

- SCHEFFER, V. B. 1960. Weights of organs and glands in the northern fur seal. *Mammalia* 24:476–481.
- STEPHAN, H. 1972. Evolution of primate brains: A comparative anatomical investigation. Pages 155–174 in R. Tuttle, ed. *The functional and evolutionary biology of primates*. Aldine-Atherton, Chicago, IL.
- STEWART, B. S., AND H. R. HUBER. 1993. *Mirounga angustirostris*. *Mammalian Species* 449:1–10.
- VAZ-FERREIRA, R. 1981. South American sea lion—*Otaria flavescens* (Shaw, 1800). Pages 39–65 in S. H. Ridgway and R. J. Harrison, eds. *Handbook of marine mammals*. Volume 1. The walrus, sea lions, fur seals and sea otter. Academic Press, London.
- WIRZ, K. 1950. Studien über die Cerebralisation: Zur Quantitativen Bestimmung der Rangordnung bei Säugetieren. *Acta Anatomica* 9:134–196.
- WORTHY, G. A. J., AND J. P. HICKIE. 1986. Relative brain size in marine mammals. *American Naturalist* 128:445–459.
- WOZENCRAFT, W. C. 1993. Order Carnivora. Pages 279–348 in D. E. Wilson and D. A. Reeder, eds. *Mammal species of the world: A taxonomic and geographic reference*. Smithsonian Institution Press, Washington, DC.

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## A DESIGN FOR A TWO-DIMENSIONAL BOAT-BOUND HYDROPHONE ARRAY FOR STUDYING HARBOR SEALS, *PHOCA VITULINA*

Hydrophone arrays have many applications for studying marine mammal acoustic behavior (Watkins and Wartzok 1985, Clark *et al.* 1986, Spiesberger and Frstrup 1990), but the design of these arrays is frequently constrained by the site and equipment available, as well as by the distribution and behavior of animals. For this study we built an array to determine the spatial distribution of male harbor seals making low-frequency vocalizations (mean of 665 Hz) during the breeding season (Van Parijs *et al.* 1997). Our aim was to use male harbor vocalizations to map distribution at sea (Van Parijs *et al.*, in press *a*). Male harbor seals perform vocal and dive displays at display sites for male/male competition and/or to attract females (Hanggi and Schusterman 1994, Bjørge *et al.* 1995, Van Parijs *et al.* 1997). The infrequent vocalizations of males (Van Parijs *et al.* 1997; Van Parijs *et al.*, in press *b*) made the use of a directional hydrophone impractical.

The wide distribution of male display areas (Van Parijs *et al.* 1997; Van

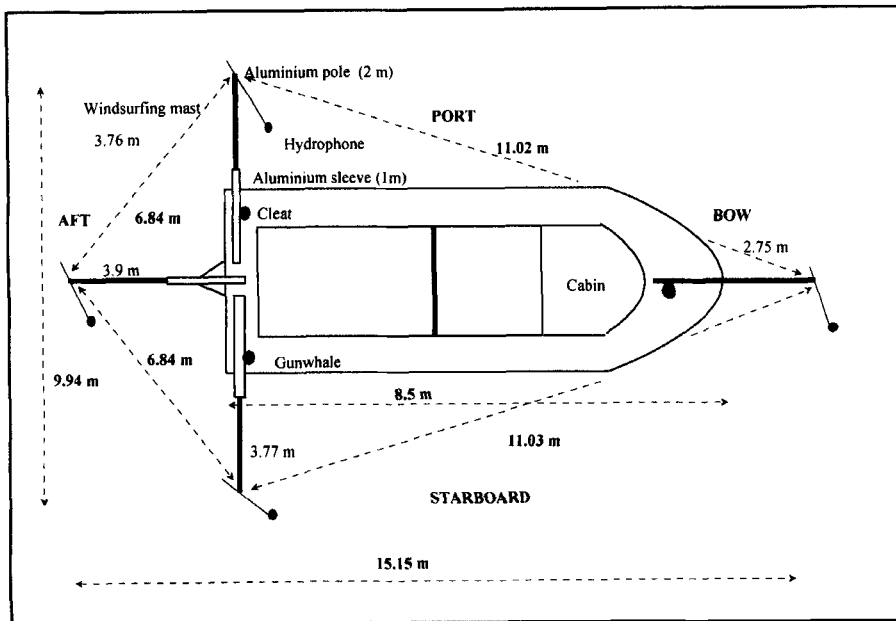


Figure 1. The design and measurements of the 4-hydrophone array on the 8.5-m Newhaven Sea Warrior power boat.

Parijs *et al.*, in press *a*) meant that we were unable to use a static hydrophone array from land or from anchored buoys. Furthermore, the low-frequency tone of the vocalizations prevented us from using a mobile towed array because engine noise would have masked most of the seals' vocalizations. Therefore, we designed an array that we could use from a stationary boat but that was sufficiently seaworthy, mobile, and easy to stow to allow the boat to move between widely dispersed sampling sites. We here discuss the design, calibration, and accuracy of this rigid two-dimensional four-hydrophone array. Although primarily designed for use in studying low-frequency harbor seal vocalizations, we also discuss its suitability for acoustic studies on other marine mammals.

Four sonobuoy hydrophones (DOWTY, SSQ906A(D)) were installed in a cross formation on a 8.5-m Newhaven Sea Warrior motor vessel to form a two dimensional array (Fig. 1). Each hydrophone was attached to a carbon-fibre pole (designed for use as a wind surfing mast) and was extended over the side of the boat. The poles were set off the port and starboard sides, stern, and bow of the boat. They were 4.76, 4.77, 4.9 m, and 3.75 m in length, respectively. The hydrophones were placed at as great a distance as was feasible from one another to enhance the accuracy of localization (Watkins and Schevill 1972, Spiesberger and Fristrup 1990). The rear and side poles were each slotted into one side of a 1-m aluminum sleeve 5 cm in diameter. A rubber joint, which allowed the poles to bend in all directions (a universal wind surfing joint) was slotted into the base of the sleeve. These three joints were bolted

to the rear of the boat, allowing the poles to be rotated in any direction. This allowed us to tie up the port, starboard, and aft poles in a vertical position while motoring and to tie them horizontally down to a cleat on the gunwale while stationary (as in Fig.1). The bow pole was lifted up and placed on the side of the boat while motoring and tied to the bow cleat when stationary. We attached 2-m long aluminum poles 1.5 cm in diameter to each of the wind surfing masts using jubilee clips, so that the aluminum poles hung into the water at 90° from the tip of the mast. A hydrophone was tied to the base of each aluminum pole using electrical cable ties. The coaxial cable from each of the four hydrophones ran along the outside of the aluminum poles, the wind surfing masts and along the side of the boat into the cabin. The hydrophone signals were amplified with custom preamplifiers and recorded on a Tascam Porta II four-track cassette recorder. The frequency response of the whole system was 40 Hz to 12.5 kHz  $\pm$  3 dB. All recordings were made in sea state of Beaufort 1 or 2, without rain.

The array was calibrated around high tide in the Cromarty Firth, Scotland (57°41'N, 4°02'E). In this area water depths range from 1.5 to 21 m and the seabed consists of mud and sand. We used two vessels, the Newhaven Sea Warrior, onto which the array was fixed and a 4.5-m inflatable with a Mariner 40-hp outboard, which was used to carry the sound source. The array vessel was anchored to a permanent mooring (in approximately 17 m of water) and two additional anchors were placed either side of the boat to minimize movement of the array in the currents. The hydrophone locations were determined by using a mobile GPS logger and a GPS base station at Culterty Field Station, (University of Aberdeen, Newborough, Aberdeen-shire, 57°27'N, 2°0'E) to provide differential global positioning. The mobile GPS logger consisted of a Navstar XR5-M GPS unit and a Hewlett Packard 100 LX Palmtop PC/1MB RAM portable laptop computer. All measurements were logged onto the computer and were later downloaded onto the base station mainframe. Corrected GPS Ordinance Survey co-ordinates were calculated. The accuracy of this system was  $\pm$ 2.0 m.

To measure localization accuracy we used an artificial sound source produced by the revving of the outboard motor of an inflatable boat. The inflatable boat was moved 360° around the fixed hydrophone array at various distances, whilst the array recorded the sounds on all four hydrophones. This was achieved by moving the sound source clockwise around the array along eight 45° line transects (0°–315°) at distances of about 10, 20, 30, 50, 100, 200, and 500 m from the array. A hand-held compass (Sestrel, Electronic laboratories) was used to determine the direction of the bow of the array vessel before we started recording at each point. Two sources of error were corrected for in the compass, the variation (7°05'W in 1997) and the deviation. No marine mammals were present during these experiments.

All data were analyzed with the SIGNAL software localization module (Engineering Design, Belmont, USA) (Beeman 1996). SIGNAL localizes a sound source based on the time difference between the arrival of the signal at each pair of hydrophones. The advantage of using a four-hydrophone array is that

it adds a certain amount of redundancy to the cross-correlation measurement, which is useful for detecting spurious hyperbolas.

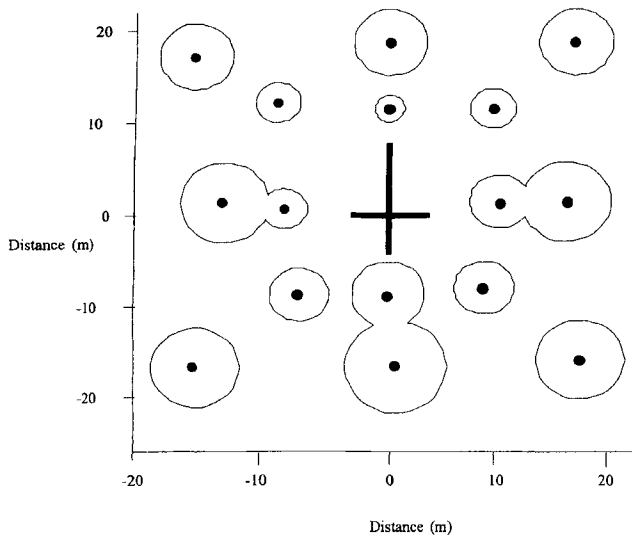
To avoid calculation errors due to a low signal-to-noise ratio (SNR), only sounds with no background noise were used for analysis. A total of eight sounds were localized for each artificial sound source. All recorded sounds were digitized at a sampling rate of 30 kHz. All spectrograms were calculated with a 75% overlap between Fast Fourier Transforms (FFT; dt: 10 msec, df: 98 Hz, FFT size: 1,024). The speed of sound was determined as 1,567 m/sec by measuring an artificial sound source over known distances between the hydrophones.

Initially we compared both waveform and spectrogram cross-correlations in this study. All cross-correlation results were cross-checked by measuring time delays manually on the computer screen. These showed that waveform cross correlation did not perform consistently with broad-band harbor seal vocalizations. Although the cross-correlation of frequency spectra results in a slightly larger error, it is more consistent (Janik *et al.*, in press). Therefore, only spectrogram cross-correlation was used for the calibration of this array.

The measured time delay for each hydrophone pair specifies a two-dimensional hyperbola; this is the set of possible locations for the source, if the measurement is correct. In the ideal case, the hyperbolas from all of the microphone pairs should intersect at exactly one point. However, many sources of error in the measurement of time delays contribute to a more complex picture, in which there are different points of intersection for each pair of hyperbolas, or the hyperbolas diverge. For sounds made within 20 m from the array, 68% of loci converged roughly to a single point and 32% of the loci formed an area polygon. For the loci that formed an area polygon, we measured the mid point of the polygon and used this point in the error analysis. For sounds made 30–500 m from the array the loci formed a bearing in the direction of the transmitter. In those cases we measured the mid-point of the bearing ( $^{\circ}$ ) from the boat to the location of the sound source. The trimmed mean was taken of the eight bearings, discarding the two extreme values and taking the mean of the remaining six. To test the accuracy of the acoustic localization, we compared its results with the locations obtained using the differential Global Positioning System (GPS).

Location errors ranged from 1.5 to 9.7 m ( $n = 128$ ) from the sound source. The mean error for sounds at  $\sim 10$  m was  $3.4 \pm 0.25$  (SE) ( $n = 64$ ) and for 20 m was  $5.62 \pm 0.2$  ( $n = 64$ ). Location errors were greatest aft of the boat in the  $135^{\circ}$  (10 m:  $4.2 \pm 0.6$ ; 20 m:  $5.7 \pm 0.4$ ),  $180^{\circ}$  (10 m:  $4.5 \pm 0.5$ ; 20 m:  $6.5 \pm 0.6$ ) and  $225^{\circ}$  (10 m:  $4.1 \pm 0.7$ ; 20 m:  $5.8 \pm 0.7$ ) quadrants (Fig. 2). Errors decreased towards the bow of the boat in the  $90^{\circ}$  (10 m:  $4.0 \pm 1.0$ ; 20 m:  $5.5 \pm 0.45$ ),  $270^{\circ}$  (10 m:  $3.6 \pm 0.6$ ; 20 m:  $5.5 \pm 0.6$ ),  $45^{\circ}$  (10 m:  $3.2 \pm 0.6$ ; 20 m:  $5.3 \pm 0.6$ ),  $315^{\circ}$  (10 m:  $2.7 \pm 0.8$ ;  $5.3 \pm 0.4$ ) and  $0^{\circ}$  (10 m:  $2.2 \pm 0.6$ ; 20 m:  $5.1 \pm 0.7$ ) quadrants.

For sounds farther than 20 m away, bearing errors ranged from  $2^{\circ}$  to  $45^{\circ}$  ( $n = 240$ ). Bearing errors increased noticeably with distance, with errors ranging from  $2^{\circ}$  to  $9^{\circ}$  at 30 m,  $5^{\circ}$  to  $19^{\circ}$  at 50 m,  $7^{\circ}$  to  $22^{\circ}$  at 100 m,  $14^{\circ}$  to



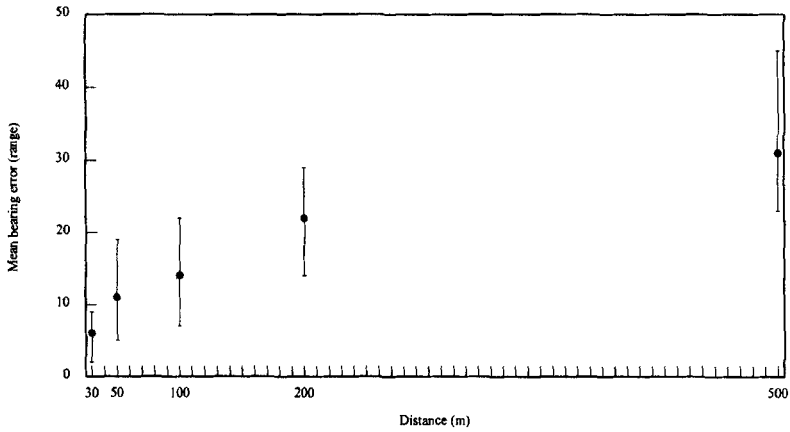
*Figure 2.* A spatial representation of the mean location errors (m) of the artificial sound source (O) compared with the actual locations (n) represented by differential GPS co-ordinates (x,y) using Arch View 3.1. Solid lines represent the four hydrophones of the array. The location errors are greatest towards the aft of the boat and increase between 10m and 20m.

29° at 200 m, and 23° to 45° at 500 m (Fig. 3a). As for location errors, bearing errors increased aft of the boat in the 135° (range: 4°–45°), 180° (4°–38°), and 225° (4°–37°) quadrants. While bearing error decreased towards the bow in the 90° (4°–36°), 270° (3°–34°), 45° (3°–35°), 315° (3°–33°), and 0° (3°–31°) quadrants (Fig. 3b).

This array provided locations of sound sources up to 20 m from the array. Localization accuracy decreased rapidly with increasing distance, and the array was able to produce bearings of the sound source only for sounds farther than 20 m away. Location and bearing errors were greatest aft of the boat.

The advantage to this array is that it is simple and cheap to build, with all components being readily available off the shelf. It is easy to manage with two people and is highly maneuverable, allowing large areas to be covered in little time. The array can be modified in many aspects to suit different boat requirements. Several simple modifications could be made to increase its accuracy. For example, the lengths of the poles in this array were dependent on the lengths that were obtainable as wind surfing masts (old broken masts were used in this case). Longer poles would increase the distance between the hydrophones and thereby increase accuracy of localization. The jubilee clips used to hold the hydrophones in place did move slightly when in strong currents. By fixing these in a more solid manner, either by clamping the aluminum poles or fixing them through the wind surfing masts, it may be possible to reduce this movement and thereby increase the accuracy of source locations.

The greatest inherent error is likely to be the limited spatial extent of the



a)

b)

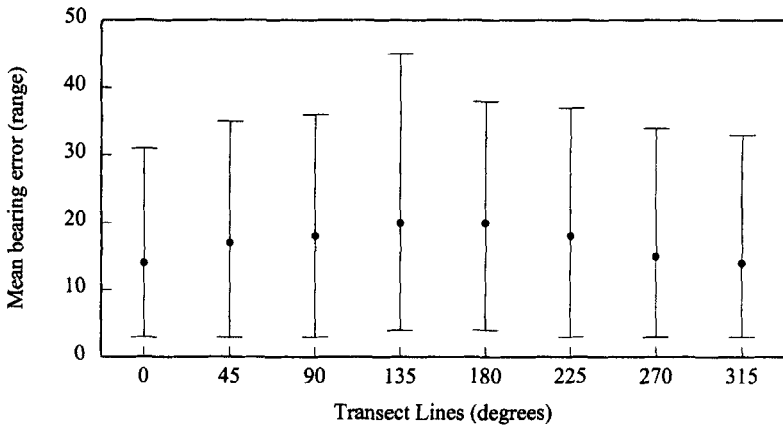


Figure 3. Trimmed mean bearing errors (range of error) for all cross-correlation calculations of the artificial sound source for (a) distance (30–500 m) and (b) transects ( $0^{\circ}$ – $315^{\circ}$ ).

array. The positions of the hydrophones were constrained by the structure of the boat. Larger distances among hydrophones increase magnitudes of the time delays. Measurement errors have a smaller effect on the accuracy of localization if delays are longer. This source of error could be overcome in other studies by placing the hydrophones farther apart, with relatively even spacing.

Topography and tidal currents can alter the sound path or reflect the sound energy of the source (Spiesberger and Fristrup 1990), causing errors in the calculations of source locations or bearings. This calibration experiment was carried out around high tide, so as to minimize the effects of tidal currents on the array, and in an area where the topography was uniform. Sea temperatures were constant. Overall, the accuracy of this array is less than that of a

range of land-based or large, towed arrays (e.g., Clark *et al.* 1986), but this system did provide valuable information.

This calibration experiment was carried out using engine sounds which were located close to the surface. It is likely that these cavitation sounds would be much more problematic for any localization than the sounds of a submerged seal. Therefore, we suggest that the localization of submerged harbor seal vocalizations (Van Parijs *et al.*, in press *a, b*) were more accurate than this calibration experiment may suggest.

In the harbor seal study, 64% of all vocalizations were recorded on all four hydrophones ( $n = 859$ ). Vocalizations with high SNR were used in this analysis, so as to minimize errors in the cross-correlation. Manual cross-checking of cross-correlation results were carried out by measuring the point at which the harbor seal vocalization produced a clear up-sweep in frequency forming the pulse part of the vocalization at around  $1.37 \pm 0.13$  Hz ( $n = 691$ ) (see Van Parijs *et al.* (1997) for a spectrogram of a harbor seal vocalization). Harbor seal vocalizations have one distinct peak, which can be used for cross-correlation calculations, although we found that it was vital that all calculations were cross-checked by hand (Van Parijs 1998).

The array allowed a wide area (700 km<sup>2</sup>) to be covered over a short time period (Van Parijs 1998; Van Parijs *et al.*, in press *a, b*). The array enabled the mapping of vocalizing male harbor seals, providing localizations from males close to the boat and bearings for males farther away (Van Parijs *et al.*, in press *a, b*). At this site, male harbor seals consistently displayed in a given area, and display areas were separated by 200–250 m (Van Parijs 1998). Therefore, the extent of the error in the array was not an issue in this study, as large distances separated males. The inherent errors with this array and processing scheme make it unsuitable for studies of vocal interactions among closely bunched individuals.

It is very important to calibrate the system when it is used in different study sites, as there are many variables that can have an impact on the accuracy of passive acoustic localization (Janik *et al.*, in press). As this array was used throughout a large study area, the inner Moray Firth, Scotland (57°41'N, 4°00' W), it was impossible to calculate localization errors in all regions. On a large scale the inner Moray Firth is an estuarine area of relatively simple bathymetry, with a seabed of predominately sand or mud and depths ranging from 1 m to >50 m (Reid and McManus 1987). In this study we did not use the array in areas of depth of 10 m or less, as the sandbanks were likely to alter male harbor seal vocalizations. Therefore, it is possible that localization errors varied between areas. However, the large scale of this study was unable to contend with this scope of potential error.

This array design was a trade-off between accuracy, call detection on all hydrophones, and mobility. The array was designed for a specific boat size and budget, limited man power, and the study species. Several modifications are possible in order to increase the accuracy of this design. Acoustic arrays are vital in facilitating the study of marine mammals at sea. In describing this

array design we hope to encourage other creative solutions to array-performance trade-offs, and wider use of this type of acoustic technology.

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#### LITERATURE CITED

- BEEMAN, K. 1996. SIGNAL localization user's guide. Engineering Design, Belmont, MA.
- BJØRGE A., D. THOMPSON, P. HAMMOND, M. FEDAK, E. BRYANT, H. AAREFJORD, R. ROEN AND M. OLSEN. 1995. Habitat use and diving behaviour of harbour seals in a coastal archipelago in Norway. Pages 221–223 in L. Walløe and Ø. Ulltang, eds. Whales, seals, fish and man. Elsevier, Amsterdam.
- CLARK C. W., W. T. ELLISON AND K. BEEMAN. 1986. Acoustic tracking of migrating bowhead whales. *Oceans 1986*, IEEE, New York, NY. pp. 341–346.
- HANGGI E. B., AND R. J. SCHUSTERMAN. 1994. Underwater acoustic displays and individual variation in male harbour seals, *Phoca vitulina*. *Animal Behaviour* 48: 1275–1283.
- JANIK, V. M., S. VAN PARIJS AND P. M. THOMPSON. 2000. A two-dimensional acoustic localization system for marine mammals. *Marine Mammal Science* 16:437–447.
- REID, G. L., AND J. MCMANUS. 1987. Sediment exchanges along the coastal margins of the Moray Firths, Eastern Scotland. *Journal of the Geological Society, London* 144:179–185.
- SPIESBERGER, J. L., AND K. M. FRISTRUP. 1990. Passive localization of calling animals and sensing of the acoustic environment using acoustic tomography. *American Naturalist* 135:107–153.
- VAN PARIJS, S. M. 1998. Reproductive strategies of male harbour seals, *Phoca vitulina*. Ph.D. thesis, Aberdeen University, U.K. 186 pp.
- VAN PARIJS, S. M., P. M. THOMPSON, D. J. TOLLIT AND A. MACKAY. 1997. Changes in the distribution and behaviour of male harbour seals in the mating season. *Animal Behaviour* 54:35–43.
- VAN PARIJS S. M., G. D. HASTIE, AND P. M. THOMPSON. In press *a*. Geographic variation in temporal and spatial patterns of aquatic mating male harbour seals. *Animal Behaviour*.
- VAN PARIJS, S. M., G. D. HASTIE AND P. M. THOMPSON. In press *b*. Individual and geographic variation in vocal and dive display behaviour of the harbour seal. *Animal Behaviour*.
- WATKINS, W. A., AND W. E. SCHEVILL. 1972. Sound source location by arrival-times on a non-rigid three-dimensional hydrophone array. *Deep-sea Research* 2:691–706.
- WATKINS, W. A., AND D. WARTZOK. 1985. Sensory biophysics of marine mammals. *Marine Mammal Science* 1:219–260.

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