Bioacoustics Research Program
Technical Report 10-04

Passive Acoustic Monitoring of Marine Mammals in the Chukchi Sea

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Executive Summary

During the late summer and early fall of 2008, 26 marine autonomous recording units (MARUs, or *recorders*) were deployed in two arrays in the Chukchi Sea for purposes of recording sounds of marine mammals, with a particular focus on detecting sounds from bowhead whales (*Balaena mysticetus*), beluga whales (*Delphinapterus leucas*), and walrus (*Odobenus rosmarus*). The Klondike array was located in a seismic survey area and recorded from 9 September through 13 October; the Burger array was in a control area with no seismic activity, and recorded from 10 September through 13 October. The recording equipment and the analysis of the resulting audio data were provided by the Bioacoustics Research Program (BRP) at the Cornell Lab of Ornithology, under contract to ConocoPhillips Alaska, Inc.

This report describes the results of the analyses of the acoustic data recorded on MARUs in the two arrays. The objectives of the acoustic data analyses were to:

1. Assess the daily presence of bowhead whale sounds for each day of data from the Burger and Klondike sites;
2. Assess the daily presence of beluga whale sounds for each day of data from the Burger and Klondike sites;
3. Assess the daily presence of walrus sounds for each day of data from the Burger and Klondike sites;
4. Locate and estimate numbers of vocalizing bowhead whales in the vicinity of the Burger and Klondike sites.
5. Assess noise conditions in the vicinity of the Burger and Klondike sites.

All 26 recorders deployed were recovered successfully. Of these, 22 yielded usable data covering the entire 35-day deployment duration. Two recorders from the Klondike array and one from the Burger array experienced hardware failures resulting in complete data loss. One recorder from the Klondike array recorded data at a severely attenuated level; data from that unit were omitted from the analysis. After recovery of the MARUs, the acoustic data from each individual recorder within an array were merged into multi-channel array recordings, with each channel containing the recorded audio from one recorder.

Daily presence of bowhead sounds on each channel of each array was assessed by (1) manual examination of the first 5 minutes of every hour of recorded data, noting the occurrence of all individual whale calls on every channel, (2) manual examination of each minute from three randomly selected hours each day, noting the first arrival of one whale sound in each minute, and (3) automated scanning of all recordings by a prototype bowhead sound detection algorithm that logged all putative bowhead sounds detected. All events found by the automated detector as potential bowhead calls were reviewed by experienced human analysts, and false detections were discarded. Daily presence of beluga and walrus sounds were assessed by methods (1) and (2).

Bowhead sounds were detected on 31 of the 35 days (89%) that all ten recorders in the Klondike array were operational and on all 35 days (100%) that all twelve recorders in the Burger array were operational. Most of the bowhead sounds occurred in structured repetitive sequences similar to the

songs previously described from recordings at various locations during the winter and spring. When considering all recorders in the Klondike array, the daily presence of bowhead sounds at individual recording sites varied between 43% of days and 69% of days. In the Burger array, the daily presence of bowhead sounds at each recording site varied between 77% of days and 100% of days.

The relative daily levels of bowhead acoustic activity varied over the course of the recording season, with two periods of heightened activity: the first in the 21-26 September period, the second from 5 October to the end of each array's recording period (13 October for the Klondike array and 14 October for the Burger array). These two periods of elevated activity probably represent "pulses" of bowheads migrating westward through the area.

Beluga sounds were detected on the Klondike array on 8 (23%) of the 35 days with complete monitoring, and on the Burger array on 3 (9%) of the 35 days with complete monitoring. In the Klondike array, beluga sounds were detected on all operational recorders. In the Burger array, beluga sounds were detected on 5 of the 12 operational recorders.

Walrus sounds were detected on 19 out of 35 days with complete monitoring (54%) on the Klondike array and on 26 days out of 35 days with complete monitoring (74%) on the Burger array. In the Klondike array, walrus sounds were detected on all 10 operational recorders. In the Burger array, walrus sounds were detected on all 12 operational recorders.

Acoustic location estimates were calculated for all bowhead sounds that were received on three or more channels in the hours for which bowhead sounds were detected by examination of the first five minutes of the hour. The number of located sounds per day varied between 0 and 385 for the Klondike array, and between 0 and 1610 for the Burger array. Over the entire recording period, a total of 1109 bowhead sounds were located in the Klondike array, and 5495 in the Burger array. Locations tended to be concentrated primarily in the southwest quadrants of both arrays.

Although it is not possible to determine unambiguously the precise number of whales that produced a set of sounds over a given time period, we estimated the minimum number of vocalizing bowhead whales in the vicinity of each array for the one hour each day in which the bowhead detector found the greatest number of confirmed bowhead sounds. Hourly minimum numbers of whale were estimated based on the rate of change in the arrival time-delays of calls on pairs of recorders within the array. [1] The estimated minimum number of vocalizing whales in a single hour (on days when any bowheads were detected) varied between 1 and 10 for the Klondike array, and between 1 and 17 in the Burger array.

To assess directional movements of calling bowheads through the area of the two arrays, we examined longitude-time and bearing-time plots showing all locatable bowhead calls for each day. Whales that call frequently while moving steadily westward or eastward through the area can be recognized by a distinctive "signature" of points along a sloping line in these plots. However, whales that either call infrequently or move on an irregular course do not yield any such distinctive

[1] This is a form of bearing-time analysis, only here we used the delay times for the occurrence of the same sound on two recorders rather than converting the delay times into actual bearings.

signature. Relatively few locatable calls were part of such signatures, which were found on 2 of the 9 days with locatable calls in the Klondike array, and 6 of the 17 days with locatable calls in the Burger array. These signatures, lasting one to several hours, suggest sustained directional movement of a whale calling repeatedly over that time interval. In all cases where these apparent tracks occurred, they indicated westward movement, as expected in this area at this time of year.

Throughout the recordings from both arrays, many instances were found of a type of sound referred to here as “grunt sequences.” Grunt sequences consisted of a series of identical or nearly identical sounds repeated at regular intervals, with an entire sequence typically lasting one to several minutes. These grunt sequences are similar to “call sequences” recorded by others in the Canadian Beaufort in September 2004 and attributed to bowhead whales. However, because these sounds are unlike any previously known bowhead sounds, and because no visual observations accompanied the recordings, we consider the identification of bowheads as the source of these sounds as tentative. In the present study, many instances were found when a given grunt sequence was recorded across most channels of the array, implying a fairly high source level for the sound. There was a strong seasonal trend of increased rates of grunt activity between approximately 17 September and 2 October in both arrays, with overall higher levels of activity in the Burger array.

Seismic survey activity was acoustically detectable on both arrays. The number of days in the Klondike array with seismic survey activity was four times greater than that in the Burger array. The Klondike array had 28 days (78% of survey days) with seismic activity compared to 7 days (19% of survey days) in the Burger array.

Noise measurements from each MARU in both arrays are provided for each day of recording in the form of 24-h linear-frequency and 1/3-octave spectrograms, plots of equivalent sound level (L_{eq}) in the nominal bowhead whale band (71 – 708 Hz) versus time, plots of the statistical distribution of noise measurements as a function of frequency over the entire day, and “noisegram” plots showing the statistical distribution of L_{eq} measurements in the bowhead band in 15-minute bins throughout each day. Illustrative examples of these graphical noise summaries are provided in the text of this report; complete summaries for all data are included in Appendices C and D on the accompanying DVD.

BACKGROUND

During the late summer and early fall of 2008, 26 marine autonomous recording units (MARUs) were deployed in two arrays in the Chukchi Sea for purposes of recording sounds of marine mammals, with a particular focus on detecting sounds from bowhead whales (*Balaena mysticetus*), beluga whales (*Delphinapterus leucas*), and walrus (*Odobenus rosmarus*). The Klondike array was located in a seismic survey area; the Burger array was in a control area with no seismic activity. The two arrays were approximately 47 km apart at their closest points. The recording equipment and the analysis of the resulting audio data were provided by the Bioacoustics Research Program (BRP) at the Cornell Lab of Ornithology, under contract to ConocoPhillips Alaska, Inc.

The objectives of the acoustic data analysis, as defined in the Statement of Work (last revised 29 May 2009) were:

1. Assess the daily presence of bowhead whale sounds for each day of data from the Burger and Klondike sites;
2. Assess the daily presence of beluga whale sounds for each day of data from the Burger and Klondike sites;
3. Assess the daily presence of walrus sounds for each day of data from the Burger and Klondike sites;
4. Locate and estimate numbers of vocalizing bowhead whales in the vicinity of the Burger and Klondike sites.
5. Assess noise conditions in the vicinity of the Burger and Klondike sites.

Additional goals for the project include refinement of software for automated processing of such recordings and development of protocols for efficient data management and analysis.

This document is the final report on the analysis efforts applied to the acoustic data collected by all the MARUs operating in the two arrays, based on the objectives listed above.

METHODS

Recording

A marine autonomous recording unit (MARU) is a digital audio recording system contained in a positively buoyant 17” glass sphere that is deployed on the bottom of the ocean for periods of weeks to months. An MARU (henceforth *recorder*) can be programmed to record on any desired daily schedule and deployed in a remote environment where it is held in place by an anchor. A hydrophone mounted outside the sphere transduces sound pressure into an analog electrical data stream, which is then filtered, digitized, and stored as a continuous series of binary files on an internal hard disk. At the conclusion of a deployment, a recovery vessel transmits an acoustic command to the recorder, which, in response, releases its anchor and floats to the surface for recovery. After the recovery, the recorded data are extracted, converted into standard audio files and stored on a server for analysis. Data recorded by an MARU are thus accessible only after the device is retrieved.

When multiple recorders are deployed in an array configuration, all units are synchronized at the start and end of the deployment, and the extracted data are merged into synchronized, multi-channel audio files[2]. Because the locations of the recorders and the speed of sound underwater are known, we can compute estimates of the locations of whales vocalizing in and near the array based on differences in the arrival times of the same sound at different MARUs, provided that the sound is recorded on three or more units.

Figure 1. Deployment of Marine Autonomous Recording Units (MARUs) in the Chukchi Sea, summer 2008.

[2] The acoustic data from each MARU is stored in one *channel* in a multi-channel data file. The term channel is thus used in this report to represent the acoustic data from one MARU. Individual channels are identified by a number (e.g., channel #3), indicating the site within the array where the corresponding MARU was deployed.

On 3 - 5 July 2007, six MARUs were calibrated at the U.S. Navy testing facility in Seneca Lake, NY. Based on these calibrations, as well as on the results of previous calibrations ($N = 18$), the sensitivity of the MARUs was determined to be -151.2 ± 1 dB re 1 µPa between 10 and 585 Hz (Parks et al. 2009).

Field deployment and recovery

Twenty-six (26) MARUs were deployed on 7 – 9 September and recovered on 14 – 16 October 2008 from the vessel *R/V Bluefin*. Thirteen (13) MARUs were deployed in each of the Klondike and Burger arrays (Figure 2). All recorders in the Klondike array were deployed from 9 September through 13 October (35 complete days), while all Burger recorders were deployed from 10 September through 14 October (35 complete days).

Within each array, MARUs were deployed with an inter-MARU distance of approximately 5 nmi (9.3 km), except for Burger units BU06 and BU05, which were both 2.5 nmi (4.6 km) from BU13. All recording sites in the Burger array were at depths of 40 – 45 m; all recording sites in the Klondike array were at depths of 35 – 40 m.

MARUs in the Klondike array recorded continuously at a sampling rate of 2000 Hz for an effective acoustic bandwidth of 5 – 800Hz[3]1000 Hz. MARUs in the Burger array recorded continuously at a sampling rate of 4167 Hz for an effective acoustic bandwidth of 5 – 1667 Hz.

Analysis of acoustic data

To assess the presence of sounds from bowhead whales, beluga whales, and walruses on a given array, analysts with expertise in marine mammal sound identification visually examined multi-channel sound spectrograms (where each channel corresponds to sound recorded by one MARU in the array), typically viewing 60 seconds of sound at a time (Figure 4). Sounds from any of the three target species were marked (i.e., annotated) as to their species identity. If the analyst judged the visual signature of the sound to be ambiguous, the sound was also reviewed aurally before being marked. The analysis software saves each marked sound's start and end time, frequency bounds, and associated annotation data in a log file for each day's multi-channel recording.

[3] This is the frequency band within which the recorder's frequency response is within 3dB of the maximum system response; where the low-frequency response is determines by signal conditioning high-pass filters and the high-frequency response is determined by the anti-aliasing, low-pass filter.

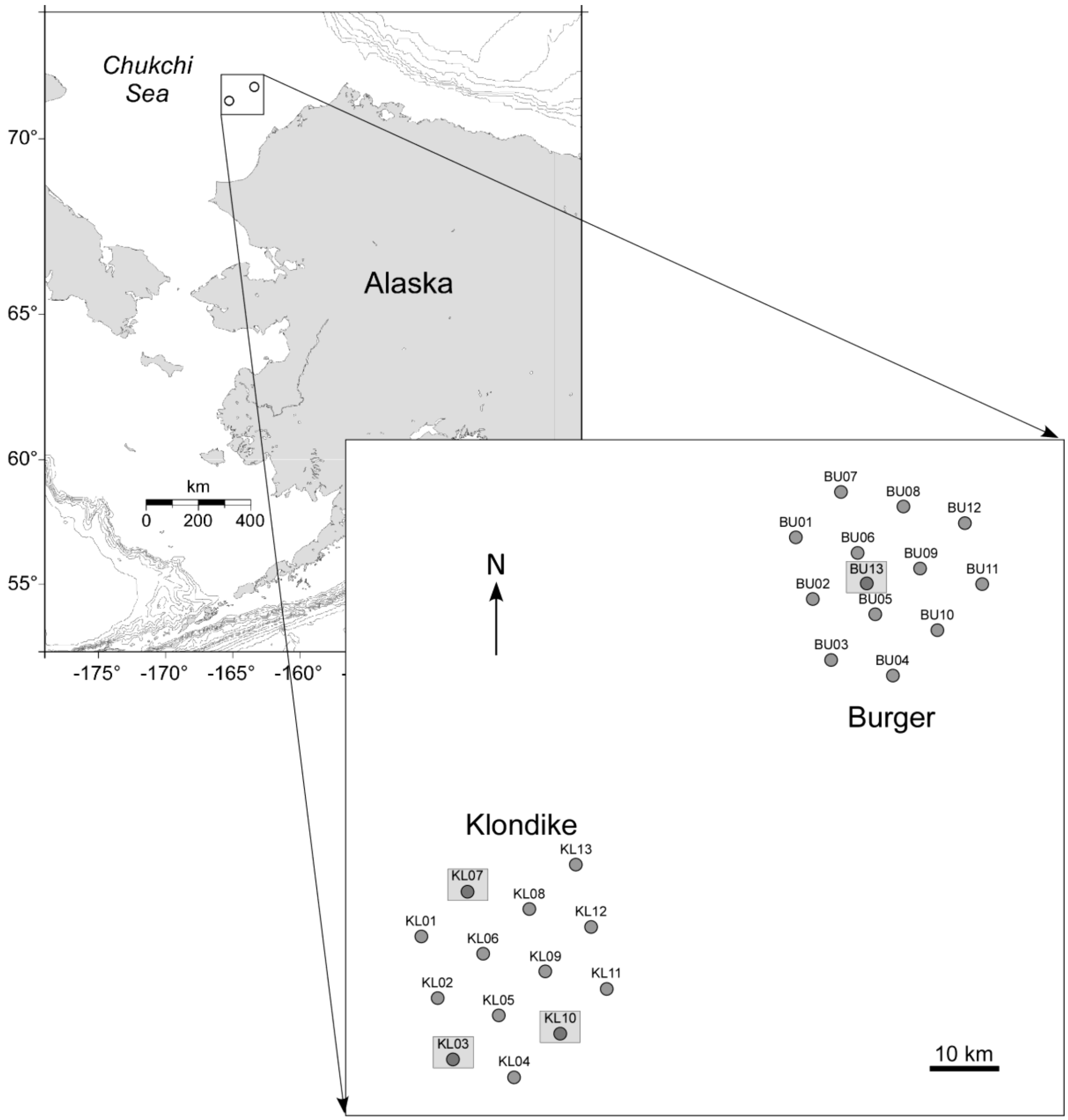

Figure 2. Locations and geometries of Klondike and Burger MARU arrays deployed in the Chukchi Sea off the coast of Northern Alaska in 2008. The separation distance between individual MARU recorders is 5 nautical miles (9.26 km), except for BU05 and BU06 which are 2.5 nmi (4.63 km) from BU13. All Klondike MARUs were at depths of 36 – 40 m; all Burger MARUs were at depths of 43 – 45 m. Gray overlaid rectangles indicate MARUs that failed to provide usable data.

Objective 1 - 3: Daily presence of bowhead whale, beluga whale, and walrus sounds

In order to identify days in which sounds of bowheads, belugas, and walrus were recorded on each channel of the two arrays, the recordings were analyzed using two methods. Additionally, a third method was used for bowhead sounds only:

- Method 1: Manual examination of the first five minutes of each hour

- Method 2: Manual examination of three hours in each day
- Method 3 (bowhead only): Automated detection

Data presented here on daily presence of each target species for each MARU site in the two arrays were based on the occurrence of at least one sound from that species in the recording from that site, as determined by one or more of these methods.

The three methods for determining daily presence are described further below.

Method 1: Manual examination of the first five minutes of each hour

For each MARU, the 5-minute segment of recording at the start of each hour was examined for the presence of sounds from each of the three target species (Figure 3). Within each 5-minute segment, analysts marked all bowhead whale sounds on each of the channels (Figure 4), but only one beluga and only one walrus sound per channel (Figure 5, Figure 6).

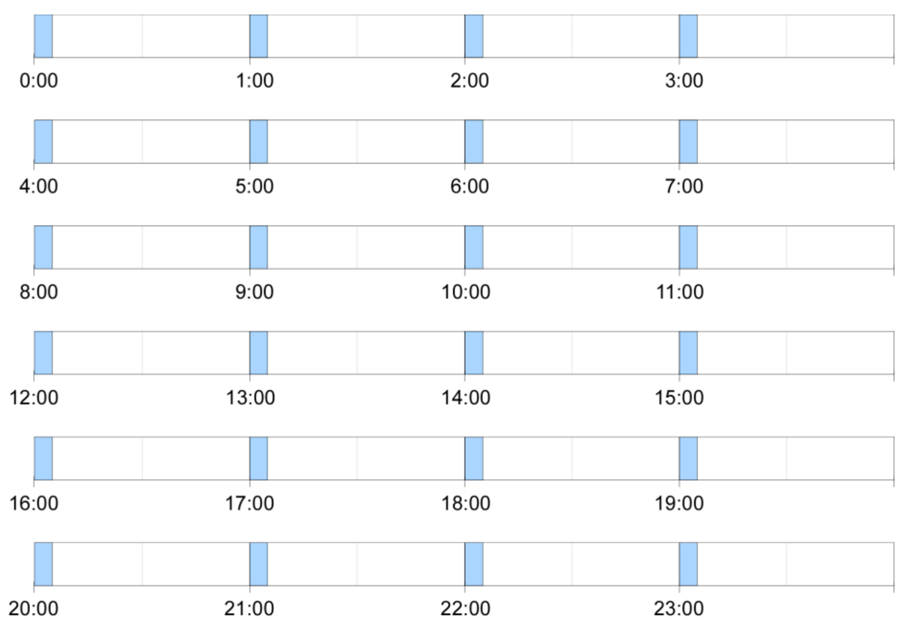

Figure 3. Illustration of method 1 sampling schedule for daily and hourly presence of bowhead, beluga, and walrus sounds, and for seismic survey activity. Shaded intervals indicate 5-minute sample periods in which analysts examined spectrograms to determine presence or absence of sounds from each of the three target species on each channel of each array.

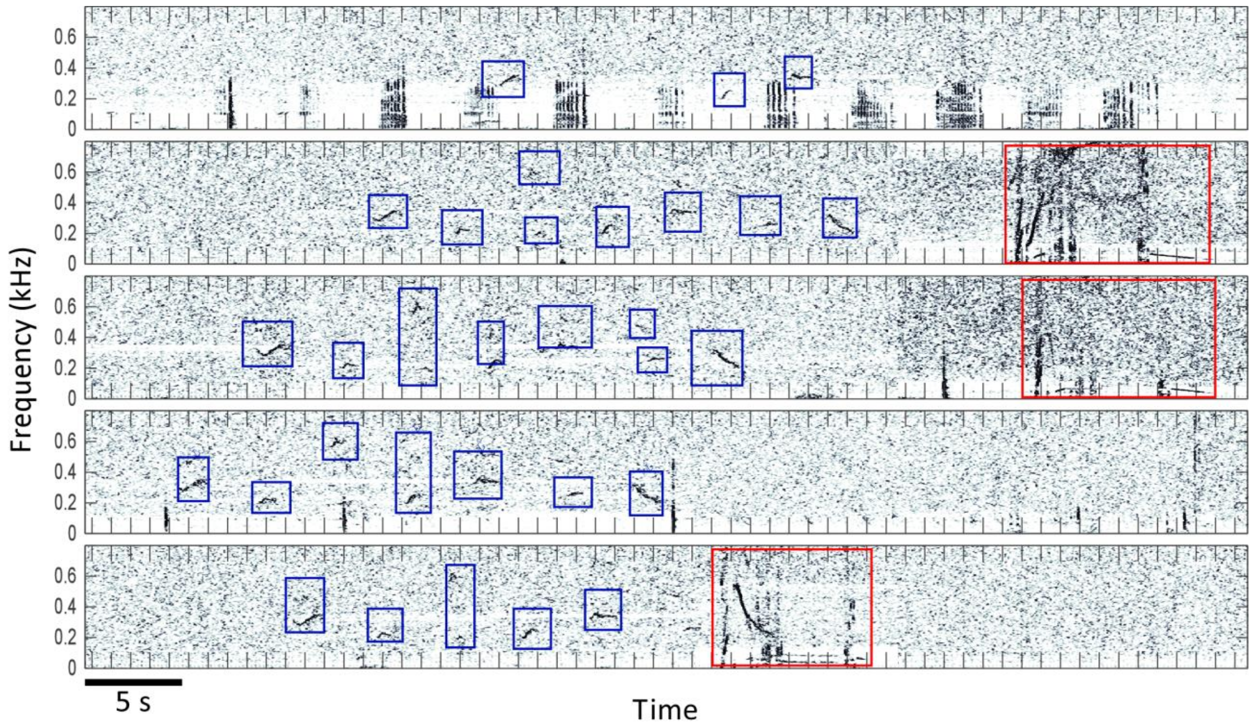

Figure 4. Spectrogram of 60 seconds of sound recorded from the Burger array on 8 October 2008. For clarity, only five of the 12 operational channels of data are shown. Each horizontal line (channel) displays data from one MARU. The boxes indicate bowhead whale calls, as marked by analysts. Sounds outlined in red boxes are noise from the MARU's hard drive spinning up to write data.

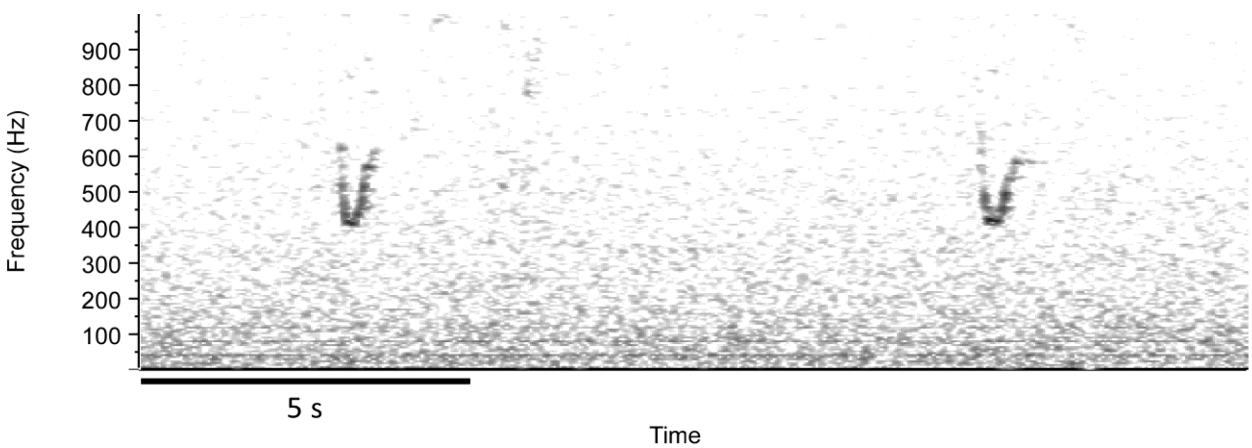

Figure 5. Spectrogram of sounds from beluga whales recorded in the Klondike array on 14 September.

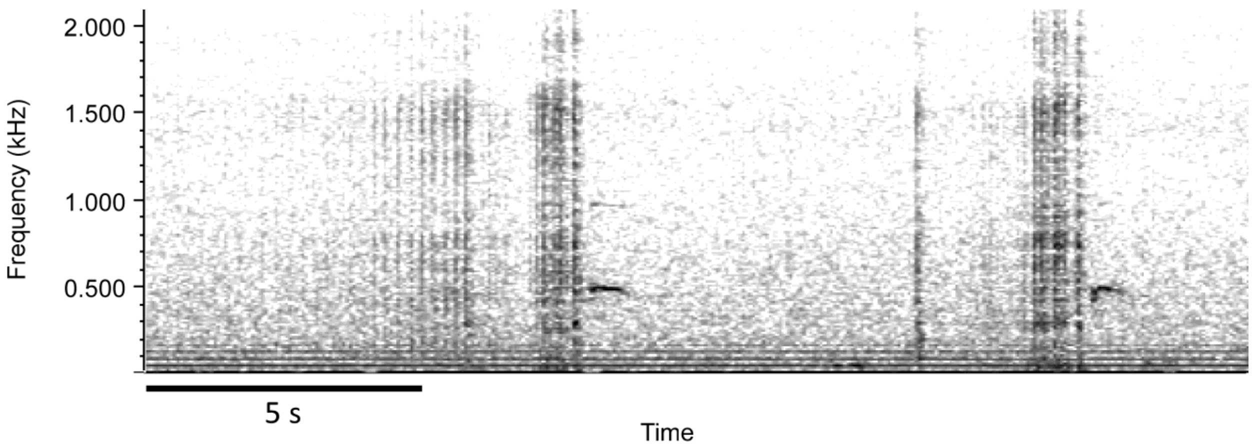

Figure 6. Spectrogram of walrus sounds recorded on the Burger array on 15 September. The continuous horizontal lines below 200 Hz are tonal electronic noise generated within the MARU.

Method 2: Manual examination of three hours each day

Three 1-hour intervals were randomly selected from each day of the recording period for each array (Klondike: 35 days, 9 September – 13 October; Burger: 35 days, 10 September – 14 October), resulting in a total of 105 1-h multi-channel samples from each array. Each 1-h sample was examined by an experienced acoustic analyst as 60 one-minute multi-channel spectrogram pages, and the first arrival of one sound from each of the target species was marked in each channel on each page that contained any sounds of that species. Only one sound from each species was marked in each channel in each minute, even if multiple sounds were recorded, because the objective of this analysis was to evaluate our ability to detect the *presence* of sounds from a given species on a one-minute time scale, irrespective of the *number* of sounds that were recorded from that species. Furthermore, marking every sound would have considerably increased the time required for the analysis.

Bowhead sounds were commonly received on multiple channels. When this occurred, each sound was marked only in the channel on which it arrived first, in order (1) to avoid double-counting the same whale sound on multiple channels, and (2) to provide information on which recorder was closest to the vocalizing whale. The result was a record of the presence or absence of first-arrival bowhead sounds in each minute of the hour for each channel.

Method 3: Automated detection (bowhead sounds only)

A prototype bowhead whale sound detector was run on all data recorded from both arrays. This detector was based on principles previously used in an automated detector for North Atlantic right whale (*Eubalaena glacialis*) sounds (Urazghildiiev et al. 2009).

The events identified by the detector were reviewed by experienced acoustic analysts, who discarded false detections. The performance of the detector was evaluated by comparison of minutes identified by the detector as containing bowhead sounds with minutes identified by human analysts as containing bowhead sounds in the three daily 1-hour samples examined in Phase 2 (see above).

Objective 4: Locations and estimated numbers of vocalizing bowhead whales

Estimated locations

When a sound is received on three or more sensors at known locations and in water of known sound velocity, the position of a sound source can in principle be determined because, under the right conditions, the source position in space determines a unique set of pairwise differences in the sound's time of arrival at the multiple sensors in an array (Clark et al. 1986a, Clark et al. 1996). In practice, estimates of sound source locations are compromised by errors from several sources of uncertainty including synchronization of recordings among sensors, sensor position, speed of sound, and background noise.

The positions of vocalizing animals were estimated using a custom correlation sum estimation (CSE) algorithm (Cortopassi and Fristrup 2005), which determines the most likely set of pairwise time of arrival differences in order to determine the most likely source location. Using the CSE location tool (K. A. Cortopassi) the most likely set of time delays is estimated by finding the time lags which maximize the sum of filtered waveform cross-correlation values over all sensor pairs. Figure 7 illustrates the location process. The CSE locator tool was configured to search for locations out to distances of 40 km from the center of the array.

For each hour in which bowhead sounds were detected in the first five minutes, analysts marked each bowhead sound on one channel (the *reference* channel). The CSE locator tool was then run on all of the marked sounds, and generated preliminary location estimates for those sounds received on three or more channels. One of the outputs of the CSE locator is a prediction of the time at which the marked sound is expected to appear in all channels other than the reference channel, based on the estimated location. Analysts assessed the reliability of all preliminary location estimates by comparing the locator's predicted times of occurrence to the actual times of occurrence of the sound in the non-reference channels. When discrepancies were found, the analyst re-ran the location estimate, adjusting parameters of the algorithm to try to achieve a reliable location. In some cases, no reliable location could be found and the sound was tagged as unlocatable.

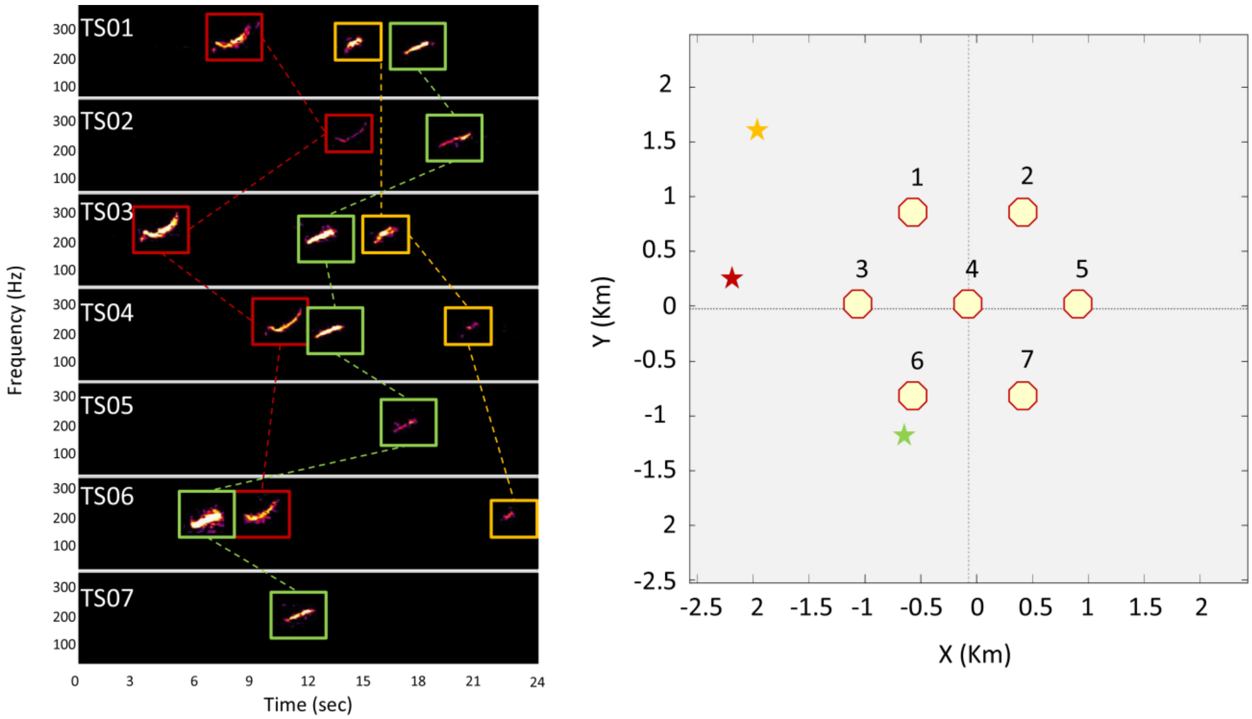

Figure 7. Estimating the location of calling bowhead whales. **Left:** Seven-channel spectrogram, showing calls from three different whales recorded on a seven-channel array over a span of 24 seconds. Colored boxes and dashed lines link arrivals on different channels of calls from each whale. Calls from each whale exhibit a unique pattern of time delays among channels, corresponding to the whale's position relative to the recorders. **Right:** Location map, showing the estimated location of each whale relative to the array. Colored stars indicate whale locations; each star's color matches the color of the boxes around the corresponding call in the spectrogram. Calls from each whale arrive at different recorders in order of their increasing distance from the whale to the recorder.

Estimated numbers of vocalizing bowhead whales

The minimum number of bowhead whales vocalizing in the vicinity of each array on each day was estimated by the following procedure.

1. For each day on which one or more bowhead sounds were detected, the one hour with the highest number of verified bowhead calls found by the automated detector was selected for analysis.
2. Analysts examined the entirety of each of these hours, and marked one arrival (in most cases the first arrival) of each call that was visible on two or more channels.
3. A software tool (the *RL-TD tool*) then estimated time-of-arrival delays between the marked arrival and arrivals on other channels by cross-correlation.
4. Analysts reviewed the output of the RL-TD tool to eliminate any erroneous time-delay estimates.
5. The minimum number of bowhead whales vocalizing in the hour was estimated by a software tool (*TDwhaleCount*) that created tracks of events (individual sounds) linked on the basis of

the rate of change of time-of-arrival delays. The basis of this algorithm is explained further below.

If a single whale calls repeatedly while moving, the time-delay for its calls between any given pair of recorders will change at a rate that depends both on the whale's swimming speed, and on its position and heading relative to the recorders. The time-delay would change most rapidly for a whale swimming at its maximum possible speed along a line connecting the two recorders. For a given swim speed, we can calculate the maximum rate at which the time-delay could change. For a maximum swim speed of 8 km/h (Sonntag et al. 1988) and a presumed sound speed of 1437 m/s, the maximum possible rate of change in time-delay is 0.186 s/min. TDwhaleCount links together successive calls within the one-hour counting period for which the time delays (on all channel pairs) change at less than the maximum possible rate. A series of calls that are linked in this way is called a *time-delay track* (Figure 8). Calls that are linked into the same time-delay track may have been produced by the same whale. Calls that are in different time-delay tracks (including calls that cannot be linked to any others) cannot have been produced by the same whale; the fact that the calls cannot be linked means that a whale would have needed to swim impossibly fast to generate the observed rate of change in arrival-time delays. The number of time-delay tracks found in an hour is taken as an estimate of the minimum number of whales vocalizing in that hour.

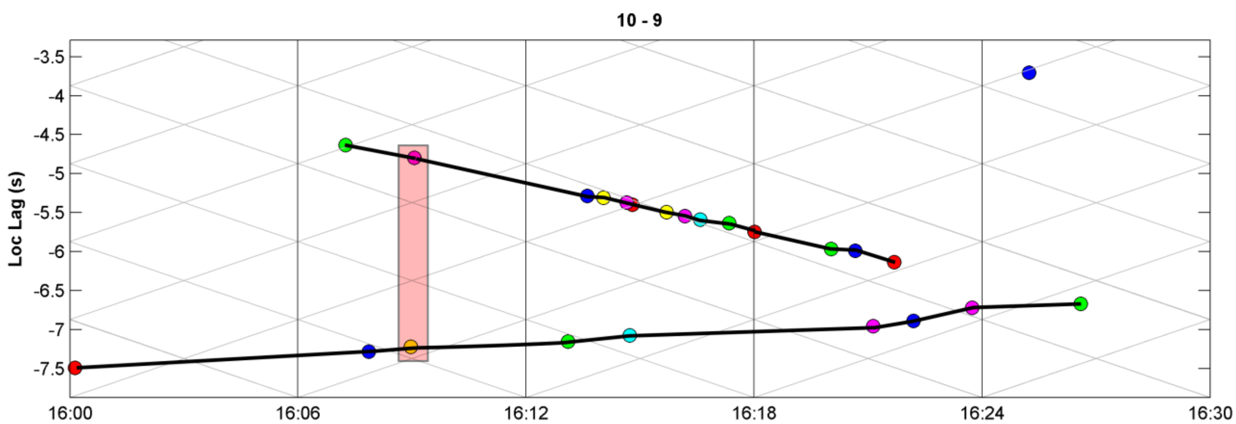

Figure 8. Schematic illustration of the algorithm for estimating the minimum number of calling whales using time-of-arrival delays. Data are shown for a 30 minute interval. Time delays for all calls received on MARUs #9 and #10 within the array are shown. Each point represents one whale call, and shows the call's time of occurrence (horizontal axis) and the delay between the arrival of the call on recorder #10 and its arrival on recorder #9 (vertical axis). Colors of the points are used to identify the same call as received on different pairs of recorders (not shown). Sloping gray lines indicate the maximum possible rate of change in time delay for a whale swimming at 8 km/h along the line between the two recorders. Black lines link calls that may have come from the same whale. The absolute value of the slope of any linkage line cannot exceed the maximum change rate represented by the sloping gray lines. Unlinked calls must have been produced by different whales. In this example, at least three whales are required to account for the pattern of time delays shown: the first track, containing 9 calls, begins at 16:00 and ends at ≈16:27; the second track, containing 14 calls, begins at ≈16:07 and ends at ≈16:22; the third track consists of a single unlinked call at ≈16:25. The two calls in the box at ≈16:09 are shown in Figure 9.

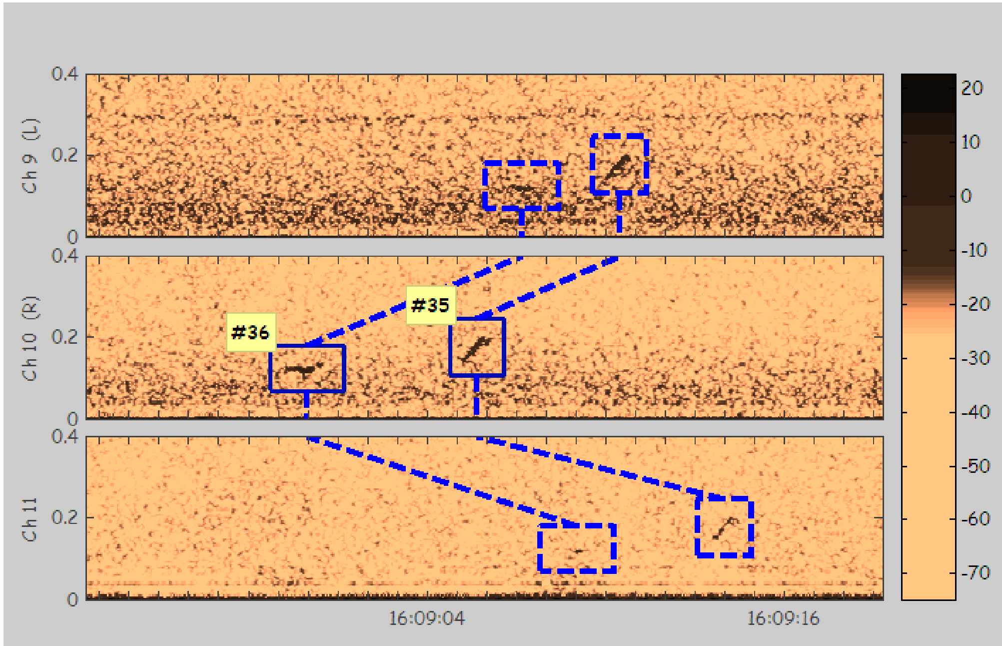

Figure 9. Spectrogram of 27 seconds of sound recorded on Channels 9, 10, and 11 of an Arctic MARU array, showing the two bowhead whale calls identified by the box in Figure 8. Blue boxes and dashed blue lines link arrivals of the same call on different channels. The different pattern of time delays between the arrivals of the calls (Figure 8) and the different intervals between the calls visible here on the different channels indicate that these calls came from two whales at different locations.

Directional movement of bowhead whales

To determine whether bowhead whales detected in and near the arrays were moving through or remaining in the vicinity, we examined plots of (1) longitude of estimated call locations versus time and (2) bearing (from the center of the array) versus time (Figure 10). Repeated calling by an individual whale can result in distinctive patterns in such plots, depending on the whale's direction of movement (Figure 11). Repeated calling during a period of sustained movement in any direction with a non-zero east-west component is represented in longitude-time plots as a series of points along a line with a negative (eastward) or positive (westward) slope. Repeated calls from the same location in space would appear in this plot directly above each other; calls from a whale moving northward or southward, with no eastward or westward movement would also align the same way. In the bearing-time plot, repeated calls from a whale moving along a straight course will also fall along a line, the slope of which depends both on the whale's direction of movement and its initial bearing relative to the center of the array.

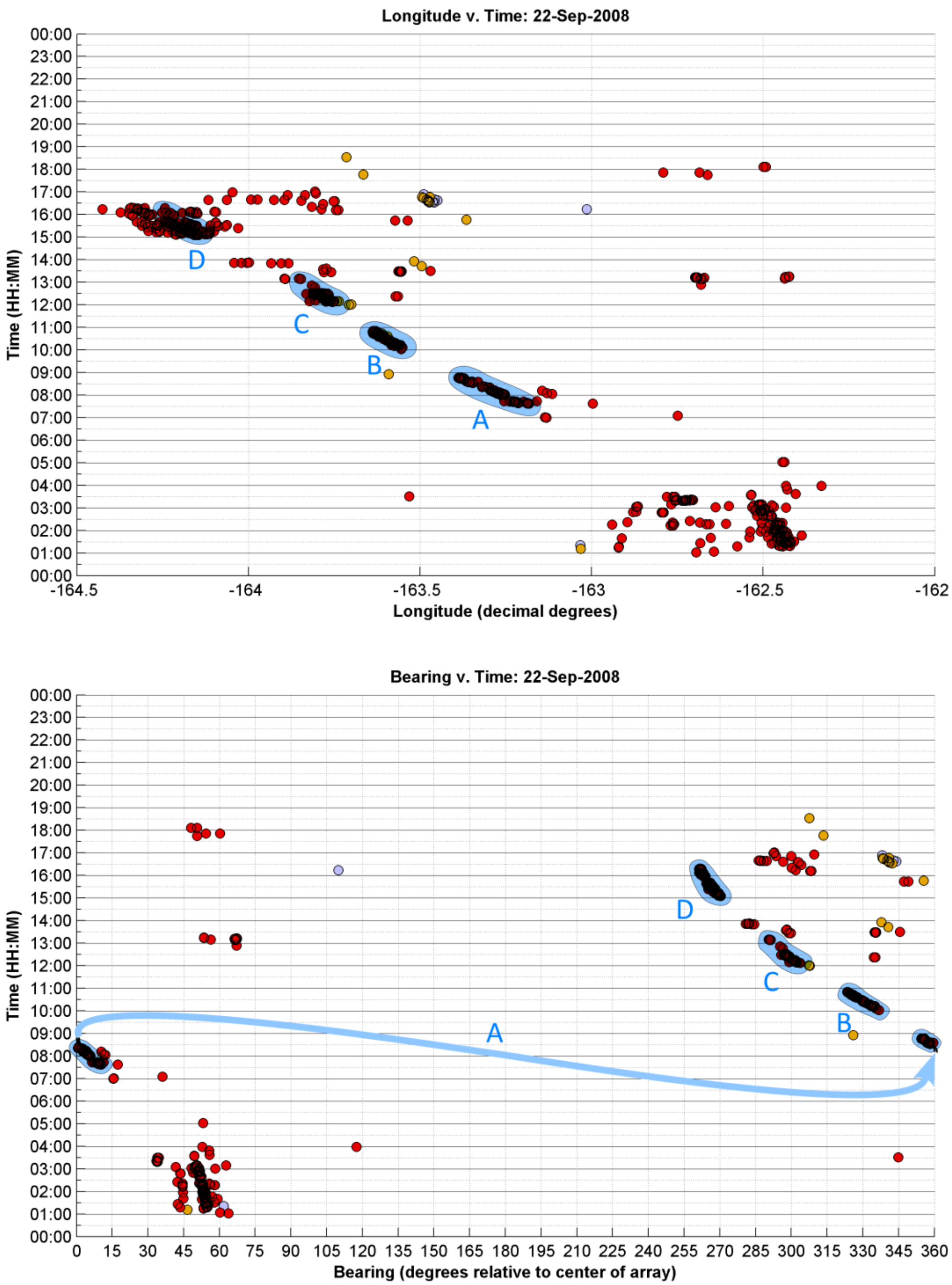

Figure 10. Longitude-time (top) and bearing-time (bottom) plots for estimated bowhead whale locations in the Burger array, 22 September 2008. The sequences of points highlighted in blue represent probable tracks of single groups, moving east to west, where a group can consist of one or more animals in close proximity to each other. Tracks A, B, C, and D are likely to be from the same group, based on consistency of travel direction. In the bearing-time plot (bottom), track A begins at a bearing of approximately 10°, then moves eastward past 0° (=360°), causing the track to wrap around from the left to the right edge of the plot, and ends at approximately 350°.

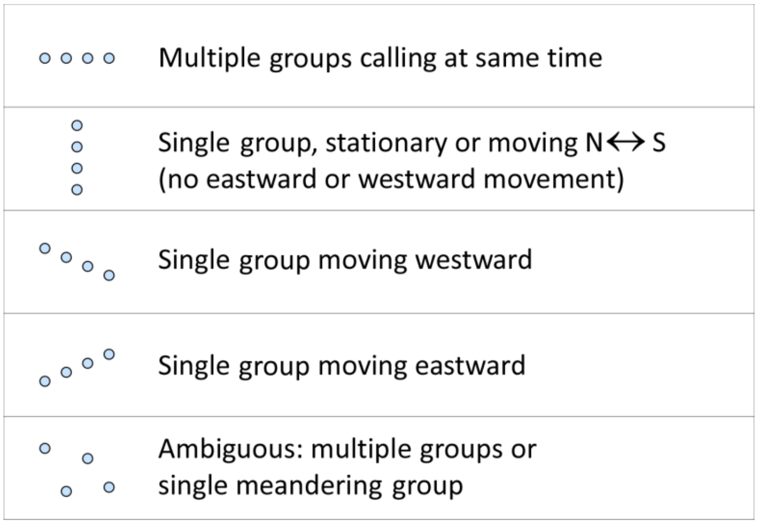

Figure 11. Interpretation of patterns in longitude-time plots (e.g., Figure 10).

Objective 5: Noise conditions

Daily occurrence of seismic survey noise

For each array, analysts noted the occurrence or non-occurrence of seismic survey sounds on any channel of the array during the 5-minute period at the beginning of each hour of recording (Figure 12). Seismic survey noise is reported for any day on which seismic activity was detected on at least one channel in the 5-minute sample from one or more hours.

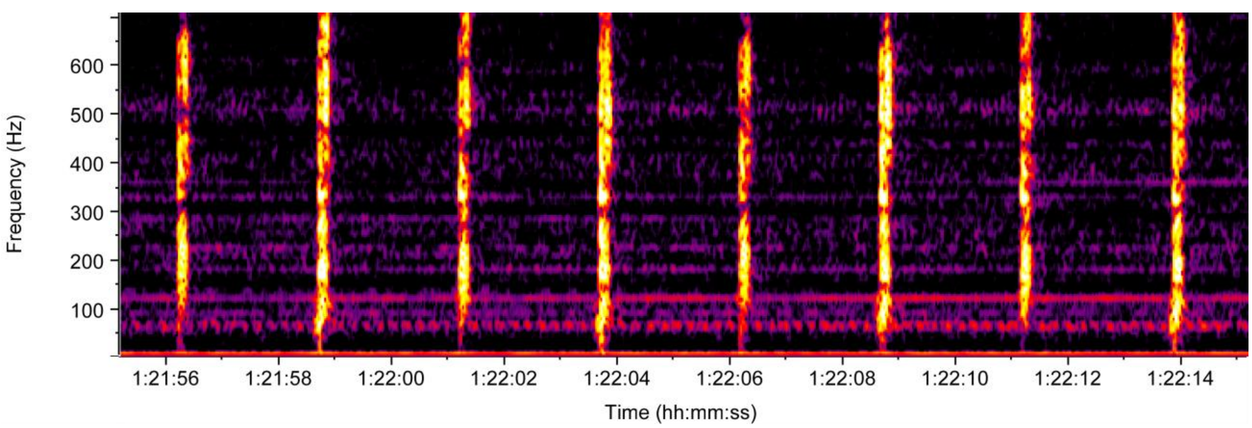

Figure 12. Spectrogram of seismic sparker sounds from nearby survey vessel recorded on channel 5 of the Klondike array beginning at approximately 01:22 on 13 September. The range between the seismic survey vessel and the MARU was approximately 837 m.

Noise measurements

We used a custom MATLAB program, written by K. A. Cortopassi, to generate long-term (LT) spectrograms of calibrated audio data, to measure root mean square (RMS) received levels (RLs) over specified frequency bands, and to estimate 1/3-octave band RMS noise levels. The program generates spectrograms with user-specified time and frequency bin sizes using non-overlapping data windows. To obtain greater time bin sizes than would normally be achievable via a given data window length, successive spectra were aggregated. Long-term spectrograms were made with a frequency bin size of 1 Hz and an aggregate noise integration interval of 10 s.[4]

Examination of the raw audio data recorded by the MARUs revealed two types of noise artifact generated by the MARU itself. *Hard drive noise* events occurred at intervals of approximately 180 s, each time the recorder's hard drive spun up to write buffered audio data; the duration of each event was approximately 8 s. *Tonal noise* consisted of a set of continuous tones at 40 Hz and harmonics at diminishing amplitudes up to 160 Hz throughout the recordings. Energy from these internally generated noises was removed and interpolated values were substituted in the long-term spectrograms before computing the final noise estimates reported here.

We estimated the broadband received noise levels over the 71 – 708 Hz band by summing power values in the corresponding spectrogram frequency bins, interpolating as needed when the band limits did not align exactly with spectrogram bin boundaries. This band is the frequency range within which most bowhead whale communication sounds occur, and is thus presumed to be the band within which bowhead whales would be most vulnerable to masking from noise and likely to be disturbed by anthropogenic noises.

RESULTS

All 26 MARUs deployed were recovered successfully. Of these, 22 yielded usable data covering the entire deployment duration. Two MARUs from the Klondike array and one from the Burger array yielded no functional data as described below.

The MARU hard drives from sites KL10 and KL03 of the Klondike array failed during the first day of deployment. The signal amplitude of the data from site KL07 was much lower than at other sites, indicating that this unit's acoustic sensitivity was much lower than the nominal calibrated value. Because data from KL07 are thus not comparable to data from other sites, they are omitted from analyses reported here. Of the 1 remaining Klondike hard drives, the drives at sites KL06 and KL04 contained a number of corrupted data sectors, which led to gaps in the recorded sound data. Data gaps occurred at site KL06 from 12 to 19 September and at site KL04 on 1, 6, and 7 October.

In the Burger array, the hard drive at site BU13 failed during the first day of deployment. However, failure of BU13 does not significantly affect our ability to survey for marine mammal sounds in this

[4] Because of the different sampling rates used in the Klondike and Burger MARUs, different spectrogram parameters were used to achieve frequency and time resolutions of 1 Hz and 10 s, respectively. For Klondike recordings, we used a 2048-point Hanning window, yielding a frequency bin size of 0.98 Hz, and a raw (unaggregated) time bin size of 1.024 s. For Burger, we used a 4096-point Hanning window, yielding a frequency bin size of 1.02 Hz, and a raw (unaggregated) time bin size of 0.98 s.

area of the Burger array, because, due to ice covering the planned location for site BU13, this recorder was actually deployed in a different location, between BU05 and BU06.

The resulting data available for analysis includes 35 full days (9 September – 13 October) of sound data from 10 MARUs in the Klondike array, and 35 full days (10 September – 14 October) of sound data from 12 MARUs in the Burger array. In addition, data are available from two partial days at the end of each array deployment (Klondike: 14-15 October; Burger: 15-16 October). Partial days are days when data were available for less than 24 hours from one or more MARUs because units were being retrieved. Data from partial days are not included in daily presence/absence statistics in this report.

Objective 1: Daily presence of bowhead whale sounds

Daily presence

Bowhead sounds were detected on 31 of the 35 days (89%) that the entire Klondike array was operational and on all 35 days (100%) that the entire Burger array was operational (Figure 13). These figures reflect days that were found to contain bowhead sounds by any method (examination of the first five minutes of each hour, examination of three randomly selected hours each day, and examination of events found by the automated detector algorithm). Most of the bowhead sounds occurred in structured repetitive sequences similar to the songs previously described from recordings during the winter and spring (Figure 14; Ljungblad et al. 1982, Clark and Johnson 1984, Würsig et al. 2002, Delarue et al. 2009).

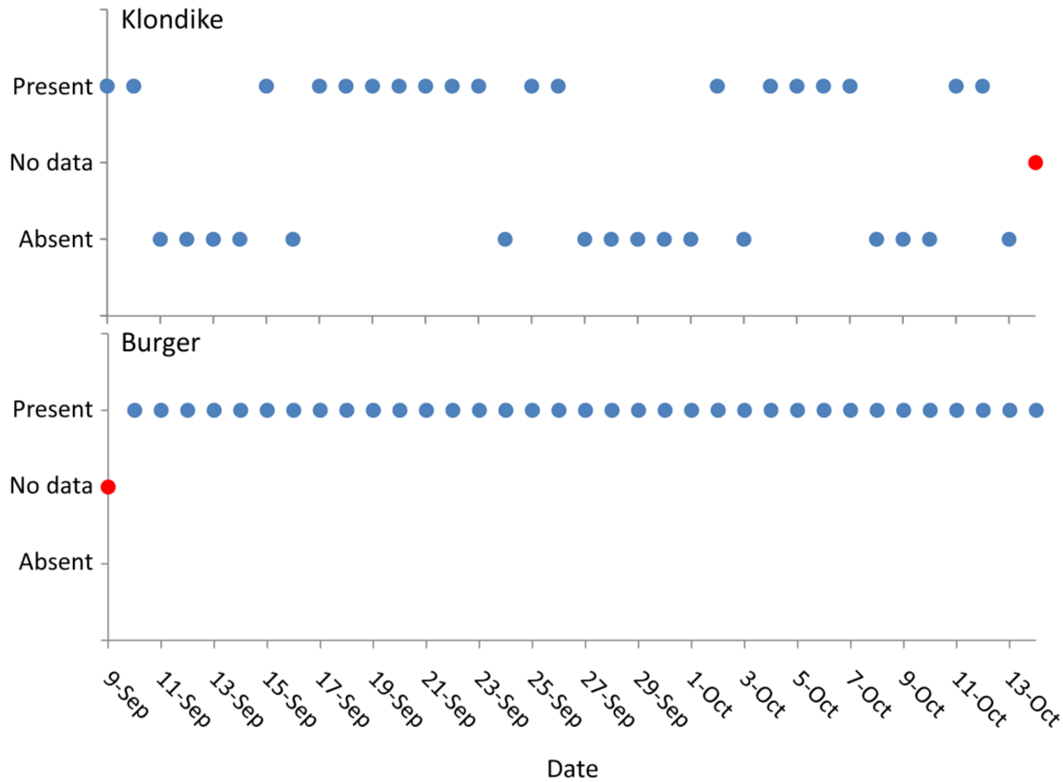

Figure 13. Daily presence of bowhead whale sounds in Klondike and Burger arrays as detected using three different sampling methods.

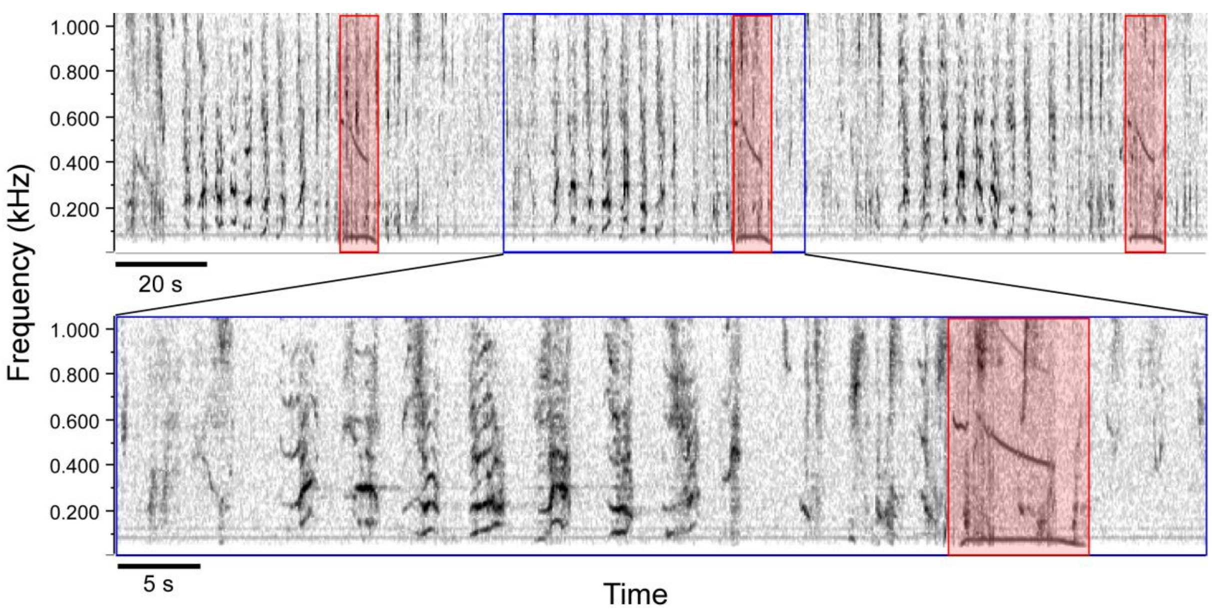

Figure 14. Example of bowhead song, recorded on channel #4 of the Burger array, starting at 06:58 on 15 October. Sounds highlighted in red are noise from the MARU's internal hard disk drive. **Upper panel:** 4 minutes, showing 3 repetitions of the song. **Lower panel:** 65 seconds, showing one instance of the song.

Figure 15 shows the percentage of days on which bowhead sounds were detected at each recording site in the two arrays. In the Klondike array, the daily presence of bowhead sounds at individual recording sites varied between 43% of days (at site KL02) and 69% of days (at site KL12). In the Burger array, the daily presence of bowhead sounds varied between 77% of days (at site BU02) and 100% of days (at site BU12).

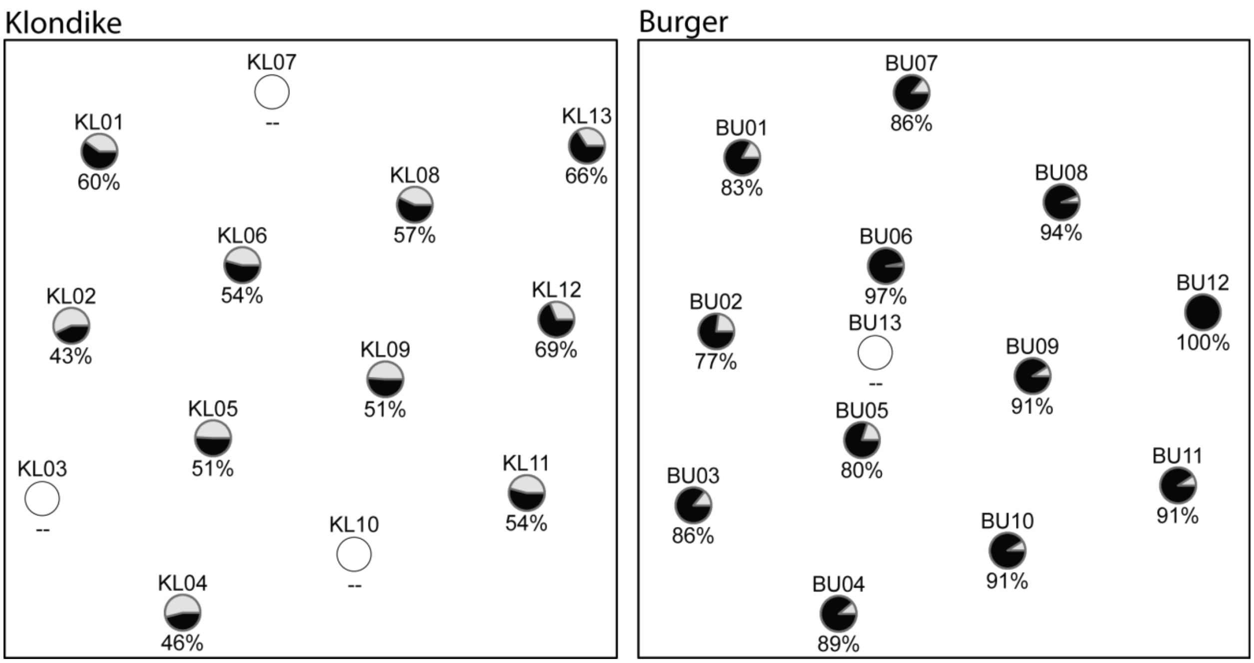

Figure 15. The daily presence of bowhead whale sounds at each MARU site in the Klondike and Burger arrays, where the proportion of black in a circle for a MARU represents the percentage of the total deployment days during which bowhead whale sounds were detected on that MARU by any one of three sampling methods. Empty circles represent MARUs that yielded no data due to unit failure or greatly reduced sensitivity.

Variation in daily levels of bowhead acoustic activity

The three methods used for assessing daily presence of bowhead whale sounds also provide relative indices of overall levels of bowhead acoustic activity from day to day and between arrays. Method 1 yielded a total number of bowhead sounds counted across each array for 120 sampled minutes (the first 5 minutes of each hour) each day. In Method 1, all arrivals of a given sound on different channels were counted, so the actual count value overestimates the number of individual whale sounds that occurred. Method 2 yielded a number of minutes in which bowhead sounds were detected, out of a total of 180 minutes (three randomly selected hours) sampled each day. In Method 2, only the first arrival of each sound was counted. Method 3 yielded a total number of bowhead sounds detected by the automated detector (including multiple arrivals of the same sound) and verified by a human analyst.

Figure 16 and Figure 17 show relative daily levels of bowhead acoustic activity as indicated by these three methods for the Klondike and Burger arrays, respectively. These data show two periods of heightened levels of bowhead acoustic activity, the first during 21-26 September, and the second during 5 – 13 October (Klondike) or 14 October (Burger). Although some bowhead sounds occur on all days in Burger and most (89%) days in Klondike, these periods stand out as periods of much higher rates of activity.

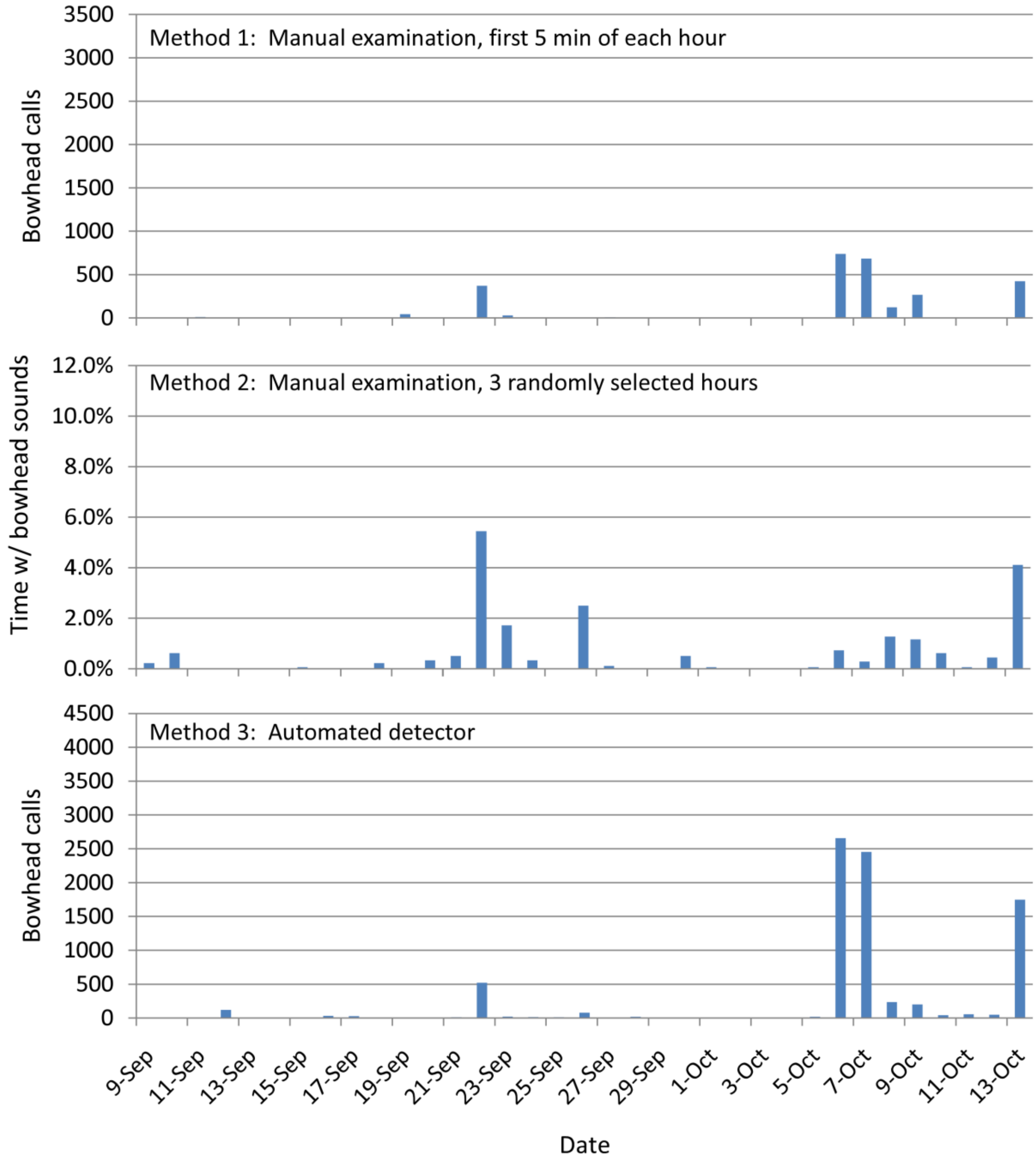

Figure 16. Relative daily levels of bowhead acoustic activity in the Klondike array, as assessed by three different methods. In Methods 1 and 3, multiple arrivals of a single sound on different recorders are included in the counts. In Method 2, the plotted value is the percentage of channel-minutes in which bowhead sounds were present.

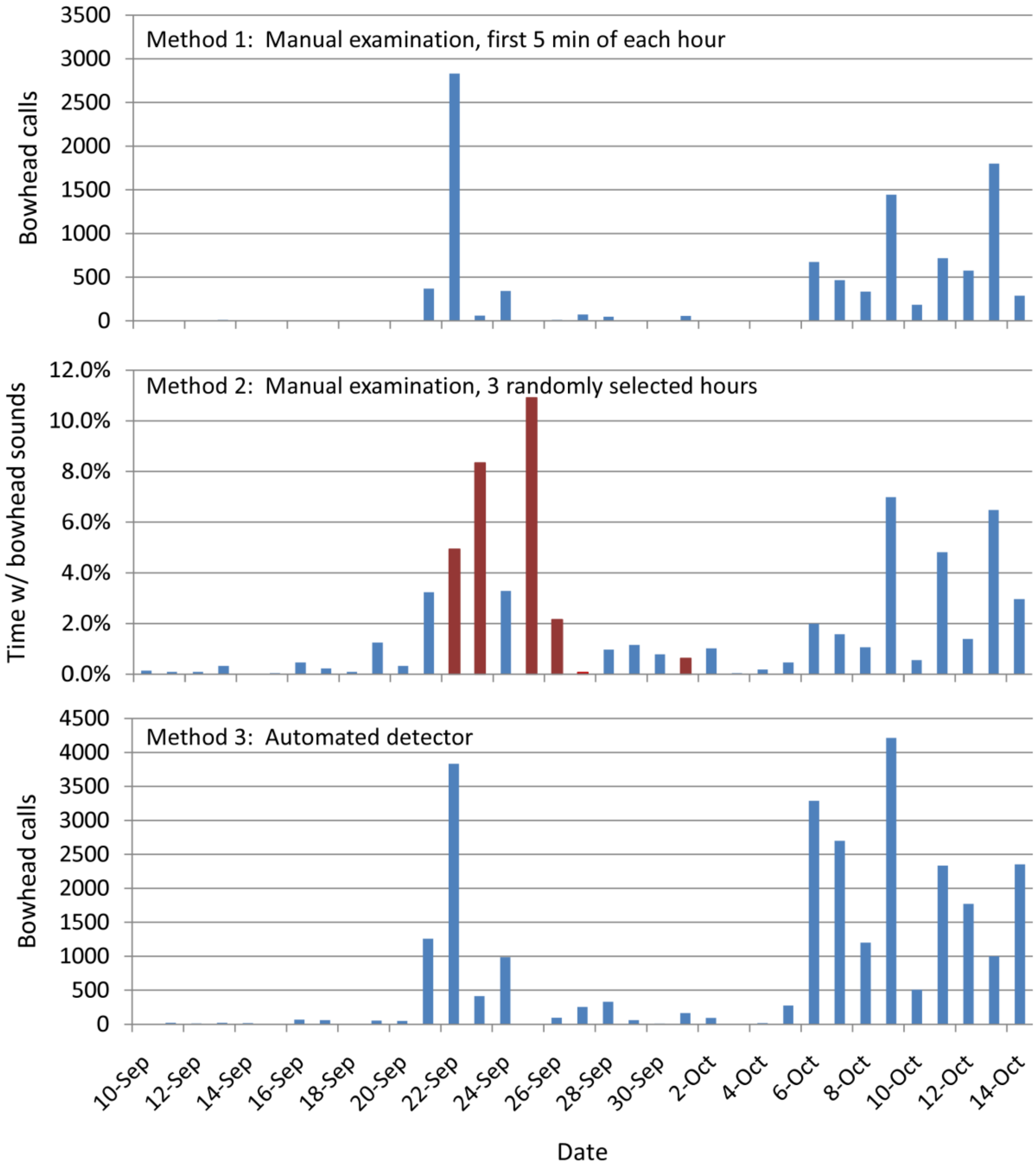

Figure 17. Relative daily levels of bowhead acoustic activity in the Burger array, as assessed by three different methods. In Methods 1 and 3, multiple arrivals of a single sound on different recorders are included in the counts. In Method 2, the plotted value is the percentage of channel-minutes in which bowhead sounds were present. Red bars in the plot for Method 2 indicate days when high levels of biological sound (from any combination of bowheads, belugas, walrus, and bearded seals) impaired the analyst's ability to reliably determine whether or not bowhead sounds were present in each minute. For those days, the true percentage of minutes with bowhead sounds is likely to be higher than the value plotted.

Daily bowhead acoustic activity levels as assessed by all three methods were significantly higher in the Burger array than in the Klondike array (Wilcoxon signed rank test, paired by day: $p = 0.0008$ for Method 1, $p < 0.0001$ for Methods 2 and 3).

Objective 2: Daily presence of beluga whale sounds

Beluga sounds were detected on the Klondike array on 8 (23%) of the 35 complete monitoring days, and on the Burger array on 3 (9%) of the 35 complete monitoring days (Figure 18). In the Klondike array, beluga sounds were detected on all operational recorders, with the greatest daily presence (5 days, 14%) at sites KL01 in the northwest corner of the array, and KL06 in the middle of the array (Figure 19). In the Burger array, beluga sounds were detected on 5 of the 12 operational recorders (Figure 19).

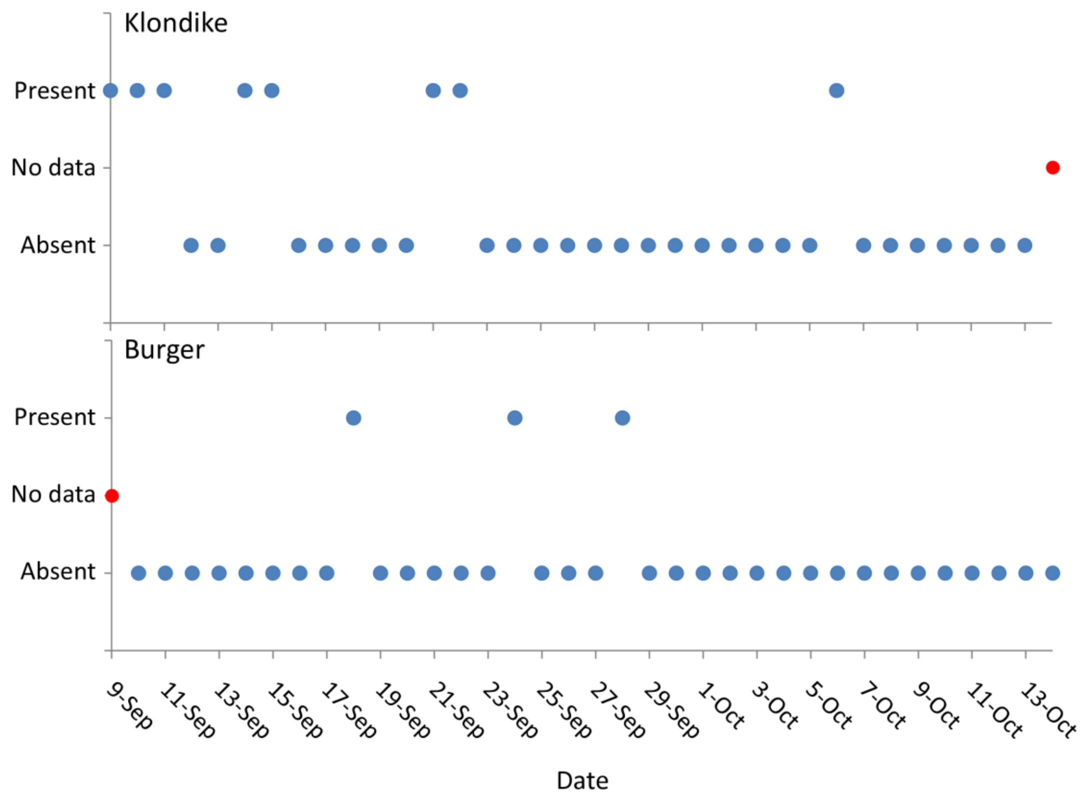

Figure 18. Daily presence of beluga whale sounds as detected by two sampling methods in the Klondike and Burger arrays.

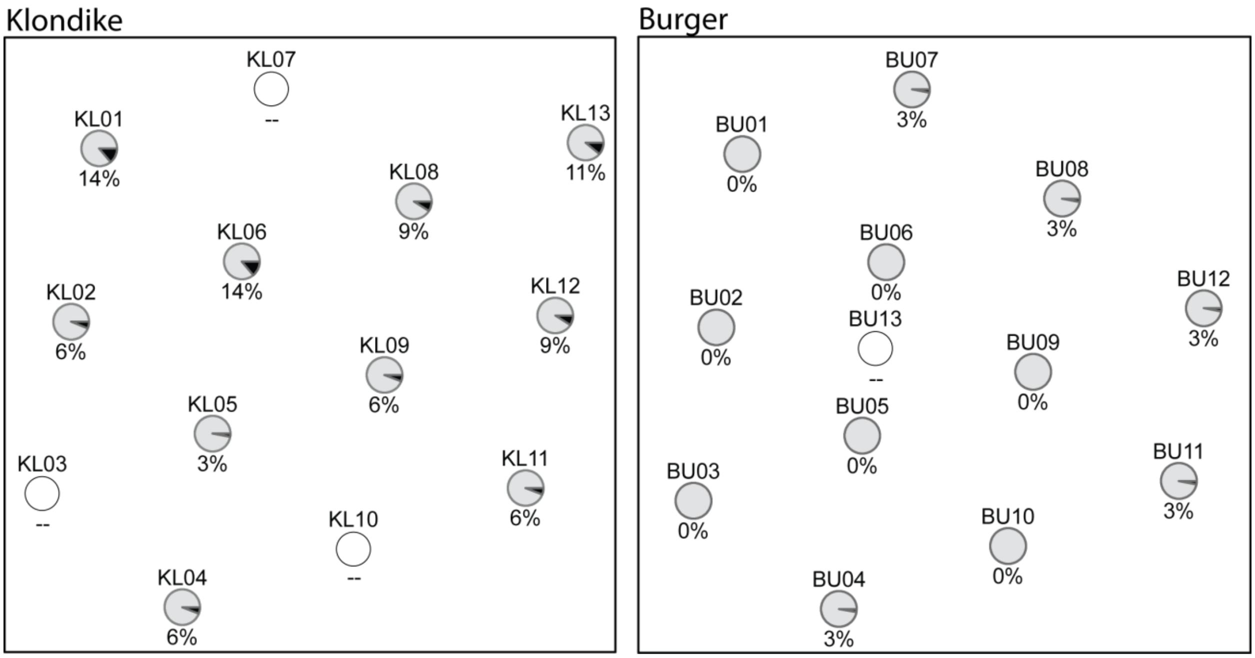

Figure 19. The daily presence of beluga whale sounds at each MARU site in the Klondike and Burger arrays, where the proportion of black in a circle for a MARU represents the percentage of total deployment days during which beluga whale sounds were detected on that MARU by either of two sampling methods. Empty circles represent MARUs that yielded no data due to unit failure or greatly reduced sensitivity.

Objective 3: Daily presence of walrus sounds

Daily presence

Walrus sounds were detected on 19 out of 35 complete monitoring days (54%) on the Klondike array and on 26 days out of 35 complete monitoring days (74%) on the Burger array (Figure 20). In the Klondike array, walrus sounds were detected on all 10 operational recorders, with the greatest daily presence (11 days, 31%) at site KL02, located on the western edge of the array. At all other sites, walrus sounds were detected on 4 to 9 days (9% to 26%) (Figure 21). In the Burger array, walrus sounds were detected on all 12 operational recorders, with the greatest daily presence (18 days, 51%) was at sites BU01, at the northwest corner of the array, and BU09, in the middle of the array. Elsewhere in the Burger array, walrus sounds were detected on 10 to 17 days (29% to 49%, Figure 21).

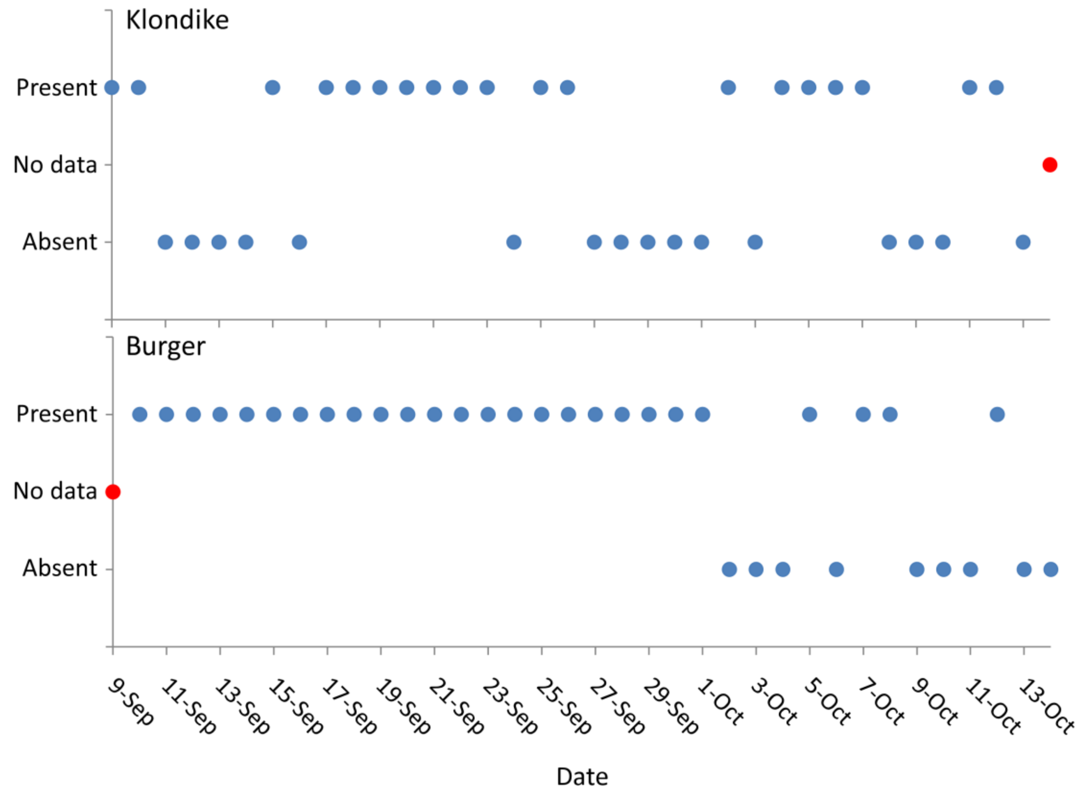

Figure 20. Daily presence of walrus sounds as detected by two sampling methods in the Klondike and Burger arrays.

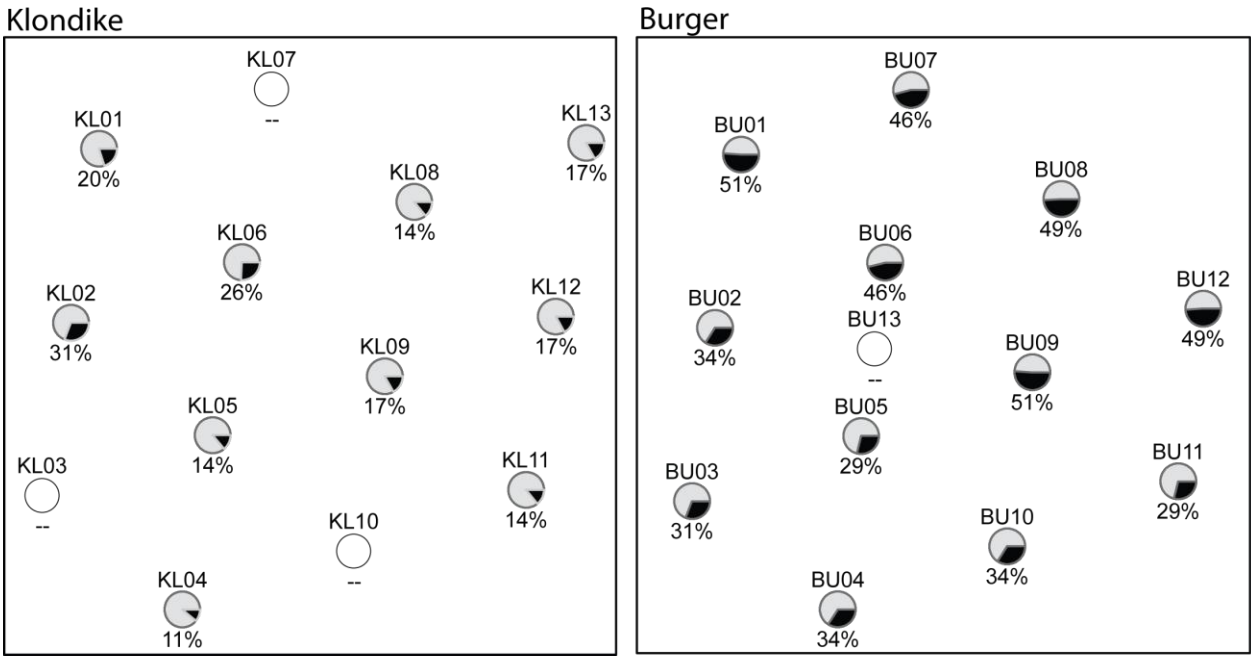

Figure 21. The daily presence of walrus whale sounds at each MARU site in the Klondike and Burger arrays, where the proportion of black in a circle for a MARU represents the percentage of total deployment days during which walrus whale sounds were detected on that MARU by either of two sampling methods. Empty circles represent MARUs that yielded no data due to unit failure or greatly reduced sensitivity.

Variation in daily levels of walrus acoustic activity

Figure 22 shows relative daily level of walrus acoustic activity in the Klondike and Burger arrays as indicated by the percentage of channel-minutes in three randomly selected hours each day that contained first arrivals of one or more walrus sounds.[5] In the Klondike array, most walrus sounds were detected during the period 20 – 26 September. Overall levels of walrus acoustic activity were significantly higher in Burger than in Klondike (Wilcoxon signed rank test, paired by day: $p < 0.0001$), with detections occurring at varying levels over a longer period, from 10 September (the first day of the complete array deployment) through 5 October.

[5] Figure 22 only shows data from days when walrus sounds occurred during the three randomly selected hours. In the Klondike array, this method found walrus sounds on 11 of the 19 days that walrus sounds were found by any method; in the Burger array, this method found walrus sounds on 22 of the 26 on which walrus sounds were detected.

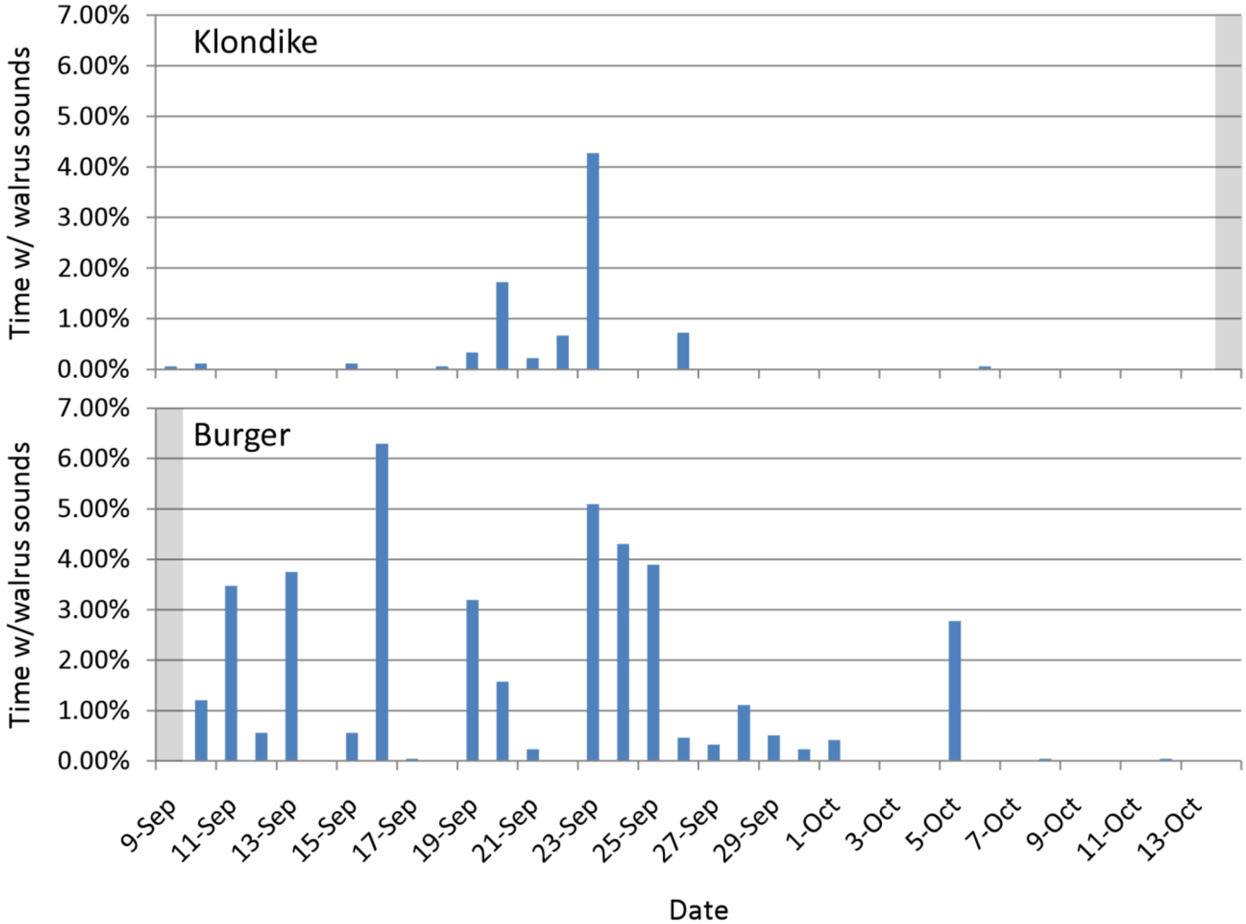

Figure 22. Percentage of channel-minutes sampled each day in which walrus sounds were detected on the Klondike and Burger arrays. These data are based on examination of 180 minutes each day, in three randomly selected 1-h blocks. This sample yielded 1800 channel-minutes in the Klondike array each day (=180 minutes x 10 channels), and 2160 channel-minutes in the Burger array (=180 minutes x 12 channels).

Objective 4: Locations and estimated numbers of vocalizing bowhead whales

Locations of vocalizing bowhead whales

Bowhead whale locations are presented here for those hours that were identified as containing bowhead sounds based on examination of the first 5 minutes of the hour. The number of locatable calls detected in each day varied between 0 and 1610 for the Burger array, and between 0 and 385 for the Klondike array (Table 1, Figure 23). Locatable sounds are sounds that are received on three or more channels. In both arrays, most locatable calls occurred in the latter portion of the survey period, beginning on 7 October.

Table 1. Number of locatable bowhead whale calls each day in the Klondike and Burger arrays. Values in parentheses are for partial days of data (<24 h of data for one or more MARUs). Dashes (‘--‘) indicate days before deployment or after retrieval of an array.

Date	Burger	Klondike	Date	Burger	Klondike
9-Sep	--	0	28-Sep	19	0
10-Sep	0	0	29-Sep	3	0
11-Sep	0	0	30-Sep	2	0
12-Sep	0	0	1-Oct	33	0
13-Sep	0	0	2-Oct	0	0
14-Sep	0	0	3-Oct	0	0
15-Sep	0	0	4-Oct	0	0
16-Sep	0	0	5-Oct	0	0
17-Sep	0	0	6-Oct	372	166
18-Sep	0	0	7-Oct	253	385
19-Sep	0	0	8-Oct	0	45
20-Sep	0	0	9-Oct	575	206
21-Sep	125	0	10-Oct	82	0
22-Sep	698	106	11-Oct	382	0
23-Sep	46	1	12-Oct	174	14
24-Sep	116	0	13-Oct	1610	183
25-Sep	0	0	14-Oct	106	(3)
26-Sep	0	0	15-Oct	(732)	(0)
27-Sep	37	0	16-Oct	(138)	--

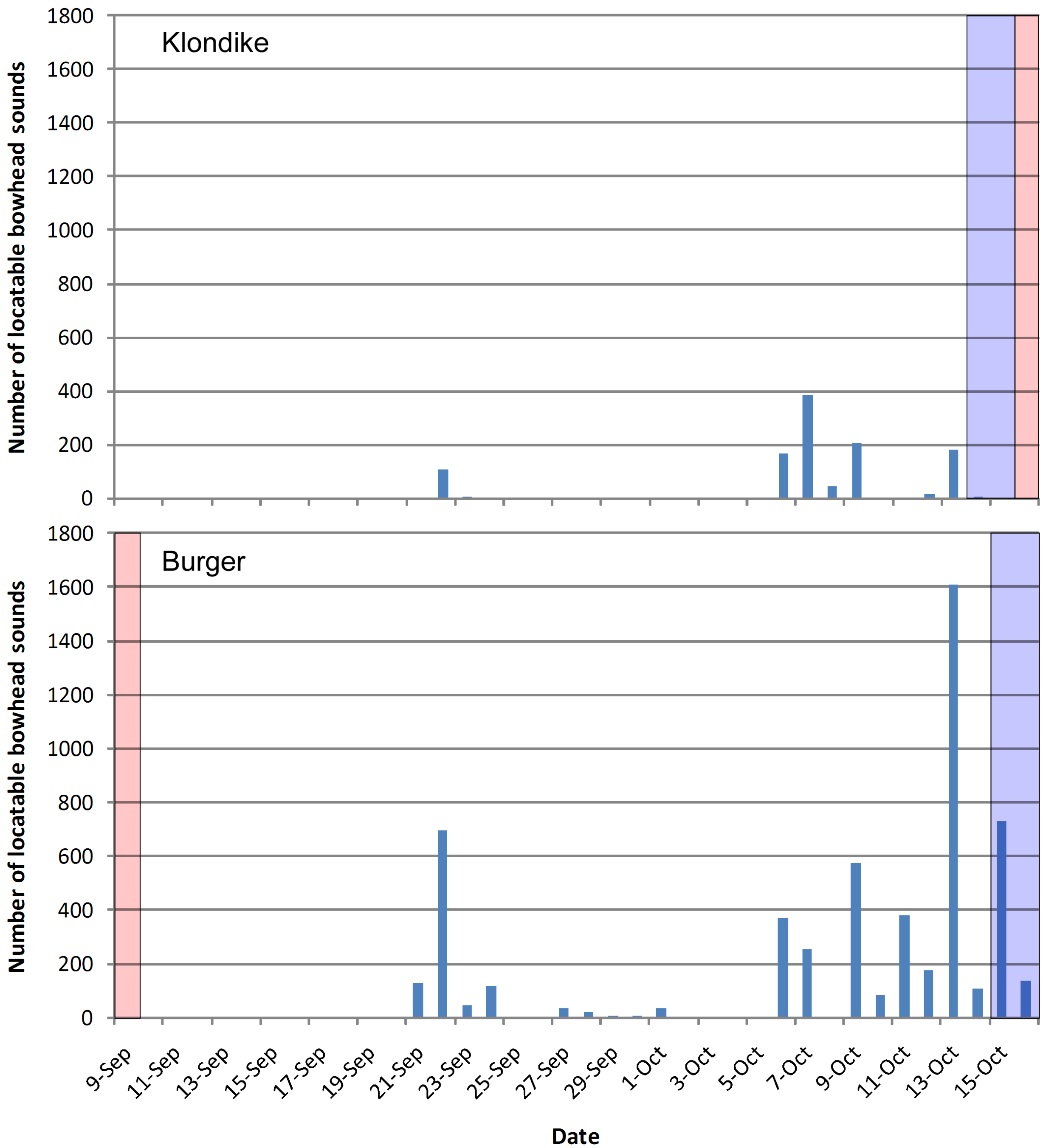

Figure 23. Number of locatable bowhead whale sounds each day for the Klondike and Burger arrays, based on examination of all hours in which bowhead sounds were detected in the first five minutes. Pink shaded areas indicate periods before deployment and after retrieval of each array. Blue shaded areas indicate days when only part of an array was deployed.

Figure 24 and Figure 25 show the estimated locations of all locatable bowhead whale sounds for the Klondike and Burger arrays, respectively. Locations tended to be concentrated primarily in the southwest quadrants of both arrays. Figure 26 shows locations from a single day in the Burger array.

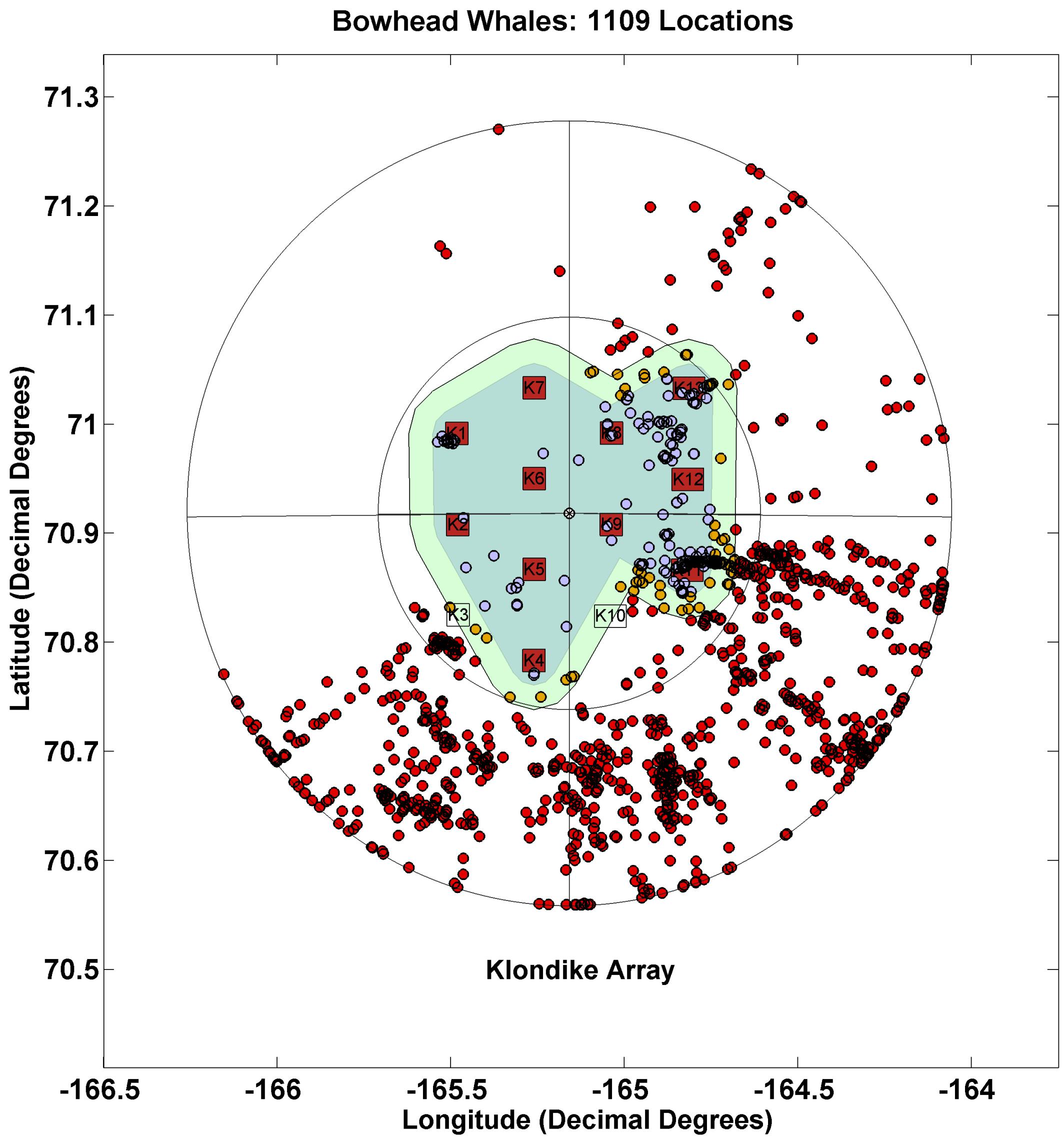

Figure 24. Estimated locations of all locatable bowhead whale sounds detected in the Klondike array over the entire survey period. Blue dots indicate “inside” locations within a perimeter 2.5 km beyond the MARU positions; orange dots indicate locations in an “edge” band 2.5 km wide; red dots indicate locations > 5 km outside the array perimeter. Concentric circles are at 20 and 40 km from the center of the array. The clustering of locations along the perimeter of the 40 km radius circle is an artifact of the location algorithm, which searched for call locations only out to 40 km. Thus, calls that originated at distances greater than 40 km would yield range estimates at the 40 km search limit.

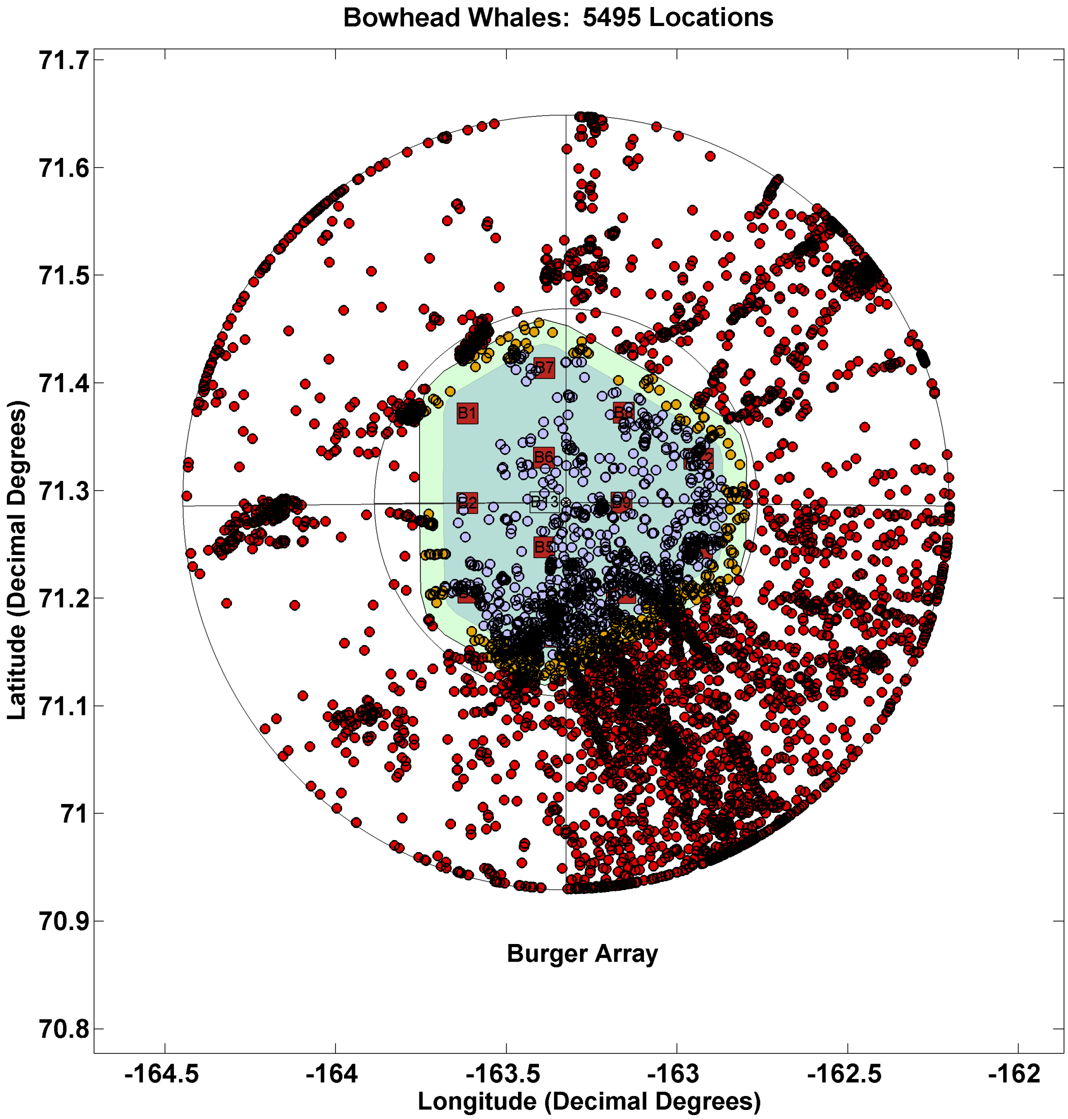

Figure 25. Estimated locations of all locatable bowhead whale sounds detected in the Burger array over the entire survey period. Blue dots indicate "inside" locations within a perimeter 2.5 km beyond the MARU positions; orange dots indicate locations in an "edge" band 2.5 km wide; red dots indicate locations > 5 km outside the array perimeter. Concentric circles are at 20 and 40 km from the center of the array. The clustering of locations along the perimeter of the 40 km radius circle is an artifact of the location algorithm, which searched for call locations only out to 40 km. Thus, calls that originated at distances greater than 40 km would yield range estimates at the 40 km search limit.

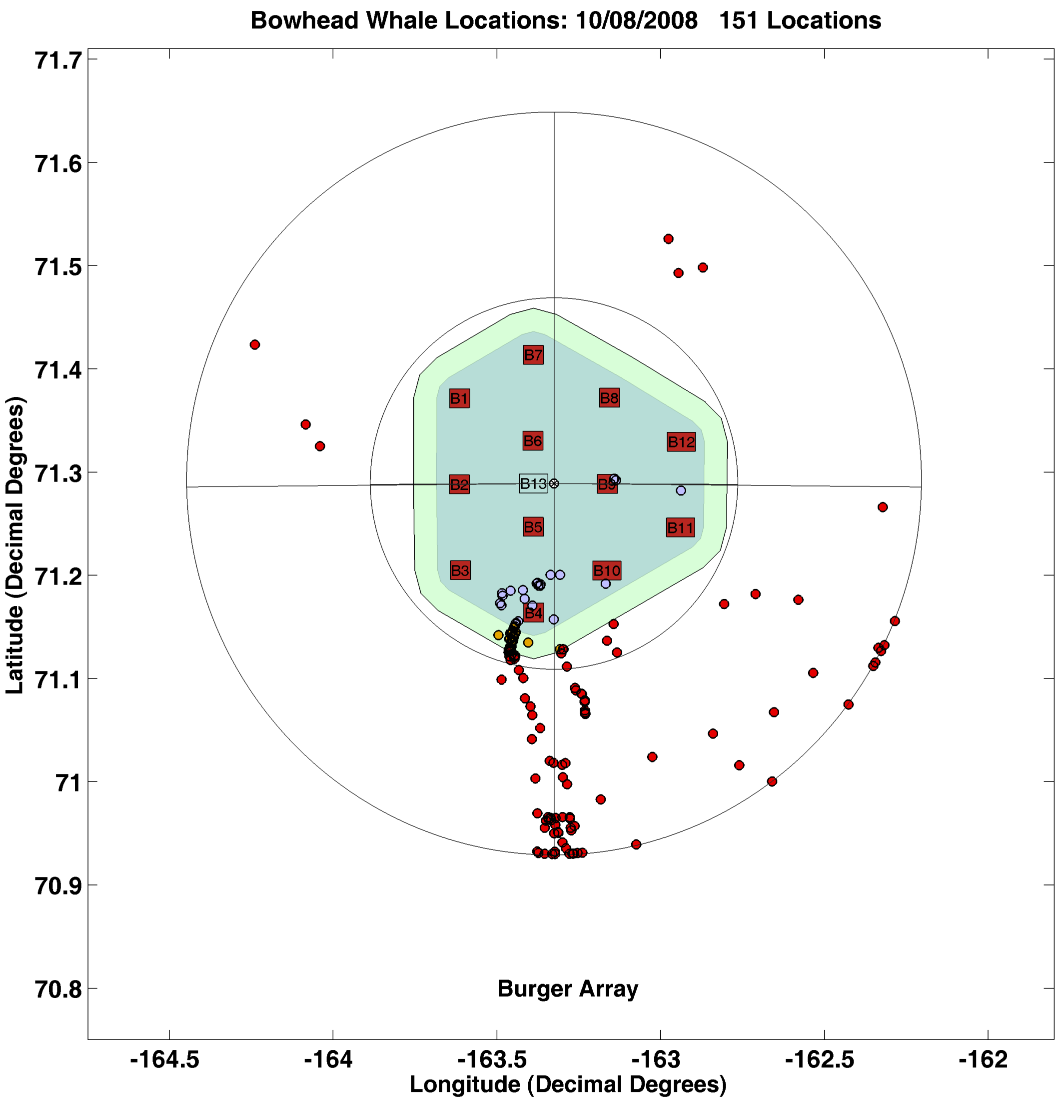

Figure 26. Estimated locations of all 151 locatable calls detected in the Burger array on 8 October 2008. Blue dots indicate "inside" locations within a perimeter 2.5 km beyond the MARU positions; orange dots indicate locations in an "edge" band 2.5 km wide; red dots indicate locations > 5 km outside the array perimeter. Concentric circles are at 20 and 40 km from the center of the array. The clustering of locations along the perimeter of the 40 km radius circle is an artifact of the location algorithm, which searched for call locations only out to 40 km. Thus, calls that originated at distances greater than 40 km would yield range estimates at the 40 km search limit.

Appendix A on the DVD accompanying this report contains plots of all estimated bowhead locations from each array for each day.

Estimated numbers of vocalizing bowhead whales

Figure 27 shows the daily estimated minimum number of vocalizing bowhead whales for the one hour each day with the highest number of confirmed bowhead sounds found by the bowhead sound detection algorithm. In the Klondike array, the estimated minimum number of whales on days when any bowheads were detected varied between 1 and 10; in Burger, the number varied between 1 and 17.

Similar to the pattern observed above for overall levels of bowhead acoustic activity, there appear to be two periods with greater numbers of whales present in both arrays, the first around 21 - 28 September and the second around 5 October to the end of each array's recording period. The minimum number of whales was higher in Burger than in Klondike on 21 out of 34 days when both arrays were operating. This trend was not statistically significant (Wilcoxon signed rank test, paired by day: $p = 0.0712$); however, if the estimated number of whales for Burger had exceeded that for Klondike on only one additional day (i.e., 22 days out of 34, rather than 21) the trend would have been significant.

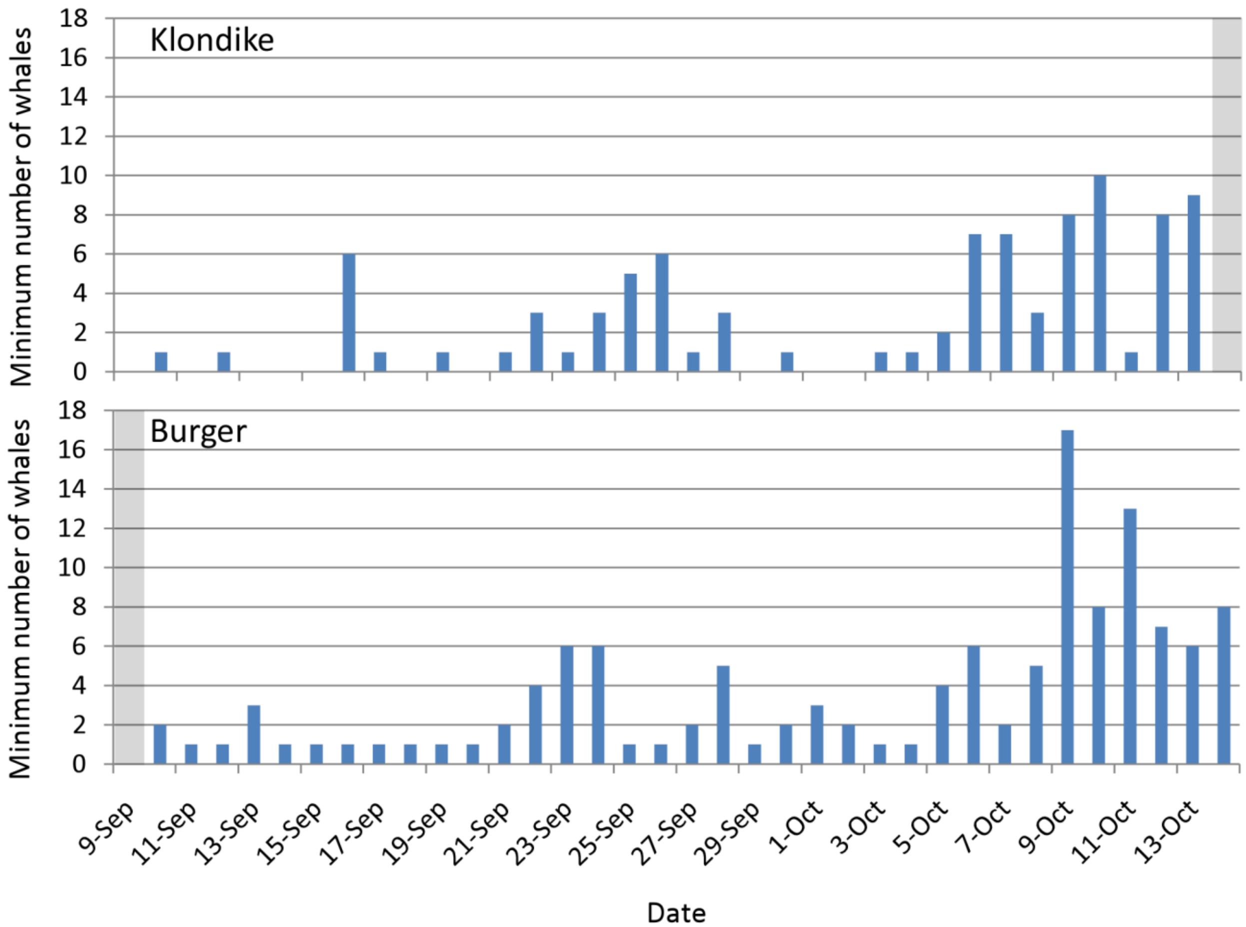

Figure 27. Estimated minimum number of vocalizing bowhead whales for the one hour each day that had the highest number of bowhead whale sounds found by the detector algorithm. Gray shaded areas indicate periods when the complete array was not recording.

Directional movement of bowhead whales

Figure 28 shows sample longitude-time and bearing-time plots from one day of recording in the Burger array, when clear east-to-west movement tracks are apparent. Such plots are provided for all estimated locations from each day of recording in both arrays in Appendix B on the DVD accompanying this report. On 2 of the 9 days with locatable sounds in the Klondike array, and 6 of the 17 days with locatable sounds in the Burger array, sequences of points occur along a line with constant slope over periods of one to several hours, suggesting sustained directional movement of a group calling repeatedly over that time interval. These apparent tracks were observed in the Klondike array on 6 and 7 October, and in the Burger array on 22 September, and 9, 11, 13, and 14 October. In all cases where apparent tracks occurred, they indicated westward movement.

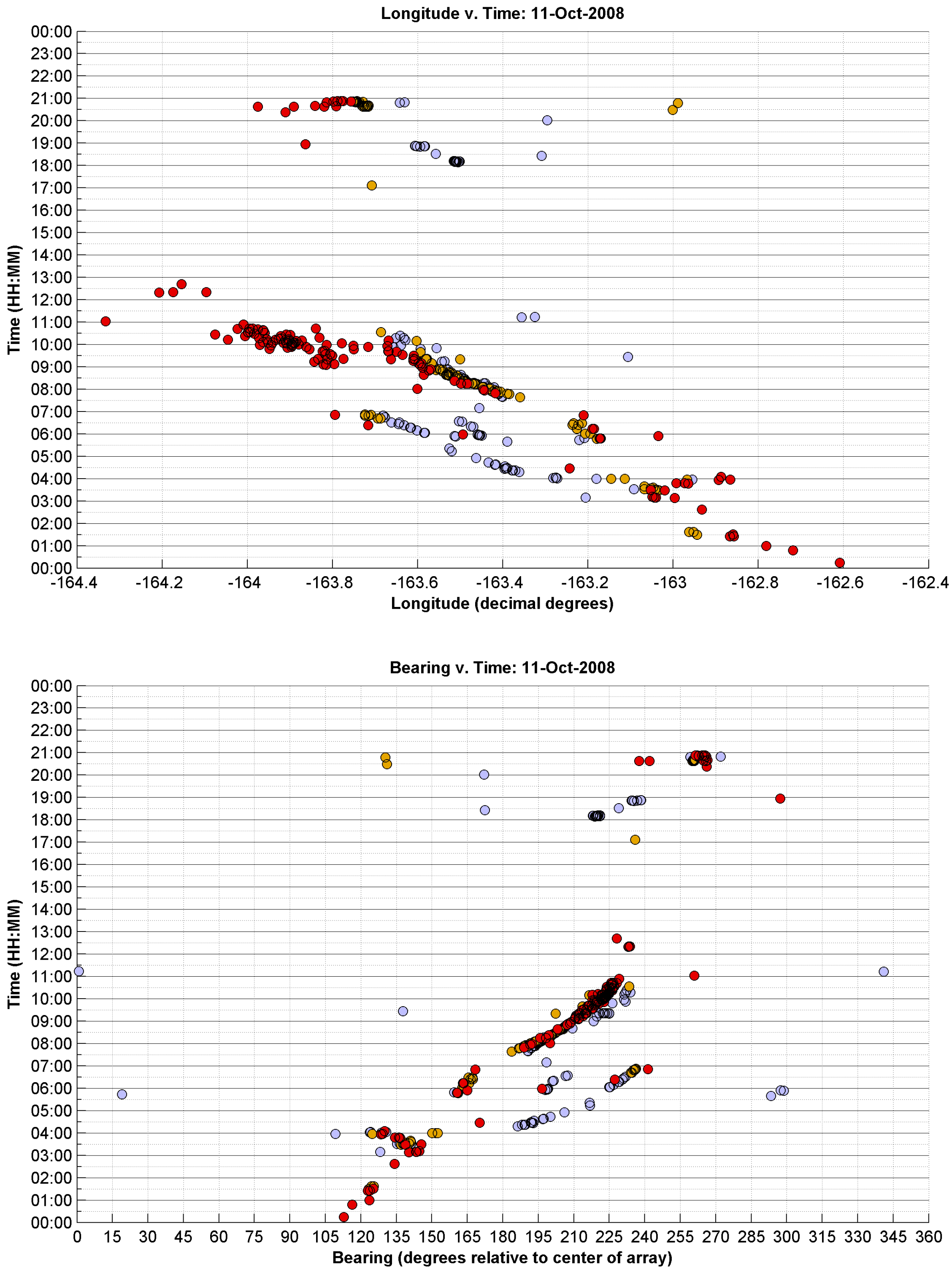

Figure 28. Longitude-time (top) and bearing-time (bottom) plots for estimated bowhead whale locations in the Burger array, 11 October 2008. Sequences of points along sloping lines indicate sequences of sounds likely to have been made by a single group of whales as it moved through the region monitored. The slopes of the lines over time (from bottom to top within each plot) indicate east-to-west movement.

Unidentified marine mammal sounds

Throughout the recordings from both arrays, many instances were found of a type of sound referred to here as "grunt sequences" (Figure 29). Grunt sequences consisted of a series of identical or nearly identical elements repeated at regular intervals, with an entire sequence typically lasting several minutes. Individual elements were typically 0.5 – 1 s in duration; the interval between the end of one element and the beginning of the next was typically 1.5 – 3 s. Each element consisted of typically 2-4 rapidly repeated grunt-like sounds, with peak energy typically in the 200 – 300 Hz range.

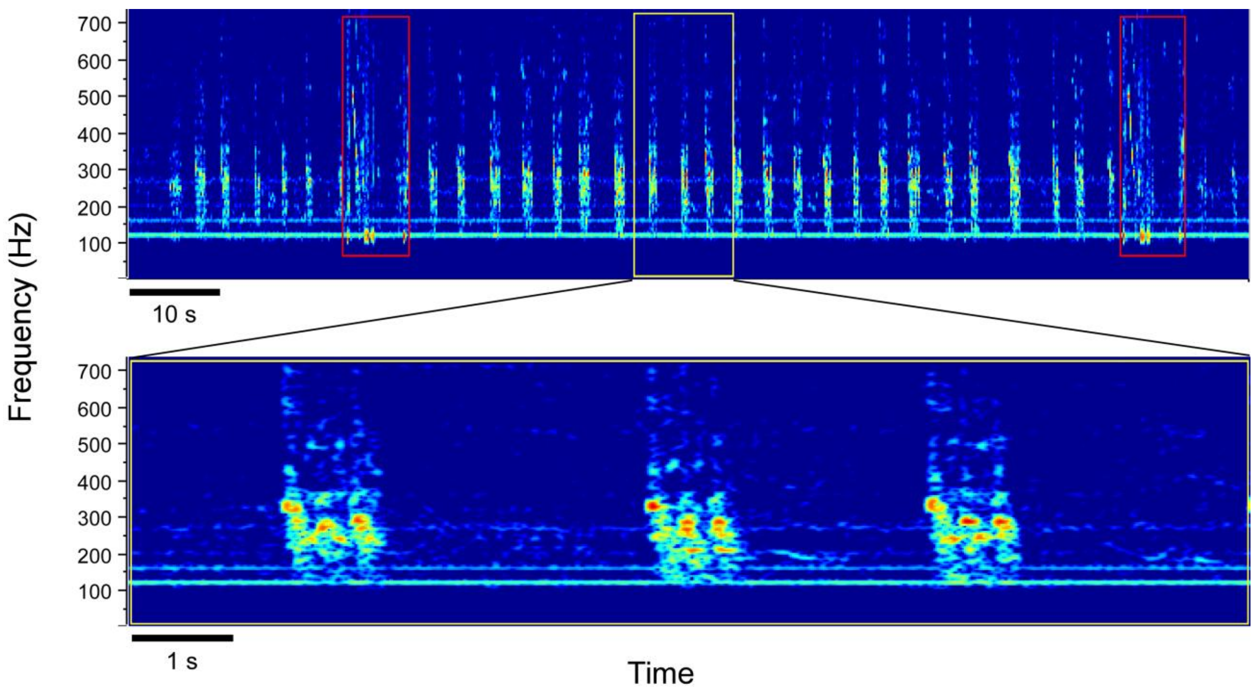

Figure 29. Example of a "grunt sequence," recorded on channel #5 of the Burger array starting at 02:02 on 13 October. These sounds are presumed to be from a marine mammal, possibly a bowhead whale. **Upper panel:** Approximately two minutes from a grunt sequence that lasted approximately five minutes. The sounds outlined in red are noise from the MARU's internal hard disk drive. **Lower panel:** A close-up of 11 seconds from the middle of the grunt sequence.

These grunt sequences are similar to "call sequences" recorded in the Canadian Beaufort in September 2004 (Blackwell et al. 2007) and attributed to bowhead whales. However, because the sounds reported by Blackwell et al. are unlike any previously known bowhead sounds, and because no visual observations accompanied the recordings, we consider the identification of bowheads as the source of these sounds as tentative. In the present study, many instances were found when a given grunt sequence was recorded across most channels of the array, implying a fairly high source level for the sound.

Figure 30 shows the daily relative rate of occurrence of grunt sequences in each array, as determined by manual examination of each minute in three randomly selected hours each day (Method 2 used for assessing presence of bowhead, beluga, and walrus sounds). Overall levels of grunt sequence occurrence were significantly higher in Burger than in Klondike (Wilcoxon signed rank test, paired by day: $p < 0.0001$).

Comparing Figure 30 to the Method 2 panels of Figure 16 and Figure 17 suggests that the periods of high levels of grunt activity do broadly tend to coincide with periods of high levels of bowhead activity. However, not all periods of elevated bowhead activity are matched by periods of high grunt activity. In particular, during the period from 6 October to the end of the deployments, when bowhead activity was relatively high on most days in both arrays, grunt sequences occurred very infrequently. Overall, there was no significant correlation between the number of minutes each day with bowhead sounds and the number of minutes with grunt sequences (Klondike array: Spearman's $rho = 0.1853$, $p = 0.2865$; Burger array: $rho = 0.1534$, $p = 0.3788$), based on the three randomly selected hours that were examined each day for minute-by-minute presence of each type of sound.

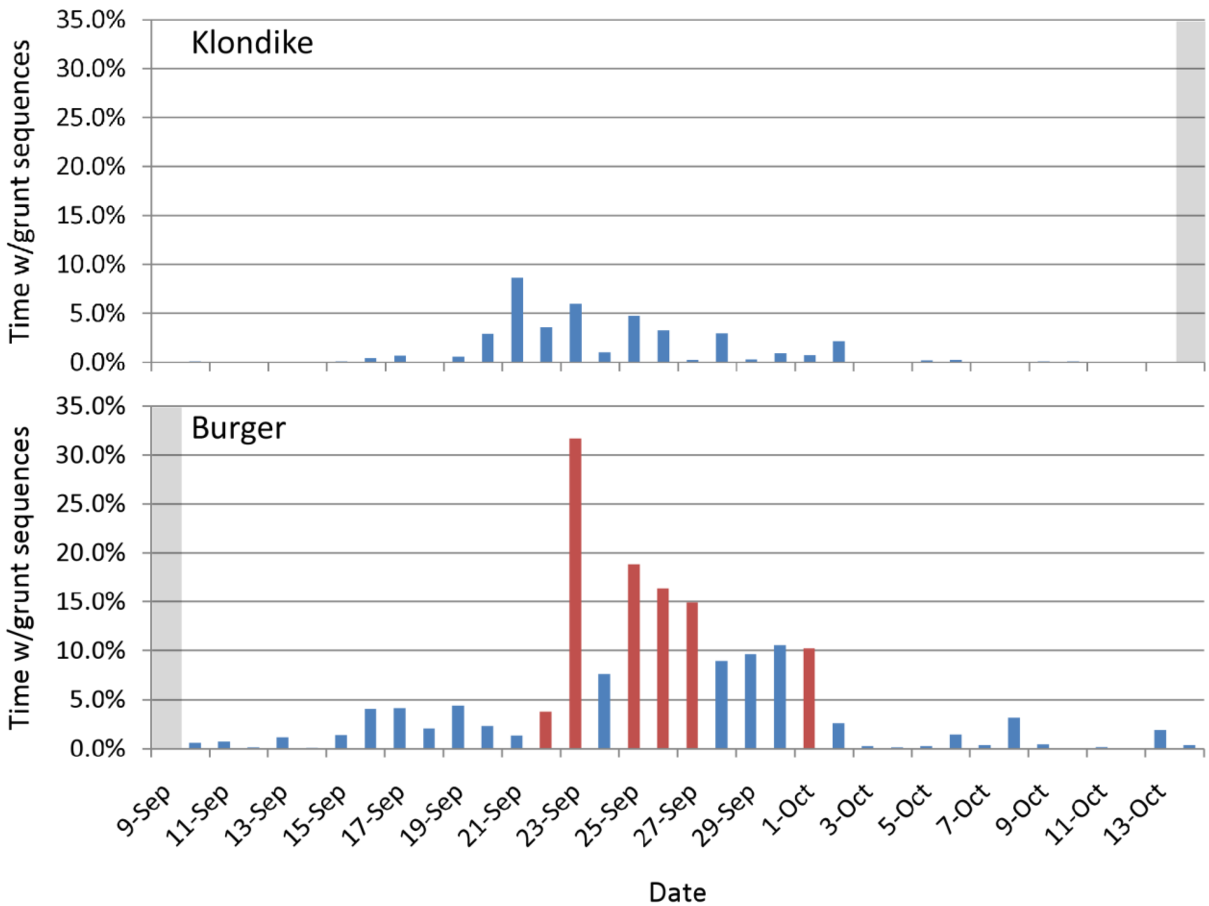

Figure 30. Percentage of channel-minutes sampled each day in which grunt sequences were detected on the Klondike and Burger arrays. These data are based on examination of 180 minutes each day, in three randomly selected 1-h blocks. These data are comparable to the Method 2 plots for bowhead activity in Figure 16 and Figure 17.

Objective 5: Noise conditions

Daily occurrence of seismic survey noise

In most cases, seismic survey sounds attributable to a seismic sparker were easily identified because of the regularity of the broadband events (Figure 12). Seismic sparker pulse events recorded on MARUs that were farther from the survey vessel often showed evidence frequency dispersion and time dilation from multi-modal propagation as indicated by spectrographic signatures that were longer than the original pulses, and that exhibited distinctive frequency banding patterns (Figure 31). The transformation of sparker impulse events with original durations on the order of 0.1 sec into signals with acoustically salient features and lasting many seconds was observed on both Klondike and Burger arrays throughout periods when the seismic sparker was operating.

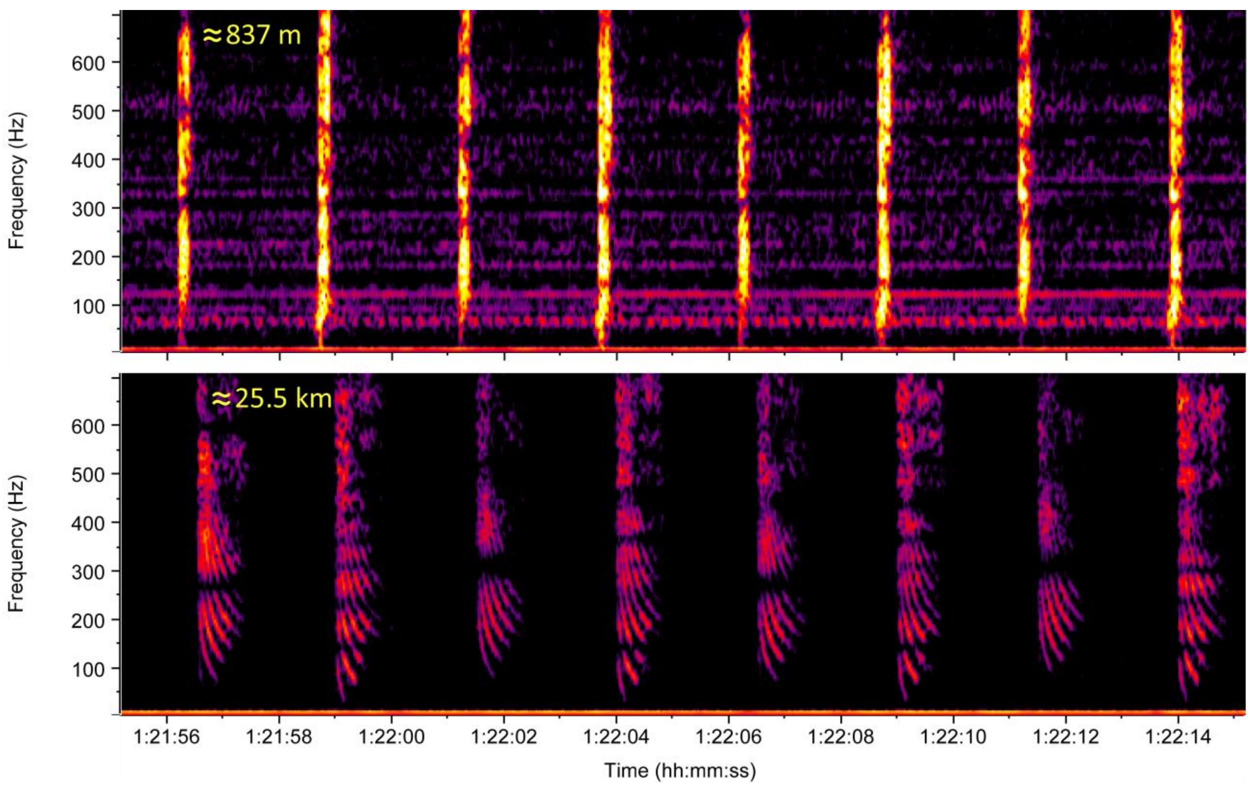

Figure 31. Seismic sparker events from one survey vessel recorded simultaneously on two channels of the Klondike array starting at approximately 01:22 on 13 September. The MARU represented by the upper channel (at site KL05) was approximately 837 m from the survey ship; the MARU represented by the lower channel (at site KL02) was approximately 25.5 km from the survey ship. The spectrographic signatures of the sparker events in the more distant recording show evidence of frequency dispersion and time dilation from multi-modal propagation, as indicated by the longer duration and banding patterns of each event.

The number of days in the Klondike array with seismic survey activity was four times greater than that in the Burger array. The Klondike array had 28 days (78% of survey days) with seismic activity compared to 7 days (19% of survey days) in the Burger array. Sixteen (16) out of the 28 days in Klondike had seismic activity for more than 12 hours of the day (Figure 32). Furthermore, the received intensity and clarity of seismic sparker sounds at the Klondike array were consistently greater than those received on the Burger array.

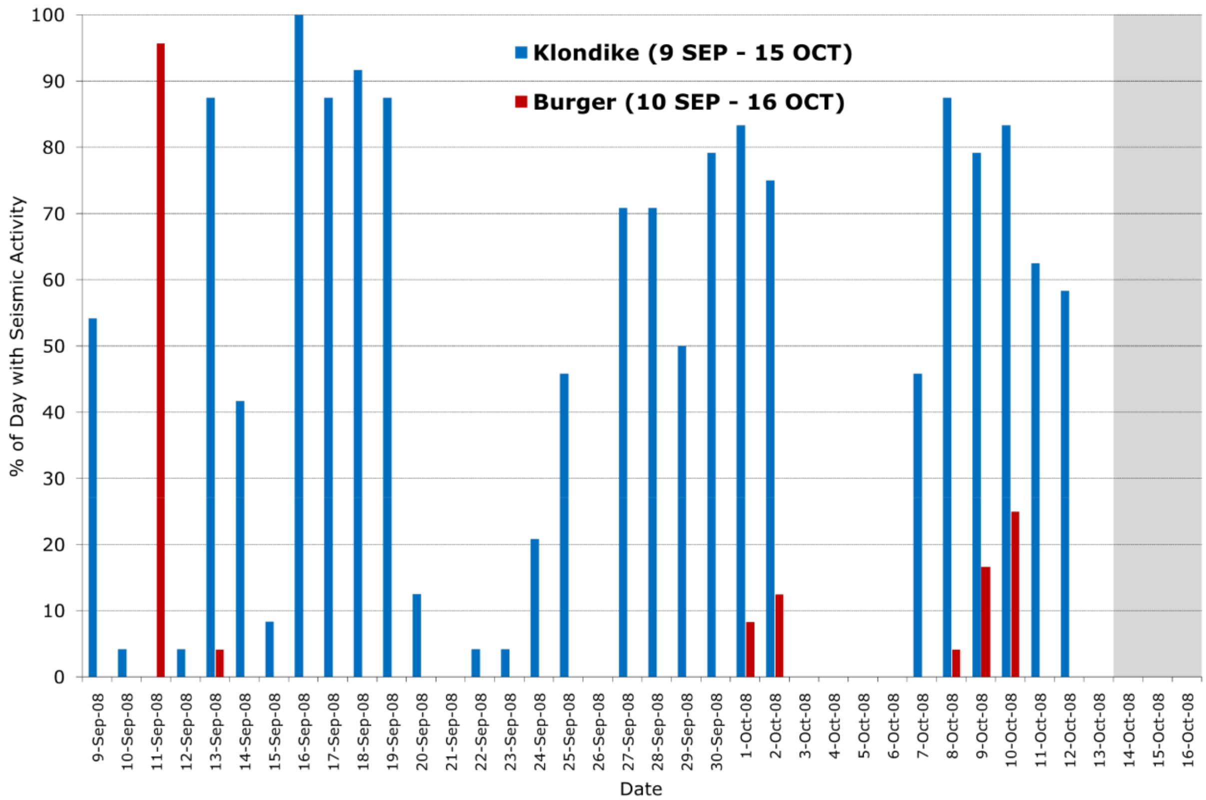

Figure 32. The daily occurrence of seismic survey activity in the Klondike (blue) and the Burger (red) arrays represented as the percentage of 5-minute samples in which seismic sounds were detected. Gray shading identifies days when only part of an array was operating: 14 October, partial day for Klondike; 15 October, partial day for both arrays; 16 October, partial day for Burger, no data from Klondike.

Noise measurements

Figure 33 shows an example of a 24-h spectrogram from one channel of the Klondike array on a day when a seismic survey vessel was operating within the array. Repeated periods of increasing and decreasing broadband noise alternating with shorter quiet periods are clearly visible as the seismic vessel transits back and forth on a series of east-west tracklines, alternately approaching and receding from the recorder, which was located near the western end of the tracklines. The shorter, quieter periods between the successive east-west transits represent periods when the ship was turning at the eastern or western end of a trackline.

Figure 34 shows the same data as Figure 33, but with received levels displayed for 1/3-octave (rather than 1 Hz) frequency bands.

Figure 35 shows the equivalent sound level (L_{eq}) in the nominal bowhead whale band (71 – 708 Hz) for the same data shown in Figure 33 and Figure 34. These values in effect show the sum of all the sound energy visible in the spectrograms in the bowhead band.

Figure 36 summarizes the distribution of spectrum-level noise measurements for the entire day shown in Figure 33 and Figure 34.

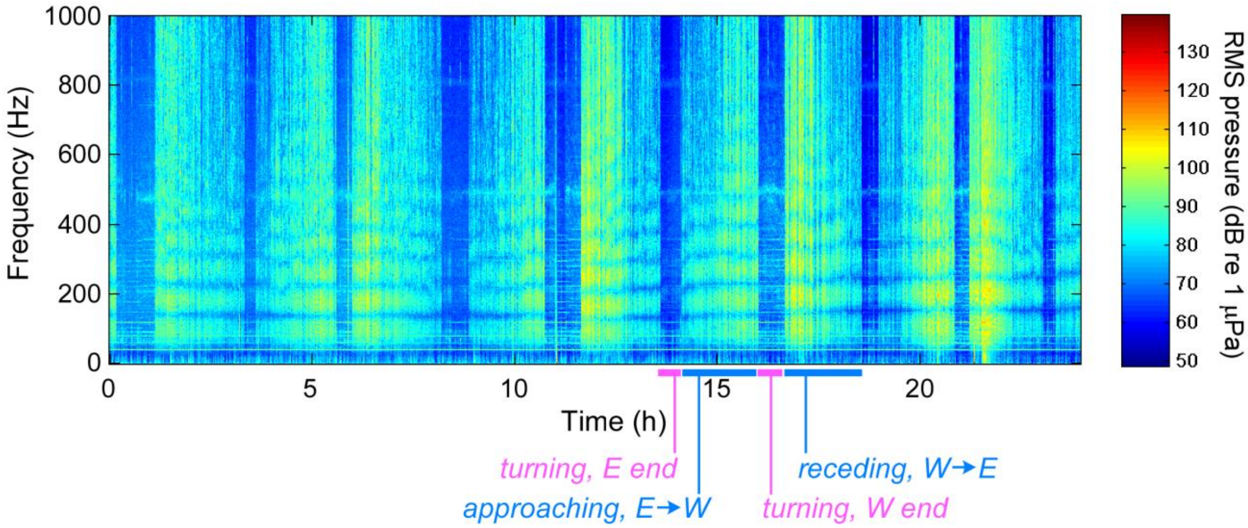

Figure 33. 24-h spectrogram for channel 6 of the Klondike array for one day when a seismic survey vessel was operating within the array (8 October 2008). Annotations below the plot indicate periods when the survey vessel was approaching or receding relative to the MARU, and periods when the ship was making a 180° turn at the east or west end of a trackline. While the ship is turning, pinging is suspended, and the principal source of noise is the ship's propulsion. Propulsion noise is higher at the western than eastern ends of the tracklines because the MARU is closer to the western edge of the area surveyed on this day.

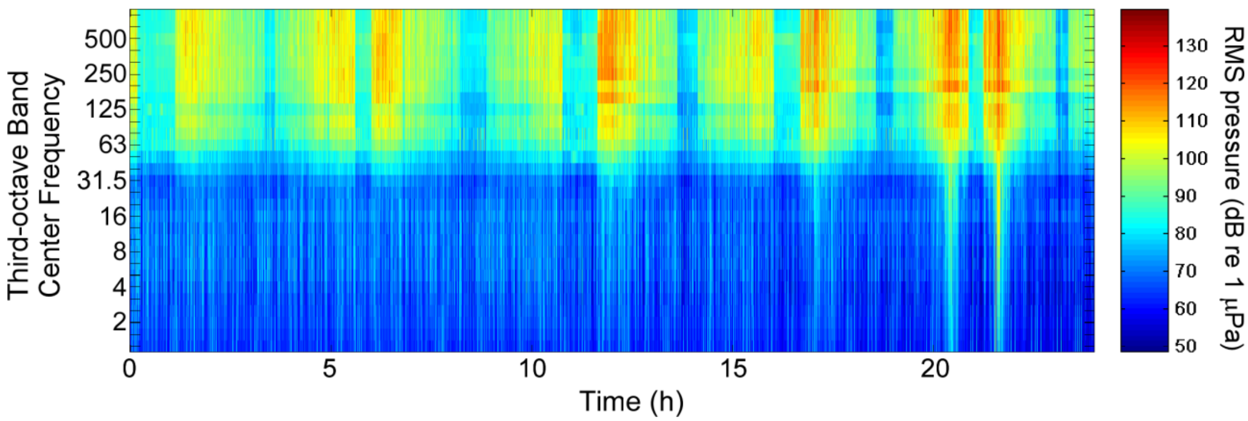

Figure 34. 24-h 1/3-octave band spectrogram for channel 6 of the Klondike array for 8 October 2008. Data are the same as those displayed in Figure 33, but here energy is aggregated into 1/3-octave frequency bands.

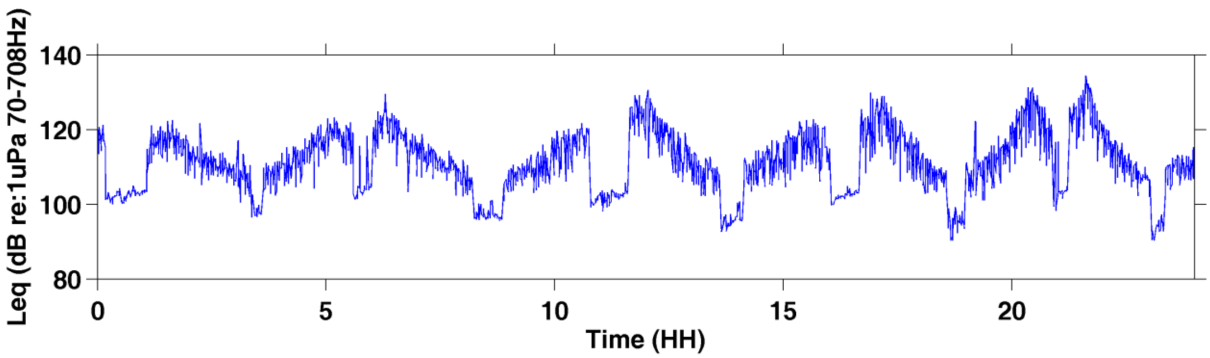

Figure 35. 24-h time-series of equivalent sound levels (L_{eq}) in the nominal bowhead whale band (71 – 708 Hz) over successive 1-second measurements for 8 October 2008. Sound data are the same as used in Figure 33 and Figure 34. The range between the recorder and the seismic survey vessel is unknown.

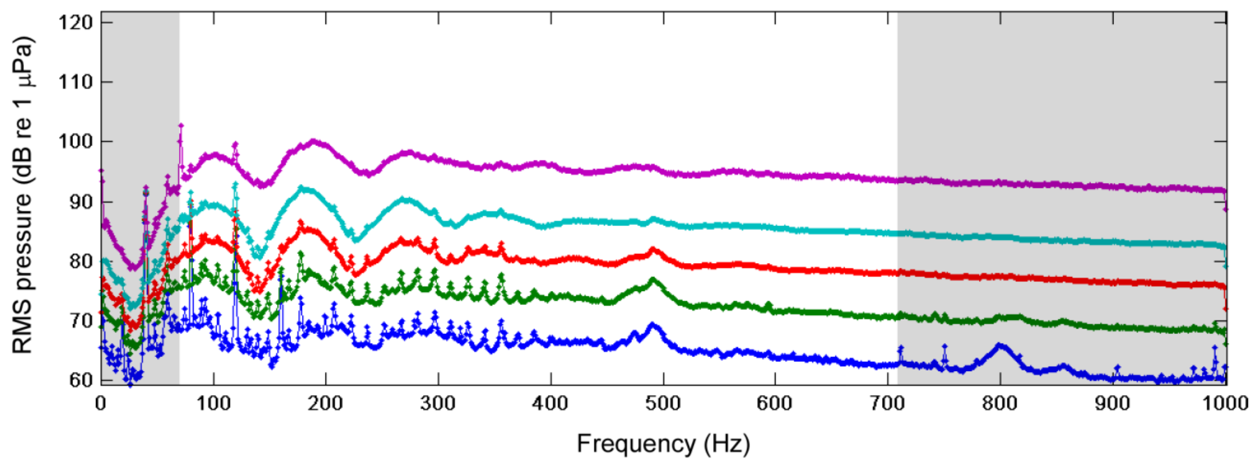

Figure 36. Spectrum-level noise measurement distribution for Klondike channel 6 for 8 October 2008. The five curves represent, from bottom to top, the 5th, 25th, 50th, 75th, and 95th percentile values for RMS pressure at each frequency for the 8437 noise samples (each over a period of 10.24 s) during the day. The unshaded frequency band is the nominal bowhead whale band, 71 – 708 Hz, for which noise level measurements are reported in other figures.

Appendix C on the DVD accompanying this report contains noise plots such as those in Figure 33, Figure 34, Figure 36, and Figure 37 for each day of recording from the Klondike and Burger arrays.

To assess the variability of noise in the bowhead whale band over a short time period, we can plot a histogram of the measurements from the individual noise samples (each 10.24 s long) for a period of 15 minutes, as shown in Figure 37. To visualize how this noise distribution varies over a longer time period, we plot a series of the histograms as a *noisegram* covering 24 hours (Figure 38). In the noisegram, each individual 15-minute histogram is represented by a column of cells in a rectangular matrix. Each row represents a particular power level value (corresponding to the horizontal axis in the histogram), and the cell's color represents the number of measurements at that power level for the given 15-minute sample (corresponding to the height of one bar in the histogram as exemplified in Figure 37).

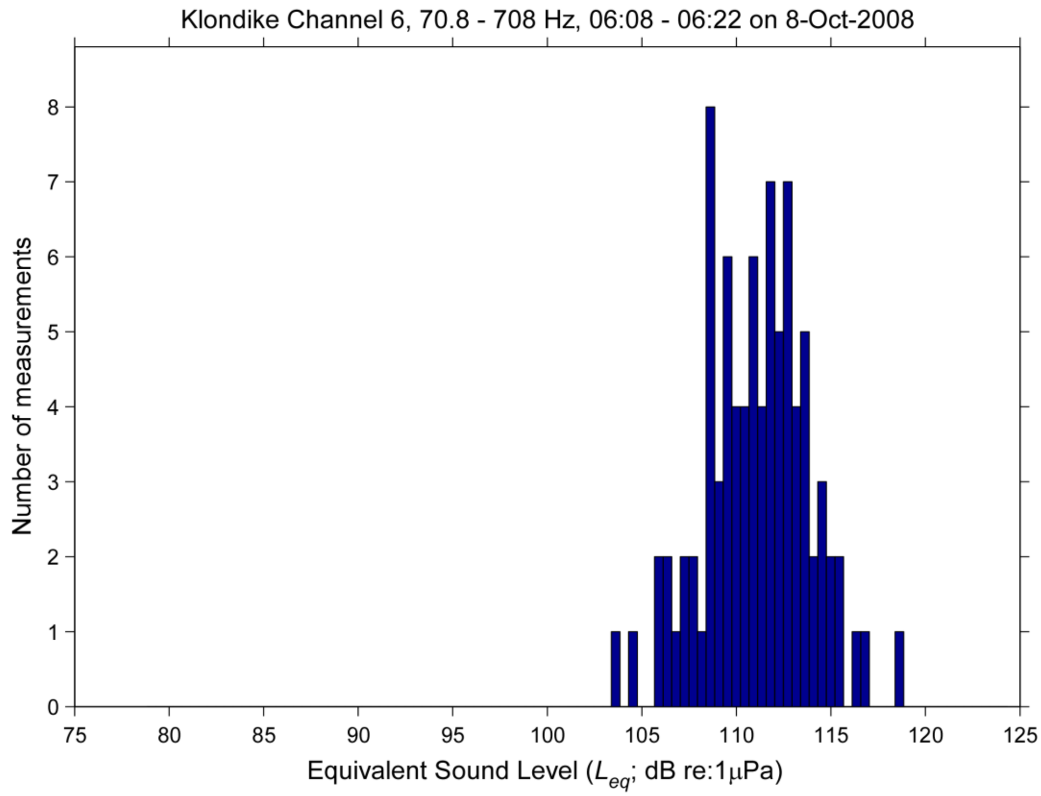

Figure 37. Distribution of noise measurements on channel 6 of the Klondike array over the 71 – 708 Hz band for one 15-minute period (centered at 06:15) on 8 October 2008. The 15-minute period contains 88 noise samples, each 10.24 s long.

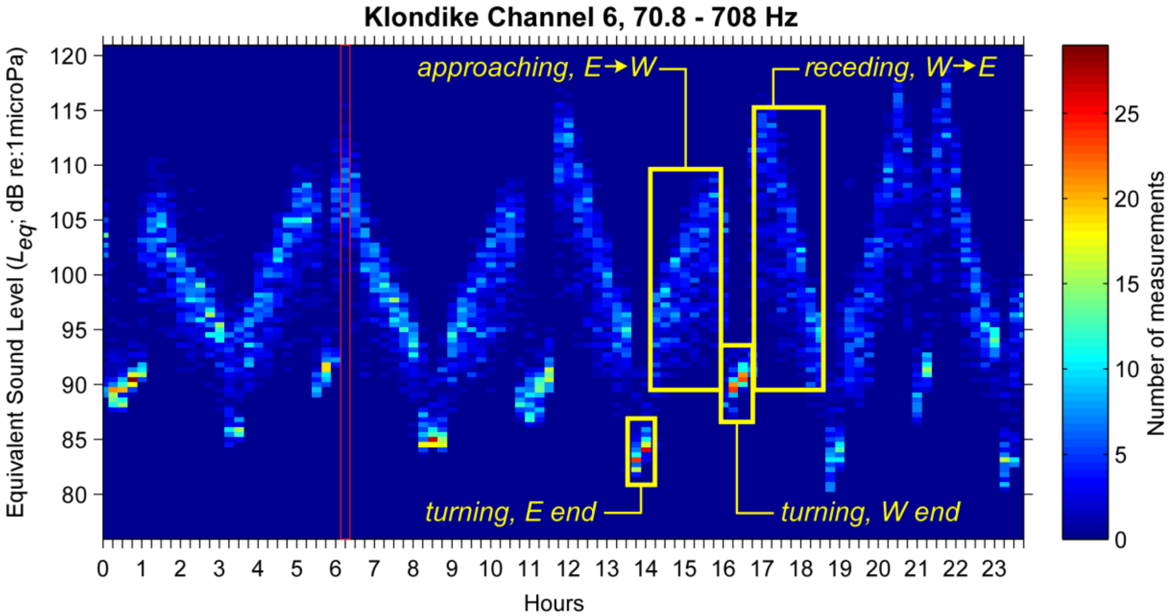

Figure 38. Noisegram representation showing the distribution of noise measurements for the 71 - 708 Hz frequency band for channel 6 of the Klondike array on 8 October 2008 while a seismic survey vessel was operating within the Klondike array area. Each time bin displays data from one 15-minute interval. The color of each cell indicates the number of 10-second measurements within the 15-minute bin equal to the L_{eq} value corresponding to the cell's vertical position. The time bin centered at 06:15, outlined in red, is the bin for which data are shown in Figure 37. Annotations indicate periods when the survey vessel was approaching or receding relative to the MARU, and periods when the ship was making a 180° turn at the east or west end of a trackline. While the ship is turning, seismic sparker activity is suspended, and the principal source of noise is the ship's propulsion. Propulsion noise is higher at the western than eastern ends of the tracklines because the MARU is closer to the western edge of the area surveyed, and therefore closer to the ship during its turns at the western ends of its tracklines.

Appendix D on the DVD accompanying this report contains noisegrams for each day of recording from the Klondike and Burger arrays.

Discussion

In considering the data presented here on acoustic detections of bowhead and beluga whales, and walruses, it is important to keep in mind that the proportion of individual animals vocalizing at any time is unknown. In the case of bowheads, this proportion appears from various studies to be highly variable (studies summarized by Blackwell et al. 2007). Although similar data are not available for belugas and walrus, their vocalization rates are likely to be highly variable as well. Thus we do not know what percentage of each species remains undetected by the acoustic arrays, or how much that percentage may vary from one time period to another.

Variation in daily levels of bowhead acoustic activity

The daily level of bowhead acoustic activity showed a consistent pattern of seasonal variation in both arrays, as assessed by three different methods (Figure 16, Figure 17). In both arrays, there were two pronounced periods of increased activity, one ≈21-25 September, and one ≈5-14 October. This is similar to the "pulses" of sounds associated with periods of increased migration traffic observed elsewhere during spring and fall migration (Clark et al. 1986b; Blackwell et al. 2007). Given that the Klondike and Burger arrays were 47 km apart at their closest points, the detection counts for the two arrays do not represent the same calls detected in the two arrays. Rather, the detection counts for the two arrays represent groups of calling animals within the respective detection areas of the two arrays. The fact that the two counts are statistically similar is not inconsistent with the hypothesis that on a daily basis the two arrays are detecting the same groups of animals, with call detection times shifted by the amount of time required for whales to swim from the Burger array area to the Klondike array area. Further analysis is required to address this hypothesis or other hypotheses related to bowhead whale movements and calling rates between the two arrays.

Spatial distribution of bowhead sounds

Overall rates of acoustic detections of bowhead whales were much higher in the vicinity of the Burger array than in and near Klondike. In both arrays, the majority of locatable sounds occurred to the southeast of the array center. The reason for these spatial patterns is unknown, but may reflect a preferred migratory path closer to shore. Bathymetric differences alone seem unlikely to account for these distributions, as the shelf area where these arrays are located is of nearly uniform depth, with only a few meters variation in depth across each array.

Minimum number of bowhead whales present per hour

The minimum number of whales recorded was estimated for the one hour each day with the highest level of bowhead acoustic activity as indicated by the number of confirmed bowhead sounds found by the detector algorithm. In the Klondike array, the maximum number of whales detected in a single hour was 10 (on 10 October). In the Burger array, the maximum number of whales detected in a single hour was 17 (9 October). The minimum estimated number of vocalizing bowheads yielded patterns that resembled those for overall bowhead activity level, in that higher numbers were typuifound in the Burger array than in the Klondike array (on 21 out of 34 days when both arrays were operating), and both arrays exhibited a seasonal pattern suggesting pulses of whales migrating through the area, as discussed above.

Whales that are vocalizing and swimming together in close proximity may be indistinguishable in the patterns of time-delays associated with their sounds, and therefore cannot be resolved as separate individuals by our whale counting algorithm. Thus, the daily minimum number of whales presented here represents the minimum number of groups tracked in an array with the conservative estimate of one whale per track.

In considering the data on minimum number of whales detected acoustically in any given period, as in other parts of this study, it should be borne in mind that the proportion of whales that call in any given period is unknown, and may change over time. Hence in any given period, there may be some unknown percentage of whales present in an area that remain completely undetected by acoustic methods.

Directional movement of bowhead whales

As already noted, in both the Klondike and Burger recordings, bowhead calls tend to occur in "pulses," with call rates gradually increasing over several days to a peak and then gradually falling off. This pattern would be consistent with most whales migrating westward through the area, and is similar to that observed in a four-year study of bowhead calling behavior during September in the vicinity of Northstar Island, near Prudhoe Bay, approximately 450 km west of Ajurak (Blackwell et al. 2007).

Whales that call frequently while moving steadily westward (or eastward) through the area should be readily recognized by a distinctive "signature" of points along a sloping lines in longitude-time and bearing-time plots like those shown in Figure 28 and Appendix B on the accompanying DVD. However, whales that either call infrequently or move on an irregular course do not yield any such distinctive signature.

Apparent tracks of individual calling whales swimming westward through the Klondike area were observed in longitude-time and bearing-time plots on 2 out of the 9 days when locatable calls occurred, and on 6 out of 17 days in Burger. No cases of eastward movement were observed. Most locatable calls could not be linked to any others on the basis of longitude-time plots.

Several factors preclude using these acoustic data to draw conclusions regarding the question of whether most whales are moving steadily through the monitoring area or lingering (e.g., to feed). First, as mentioned earlier, we do not know what percentage of bowheads are undetected by the acoustic array, or how much that percentage may vary from one time period to another (e.g., feeding whales are mostly silent and meandering in the area). Second, there are no known consistent associations between either the types or the rates of calls given by bowheads and specific activities such as feeding, traveling, or socializing (Würsig and Clark 1993). Thus, we cannot currently use call types or rates to infer what whales are doing at the time the calls were made. Third, we can make inferences about the movements of a whale group only if that group calls repeatedly and fairly frequently. Fourth, if a whale group does call frequently over a period of time, movement in a more or less straight line ("travelling" in the terminology of Würsig et al. 2002) will be easier to detect than more irregular patterns of movement, such as might be expected during other activities such as feeding.

This situation underscores the need for further research to better understand the associations between acoustic communication behaviors and types of activity and context.

Unidentified marine mammal sounds

"Grunt sequences" were widespread in the recordings from both arrays, with higher rates of occurrence in Burger than in Klondike. Most grunt sequences occurred in both arrays beween16 September and 2 October, which includes the first of the two periods of elevated bowhead acoustic activity. These sounds appear to be very similar to sounds recorded in September 2004 in the Canadian Beaufort Sea (Blackwell et al. 2007), and are unlike any sounds previously associated with bowhead whales. Although Blackwell et al. (2007) attributed the sounds to bowheads, this identification is a presumption that we presently regard as speculative. The fact that these sounds are commonly recorded over many channels of an array implies a high source level, which in turn suggests a large animal as the source, rather than, for example, a pinniped.

In addition to bowheads, gray and minke whales (*Eschrichtius robustus*, *Balaenoptera acutorostrata,* respectively) were observed in the Klondike-Burger area during visual surveys in 2008 (Brueggeman 2009), and may be candidate sources for these sounds. Grunt sequences do not match sounds known from any of these three species (bowhead: Ljungblad et al. 1982, Clark and Johnson 1984, Würsig and Clark 1993, Stafford et al. 2008, Delarue et al. 2009; minke: Mellinger et al. 2000, Gedamke et al. 2001, Rankin and Barlow 2005; gray: Cummings et al. 1968, Crane and Lashkari 1996). The fact that very similar sounds were recorded in the Canadian Beaufort Sea (Blackwell et al. 2007) might seem to suggest bowheads as the most likely of these three candidate species, since bowheads are common there, whereas gray and minke whales do not occur in that area or do so very rarely. However, in the Blackwell et al. study, grunt sequences were recorded in only one of four years, despite thousands of bowhead sounds being recorded in all years. In the present study, very few grunt sequences were recorded on either array during the period after 6 October, when bowhead acoustic activity was high, and when the estimated number of bowheads present peaked in both arrays (compare Figure 30 to Figure 16, Figure 17, and Figure 27). Overall, there was no correlation from day to day between the numbers of channel-minutes with grunt sequences and bowhead sounds. These data suggest either that these sounds come from a source other than bowheads, or that they are produced by bowheads in very specific seasonal or behavioral contexts that are different from those associated with known bowhead sound types. Further analyses of the fine-scale temporal pattern of occurrence of grunt sequences and bowhead sounds, and on the spatial distributions of grunt sequence locations, may shed further light on the source of these sounds.

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