SUPPLEMENTARY MATERIALS – SIMULATION AND CASE STUDY DETAILS, ADDITIONAL FIGURES AND TABLES

Supplementary details to Section 5.4 - Simulation details

In all simulations, a 3D survey area was created using a specified maximum detection range and a maximum depth (2000 m in both cases). For towed acoustic surveys, a specification of a maximum line length (4000 m) was also required. The size of the detection monitoring bearing was defined in radians and divided by two, as discussed in Section 3, giving a maximum monitoring bearing size of $\pi/2$. Density or abundance in the surveyed area was also specified (density could then be used to calculate abundance or *vice versa*). All animals in the created population were then assigned a random position using appropriate distributions for depth and horizontal distance. The vertical radial distance and bearing were calculated for each animal's position. The detection function (with known scale parameter) was evaluated for each animal's distance and a draw was made from a Bernoulli trial, using the estimated probability of detection, to simulate whether that animal was detected or not. Density and sigma values were adjusted between simulation scenarios (numbered 1-12 in Table 1) to obtain a similar expected sample size of detections ($n \approx 270$) for each scenario. The sample size was chosen to reflect a realistic sample size from an acoustic survey. The observation data were then created from the "detected" animals and saved as either radial distances or bearings, depending on the simulation. Using the observation data, a maximum likelihood algorithm in R version 3.1.2 (R Core Team, 2022) estimated the scale parameter, searching between values of 0 and 10000 using the optimise function. The maximum likelihood estimate of the scale parameter was then used to estimate the average probability of detection. The estimated density of animals was compared to the known true value by calculating the median percentage bias. The median percentage bias was also calculated for the scale parameter. Interquartile ranges for both estimated parameters were also calculated from the 1000 estimates. Simulation parameters are given in Table S1.

Supplementary details to Section 6.1 - Cuvier's beaked whales in the Gulf of Alaska

Full details of the survey design and data analysis are given in Rone *et al*. (2014). Approximately 6300 km of line transect acoustic survey effort was undertaken including four types of habitat: inshore, shelf, offshore and seamounts. Cuvier's beaked whales were successfully localised in the shelf, offshore and seamount regions. The DDDS methods currently cannot account for a continuously changing bathymetry and so a constant maximum depth was assumed and data were selected from the offshore and seamount regions only for this comparison. The modal depth (rounded to 100 m) for these two regions was 3800 m and was obtained from the ETOPO1 1 Arc-Minute Global Relief Model (Amante & Eakins, 2009).

The data were first analysed as perpendicular distances (i.e., ignoring the vertical location of the whales) using conventional distance sampling in the software Distance version 6.2 (Thomas *et al*., 2010). Distance can fit multiple detection function types and perform complex distance sampling analyses. To directly compare fitted detection functions, a half-normal detection function model was fitted to the data. Distances beyond 5 km (n = 2) were truncated due to uncertainty in the estimation of larger ranges. Truncation is commonly used in distance sampling analyses (Buckland *et al*., 2015). The scale parameter and probability of detection corresponding to a 5 km truncation distance were estimated. Abundance across both habitats and the corresponding average density (calculated as the mean weighted average of the density in both habitats, weighted by the area of both regions) were also estimated. Confidence intervals (95%) for all estimated parameters were produced using a non-parametric bootstrap procedure (run 999 times) that re-sampled the transect lines with replacement.

The data were then analysed using DDDS, specifically for a towed acoustic survey using range data. The maximum detection range was defined as 5000 m and the maximum bearing range that could be monitored was set to $\pi/2$ radians. Line length was equal to 3442 km (the amount of effort conducted in the offshore and seamount regions). The generalised beta depth distribution was similar to the distribution used in the simulations but the shape parameters were adjusted to match known information about Cuvier's beaked whale clicking behaviour taken from Tyack *et al.* (2006). Animals tagged in the Ligurian Sea near Italy with acoustic tags were found to start clicking at a minimum depth of 136 m and had a maximum foraging dive depth (where clicks were produced) of 1888 m. Their mean deep foraging dive depth was 1070 m (with a standard error of 210 m). Therefore, a scaled beta distribution where $s_1 = 5$, $s_2 = 15$, $l = 0$ m and $u = 3800$ m was defined (Figure S2). The scale parameter, probability of detection, abundance and density were estimated. Scale parameter values up to 10000 were considered in the maximisation routine. Confidence intervals were produced for all parameters using a non-parametric bootstrap procedure (run 999 times).

Supplementary details to Section 6.2 - Fin whales in the Atlantic Ocean

Matias & Harris (2015) suggested refinements to the range estimation method used in Harris *et al.*, (2013). These refinements were incorporated into the 1-day dataset. The estimated ranges were adjusted to use a ray tracing model for sound propagation, P-wave velocity in the sediment was updated to 1.7 km/s, and S-wave velocity in the sediment was set 0.3 km/s. The amplitude adjustment factor of 0.5 identified in Matias and Harris (2015) was also used. The instruments could not monitor across all incidence angles. Vertical bearings could not be estimated beyond a critical angle, which was determined by sound velocity properties in the water column and the seafloor sediments. The estimated critical incidence angle for this study area was 61.9 degrees/1.08 radians, based on an assumed P-wave velocity in the water of 1.5 km/s (Harris *et al*., 2013).

As in the previous case study, a half-normal detection function model was fitted in Distance to the horizontal distance data to compare conventional distance sampling results with results using the depth distribution methods. The scale parameter, probability of detection and average fin whale call density (calculated as the mean weighted average of densities around each OBS, weighted by the monitoring area) were estimated. Animal density could not be estimated due to a lack of information about the calling rate of fin whales, which is required to convert call density to animal density. Confidence intervals (95%) for all estimated parameters were produced using a non-parametric bootstrap procedure (run 999 times) that re-sampled the separate OBSs with replacement.

To implement the DDDS methods, the maximum detection range for each instrument was estimated for each OBS (4235 m, 4392 m and 4397 m), given the critical angle and deployment depth. The maximum bearing was set to the critical angle (1.08 radians). Based on limited information about calling fin whales, which suggests that whales call in the top tens of meters of the water column (Watkins *et al*., 1987; Rebull *et al*., 2006), the scaled beta depth distribution was restricted to the top 100 m of the water column. Within the top 100 m of the water column, a generalised beta distribution with $s_1 = 10$ and, $s_2 = 5$ was implemented. The upper limit was set to the maximum depth (interpreted as elevation for a seafloor-mounted fixed sensor) and the lower limit was 100 m less than the upper limit (Figure S3). The scale parameter, probability of detection for each instrument and the weighted average fin whale call density were estimated. Confidence intervals (95%) for all estimated parameters were produced using a non-parametric bootstrap procedure (run 999 times).

Supplementary References

Amante, C. and B.W. Eakins (2009) ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis. NOAA Technical Memorandum NESDIS NGDC-24. National Geophysical Data Center, NOAA. doi:10.7289/V5C8276M [15 Oct 2014].

Buckland, S. T., Rexstad, E., Marques, T. A., & Oedekoven, C. S. (2015). Distance sampling: methods and applications. (Methods in statistical ecology). Springer. https://doi.org/10.1007/978-3-319-19219-2

Matias, L. & D. Harris. (2015) A single-station method for the detection, classification and location of fin whale calls using ocean-bottom seismic stations. The Journal of the Acoustical Society of America 138(1):504. doi: 10.1121/1.4922706.

Rebull O. G., Cusí J. D., Fernández M. R. & Muset J. G. (2006) Tracking fin whale calls offshore the Galicia Margin, north east Atlantic ocean. The Journal of the Acoustical Society of America, 120(4): 2077-2085.

Rone, B.K., A.B. Douglas, T.M. Yack, A.N. Zerbini, T.N. Norris, E. Ferguson, and J. Calambokidis. 2014. *Final Report for the Gulf of Alaska Line-Transect Survey (GOALS) II: Marine Mammal Occurrence in the Temporary Maritime Activities Area (TMAA)*. Submitted to Naval Facilities Engineering Command (NAVFAC) Pacific, Honolulu, Hawaii under Contract No. N62470-10-D-3011, Task Order 0022, issued to HDR Inc., San Diego, California. Prepared by Cascadia Research Collective, Olympia, Washington; Alaska Fisheries Science Center, Seattle, Washington; and Bio-Waves, Inc., Encinitas, California. April 2014.

R Core Team (2022). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Thomas L., Buckland S. T., Rexstad, E. A., Laake, J. L., Strindberg, S., Hedley, S. L., Bishop, J. R. B., Marques, T. A. & Burnham, K. P. (2010) Distance software: design and analysis of distance sampling surveys for estimating population size. Journal of Applied Ecology 47:5–14.

Watkins, W. A., Tyack, P., Moore, K. E. & Bird, J. E. (1987) The 20-Hz signals of finback whales (Balaenoptera physalus). Journal of the Acoustical Society of America 82: 1901–1912.

Supplementary Figures and Tables

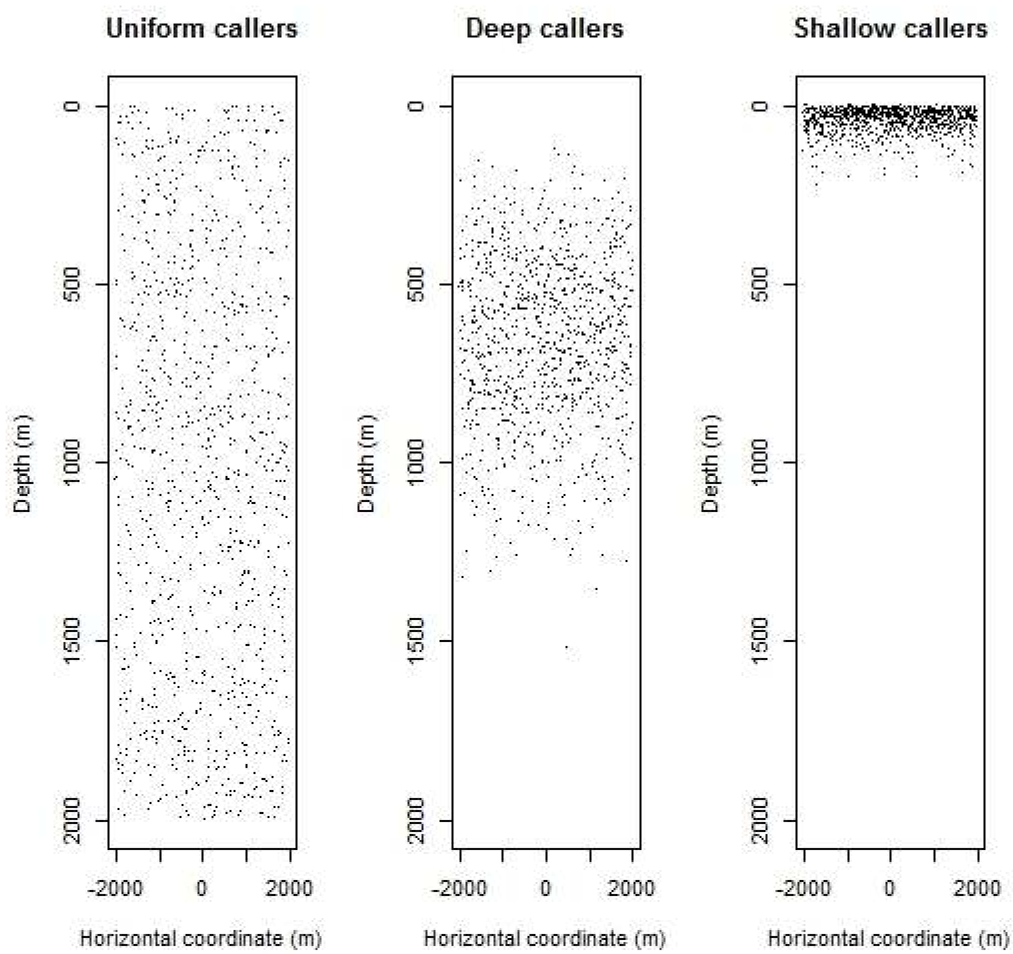

Figure S1a-c Examples of simulated populations with different vocal behaviour. For all plots, 1000 animals have been simulated, with maximum depth and detection range both set to 2000 m. Figure S1a depicts a population that vocalises at all depths, simulated using a uniform distribution. Figure S1b depicts a population that vocalises at deeper depths, simulated using a scaled beta distribution (s_1 = 5, s_2 = 10, l = 0 m, u = 2000 m). Figure S1c depicts a population that vocalises at shallower depths, simulated using a scaled beta distribution (s_1 = 5, s_2 = 10, l = 0 m, u = 2000 m).

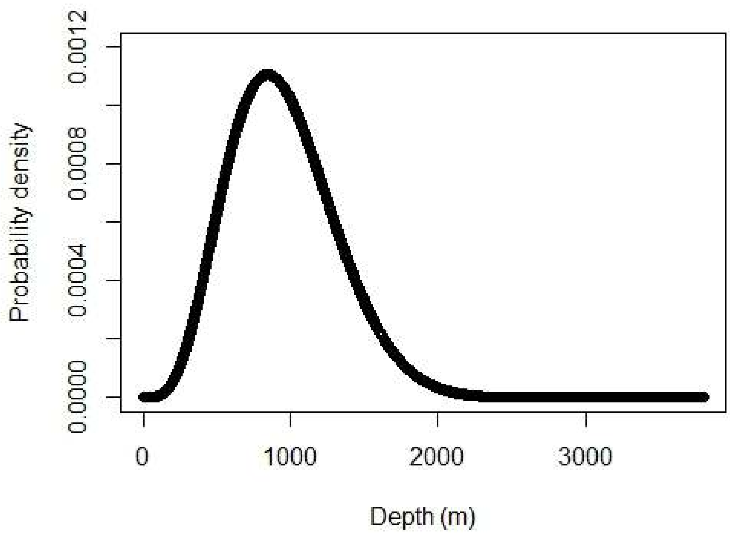

Figure S2 Scaled beta probability density function used for the depth distribution of Cuvier's beaked whales ($s_1 = 5$, $s_2 = 15$, $l = 0$ m and $u = 3800$ m).

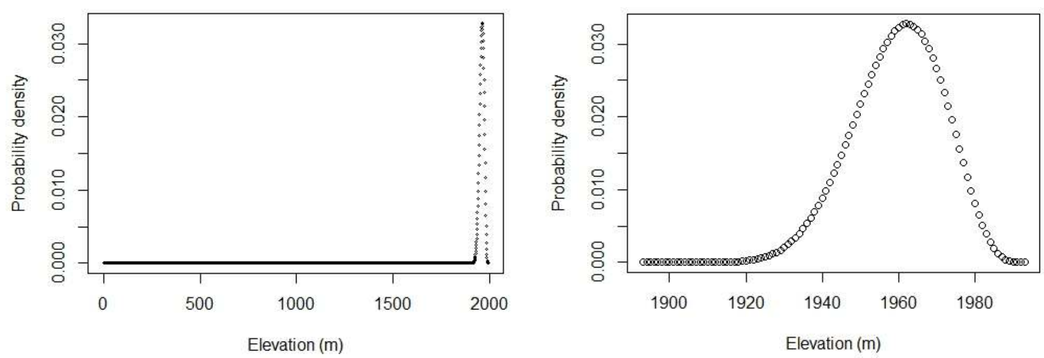

Figure S3 Illustrative samples taken from the scaled beta probability density function used for the depth distribution of fin whales ($s_1 = 10$, $s_2 = 5$, l = maximum elevation - 100 m and u = maximum elevation). These figures show a maximum depth of 1993 m.

Table S1. Inputs for a simulation study to measure the bias in density estimates using Depth Distribution Distance Sampling. Each simulation was run 1000 times. Maximum depth for all simulations was 2000 m.

The maximum bearing for all simulations using was set to 1.57 radians, or 90 degrees. When simulating a towed survey, line length was set to 4000 m. The scale parameter range used in the maximum likelihood algorithm was 0 – 10000.

Simulation number	**Survey type**	**Data type**	**Depth distribution**	**True density (animals/km^2)**	**True scale parameter**	**Maximum detection radius (m)**
1	Towed	Range	Uniform	156	500	2000
2	Fixed	Range	Uniform	156	800	2000
3	Fixed	Elev. angle	Uniform	156	800	2000
4	Towed	Range	Scaled beta - deep	125	500	2000
5	Towed	Elev. angle	Scaled beta - deep	125	500	2000
6	Fixed	Range	Scaled beta - deep	250	800	2000
7	Fixed	Elev. angle	Scaled beta - deep	250	800	2000
8	Towed	Range	Scaled beta - shallow	63	500	2000
9	Towed	Elev. angle	Scaled beta - shallow	63	500	2000
10	Fixed	Range	Scaled beta - shallow	1250	800	2000
11	Fixed	Elev. angle	Scaled beta - shallow	1250	800	2000

Table S2. Estimated probabilities of detection for three OBS instruments, deployed at similar depths in the Gulf of Cadiz. Each instrument had a different maximum horizontal monitoring range, resulting in differing probabilities of detection. A non-parametric bootstrap was run (999 times) to generate 95% confidence intervals (given in parentheses).

OBS label	Maximum horizontal monitoring range (m)	Estimated probability of detection
OBS04	4235	0.051 (0.003 – 0.350)
OBS10	4392	0.042 (0.002 – 0.326)
OBS16	4397	0.042 (0.002 – 0.326)