PAMBuoy® Beluga Monitoring

Contract Report by SMRU, LLC and Marine Instruments Ltd

Real-time monitoring for beluga whales (*Delphinapterus leucas*) in the Eagle River, Alaska using a PAMBuoy® detection system

Project Name:	PAMBuoy® Beluga Real-Time Monitoring
Client:	U.S. Air Force, Joint Base Elmendorf-Richardson & State of Alaska, Dept. of Fish & Game (#IHP-13-005)
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Executive Summary

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The Army and Air Force teamed with the Alaska Department of Fish and Game (ADF&G) and the National Marine Mammal Laboratory (NMML) to investigate the use of real-time passive acoustic monitoring for belugas. SMRU Ltd, SMRU, LLC and Marine Instruments Ltd were contracted to conduct a trial of their PAMBuoy® system in Eagle River as part of a multi-year effort led by ADF&G and NMML to conduct applied passive acoustics research on Cook Inlet belugas (CIBA project).

A PAMBuoy® detection system was deployed in the mouth of the Eagle River, Alaska between 12 and 31 August 2012, close to the point at which the river flows out into Eagle Bay. The system was configured to detect both the echolocation clicks and the whistles of beluga whales (*Delphinapterus leucas*) known to be regular visitors to both the Bay and the River at that time of year.

The PAMBuoy® system utilizes a low power digital signal processing system to automatically detect certain types of sound and then sends that information in near real time over a wireless communications system to a remote base station.

The primary purpose of the deployment was to assess how effectively the system can detect beluga whales with the eventual aim of setting up a system which can automatically alert staff at the nearby Joint Base Elmendorf-Richardson (JBER) military base when animals approach or are in the river.

The system was effective at detecting both clicks and whistles during the trial period, successfully detecting all (100%) sightings from within the river and 430 out of all 432 (99.5%) recorded sightings at ranges varying from 10 to 1035m from both within and from outside the river. A negligible false alarm rate and high efficiency could be achieved by requiring multiple click detections within a short time window (e.g. 20 clicks in 10s). These results indicate that the system efficiency is more than adequate for the primary purpose of detecting whale presence within or close to the river.

When comparing individual detection events detected by the fully automatic system with those picked out by an experienced human operator, the automatic system was unable to perform as well as the human, successfully detecting only 75% of human detected events. However, these missed events were generally short, relatively quiet click trains which were often close in time to louder events, presumably from the same beluga encounter, which were successfully detected, thus not missing encounters. A recall of 98% with 98% precision was achieved using a 15 minute encounter interval.

A future long term monitoring program may require two PAMBuoy® systems, one deployed at the mouth of the river and one further upstream if there is a need to distinguish between whales in the bay, close to the river and whales in the river system itself. A second system was deployed outside the river mouth for a single day and the two systems operated simultaneously. Animals can clearly be detected on the system outside the river mouth, a short time before being detected in the river.

While the main PAMBuoy® system can be considered to be at a high level of "Technology Readiness" a long term monitoring installation would require some work to be put into the wireless communications system in order to transmit the signal all the way to the joint base and considerable investment may also be needed to develop an ice and debris proof mounting system for the hydrophone if monitoring is to take place for extended periods and during winter months.

Once information on costs and practicalities of long term hydrophone mounting and data transmission become available, the final decision as to hydrophone configuration and placement and operational alarm thresholds will require detailed discussions with the relevant representatives from the joint army and air force base and regulators before a final system can be specified.

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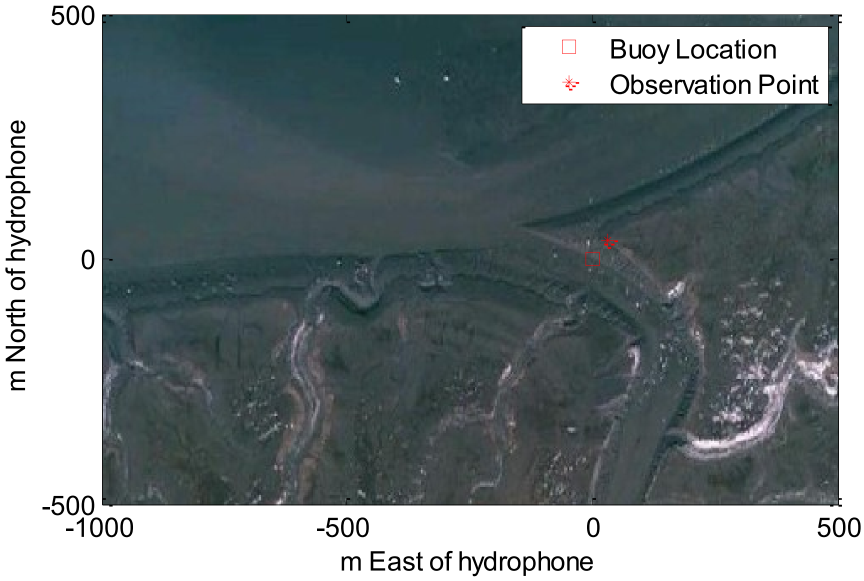

Figure 1. Aerial photograph of the region showing the location of the hydrophone and the visual observation point.

1 Introduction

The U.S. Army in Alaska conducts live fire exercises with indirect weapons systems (mortars and artillery) into a tidal estuary, the Eagle River Flats Impact Area located on the Air Force-managed Joint Base Elmendorf-Richardson (JBER). These exercises are currently conducted only during the winter but there is a need to expand operations into non-frozen months. Eagle River flows through the impact area to its saltwater terminus in Eagle Bay of Knik Arm of Cook Inlet. Eagle Bay and Eagle River are used seasonally by the endangered Cook Inlet beluga whale (*Delphinapterus leucas*). Belugas often enter Eagle River during the late summer and fall to feed on salmon, sometimes making forays as far as 2.5 river-miles upstream. In order to increase its ability to detect and respond to the presence of belugas in or near the river, the Army and Air Force teamed with the Alaska Department of Fish and Game (ADF&G) and the National Marine Mammal Laboratory (NMML) to investigate the use of real-time passive acoustic monitoring for belugas. SMRU Ltd, SMRU, LLC and Marine Instruments Ltd were contracted to conduct a trial of their PAMBuoy® system in Eagle River as part of a multi-year effort led by ADF&G and NMML to conduct applied passive acoustics research on Cook Inlet belugas (CIBA project).

A PAMBuoy® data collection system was deployed in the mouth of Eagle River (Figure 1) between 12 and 31 August 2012. The PAMBuoy® detectors were configured to detect both echolocation clicks and whistles from beluga whales know to be present in the area at that time of year.

Data were collected using Pelicase, shore based version of PAMBuoy® (Figure 2). This was connected to a hydrophone (Cetacean Research Technology C75) mounted in a frame sat in the mud of the river bank. The analogue signal from the hydrophone was routed up the river bank to the PAMBuoy® unit, on which data were processed in real time. Detection data (candidate clicks, whistles and background noise measurements) were then transmitted a short distance using a 2.4GHz wireless modem to a "Base Station" comprising a receiving modem and laptop computer. For convenience of operation through most of the trial, the base station was positioned a few meters from the PAMBuoy® box. For long term operational monitoring however, the intention would be to move the receiving base station to a location ideally within the Elmendorf-Richardson air base or maybe at the location where the gunnery is controlled.

While clearly effective at picking up beluga whales at the time of the trial, it was also evident that there were at least some false positive detections from other noise sources. The data have therefore been examined in more detail offline in order to develop an "Event" trigger which will fire only when it is certain that Beluga are in the river or close to the river mouth. The output of this event trigger has been compared to a human analysis of the acoustic data and also to the sightings of beluga logged by visual observers during the trials.

The Monitor base station use a modified version of the PAMGuard software (Gillespie et al., 2008; www.pamguard.org) to view data in real time. PAMGuard was also used to review files offline during data analysis. Figure 3 shows the click detector display during a typical beluga encounter. On the upper display panels, each click is represented by a coloured symbol on a plot of amplitude vs. time. Different classes of clicks are shown using different symbol types and colours. The only difference between the two upper displays is their duration, one being set to 15 minutes and the other to 10s. Both displays have the start time, to the detailed amplitude modulation of the received click amplitude in the right hand display is in fact the burst of clicks

Figure 2. The Pelicase based PAMBuoy® system used for the 2012 trials.

2 Methods

2.1 PAMBuoy® Detector Configuration

Prior to digitisation, signals were filtered with a 100Hz high pass filter. Digitisation was at a sample rate of 500kHz, giving a system bandwidth of 100Hz to 250kHz which covers the full range of beluga communication and echolocation. The data flow is shown in Figure 4. The click detector was configured to process the raw rata at its full 500kHz sample rate, however, for whistle detection, the signal is first decimated (down-sampled) to a rate of 50kHz prior to the system calculating the spectrogram of the data and searching for tonal vocalisations between 1kHz and 20kHz using the algorithms described in Gillespie et al., (in press).

On several days during the trial raw data were also recorded as wav files (the HFRec module in Figure 4), which were retrieved from the device at the end of each day. Detected clicks, whistles and background noise measurements were both stored on the device and also sent via a wireless network

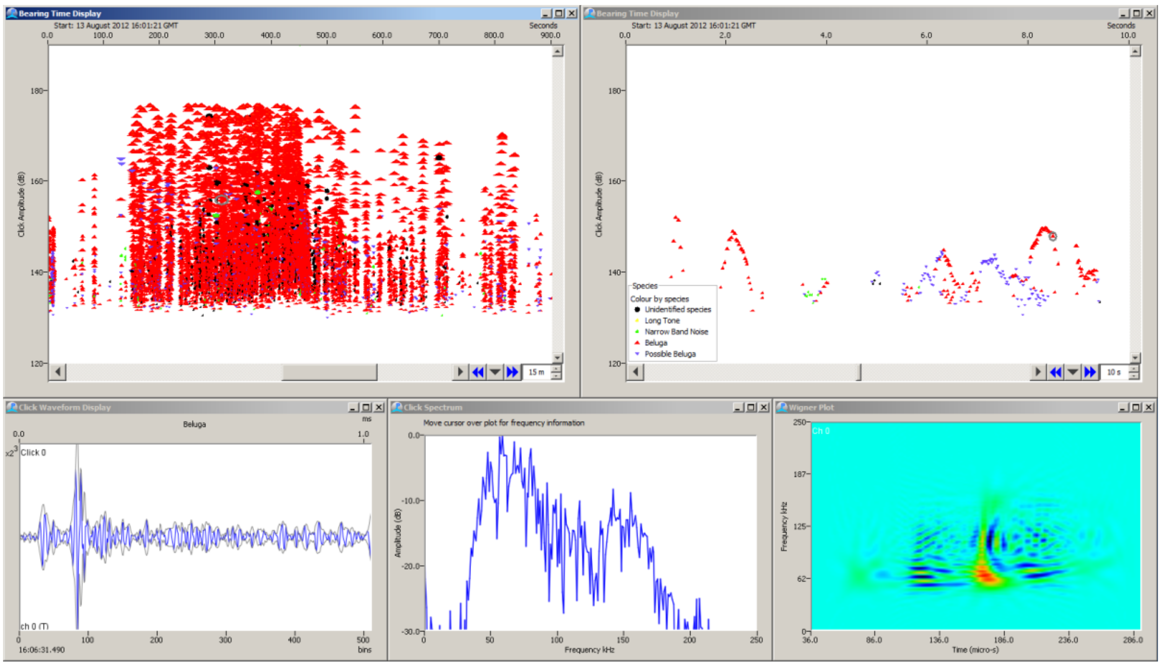

Figure 3. Click detector display during a Beluga encounter. The top two displays show the amplitude of single clicks over 15 minute and 10s intervals respectively. Clicks classified as Beluga are shown in red. The lower plots show the waveform, power spectrum and Wigner plot of single clicks selected from the upper displays using the mouse.

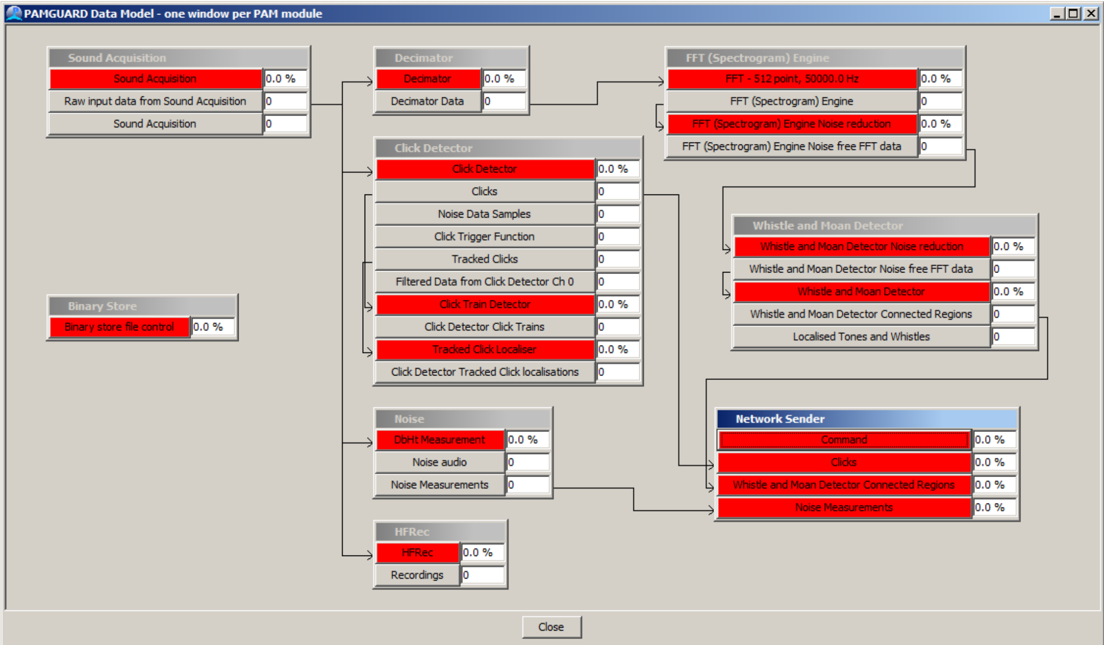

Figure 4. Detector configuration deployed on Cook Inlet PAMBuoy® modules in 2012

link for real time monitoring at the base station laptop.

The type of data stored or transmitted was different for each detector or background noise measurement. The click detector saves / sent a short waveform clip for each detected click (typically a few hundred samples). The whistle detector saved / sent the time frequency contour of each detected call and the background noise monitor output rms and peak signal levels in dB re.1μPa. Generally, the output of the whistle detector is very robust, it having been shown to have a recall of 79.6% for calls with a signal to noise ration of 10dB or over and a precision of 88%. While it is possible to perform additional classification of detected whistles in order to identify groups of whistles to species (Gillespie et al., in press), that is not necessary for this application where only a single species is present (harbour porpoises have rarely been sighted in the area, but this species do not emit whistles). The first stage of the click detector, on the other hand, generally runs at quite a high false alarm rate, generating many candidate clicks which do not originate from the target species. The number of false positive detections from the first stage of the click detection was therefore reduced by running an additional click classifier in order to pick out Beluga clicks with a higher degree of confidence.

Clicks were classified according to parameters extracted both from the waveform and from the power spectrum of each click. Click length was measured by first calculating the envelope (or outline) of the click waveform. This was then smoothed using a 5 point moving average filter. The maximum of the smoothed envelope was taken and points 6dB down from that maximum found on either side of the maximum position. The length was then taken as the time between those -6dB points. Clicks with a length greater than 50μs were rejected. From the power spectrum of each click, the energy was summed in two bands, the first from 30 to 120kHz and the second from 10 to 25kHz. Clicks were rejected if the energy in the 30-120kHz band did not exceed the energy in the other band by at least 10dB. Clicks were also required to have both a peak and a mean frequency somewhere between 25 and 80kHz. This upper limit is lower than the peak frequencies of some beluga echolocation clicks (Au et al., 1985; Castellote et al., 2012; Lammers and Castellote, 2009). It was however found that raising the upper limit to 120kHz allowed false triggers caused by a vessel's echo-sounder.

2.2 Human Post Processing

2.2.1 Clicks

Data files recovered from the buoy were reviewed by Dr. Ursula Verfuss of SMRU Ltd, a researcher with 20 years of acoustic analysis experience. Groups of clicks considered to be Beluga click trains were marked using the annotation tools in the PAMGuard click detector. These tools allow the user to assign groups of clicks to events. Event details, including start and end time, event type (as input by

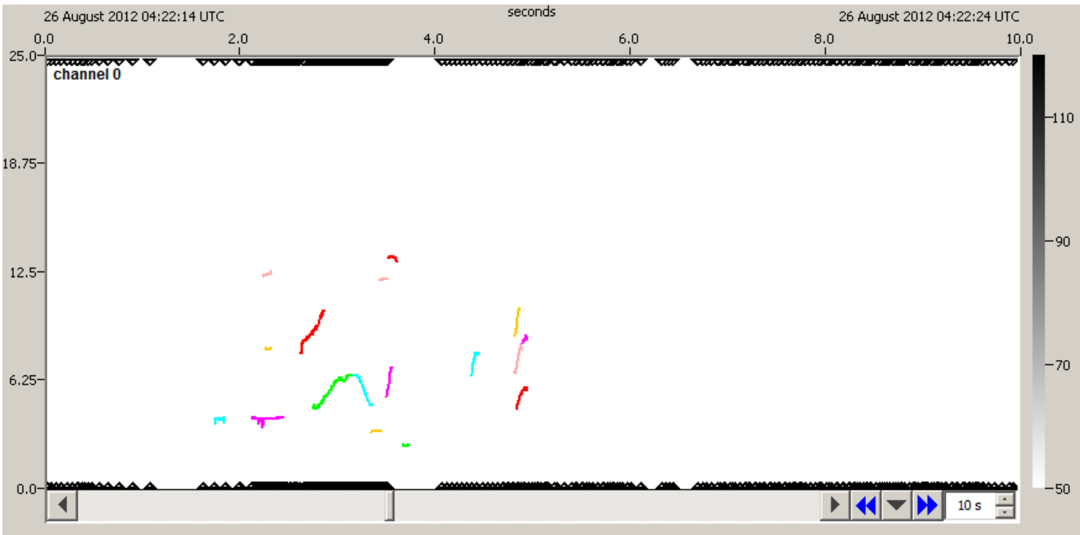

Figure 5. Screen shot of 10s of spectrogram data showing a number of whistle contours (coloured lines) and the times of echolocation clicks (black triangles).

the user) and the time of each click are written to a database. Groups of clicks were marked using the following criteria:

Beluga: groups of clicks clearly identifiable as Beluga, i.e. containing a majority of clicks which had passed the Beluga click classification criteria outlined above, a consistent Inter Click Interval between multiple clicks and waveforms and spectra consistent with published data on Beluga vocalizations.

Non-Beluga Click Train: groups of clicks which are clearly grouped together and have a consistent Inter Click Interval, but individual clicks do not appear to be from beluga whales and the pattern of Inter Click Intervals is also inconsistent with what we'd expect from Belugas

Single Clicks: One or two Beluga like clicks that are not part of a "Beluga" event.

Boat Noise: Groups of clicks identifiable as boat prop noise.

Unidentified: Unidentified noise.

Non Beluga Buzzes: – rapid click trains, but not obviously coming from Beluga. Possible sources include distant Beluga, rain and small objects in the water hitting the hydrophone.

Some additional annotation was made to mark specific sub-events, such as buzzes, within Beluga events. However, no attempt was made to annotate all such sounds since they are not required for the primary purpose of animal detection and to do so would have taken considerably more than the available amount of time.

When marking beluga events, a new event was started if there was an interval between clicks considered part of a beluga event greater than around 60 seconds.

2.2.2 Whistles

Whistle detections were reviewed offline in the PAMGuard viewer by Douglas Gillespie. The whistle detector (Gillespie et al., in press) stores the time frequency contour of every detected whistle. If raw audio data were also available, the display can show both the underlying spectrogram (recalculated from the raw audio) and the contours of the detections. If the raw audio data are not available, then only the contours are shown. The start and end times of whistling was noted in a spreadsheet since mouse driven annotation tools of the type built into the click detector do not exist for the whistle detector.

2.3 Sightings Data

Sighting data were collected and processed by JBER and NMML and provided to SMRU Ltd to be incorporated into the analysis presented in this report. Visual observations were made from an observation point close to the buoy deployment site (Figure 1) at the mouth of Eagle River. One of two JBER marine mammal technicians experienced with beluga observations and distance estimation at the study site, made observations for 13 days during the trials for a total of 91 hours. The following data were gathered on a standard datasheet: Time of observation to the minute (gps), magnetic bearing (changed to true bearing in excel) from the observer to the closest whale, estimated distance of the closest whale from the observer, behavioural state of the whale (s), direction of movement of the whale (s) (either up or down river- referring to Eagle River), indication of a split or merge event among a group or groups, number of groups within 1 km distance of the observer and other notes pertinent to the observation. In Excel, a projected location of the closest whale in the group was determined per observation time. This projected location was determined using scripts created by Chris Veness (http://www.movable-type.co.uk/scripts/latlong.html). These scripts were integrated into an Excel spreadsheet as follows:

Estimated latitude of the whale (lat2):
=ASIN(SIN(lat1)*COS(d/R) + COS(lat1)*SIN(d/R)*COS(θ))

Estimated longitude of the whale (lon2):
=lon1 + ATAN2(COS(d/R)-SIN(lat1)*SIN(lat2), SIN(θ)*SIN(d/R)*COS(lat1))

Where lat1 is the latitude of the observation point in radians clockwise from north, lon2 is the longitude of the observation point (radians), θ is the bearing (radians), d is the estimated distance to the whale, and R is the earth's radius (d/R is the angular distance, in radians).

NOTE: To convert from degrees to radians the coordinates were first converted to decimal degrees and then multiplied by $\pi/180$. Conversely, to convert from radians to degrees for the output, the coordinates in radians were multiplied by $180/\pi$.

A value of 6371 km was used for the earth's mean radius. This was converted to meters (6371000) to remain consistent with scale of this study, which used meters rather than km.

Using the resulting coordinates, the bearing and distance from the PAMBuoy® hydrophone was derived using the following scripts from Chris Veness:

Bearing to whale from the PAMBUoy hydrophone:
=ATAN2(COS(lat1)*SIN(lat2)-SIN(lat1)*COS(lat2)*COS(lon2-lon1), SIN(lon2-lon1)*COS(lat2))

Where lat1 is the latitude and lon1 is the longitude of the hydrophone in radians and lat2 is the latitude and lon2 is the longitude of the whale in radians.

NOTE: the function ATAN2 (in Excel) returns values in the range -180 to +180 which is appropriate for longitude and latitude measurements but not for compass measurements (0 to 360). To normalize the output to a compass bearing (with negative values transformed to the range 180-360), the output in radians was converted to degrees and then transformed using the modulo function in Excel: =MOD((non-normalized bearing+360),360)

Distance of the whale from the hydrophone:
=ACOS(SIN(lat1)*SIN(lat2)+COS(lat1)*COS(lat2)*COS(lon2-lon1))*6371000

Where lat1 is the latitude and lon1 is the longitude of the hydrophone in radians and lat2 and lon2 are the latitude and longitude, respectively, of the whale.

2.4 Hydrophone Depth

At extreme low tides, the hydrophone was uncovered and therefore not usable. The deployment location was selected this way to allow visual inspection and access to the hydrophone frame and because water depth at low tide at the mouth of the river is too low for belugas to access the area. Tidal data (relative to map datum) for the port of Anchorage were extracted from the NOAA database (http://tidesandcurrents.noaa.gov/ports/index.shtml?port=ak) for the period of the deployment. Visual observations indicate that tide times at the study site are between 20 and 80 minutes behind tide times at Anchorage, so the Anchorage times were corrected by the mean of 50 minutes. The hydrophone was just covered when the Anchorage tidal height was 2m, so a 3m depth on the tide chart would indicate that the hydrophone was 1m below the water surface. Only data where the hydrophone was at a depth of greater than 1m have been used in this study.

2.5 Event Detection

Clearly, from examples such as the one shown in Figure 3, when beluga were close to the hydrophone, many 10's, 100's or even 1000's of clicks would be received over an interval of 10's of seconds. An event detector was therefore developed which simply counted the number of clicks that had passed the Beluga classification criteria (section 2.1) in a set time interval. Echo's and some very rapid groups of false detections which appeared to come from rain drops were rejected if they were within 10ms of the preceding detection. For development purposes, this was implemented in Matlab® but an identical algorithm is now also available in the PAMGuard software which could be used for operational purposes. Counts and integration times were varied and the output compared to both the human detections and the sightings data.

2.6 Comparison of Detected Events with Human Acoustic and Visual Data

The two parameters which best describe the performance of a detector are its efficiency (how many of the things it's supposed to detect it does actually detect) and it's false alarm rate (how many things it detects which it shouldn't have done). These can be expressed in terms of

Recall: The percentage of visual or human detected events which were also detected by the automatic detector

Precision: The percentage of automatic detections which were indeed detections and not false alarms.

The automatically detected events were compared with both the Human Detections and with the visual data in order to assess Precision and Recall for the beluga event detector. When comparing Automatic Acoustic Detections (AAD's) with the Human Acoustic Detections (HAD's), a HAD was said to have been detected automatically if there was an AAD within 10s of the HAD. Conversely, an AAD was said to be a false detection only if it occurred more than 15 minutes from any HAD. This allowed for the fact that as animals moved out of the vicinity of the PAMBuoy®, there would often be a period of a few feint clicks which would still be detected on the PAMBuoy® system but may not have been marked by the human operator.

When comparing with visual data, a 15 minute time window was allowed between the sighting time and the AAD to allow for the fact that the animals may not be vocalizing continuously. Similarly, to allow for animals not being spotted immediately they entered the river, AAD were only considered to be a false detection if they occurred at least 30 minutes before or after the closest sighting time. All sightings data were used in the comparison, irrespective of the number of groups present at any one time.

The different criteria used for comparing the AAD's with HAD's and with the sightings are necessary since the two acoustic methods (Automatic and Human) were operating on the same data, so the two types of detection should be expected to be well correlated in time. The sightings on the other hand should be expected to match less precisely with the acoustic detections, so for comparing acoustic and visual data, wider time windows were used when comparing data sets.

3 Results

3.1 Acoustic Effort

The system was deployed on most days between 12 and 31 August and was generally left running unattended overnight. Although data were collected for a total of 367.5 hours in that period, some data had to be discarded either because the hydrophone was insufficiently covered at low tide (42.5 hours) or due to problems with the hydrophone battery power supply (59.4 hours). This left a total of 273 hours of useful acoustic data.

3.2 Human Processing

3.2.1 Clicks

The total number of events of each type logged by the human operator is shown in Table 1.

Beluga event lengths varied in length from less than a second to 85 minutes. These figures do not however give a good representation of the times for which animals were within acoustic detection range since there were several occasions when the interval between events was little over a minute.

The exact number and duration of events is of course dependent on the time interval allowed between events. As the minimum interval between separate events increases, individual events become longer and the total number of events reduces as shown in Table 2. It can be seen that if the minimum interval between events is 5 minutes, then the longest encounter lasts for nearly three hours. If the interval is increased to 30 minutes, then beluga whales were present for over five hours.

Table 1. Numbers of marked detections in each category

Event Type	N
Beluga	312
Click Train	166
Single Clicks	18
Boat noise	0
Unidentified	14
Non Beluga buzzes	44

3.2.2 Whistles

Whistles were detected most days during the deployment. A sample screen shot of a period of whistling is shown in Figure 5. A summary of whistle detection times is shown in Appendix A. Of 42 periods of whistling, 26 were a minute long or shorter, many of them being just one or two isolated whistles. On no occasions were whistles detected in the absence of echolocation clicks.

3.3 Comparing Automatic Acoustic Detections with Human Acoustic Detections

The precision and recall for AAD's compared to HAD's is shown in Figure 7. Results are shown for varying count times (5, 10, 30 and 60s) and varying minimum numbers of clicks (5 – 30). Clearly as the count time increases, or the required number of clicks is reduced, recall (efficiency) increases, but at the expense of a loss of precision. It is not possible for the automatic detector to select every HAD without also getting some false detections, or for it to get no false detections without also missing some of the HAD's.

A selection of false detections and missed detections were examined visually and aurally in order to determine the source of these detection errors.

Missed detections appeared mostly to be relatively faint click trains with clicks that had a peak frequency over 100kHz, causing them to fail to meet the Beluga classification criteria. However, most faint detections were close in time to a much louder event, so the probability of automatically detecting an animal (rather than a specific click train) is much higher. Figure 7 also shows the precision and recall of the detector when up to 15 minutes are allowed between the HAD and AAD for an alarm count time of 10s. In this case recall rises to over 98% for 98% precision.

Table 2. Numbers of encounters and minimum and maximum encounter durations for varying minimum intervals between encounters.

Minimum Interval (minutes)	Number of events	Shortest Event (s)	Longest Event (hh:mm)
1	304	< 1s	01:25
5	144	< 1s	02:55
15	100	1s	05:19
30	70	13s	05:19

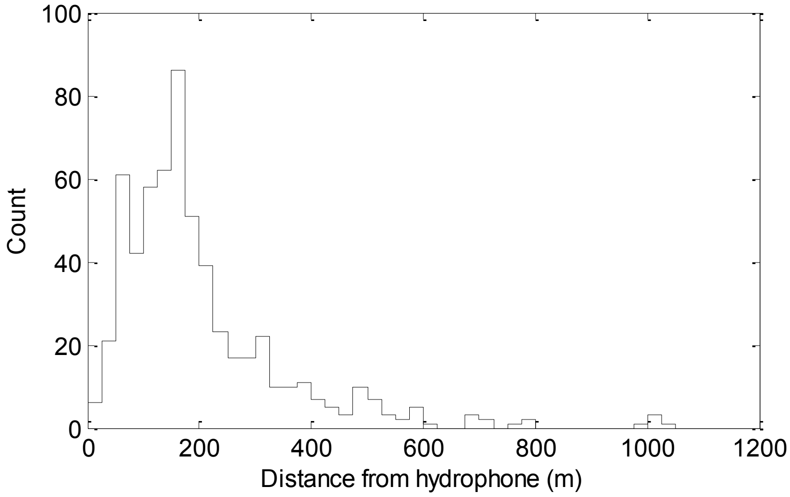

Figure 6. Ranges to sightings from the hydrophone location

Of eleven false detections examined in detail, two were click trains which seemed biological in nature and quite possibly did originate from Beluga. Five were due to electrical noise and four appeared to be caused by a passing vessel. Unfortunately, the buoy was not recording at the times of these false detections, so further examination of the raw audio files is not possible.

3.4 Comparing Automatic Acoustic Detections with Visual Data

The distribution of sighting location range from the hydrophone in meters is depicted in Figure 6. The majority were within 400m

During the 91 hours of visual observation, a total of 592 observations were recorded, although many of these were successive observations of the same group and shouldn't therefore be considered as independent events. Sighting locations are shown in Figure 8 and the distribution of ranges from the hydrophone in meters. Ranges varied from 10m to 1035m, although most sighting ranges were below 400m. It can also be seen from Figure 8 that several of the sighting locations are on land,

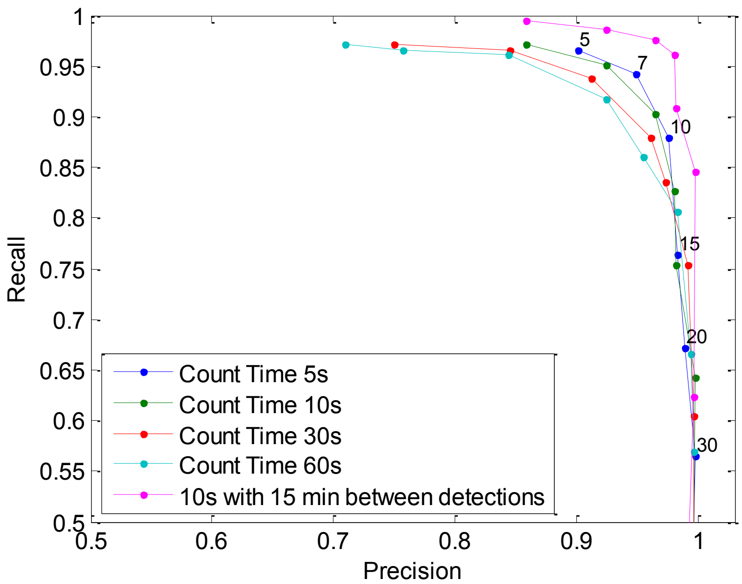

Figure 7. Precision and recall for automatic acoustic detections (AAD) compared with human acoustic detections. An AAD is said to have occurred if a minimum number of clicks is detected within some set time period. The numbers 5 through 30 are the numbers of clicks within a time interval (only shown for the 5s count time). Also shown (pink line) is the detection efficiency and false alarm rate when a 15 minute interval is allowed between HAD and AAD's.

Table 3. False positive detections – Automatic acoustic detections during times of visual effort which did were at least 30 minutes from the closest sighting.

Date and time (UTC)	Remarks
16 Aug 18:45:46 - 18:47:38	Loud click trains, presumed to be Beluga.
20 Aug 20:01:22 - 20:01:51	Loud click trains, presumed to be Beluga.
21 Aug 01:41:03 - 01:41:03	What appears to be boat noise (no recordings available to confirm this)
25 Aug 04:04:15 - 04:05:39	Loud click trains, presumed to be Beluga.
27 Aug 15:15:39 - 15:17:16	Loud click trains, presumed to be Beluga.
27 Aug 17:38:25 - 17:59:50	Loud click trains from 17:38 to 17:46, then intermittent quieter ones.

indicating a degree of inaccuracy in either the bearing or the range estimation or both.

For the 91 hours of visual observation, the PAMBuoy® was operational for 63.5 hours although the hydrophone was only covered (minimum water depth of 3m) for 48.3 hours. Of those 48.3 hours, 19.5 hours were within 15 minutes of a whale sighting, and 21.9 hours of acoustic data occurred at least 30 minutes from any whale sighting. 432 of the 592 sightings occurred when the acoustic system was operational.

An acoustic event was said to match a sighting if the sighting occurred within 15 minutes of the acoustic event. This allows for the fact that animals may not be vocalizing continuously or in the case of echolocation, the acoustic beam may not be projected towards the hydrophone location. For the comparison with the visual data a relatively strict acoustic detection criteria of 20 clicks in a 10s interval was selected. According to the comparison with the HAD data, this has a high precision, but a recall rate of only 75%. With these criteria however, it was found that only two sightings were not detected acoustically (Figure 9a). The acoustic system also detected Beluga on six occasions when visual observers were active, but no sightings were recorded. The acoustic data for these times has been examined in detail (Table 3). In five out of six cases, clear click trains were visible in the data and the human analysis had marked the presence of Beluga click trains. On a single occasion, clicks coming from what appears to be a boat were mistaken for beluga clicks and caused a false AAD.

Increasing the detection event detection criteria to 30 Beluga clicks in 10s removed the false detection on 21 August, but at the expense of additional missed detections, some of which were close to the river mouth (Figure 9b).

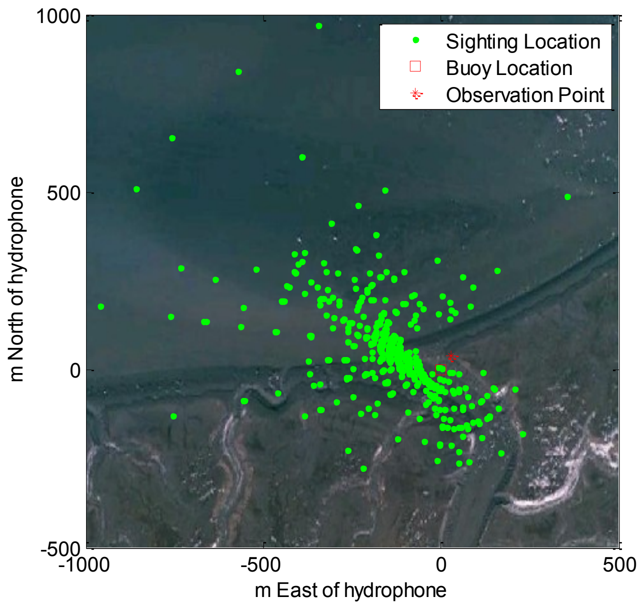

Figure 8. Locations of visual sightings of Beluga.

4 Operational Tests

4.1 Multi hydrophone deployment

Long term monitoring of the Eagle River may require more than one hydrophone. For example it may be necessary to deploy one hydrophone close to the river mouth to provide advanced warning of animals approaching the river and a second hydrophone slightly upstream to detect animals only once they have entered the river.

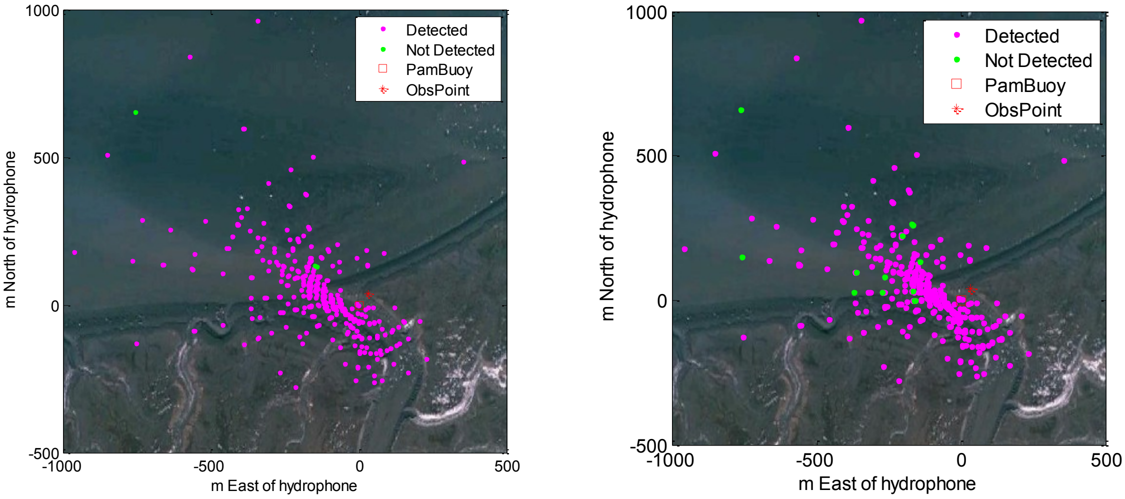

Figure 9. A comparison between visual sightings and automatic acoustic detections with a) a requirement of 20 clicks in 10s and b) 30 clicks in 10s.

A single PAMBuoy® receiving base station is capable of receiving data simultaneously from up to 32 separate detection stations, or from a smaller number of stations equipped with multiple hydrophones (so long as the total hydrophone count does not exceed 32). Generally, if multiple hydrophones are attached to the same station, it is not possible to run separate detectors on each hydrophone due to limitations of processing power. It is however possible to make time difference of arrival measurements of the signal on multiple hydrophones and to use this information to estimate bearings to the detected sounds. An alternative to multiple separate hydrophones might therefore be to mount two or three hydrophones at the river mouth and to use bearing information to determine whether the animals are within or outside the river.

The multi-hydrophone bearing system was not tested during the 2012 trials. However, two separate PAMBuoy® units were run simultaneously during 19 August for a single day, with the second unit placed just outside the river mouth as shown in Figure 10. The first sighting was made at 20:18, north east of the river mouth. Animals were first sighted in the river three minutes later at 20:21.

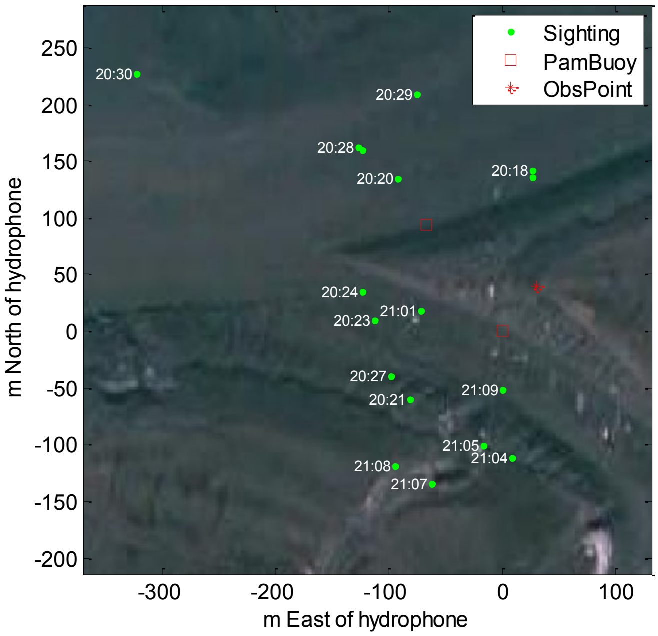

Figure 10. Locations of PAMBuoy® units on 19 August. Also shown are the locations and times of sightings during a 90 minute period between 20:00 and 21:30.

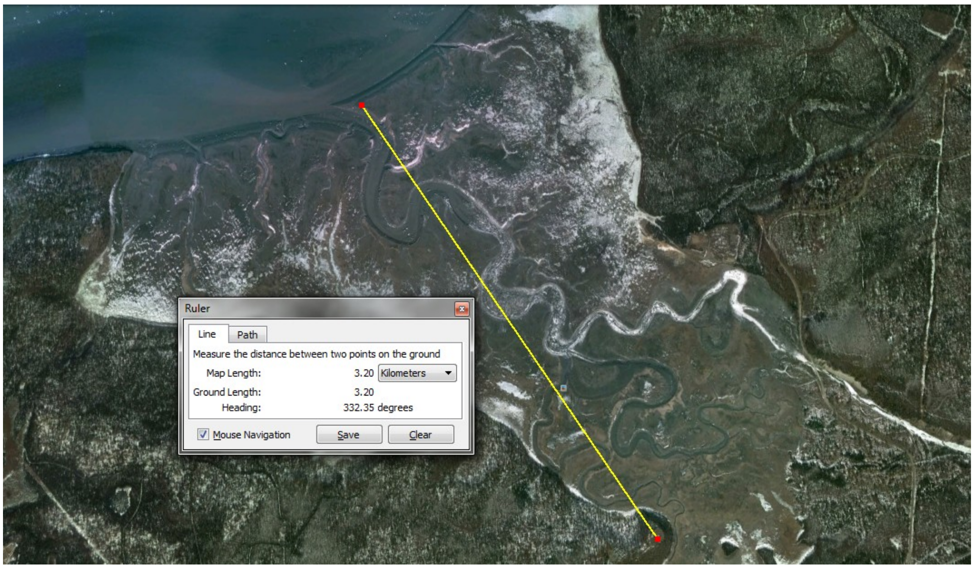

Figure 12. Range test location for wireless communications between PAMBuoy® and the receiving base station.

Figure 11 shows a screen grab from PAMGuard for part of the same time period. Data from both hydrophones are shown on the same display with color used to distinguish between them. It can be seen that large numbers of clicks started to be detected on the hydrophone outside the river mouth at 20:15:15 and on the hydrophone in the river 2.5 minutes later at 20:17:45. These times correspond well to the sighting times – although there does appear to be a 3 minute offset between sightings and acoustic detections.

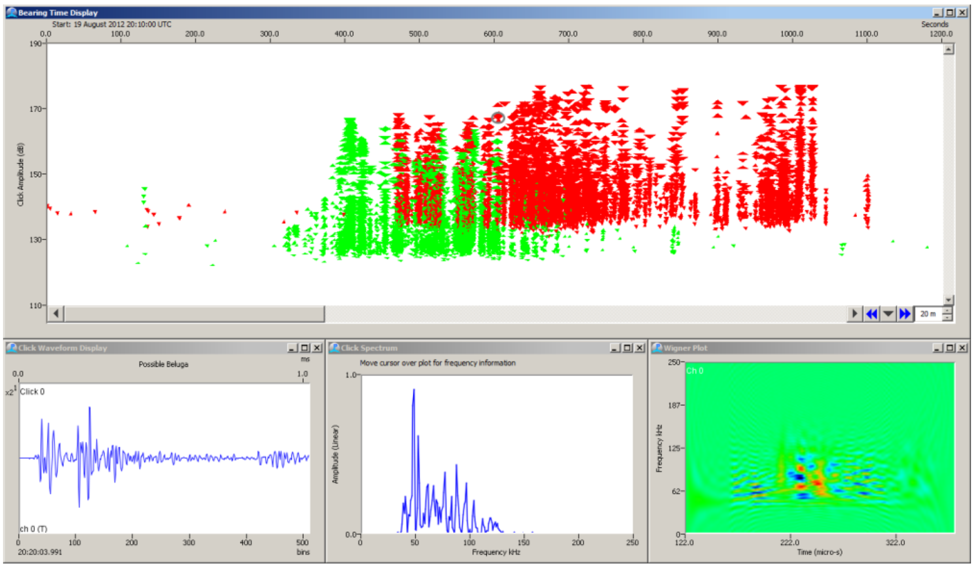

Figure 11. Screen grab of the PAMGuard display showing data from 20:10 to 20:30 on 19 august. The red dots represent clicks detected on the hydrophone in the river and the green dots clicks detected on the hydrophone outside the river.

a) b)

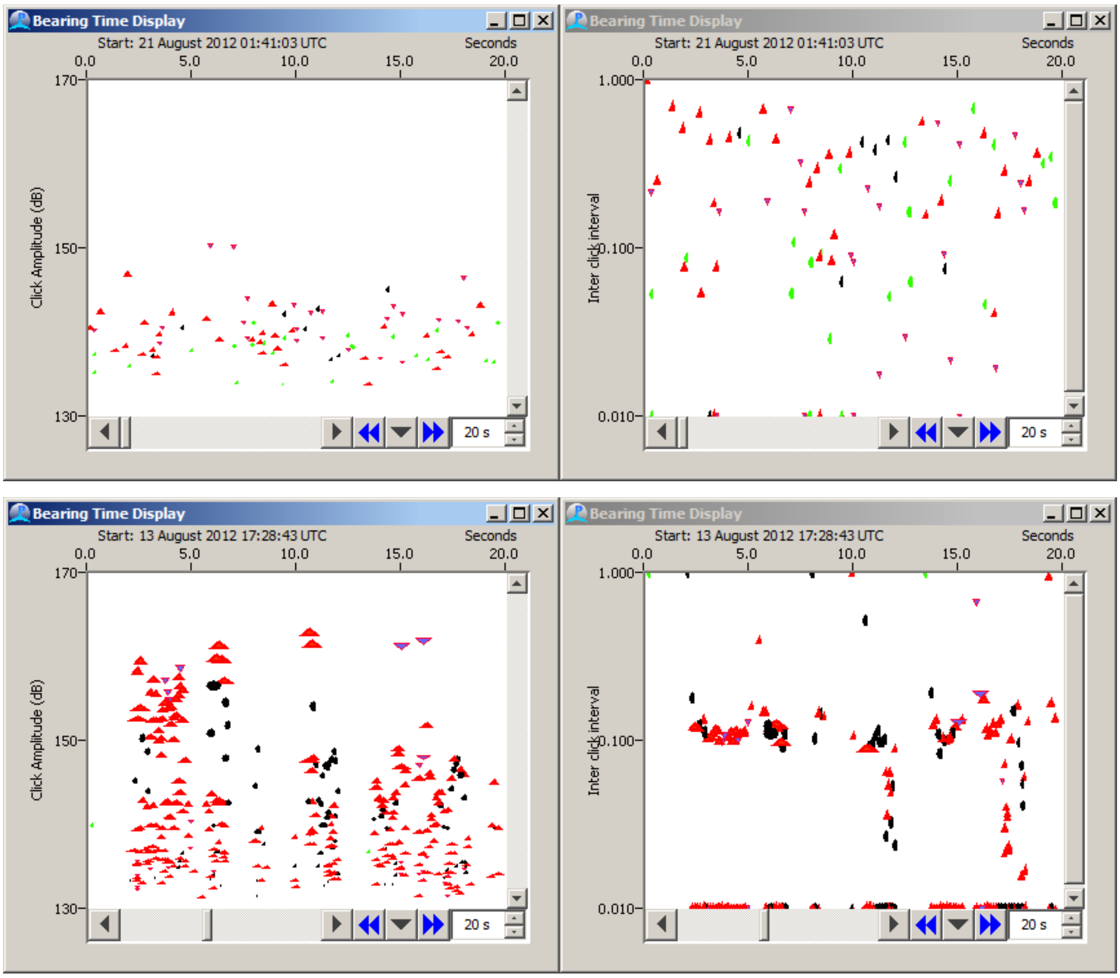

Figure 13. PAMGuard Amplitude and Inter Click interval displays for a) a non-Beluga false detection (believed to be a vessel) and b) a true Beluga event.

4.2 Wireless Modem range testing

For most of the trial the receiving base station was positioned close to the PAMBuoy® units. A short trial was conducted during which the system was tested to a range of 3.2 km along the Eagle River flats firing range as shown in Figure 12. While in principle, the wireless modems have a range of several 10’s of km, such ranges would require a clear line of sight between the two locations which is not easily achieved between the Eagle River and the base.

5 Discussion

A PAMBuoy® system was operational in the mouth of the Eagle River for 19 days in August 2012. Data were collected for a total of 273 hours. Beluga clicks were clearly visible for much of the time and during the trial it was clear that these detections corresponded well to beluga presence in the river and up to at least 1 km from the river mouth when using Eagle Bay.

The single click detection and classification system is prone to errors in the form of false positive detections (i.e. saying there is a Beluga click present, when in reality there isn’t one). To reduce the risk of false positive detections, an event detector was created which requires a minimum number of clicks to arrive in a set time period. By adjusting the minimum number of clicks and the time period it is possible to adjust the recall and precision of the overall detection system. The event detector was tested with range of time periods and click counts (section 3.2) and it was found that a count time of 5 or 10s with click counts of between 7 and 20 clicks could detect most beluga events picked out by a human with a low false alarm rate. Further refinement of these criteria may be possible with additional data collection and may also be required should a different noise source be encountered at the site.

The automatic system was unable to detect all of beluga events picked out by a human operator (HAD’s). However, many of the HAD’s had few clicks or only quite quiet clicks. Generally, human observers do perform better than automatic detectors and the human observer had two important sources of information which are not available to the automatic event detection algorithm. The first was the ability to listen to the audio data, which enables the observer to aurally pick out the patterns of click trains. The human observer also had the ability to look at the pattern of intervals between clicks on the computer screen. For instance, Figure 13a shows the Inter Click Interval (ICI) and amplitude of detected clicks over a 20s period at the time of the false detection listed in Table 3. Figure 13b shows similar plots for a true Beluga detection. It can be seen that there is considerably more amplitude variation in the true detection and also that the ICI's in the true detection have a greater consistency than in the false detection.

While there may be a case for including additional ICI information in the automatic event detector, the acoustic behavior of Belugas is highly variable, and particularly when several animals are present, ICI measurements can become very irregular. Incorporating such a feature into an automatic event detector would therefore not be a straight forward task and may lead to an unstable and unreliable system. Unless shown to be necessary following further data collection, development of an ICI based detector would probably not be an efficient use of resources.

Despite performing less well than a human observer, the system was able to reliably detect all whales approaching or entering the river. The only false detection that passed the event detection criteria was caused by a passing vessel. Presumably, during firing exercises there would be no vessels in the river and it could be argued that if there were for any reason, then detecting them might be a good thing.

Most sightings data were collected within 400m of the hydrophone and nearly all sightings out to the maximum sighting range of just over 1km were detected acoustically. It is therefore impossible to say very much about the detection range of the system except that it is greater than 400m. Depending on the exact operational requirements of a future mitigation system, distinguishing between animals in and outside the river mouth may be important for operational reasons. Two possible approaches could be used to address this issue. The first would be to raise the detection threshold of the system in order to reduce its range by only detecting louder clicks that would correspond to belugas inside the river or very near the river mouth. The second would be to position the hydrophone further up the river so that sounds from outside the river are masked by the river bank. Practically, the latter of these is likely to be the most effective option since (as can be seen in Figure 3 and Figure 13b, there is several 10's of dB variation in the amplitude of received clicks over time periods of < 10s, i.e. periods short enough that the animal is unlikely to have altered its range from the hydrophone significantly. We can therefore assume that amplitude is a poor proxy for range to animal. However, if higher quality sightings data were available (e.g. theodolite based sightings with a longer range) it may be possible to extract a useable parameter, such as peak amplitude within an event, which may correlate with range to the animals.

Whistles were detected on most days of the deployment. However, most whistle "events" contained very few whistles and whistles were never detected in the absence of clicks. It would appear therefore that whistles would not be a good choice for animal presence detection. It is however possible that the behavioral state of the animals may change with season and this short trial should not be used to conclude that there are never periods when beluga produce more whistles than clicks. Whistles should not be ruled out at this stage. The PAMGuard whistle detector seemed to be doing a good job of picking out whistles from background noise with a low false alarm rate. Tools exist within the software to send short clips of audio data for detected whistles over the wireless modem link so that they can be displayed on the base station for confirmation by a human operator.

5.1 Future Monitoring Configuration and Operation

5.1.1 PAMGuard Event Detector and Alarm

While the analysis conducted in this report was all carried out using bespoke Matlab® scripts, an Alarm module with the same functionality as the Matlab® automatic event detector has been implemented in the PAMGuard software. During real time operations, this would count clicks in the way described in section 2.5 and can issue an alarm when the count threshold is exceeded. Currently, alarm status information is displayed on the screen and the software can issue an audible alert when the alarm threshold is exceeded. Other alarm actions could be implemented according to client needs (e.g. sending an email or an SMS message, sending information via a network to another computer, etc.).

The final choice of settings for the alarm must be decided based on the relative cost of a false detection verses the cost of a missed detection. For mitigation against harmful activities, then it will probably be necessary to deploy a low alarm threshold so that there is never a risk of missing an animal that has entered the river mouth. Lowering the threshold may cause a small number of false detections, but these can be relatively easily confirmed as false detections manually in order that operations may continue. As additional data become available, it is also likely that the alarm system can be further refined.

The system has not been tested in the presence of live firing detonations and it is unlikely, but not impossible that these would trigger the detector in some way, causing false alarms. It may however be necessary to perform some re-tuning of the system once such data become available. It should also be noted that the noise monitoring modules within PAMBuoy® could be used to measure received sound levels from such detonations.

5.2 Operational configuration

While originally designed to be deployed on a solar powered buoy, mooring a large buoy in the Eagle River would pose significant challenges due to the high water flow rate and large amount of ice and debris in the river at certain times of year. A solar powered buoy would also be impractical for use at high latitudes for much of the year. It is therefore likely that the shore based system will remain the most practical.

The system deployed in 2012 mostly used a single deployed hydrophone and a single receiving computer receiving the signal over a wireless modem link. In order to provide an early warning of animals approaching the river mouth and also of animals actually being in the river, it may make sense to deploy two systems, one more or less in the position of the 2012 deployment and a second one further up the river, close to the bend 200m upstream. It is possible for multiple PAMBuoy® units to transmit to a single base station which combines the data from both into a single display. Another option might be to use a pair, or a triangular arrangement of three hydrophones mounted close together in the river mouth. Time difference of arrival measurements of the clicks on different hydrophones could then be used to assess whether the sounds are coming from inside or from outside the river and obtain and estimate of the range.

During the 2012 trial, the base station was positioned close to the PAMBuoy® unit. For future operations, it would be desirable to position the base station within the confines of the military base. In principle, the wireless modems have a maximum range of 10’s of km when used with directional antennae. However, this is likely to be much reduced if there is not a good line of sight between the transmitter and receiver as is the case here. Further work is required to address this specific problem. Options include:

1. A single high directional antenna mount transmitting directly to the base
2. One or more intermediate relay stations at strategic points
3. Use of 3G phone networks rather than wireless modem. This would not however provide the real time display capability of the wireless modem system.

Another issue that will require serious consideration is hydrophone mounting. During 2012, the hydrophone was mounted in a relatively simple frame resting in the river mud with walking access during low tides. This deployment method was not designed to withstand long-term deployment periods or ice presence. We have no direct experience of working in such a harsh environment and recommend that local engineers with experience of mounting equipment in that environment are consulted. Given the likely high cost of such an installation, a single mounting, with multiple hydrophones, may be the most practical and economic option.

Finally, the system requires power. When both detecting and transmitting to the base station via the wireless modem, an average power of 10W is required. This means that a 100 amp-hour car battery would power the system for up to five days which would be OK for short deployments. For longer deployments an alternative power source such as a small wind generator may be more practical.

6 References

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Appendix A: Whistle Detection Summary

(All times are UTC)

Date	Start	End	Duration (minutes)	Comment
13/08/2012	16:03	16:15	12	A small number of isolated whistles
13/08/2012	16:30	17:50	80	Isolated whistles, very spread out over time.
14/08/2012	17:21	17:21	0	1s burst of 11 whistles
14/08/2012	19:20	19:20	0	1s burst of 9 - 10 whistles. All above 4.6kHz
14/08/2012	20:33	20:33	0	Andy whooping at hydrophone. (low tide)
15/08/2012	09:22	09:22	0	About 5s with lots of whistles.
15/08/2012	17:56	17:56	0	5s with several whistles, no recording
16/08/2012	06:58	06:58	0	ditto
16/08/2012	07:02	07:02	0	ditto
16/08/2012	19:13	19:30	17	Many social sounds at lower frequency 2 - 10kHz
17/08/2012	22:20	22:30	10	Out of water, can hear people talking
18/08/2012	22:40	23:10	30	Out of water, bad electrical noise causing FD.
20/08/2012	08:32	08:33	1	A few dozen whistles.
20/08/2012	21:28	21:28	0	Short burst, no audio confirmation
21/08/2012	09:55	11:51	116	Many whistles
21/08/2012	20:48	20:48	0	Short burst, no audio confirmation
26/08/2012	04:18	06:50	152	Many whistles
26/08/2012	14:42	14:42	0	A couple of short bursts.
26/08/2012	16:01	16:01	0	single calls with harmonics
26/08/2012	16:10	16:10	0	single calls with harmonics
26/08/2012	16:12	16:12	0	single calls with harmonics
26/08/2012	16:18	16:18	0	A few consecutive calls over about 30s

27/08/2012	04:14	04:14	0	single calls without harmonics
27/08/2012	06:29	06:29	0	Short burst of a few whistles
29/08/2012	01:44	01:44	0	Short burst of a few whistles
29/08/2012	04:26	04:48	22	Lots of whistles
29/08/2012	05:42	05:42	0	couple of whistles
29/08/2012	06:35	06:43	8	Lots of whistles
29/08/2012	07:05	07:06	1	Small number of whistles
29/08/2012	08:39	09:33	54	looks like LF noise with 1 or 2 real whistles at 09:17
29/08/2012	12:06	12:06	0	Possible 1 or 2 calls - not very clear though
29/08/2012	17:47	17:50	3	Quite a lot of whistles in 2 minute period
29/08/2012	18:16	18:16	0	1 - 2 calls
29/08/2012	18:25	18:26	1	a few calls spread over 1 minute
29/08/2012	18:55	18:55	0	1 - 2 calls
29/08/2012	02:31	02:31	0	12 second long burst of noise
30/08/2012	03:03	03:03	0	Single whistle with harmonics. 5 - 17kHz
30/08/2012	04:19	04:19	0	A couple of whistles over 20s period.
30/08/2012	06:19	06:50	31	Lots of whistles
30/08/2012	11:36	11:38	2	short burst of whistles
30/08/2012	13:11	14:40	89	Lots of whistles
30/08/2012	18:34	18:35	1	Many whistles over about a minute
30/08/2012	20:12	20:28	16	Low rate / occasional whistles over several minutes.