	30	This study
Ringed seals (*Pusa hispida*)	452	235	Canadian Beaufort Sea	Simrad EK60 echosounder	38	120	This study

Table 4. Summary of marine mammal *TS* reported in literature and during this study.

Species and length	Min. *TS* (dB)	Max. *TS* (dB)	*TS* near broadside (dB)	*TS* near tail-on (dB)	*TS* near head-on (dB)	*TS* unknown aspect (dB)	Studies
Adult humpback whales (14 m)	−4	8	6–8	–	−4	–	Love (1973)
Juvenile humpback whale (9 m)	–	0	–	–	0	–	Love (1973)
Adult humpback whale (14 m)	<−16	−4.2	−11.7 to −9.5	–	–	−16 to −10.5	Bernasconi *et al.* (2013b)
Humpback whale (15 m)	–	4	4	–	–	–	Miller and Potter (2001)
Fin whale (16–18 m)	−19.3	−5.6	−16.7 to −5.6	−19.3 to −12.2	−16.4 to −13.1	–	Bernasconi *et al.* (2013a)
Adult northern right whales (13–15 m)	−8.3	−1.4	−8.3 to −1.4	−6.6 to −2.3	–	–	Miller and Potter (2001)
Juvenile northern right whales (8 m)	−12.4	−7.4	–	–	−12.4 to −7.4	–	Miller and Potter (2001)
Grey whales (unknown length)	3	11.1	8.7 to 11.1	3 to 4.2	–	–	Lucifredi and Stein (2007)
Sperm whales (unknown length)	−8.5	−7.3	–	–	−8.5 to −7.3	–	Dunn (1969)
Sperm whales (unknown length)	−2.5	10.8	–	–	–	−2.5 to 10.8	Levenson (1974)
Orca whales (unknown length)	−10	−5	–	–	–	−10 to −5	Knudsen *et al.* (2007)
Orca whales (unknown length)	−50	−4	−50 to −4	−44 to −8	−50 to −8	–	Xu *et al.* (2012)
Dusky dolphins (unknown length)	−39.9	−22.7	–	–	–	−39.9 to −22.7	Bernasconi *et al.* (2011)
Dusky dolphins (unknown length)	−30	−26	–	–	–	−30 to −26	Benoit-Bird *et al.* (2004)
Spinner dolphins (unknown length)	−29	−25	–	–	–	−29 to −25	Benoit-Bird and Au (2003)
Unknown dolphin species	−18 (wake)	−12 (wake)	–	–	–	–	Selivanovsky and Ezersky (1996)
Bowhead whales (unknown length)	−14.4	10.1	−2.3 to 10.6	−14.4 to 10.1	–	−14.8 to −12.7	This study
Bearded seals (unknown length)	−24.5	−10.1	–	–	–	−24.5 to −10.1	This study
Ringed seals (sonar detections; unknown length)	−36.7	−2.9	–	–	–	−36.7 to −2.9	This study
Ringed seals (echosounder detections; unknown length)	−55.6	−12.2	−45.3 to −18.9	−52.1 to −26.0	−54.9 to −28.8	−53.7 to −12.2	This study

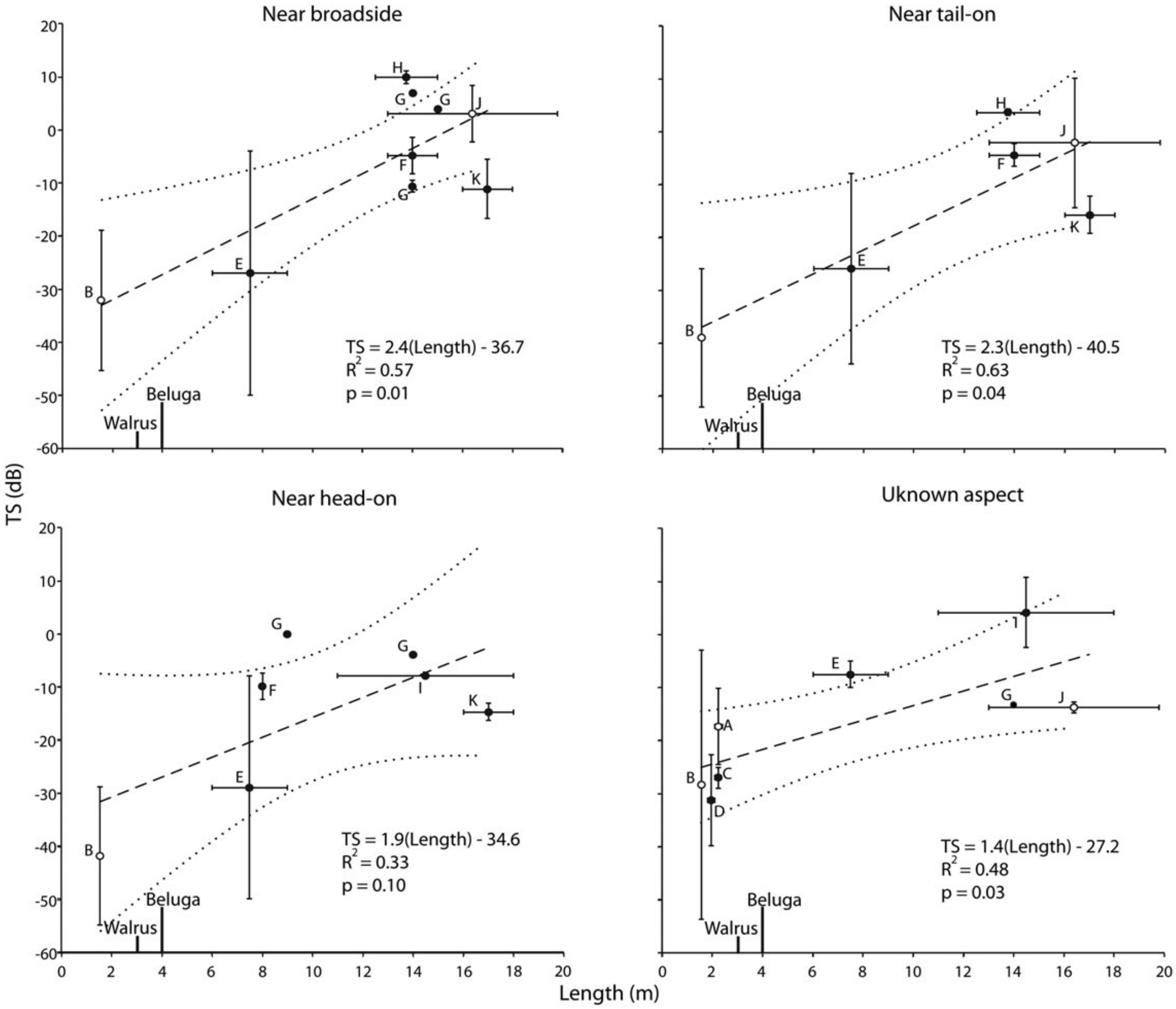

Figure 7. Relationships between size and *TS* of marine mammals for different aspects based on previous studies (black dots) and this study (white dots). Dots represent middle values and error bars represent minimum and maximum values. (A) Bearded seals, (B) ringed seals, (C) spinner dolphins, (D) dusky dolphins, (E) orca whales, (F) northern right whales, (G) humpback whales, (H) grey whales, (I) sperm whales, (J) bowhead whales, and (K) fin whales. References for *TS* and length values can be found in Table 4. For insonified animals that could not be measured in the field, body length is based on Schell *et al.* (1989), Reeves *et al.* (2002), and on the "Groupe de recherche et d'éducation sur les mammifères marins" (GREMM, 2015). Middle size of Pacific walruses and belugas is also indicated. The dashed lines represent the regressions, the dotted lines the 95% CI, and R^2 the adjusted coefficient of determination.

This procedure was not applicable here because bowhead whales vocalize at frequencies lower than the sonar frequency range (Blackwell *et al.*, 2007).

In the lower part of its range, the *TS* of seals detected by the sonar (−36.7 to −2.9 dB) overlaps with that of large swimbladder-bearing fish, for instance, bigeye tuna *Thunnus obesus* (−32 to −21 dB) and yellowfin tuna *Thunnus albaceres* (−35 to −26 dB; Bertrand and Josse, 2000). A potential overlap in ringed seal *TS* with that of large fish is more probable with the echosounder (−48.0 to −12.2 and −55.6 to −16.1 dB at 120 kHz). The largest pelagic finfish in the Beaufort Sea is the anadromous Arctic charr (*Salvelinus alpinus*), with reported length up to 59.5 cm (Craig, 1978) and *TS* values less than −35 dB (Snorrason *et al.*, 1992). Hence, seals and large fish are unlikely to be confounded by the sonar in the area but could be mistaken by the echosounder.

The overlap of *TS* ranges for seals, dolphins, and large fish stresses the importance of considering interferences from other animals when using active acoustics for marine mammal detection. When large fish are present, echotraces may help differentiation. For instance, the trace of a fast swimming fish avoiding a ship should differ from that of a stationary seal at the surface or that of a dolphin swimming/breathing near the surface.

TS measurements were based on the point-scattering and spherical spreading models, which imply that measurements should be taken outside the nearfield region (Simmonds and MacLennan, 2005). Detections of the calibration sphere and of all marine mammals occurred outside the acoustic nearfield of the sonar transducer which, based on an active diameter of 54 cm (FRK, unpublished data) and a sound speed of 1500 m s^{-1}, is <12 m at 20 kHz (Simmonds and MacLennan, 2005). However, considering the lungs of a bowhead whale as a sound source with an active diameter up to 90 cm (Henry *et al.*, 1983), its nearfield could reach 32 m at 20 kHz and perhaps interferences within the nearfield of marine mammals biased our *TS* measurements. Bernasconi *et al.* (2013a) estimated this bias to be minor for fin whales, and the uncertainties resulting from the large diameter of the targets are likely to be within the confidence interval of *TS* measurements.

The use of the spherical model of attenuation to calculate TVG in the acoustic duct could have resulted in an overestimation of *TS* at long ranges. This positive bias would be similar to that from previous studies that used the spherical model to calculate *TS* of marine mammals (e.g. Dunn, 1969; Levenson, 1974; Bernasconi *et al.*, 2013a). Here, the maximum variation in *TS* for a single bowhead whale detected at a given frequency in both the acoustic duct and the main ray propagation path was 3 dB. We thus conclude that biases resulting from the use of the spherical model were <3 dB, which is within the confidence interval for *TS* of bowhead whales.

Pulse duration increases with the detection range of the sonar and reaches 72 ms at 2000 m. For such pulses and assuming a sound speed of 1500 m s^{-1}, targets must differ in range by at least 54 m to produce separate echoes (Simmonds and MacLennan, 2005). In this study, as bowhead whales detected at long ranges were generally several hundred metres away from congeners (Pyć *et al.*, 2015), the bias resulting from multiple target detections is likely negligible. Future sonar surveys using recognition criteria provided here should however be aware of possible multiple target detections, if marine mammals are closely distributed.

Lung compression, anechoic properties of blubber, and *TS* of diving ringed seals

Under experimental conditions, Au (1996) observed that the air contained in the lungs was the most powerful source of backscatter in Atlantic bottlenose dolphins, with reflection from other parts of the body at least 10 dB lower. Miller and Potter (2001) suggested that bones were the second strongest acoustic reflector, but the *TS* of the skeletal structure of the head of a dolphin was not significantly higher than that of the rest of the body (Au, 1996). More recently, Bernasconi *et al.* (2013b) have measured the variation of *TS* with depth of a diving humpback whale. They have observed a diminution of the average *TS* of ~5 dB at depths between 60 and 80 m and of ~12 dB at 170 m, after the lung collapse limit. These observations suggest that lungs would be the main backscattering organs until marine mammals reach a depth where their lungs collapse. At greater depths, most of the backscatter would come from bones and flesh (Bernasconi *et al.*, 2013b).

In the present study, the similarity of the echoes from bowhead whales and from the air they expulse during breathing is consistent with the notion that *TS* is related to the air contained in the lungs near the surface. As *TS* measurements from sonar detections were conducted on surfacing animals, some of the variability in the *TS* value of a given whale may be explained by a varying lung volume or cross section during inhalation and exhalation (e.g. Bernasconi *et al.*, 2013a).

Because the air within the lungs is compressed with increasing surrounding pressure, previous studies have suggested an inverse relationship between *TS* and depth in diving marine mammals (e.g. Au, 1996; Doksaeter *et al.*, 2009; Bernasconi *et al.*, 2013b). However, *TS* showed little attenuation with depth in diving spinner dolphins *Stenella longirostris* (Benoit-Bird and Au, 2003) and dusky dolphins *Lagenorhynchus obscurus* (Benoit-Bird *et al.*, 2004). In the present study, *TS* of ringed seals diving above the depth where their lung collapse (100–170 m; Moore *et al.*, 2011) were relatively constant over depth intervals of 55 m or more. The lack of dependence of *TS* on the contraction of lungs with depth for small marine mammal species such as seals and dolphins might be related to the anechoic properties of blubber. At a given frequency, attenuation increases with blubber thickness (Miller and Potter, 2001). Hence, in seals and dolphins, the thickness of blubber relative to lung cross section could be sufficient for the blubber to attenuate most of the lung backscatter. Compression of the lungs would then have a negligible impact on *TS*, as the backscatter signal would be related to a relatively constant body cross section rather than a variable lung cross section. Whatever the cause, the constancy of *TS* in small species indicates that *TS* values calculated near the surface can be used to identify individuals at depth. In contrast, the *TS* of whales is likely related to lung cross section due to a smaller blubber thickness to body length ratio and one could rely on the model proposed by Bernasconi *et al.* (2013b) to estimate the decrease in *TS* with depth for whales.

In the present study, the relatively small ringed seals (up to 80 kg; Ryg *et al.*, 1990b) and the much larger bearded seal (up to 300 kg; Andersen *et al.*, 1999) presented similar *TS*. Again, the anechoic properties of blubber may explain this paradox. By comparison to ringed seals, the larger relative and total blubber mass of bearded seals (Ryg *et al.*, 1990a) would result in a stronger attenuation of the acoustic signal, thus dampening *TS* differences between both species.

Summary and conclusions

This study provides some guidelines to detect Arctic marine mammals using active acoustics. When a sonar is used, bowhead whales near the surface can be detected at a distance up to 2000 m and differentiated from seals based on *TS* and echotraces, the backscatter of large whale species being significantly stronger than that of small marine mammals and their echoes being followed by fluke prints. Variability in the *TS* of bowhead whales and seals was comparable to that in previous studies, and can be explained by size, changes in the swimming aspects of the animals, and variations in the cross section of their lungs (whales) or body (seals). Differentiation to species cannot be based solely on *TS* in areas where similar sized species are present, and the behaviour-related characteristics of echoes should be considered when interpreting the signal. Further developments would improve the usefulness of sonars in detecting marine mammals in the Canadian Arctic, in particular: (i) cataloguing recognition criteria for other marine mammal species such as beluga whales and walruses; and (ii) implementing real-time *TS* calculations within the sonar software interface.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

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