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Empirical measures of accuracy using small sensor arrays to localize animal vocalizations

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Abstract

Field studies using 3 and 4 sensor arrays were conducted to determine the accuracy and range of sound localizations. Under-ice and in-air trials examined the range/precision problems associated with deploying small arrays (77 m underwater, 14 m in air). The errors of the localized sound sources were determined within and outside of different array configurations in reverberant conditions. Using four receivers resulted in greater sound source localization accuracy than three. Variability of the sound source location errors within and outside of the arrays was high. The location accuracy and precision decreased when the sound source was located outside of the array. The measurement accuracy of the receiver positions was less important than the ability to determine very accurate time of arrival differences (TOAD) for each of the receiver pairs. The ability to cross correlate signals to determine TOADs appears to be the major difficulty. Also, there is a trade-off between the size of an array and the dynamic range of the call source levels that can be located. Only high amplitude calls can be localized using large (km wide) arrays. When using passive acoustic monitoring to locate fish and mammals, small hydrophone arrays will only provide accurate information when the sound source is within, or very close to the array. [JMATE. 2010;3(1):10-19]

Keywords: Passive acoustic monitoring, hydrophone, seals, acoustics

Introduction

Hydrophone arrays have been used to study a variety of marine mammal and fish activities, such as calling behaviours, locations, and movements (15, 24, 25). Shallow water and under ice acoustic monitoring of species presents a wide variety of obstacles. As a signal reaches the surface (open water), or the under-surface of sea ice and the bottom, it may be reflected and create a continuous backscatter (multipath) until the sound dissipates. In reverberant conditions, each hydrophone will receive the direct signal and multipath reflections (1, 15). This reverberation makes it difficult to locate the original source of the signal. In areas that are ice-covered, the sound may also be masked by ice noise (ice cracking and rubbing), and other background noises (both abiotic and biotic).
Under pack ice, noise levels can be 5-10 dB higher than those measured in comparable ice-free waters (2).

Rossong and Terhune (16) examined the three dimensional (3D) locations of harp seal calls under ice using portable low budget small hydrophone arrays. They found that under-ice sound transmission was more variable than expected, and that even at very short distances from a shallow sound source there were high levels of reverberation (echoes). It was likely that the reverberations would interfere with the arrival times used in deriving the source location. The time of arrival differences (TOAD) between sets of hydrophone pairs are used in hyperbolic equations for 2D space, or hyperboloid equations for 3D space, to determine the location of the signal at a point of intersection (2).

The size of the hydrophone array affects the operational range of the system. In a study by Rossong and Terhune, the locations of the seals' calls were limited to a distance no further than one equal to the array size (~20 m in this case) outside of the array (16). For arrays in general, as the distance between the sound and the receivers increases, the error associated with location increases as well (3, 11, 15, 22). With widely spaced hydrophone arrays there are larger time of arrival differences of sounds between hydrophones which makes signals easier to cross correlate. Due to the smaller distances between hydrophones, however, the signals have small (ms) time of arrival differences which makes the cross correlations used to determine TOADs more difficult.

The accuracy of acoustic localization depends on the precision of the measurements of sound velocity, TOADs, receiver position, and array geometry. Field conditions on sea ice often provide less than ideal conditions for deploying arrays due to the wind, drifting ice floes, uneven ice surface, ice rafting and the

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reverberant acoustic conditions caused by the shallow water sound propagation. When travelling by helicopter, the total amount of equipment is limited and the deployment, operation and retrieval times are typically a few hours per site (5, 16). Our field trials examined the range/precision problems, along with practical considerations, for deploying small arrays with limited operational equipment and support, likely to be deployed by small research teams with limited funding.

A study of sound localizations using a shallow sound source and a four hydrophone array with various depth and size configurations was conducted on sea ice in the Gulf of St. Lawrence, Canada (5). In these conditions, often seen when examining polar species, the signals are often received along with multipaths and harmonics. A number of potential problems were identified (5) and are examined individually here under more controlled conditions. Localization errors were measured using underwater and in-air sound sources and arrays of various configurations to examine the influences of varying the depth of the hydrophones, locating the sound source inside or outside of the array, the relative accuracy of 2D or 3D analyses, using 3 versus 4 receivers and inaccurate locations of the receivers.

Because of spreading losses over distance, there will be a trade-off between the array size and the source levels of the vocalizations that can be detected at each hydrophone or microphone within an array. Calls that are too quiet to reach all of the hydrophones will be missed. Smaller hydrophone arrays are capable of picking up quieter calls of nearby animals. While the larger arrays will enable locating animals over a larger area, only the calls with higher source levels will be received at all hydrophones. The source levels of the underwater calls of some pinnipeds can vary by at least 77 dB (16). The effect of variable source levels and different hydrophone separation distances in an array and the proportion of calls that would be detected, was modeled using data from harp seal (*Pagophilus gronlandicus*) call source levels (16).

Methods

A) Under Ice River Trial

Underwater localizations were made on February 17 and 21, 2009 on the ice-covered Kennebecasis River in New Brunswick, Canada. There were no open water areas in or near the study area. The water depth was between 18 and 23 m and the site was at least > 0.5 km from the shore.

Two diamond shaped array configurations were used (Figure 1). The distance between hydrophones 1 and 2 was 13.8 m, and between hydrophones 3 and 4 was 77.2 m (Figure 1). For the first array, all of the hydrophones were lowered to a depth of 5 m below the ice surface. For the second array, hydrophones 3 and 4 were lowered to 10 m below the ice surface, while hydrophones 1 and 2 remained at 5 m below the ice surface.

To provide access for a sound source, a series of holes were drilled through the ice using a 20 cm ice auger. One hole was located at the mid-point of the array, directly between hydrophone pairs 1 and 2, and 3 and 4. Four holes were drilled along a line between the center of the array and hydrophone 3 at distances of 8, 16, 32, and 64 m from the center (arbitrarily designated as a 0° angle to the long axis of the array). Another set of holes were drilled along a line between the center of the array and hydrophone 1 at distances of 8, 16, 32, and 64 m at an angle of 90° to the first transect. A third set of holes at 8, 16, 32, and 64 m from the center ran at a 45° angle between the other two transects (Figure 1).

The sound source was a truck back-up alarm attached to a 12 v battery and housed in an air-filled waterproof PVC tube (diameter = 8.5 cm, height = 20 cm). The alarm produced consistent 0.5 s pulse tones at 2.5 kHz (Figure 2A). This particular sound source was used because it was small, inexpensive, and readily available. The sound source was lowered to a depth of 5 m. At each transmitting location and for both array configurations, the sound was recorded for 30 s using Vemco VLHF hydrophones and an Edirol R4 digital recorder with a sampling rate of 44.1 kHz

All acoustic localizations were performed using the Ishmael 2.0 program (13). Ten single tones, which were unmasked by background noise, from each 30 s recording were localized. Each series of sound source recordings from both array configurations were analyzed using 2D (x, y) and 3D (x, y, z) space to determine the calculated locations of the sound source. The difference between the calculated and the actual locations was determined using equation 1.

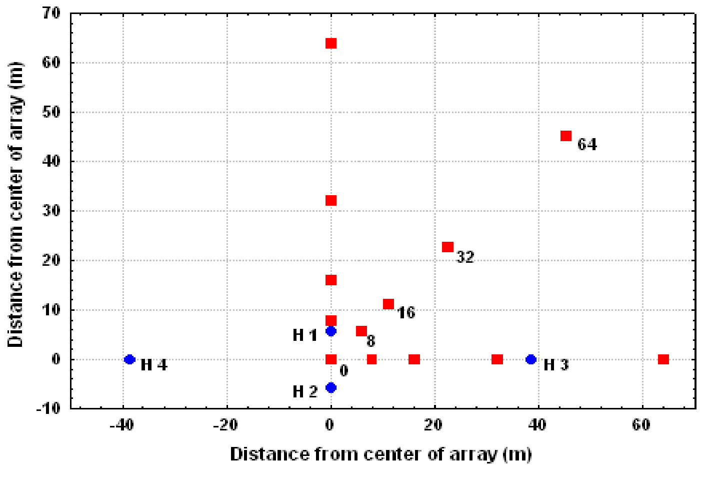

Figure 1 *- Map of the under ice freshwater hydrophone array configurations. All hydrophones (●) in array "a" were lowered to a depth of 5 m below the ice surface. For array "b" hydrophones H3 and H4 were lowered to 10 m below the ice surface, while hydrophones H1 and H2 remained at 5 m depth. The sound source locations (■) were at distances of 0, 8, 16, 32 and 64 m from the center of the array and were along transects that were 0°, 45° and 90° relative to the long axis of the array. Receiver measurements are relative to a center point (0,0) on an x-y-axis and negative distances are used to facilitate the geometric calculations of the sound source locations.*

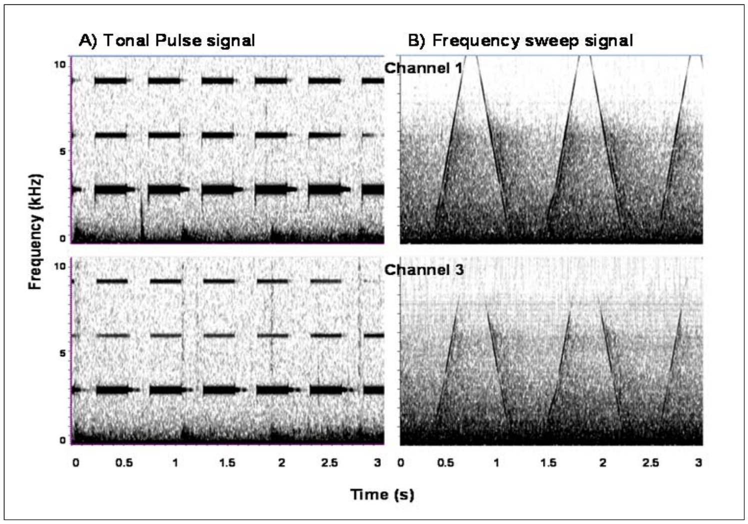

Figure 2 *- Spectrograms showing the source signals as they were received on arrays of A) the under ice river trial and B) the in-air trial. The underwater signal used during the river trial was composed of tonal pulses. The signal used during the in-air trial was composed of frequency sweeps. Channel 3 was the most distant receiver. The analyzing bandwidth was 86 Hz.*

$$\text{Error} = \sqrt{[(X_{\text{calculated}}-X_{\text{actual}})^2 + (Y_{\text{calculated}}-Y_{\text{actual}})^2 + (Z_{\text{calculated}}-Z_{\text{actual}})^2]} \quad \text{(Eq.1)}$$

The error between the 2D and 3D actual and calculated locations was examined using an ANOVA. The error for sounds source locations that were inside versus outside of the arrays were compared using an ANOVA.

All of the sound source tones for both sets of hydrophone depths were localized using only 3 hydrophones instead of 4. This was done by eliminating channel 2 (HP2) from the sound file during playback and analysis in the Ishmael program. The 2nd receiver was removed just for the purpose of examining the impact of the number of receivers (3 or 4) on the location accuracy.

The localization error (m) using 3 receivers versus 4 receivers was examined using an ANOVA. Also, the error of sound source locations that were inside versus outside of the array for both the 3 and 4 receiver arrays were compared using an ANOVA.

B) In-air Trial

A microphone array was set-up in the center of a 75 x 36 x 10 m gymnasium. Four Realistic 33-2050 sound level meters were used as microphones. Each microphone was mounted on a tripod, 1.15 m above the floor (Figure 3). The microphones were arranged in a diamond pattern with a separation 10.10 m along the outside of the square and 14.28 m across the square. Sound transmission locations were along a transect at a 45° angle to the orientation of the diamond-shaped array at distances of 2.47 (L1), 4.96 (L2), 9.93 (L3), and 19.86 (L4) m from the center of the array (Figure 3).

Sounds were projected using 3 Wavetek generators (model 112 and 2 model 20), a Brüel and Kjaer (type 2706) power amplifier and a loudspeaker (9 cm diameter) housed in a wooden speaker box (14.5 x 13.5 x 25.5 cm high). The source signal used for this part of the study was changed to a wider bandwidth frequency sweep in effort to increase the clarity of the received signals. The sounds were repeated, alternating upswept and downswept (0-8 kHz) tones of 0.5 s duration (Figure 2B). The loudspeaker was held at 1.1 to 1.2 m above the floor at each of the four sound transmission locations. The sounds were recorded for 20 s at each location using

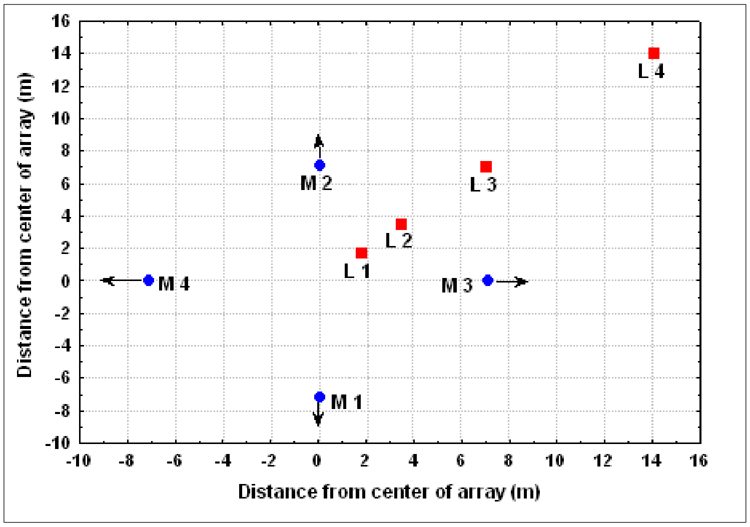

Figure 3 *- Map of the gym microphone array configuration showing the initial accurately measured locations of the four microphones (●, M1 to M4) and the sound source locations (■, L1 to L4). The arrows indicate the directions in which the microphones were moved in 10 cm increments when examining the implications of inaccurate receiver locations. Receiver measurements are relative to a center point (0,0) on an x-y-axis and negative distances are used to facilitate the geometric calculations of the sound source locations.*

an Edirol R4 digital recorder with a sampling rate of 44.1 kHz.

The microphone location precision accuracy required for an array was examined by first recording the test signals with the microphones in the original locations and each of the four sound source locations. For the next series of measurements, each microphone was moved outwards (away from the center of the array) by 10 cm and the sound source was recorded at each of the four locations. This procedure was repeated by moving the microphones outward in 10 cm steps until each microphone was displaced 1.00 m from its original position.

All acoustic localizations were calculated using the acoustic program Ishmael 2.0. Each series of sound source recordings were analyzed using 2D (x, y) space and 3D (x, y, z) space to determine the calculated locations of the sound. For each 20 s sound segment, 10 localizations were calculated using a single cycle of the upswept and downswept tones. The 4 sound source locations were categorized as to whether they were located inside or outside of the array. The location accuracy of the sound source being located within or outside of the array was examined using an ANOVA and regression analysis.

The sound source locations determined by Ishmael were all calculated based on the initial locations of the four microphones. That is, in the microphone location (phone array) file used by Ishmael, the microphone position data were not changed even though the actual locations of the microphones were displaced outward by 10 cm for each set of measurements.

The distances between the calculated and the actual locations (error: Eq. 1) were determined for the different distances away (from 10 -100 cm) from the actual measure of the array. The calculated location errors were then examined for an effect of sound source location by use of a multiple regression.

The differences in the time of arrival delays (TOAD) were examined for microphone pair 3-4 (in their original/accurate locations) using sounds recorded at each of the four transmitting locations. The time of arrival differences for five single frequency swept tones from each of the four sound source locations were determined using the phone-pair bearing feature in Ishmael. The mean time differences, standard deviations, ranges, and percentage variation of the means were calculated for each location.

C) Dynamic Range Model

A conceptual model of the percentages of harp seal calls that would be expected to be detected by two hydrophones as the hydrophone separation distances increased was constructed. If two hydrophones were 100 m apart, and the vocalizing seal was close to one of them, spherical spreading losses would amount to 40 dB. In this case, the source level of the call would have to be 40 dB above the detection threshold of the farthest hydrophone (including background noise etc.) in order for it to be detected by both hydrophones. Calls would only be detected by two hydrophones when the distance between the hydrophones was such that the spreading loss from the seal to each hydrophone was equal to, or less than, the difference between the source level of the call and the detection limits of the hydrophone. The detection ranges of underwater calls using the source levels and communication distances in a noisy and quiet sea under conditions of spherical spreading, (as modeled for harp seals by Rossong and Terhune (16; Figure 3) were calculated. The Rossong and Terhune (16) model includes the effect of high frequency absorption. The source levels of 579 harp seal calls (16) ranged from 103 to 180 dB (re 1 µPa at 1 m). The noisy model takes into account the auditory masking caused by the high rates of conspecific calling and the quiet model assumes a sea state of 0 and no conspecific calling or other noise sources (16). The data were plotted to indicate the proportions of calls that would be detected by two hydrophones separated by distances of 1 m to 50 km.

Results

A) Under Ice River Trial

There was considerable variation between and within the localizations calculated by the program Ishmael for the various underwater signal source locations. The mean errors reported in Table 1 include only recordings in which at least 5 of the 10 individual sound pulses (from a single recording) were localized. Many of the sound localizations could not be resolved, especially at the 64 m distance from the center of the array.

The different hydrophone depths had no effect on the size of the location errors for either 2D (F = 0.38, df = 1,27, p = 0.54) or 3D (F<0.01, df = 1, 26, p = 0.99) localizations.

For 2D localizations and 4 receivers, the mean location distance error increased significantly (F=11.4, df= 1,94, p=0.001) from 3.42 ± 4.00 m (mean ± SD) when the sound source was located inside of the array to 10.31 ± 11.86 m when the sound source was located outside of the array. When only 3 receivers were used in the calculations, the mean location errors increased from 12.28 ± 5.64 m for sources located inside the array to 23.3 ± 20.98 m for sources located outside of the array. Even at locations within the arrays, low precision were observed in this trial.

For 3D localizations and 4 receivers, the mean location distance error increased significantly (F=11.4, df=1,92, p= 0.001) from 3.74 ± 3.16 m when the sound source was located inside of the array to 12.64 ± 12.88 m when the sound source was located outside of the array. When only 3 receivers were used in the calculations, the mean location errors increased from 19.00 ± 8.23 m for sources located inside the array to 26.22 ± 15.93 m for sources located outside of the array.

B) In-Air Trial

When the microphone placements were at the correct locations, the mean location errors increased with increasing signal location distance from the center of the array for the 3D measures (range 0.62 to 5.02 m; R^2= 0.52, t(39) = 6.45, F=41.62, n=41, p<0.01) but not the 2D measures (range 0.42 to 1.14 m; R^2= 0.02, t(39) = 2.36, F=0.76, n=41, p=0.39). There was a statistically significant increase in error when the signal was located outside of the array for both 2D (F=73.94, df= 1,86, p< 0.0001) and 3D localizations (F=6.45, df= 1, 80, p=0.01).

For the 2D analyses, as the microphones were moved outwards in 10 cm steps, at Location 4, the location error increased from 1.13 ± 0.15 m to 21.46 ± 2.67 m in a quasi-linear manner. The errors at Locations 1-3 all ranged between 0.04 ± 0.05 m and 3.70 ± 4.30 m in an irregular manner. There was a small positive relationship between the location error and the displacement of the microphones (R^2adj= 0.04, F=16.24, t(339)= 7.2058, n=341, p<0.0001).

For the 3D analyses, as the microphones were moved outwards in 10 cm steps, at Location 4, the errors increased from 5.02 ± 0.63 m at zero displacement and the equations would not solve for displacements ≥ 50 cm. The errors at Locations 1-3 all ranged between 0.55 ± 0.07 m and 5.74 ± 6.52 m in an irregular manner. There was a small positive relationship between location error and the displacement of the microphones (R^2adj= 0.03, F = 11.40, t(348)= 6.380, n=350, p=0.0008).

The mean time of arrival differences (m/s) of the signals between microphones 3 and 4 from each of the four signal locations are given in Table 2. The TOADs at L1 were negative even though the sound source was closer to M3 than M4.

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C) Dynamic Range Model

As the distance between the two hydrophones increased, the percentage of harp seal calls that would be detected by both decreased (Figure 4). In a very quiet sea with the calling seal close to one hydrophone, 50% of the calls would be detected at hydrophone separations of 1.8 km but only 5% if the hydrophones were 11.2 km apart. In the noisier situation when many conspecifics were calling, only 50% of the calls would be detected if the hydrophone separation was about 100 m and only 5% at hydrophone separation distances of 1.1 km.

3D Localization Error (m) mean						
		Distances (from center of array) (m)				
Array	**Angle(°)**	**0**	**8**	**16**	**32**	**64**
A	0	3.26	2.09	UL	6.90	UL
A	45	2.38	2.70	7.68	5.44	UL
A	90	2.09	8.68	3.64	5.01	UL
B	0	2.99	7.84	4.69	13.9	UL
B	45	1.82	3.24	3.28	14.3	31.6
B	90	1.43	3.31	2.68	19.7	25.5

UL = unable to localize
Table 1 *- Calculated vs. actual locations (error in meters) of a sound source using 2 arrays with hydrophone depths of 5 m (A) or (B) with two hydrophones at 5 m and two at 10 m (n≥5).*

	Time of Arrival Difference (ms)					
Location	**Mean**	**S.D**	**Min**	**Max**	**Range (ms)**	**COV (%)**
L1	-0.23	0.43	-0.02	-1.00	0.98	186.9
L2	18.01	1.34	16.67	19.80	3.13	7.44
L3	28.02	0.58	27.39	28.48	1.09	2.06
L4	33.08	0.04	33.04	33.15	0.11	0.12

Table 2 *- Time of arrival variability between microphones M3 and M4 under constant conditions. N=5 for all locations. L1-4 represents the location of the sound sources, with L1 being closest to the center (0, 0) of the array and L4 being the furthest (Figure 3).*

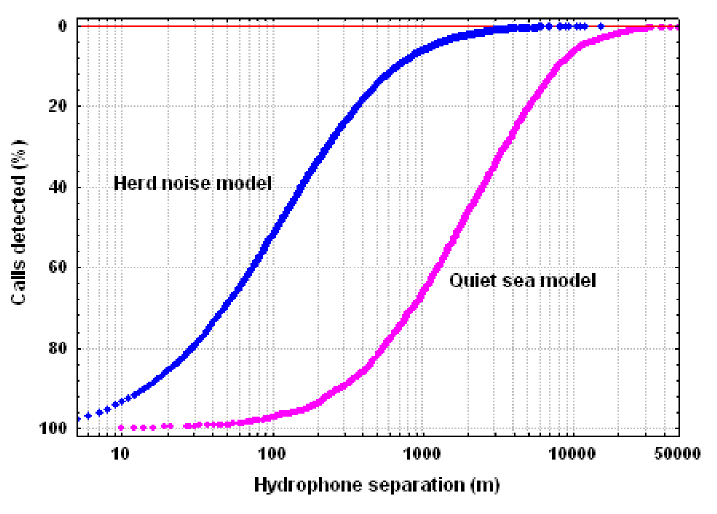

Figure 4 *- A model of the proportions of harp seal underwater calls that would be detected by each of two hydrophones under very quiet (●) and noisy (♦) conditions, spherical spreading and with the calling seal being very close to one of the hydrophones (data from Rossong and Terhune, 2009). The source levels of the calls ranged from 103 to 180 dB re 1 μPa at 1 m. The models presented here are intended to show only the variability associated with the size of a hydrophone array and do not represent actual measurements.*

Discussion

Reverberant environments observed in under ice acoustic monitoring of species presents a wide variety of challenges. Emery (5) found that the variability in TOAD measurements and the resulting difficulties in measuring them were the main source of errors when using a small array for signal localization in a reverberant environment. These errors occurred even when the TOAD exhibited only a 1% error (5). The mulitpath arrivals from several different directions can be viewed as directional interferences partially correlated with the emitted process (8). Previous studies have examined the detection of signals and time of arrival location solutions and provide mathematical models that have capabilities to deal with inaccurate multipath time delays (7, 8, 9).

With widely spaced hydrophone arrays there are larger time of arrival differences of sounds between hydrophones which makes signals easier to cross correlate. Au and Hastings (2), and Mellinger (12) have suggested using a location distance that ranged up to 5 times the size of the hydrophone array in open ocean environments. Clark and Ellison (4) found that sound source locations were reliable at distances up to 2-3 times the size of a large array when studying bowhead whales (*Balaena mysticetus*). When working in air examining bird vocalizations, Bower and Clark (3) found that sound source locations were reliable up to 2 times the size of the array. A calibration of a 2D localization study of bearded seal (*Erignathus barbatus*) underwater vocalizations that used a three hydrophone linear array with a maximum separation distance of 73.2 m found that although location error increased with distance from the hydrophones, the maximum location error was only 201 m at a range of 3.8 km while the minimum was 4 m close to the array (22). That study also reports that only 49 % of the calls were received on all three hydrophones and the cross correlations of some call types were more reliable than others (22).

The variability in the error levels of the underwater sound source locations within and outside of the arrays was high. The repeat measurements at the center of the array varied by over 1 m and many of the signals at 16 and 64 m distances from the center of the array could not be resolved (Table 1). For the more accurately measured in-air array, the lowest error was 0.42 m (2D) but the range was high, especially for the 3D calculations. In both the underwater and in-air arrays, the location errors were higher once the sound source was located just outside of the array. The accuracy of the measurement was low, but it was also observed that the precision was greatly decreased as well. The location distance error observed in the river trials also exhibited a decrease in precision.

In the underwater measurements, the slight alteration of the hydrophone depths did not influence the location accuracy. Performing a 2D analysis usually resulted in slightly lower location errors than when a 3D analysis was performed for both the underwater and in-air measurements. This observation is compromised because the sound source was on a similar plane with the receivers, however.

When the microphones of the in-air array were displaced, the location errors of the sound sources located within or close to the array were variable and only slightly related to the amount of displacement. This suggests that the location error inherent in the analysis methods is greater than the error associated with small differences in the actual TOADs (5).

Variability in the TOAD measurements between adjacent frequencies suggests that difficulties in measuring the TOADs may be the main source of the location errors for this particular circumstance (5). Janik *et al*. (6) state that an advantage of longer distances between hydrophones is that an error of a few meters in the position of the hydrophone does not affect the location accuracy as much as it would in smaller arrays.

For a three hydrophone array there are 2 pairs of TOADs contributing to the localization equations which will intersect. The point of intersection of the third pair is dependent upon on the other two, and thus is redundant (18) if the TOAD measures are accurate. For a four hydrophone array, there are 6 pairs of TOADs, but only 4 pairs are unique. If TOAD measurement errors occur, the intersections of the hyperboloids will not converge at a single point, but at a number of points, thus leading to uncertainty about the sound source location. The number of receivers affected the amount of error observed in the localization. In 2D and 3D systems, the addition of a 4th and 5th receiver, respectively, would eliminate location ambiguities, and therefore decrease the amount of errors associated with the calculated locations (18). Alternative hydrophone configurations may also avoid this problem however (21). A study on acoustic location system accuracy was conducted on songbirds in a tropical forest, which is also a reverberant environment (14). The study used an array of 8 microphones and provided estimates (+/- 2.82 m) of the positions of the loudspeakers broadcasting calls (14). For deployments where transportation logistics limit the available space for equipment and data gathering time to a few hours such as helicopter travel to pack ice, it may be impractical to establish arrays with large numbers of receivers (16).

The magnitude of background noise interference depends on the signal and noise frequencies and is the greatest when they are similar (17). In pack ice, noise levels can be 5-10 dB higher than those measured in comparable ice-free waters (2). Lower frequencies are more subject to masking from biotic and abiotic noises in part because the higher frequencies have a greater absorption over distance (10) and will attenuate sooner than lower frequencies in a reverberant situation. As the distance of a sound source outside of the array increases, the spreading loss will increase and thus the signal to noise ratio of the received sound will be lower. A consequence of this is that it will be more difficult to accurately determine the TOADs, especially when ice noises overlap the call. In this situation it may be beneficial to examine the *ad hoc* detector methods as described in Lourtie and Carter (7, 8, 9) which were developed to deal with inaccurate multipath time delay modeling, and would provide more optimal performance under increasing misadjustments in the delay assumptions.

In reverberant conditions, such as the conditions present in this study (shallow environments under ice and in-air), TOAD inaccuracies are potentially the major contributing factor to location error. There were noticeable echoes that we could detect during sound trials but, they would be extremely difficult to accurately quantify. The structure of the call may lead to variability in the time of arrival differences. Very short duration clicks, such as sperm whale clicks in deep water (23), will facilitate cross correlation analyses. Tonal calls with an abrupt start and end will present time clues, but they will be obscured by multi-path transmission with decreasing time clues over distance. Tonal calls with long rise and fall times will not permit clear time of arrival clues, and will be further obscured by amplitude loss over distance between hydrophones. During the underwater trials in the freshwater river (trial b) tonal pulses were used as the source signal. These signals exhibited harmonics when analysed using a spectrogram. During the in-air trials, the source signal was switched to wider bandwidth frequency sweeps in order to facilitate better cross-correlations of the signals. Calls that contain both abrupt start and end times with a broadband frequency sweep between them will be the most ideal signals to localize in terms of arrival time cues.

The harp seal call detection model presented here (Figure 4) applies only for the case of the sound source being very close to one of the hydrophones in the pair. Depending upon the configuration of the array, including the number of hydrophones being used, the probability of detecting a call will vary with the distance from each receiver. For sound sources outside of the array, the detection distances will be lower because, for a given source level, spreading loss will already have occurred before the sound reaches the closest hydrophone. Overall, the probability of detecting a single call at each of at least four receivers of an array, (or the area effectively being sampled), will vary with the geometry of the array (21), the relative location of the sound source and its source level. For very small arrays, while only nearby calling animals could be localized, the system would detect calls with low amplitude source levels. Such call detection would be limited by the ambient noise level, the distance of the animal from the farthest receiver and possibly the sensitivity of the hydrophone and recording system. Small arrays deployed close to the animals will be required to document the full acoustic repertoire of a species.

Arrays with hydrophones deployed km apart will have a much greater location range but will be limited to calls with high source levels. In a detection range model study, Stafford *et al*. (19) report that most of the high amplitude, low frequency calls of large baleen whale species in the Gulf of Alaska would be detectable less than 50 km from their moored hydrophone systems although some calls would be detectable up to 250 km. Their model used fixed source levels of 160 to 180 dB re 1 µPa at 1 m, depending upon the species concerned. The Stafford *et al*. models indicate a wide range of detection probabilities over distance based on the various ambient noise and propagation loss data used in the models (19). The addition of variation in the call source levels and the configurations of the hydrophone arrays (relative to the location of the sound sources) will add additional variation to the models. When large aperture arrays are being used to localize calling marine mammals, the area that is being sampled will vary with the source level of the call, the distances of the calling source with respect to each of the hydrophone locations and sound propagation losses.

Conclusion

The location of the sound source inside or outside of the array, and the ability to determine accurate time of arrival differences, are important limiting factors in reverberant environments. When a sound is localized outside of an array the error surrounding that location is much greater and it may not be possible to locate a calling marine mammal to a precise location but only to a general region (2).

When working in a reverberant environment (such as under ice in shallow waters), it is recommended that to attain accurate locations the calculated locations be limited to sources within or very close to the array. When longer ranges are required, the assessment of the data collection will have to consider the influences of variation in the source levels of the calls, ambient noise levels, an inability to localize all call types and use sound sources to calibrate the localization equipment and analysis procedures. Valuable information can be gained under such limitations (22) but where animals are being located at great distances, it must be realized that only a portion of the calls are likely being received.

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