



## A dive counting density estimation method for Blainville's beaked whale (*Mesoplodon densirostris*) using a bottom-mounted hydrophone field as applied to a Mid-Frequency Active (MFA) sonar operation

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### ABSTRACT

We present a passive acoustic method for estimating the density of echolocating cetaceans that dive synchronously, based on isolation of dive starts using a field of distributed bottom-mounted hydrophones. The method assumes that all dive starts of the target species within a defined area are detected, and that independent estimates of dive rate and group size are available. We apply the method to estimate the density of Blainville's beaked whales (*Mesoplodon densirostris*) at the Atlantic Undersea Test and Evaluation Center (AUTEK) in the Bahamas during the time of a multi-ship active sonar exercise. Estimated densities for the 65 h before the exercise, 68 h during, 65 h after, and the final 43 h monitored were 16.99 (95% CI 13.47–21.43), 4.76 (3.78–6.00), 8.67 (6.87–10.94), and 24.75 (19.62–31.23) respectively, illustrating a possible avoidance reaction. Results for the 65 h before were compared with those from the click count density estimation algorithm developed by Marques et al. [Marques T, Thomas L, Ward J, DiMarzio N, Tyack P. Estimating cetacean population density using fixed passive acoustic sensors. An example with Blainville's beaked whales. *J Acoust Soc Am* 2009;125(4):1982–1994]. The click count-based estimate was 19.23 animals/1000 km<sup>2</sup> (95% CI 12.69–29.13)—similar (13% higher), but with higher variance (CV 21% for click count method versus 12% for the dive count method). We discuss potential reasons for the differences, and compare the utility of the two methods. For both, obtaining reliable estimates of the factors that scale the measured quantity (dive starts or detected clicks) to density is the key hurdle. Defining the area monitored in the dive count method can also be problematic, particularly if the array is small.

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### 1. Introduction

Increasingly, passive acoustic methods are promoted as viable means of monitoring marine mammals *in situ*. If populations are to be studied using such methods, a means of passive acoustic density estimation must be developed, where density is defined as number of animals per unit area. This is particularly important in regions of concentrated anthropogenic disturbance. One such location, the US Navy's Atlantic Undersea Test and Evaluation Center (AUTEK), is a site of repeated sonar use. On-going tests have isolated Blainville's beaked whales year-round [1]. AUTEK is located in the Tongue Of The Ocean (TOTO) in the Bahamas and contains a distributed set of 82 bottom-mounted hydrophones that have been used successfully to monitor cetacean vocalizations in real-time [2]. In particular,

these hydrophones are used to detect Blainville's beaked whales (*Mesoplodon densirostris*), a species of beaked whale that has been associated with mass stranding events involving Mid-Frequency Active (MFA) sonar at other locations including the NW Providence Channel less than 50 miles north of AUTEK [3,4].

Blainville's beaked whales are known to vocalize only during deep foraging dives [5]. The vocalizations typically consist of a short  $\sim 270 \mu\text{s}$  upsweep with a  $-10 \text{ dB}$  bandwidth of 26–51 kHz [6]. The estimated source level is over 200 dB re  $\mu\text{Pa}$  @ 1 m [7] with a mean inter-click interval of 0.31 s [8]. A passive acoustic density estimation method based on isolating the start of Blainville's beaked whale foraging dives is presented. The start of a foraging dive is considered as the time of the first detected echolocation click. This method is applied to a multi-ship active sonar operation at AUTEK. The density of animals before, during, and after the operation is estimated using passive acoustic dive counting and compared to a previous method, click counting [9], based on counting the number of echolocation clicks.

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## 2. Methods

### 2.1. Passive acoustic density estimation: click counting and dive counting

This paper presents a new method called dive counting for estimating the density of Blainville's beaked whales using passive acoustics. Dive counting uses the number of dive starts to determine the number of animals present. This method is compared to a method previously published for passive acoustic density estimation that we refer to as click counting [9]. Dive counting and click counting are both examples of cue counting [10]: in dive counting the start of a dive is considered the cue, whereas in click counting the cue is an echolocation click. While both are cue counting methods, the dive counting method described here assumes we accurately count all the cues, while the click counting method allows both for missed cues and false positives.

### 2.2. Click counting

For Blainville's beaked whale, a passive acoustic cue counting method has been developed to estimate density [9] where an echolocation click is used as the cue. The total number of clicks detected over a fixed time period is assumed proportional to the number of animals present. This method requires estimation of the probability of detecting a click at a given distance, and rate of false positives (i.e., the rate of detecting a different signal but classifying it as a cue of interest). The equation used to estimate animal density is:

$$D = \frac{n(1-c)}{K\pi w^2 p T r} \quad (1)$$

where  $D$  = animal density;  $n$  = number of detected cues;  $c$  = proportion of false positives;  $K$  = number of replicate sensors;  $\pi w^2$  = circular area defined by some range,  $w$ , beyond which no cues can be detected;  $p$  = average probability of cue detection within range  $w$ ;  $T$  = time period over which the measurement was made;  $r$  = cue production rate

Given estimates of the necessary parameters ( $c$ ,  $p$  and  $r$ ), an estimate of density can be made by counting the number of click detections over a specified period ( $n$ ) and applying the above formula. Marques et al. [9] suggest estimating variance by applying the delta method [10], which leads to the formula:

$$\text{var}(\hat{D}) \approx \hat{D}^2 [CV(n)^2 + CV(\hat{r})^2 + CV(\hat{c})^2 + CV(\hat{p})^2] \quad (2)$$

where  $CV(\hat{x})$  denotes the coefficient of variation of  $\hat{x}$ —i.e., standard error of  $\hat{x}$  divided by  $\hat{x}$ .

Confidence limits on  $D$  can be obtained by assuming that  $D$  follows a log-normal distribution (Buckland et al. [11], p. 77). Student's  $t$ -based intervals may be more appropriate where some of the parameters making up  $D$  are estimated with low degrees of freedom [11], but for simplicity log-normal intervals are used here. Estimation of the required CVs depends on how the parameters are measured—usually they are the mean or weighted mean of some measurements and standard methods can be used.

Note that the method is not sensitive to choice of  $w$ , so long as it is large enough that no cues can be detected at larger ranges. The method is also insensitive to detector performance, but does require knowledge of the detectors performance *in situ*.

The performance of a signal detector in Gaussian white noise is readily characterized. Typically, a Receiver Operating Curve (ROC) is generated which presents the probability of detection (PD) for a given false alarm rate (FA) [12,13]. But the ocean environment is complex. For marine mammals, the real-world performance in terms of the proportion of false positives ( $c$ ) is often a function of non-Gaussian interferers. The detection and correct classification

of vocalizations for Blainville's beaked whale is highly dependent on the density of interfering marine mammal species as well as anthropogenic noise sources such as shipping, depth finders, and ancillary pingers. This means that the false positive rate (FA), or in the above formula, the estimated proportion of false positives ( $c$ ) is time and site specific.

In addition, estimation of animal density requires characterizing the detection performance over a given range. Such range dependency must be derived and included in the methodology. For a given detection algorithm, normalization of FA through changes in the detection threshold will directly affect the probability of cue detection ( $p$ ), the range over which this is calculated ( $w$ ), and the proportion of false positives ( $c$ ). The probability of detection ( $p$ ) over range ( $w$ ) will be directly affected by site-specific acoustic propagation from source to receiver. Sensors distributed over a particular site may be sensitive to both temporal and spatial variation. Hence,  $p$  as well as  $c$  is time and site specific.

*In situ* measurement of  $c$  is relatively straightforward, if a human operator can be taken to be the “gold standard”: it simply involves taking a sample of detections and manually checking how many are incorrect. This “gold standard” assumption relies on a visual verification method with a higher probability of detection (PD) and lower false alarm rate (FA) than the detection algorithm under test which can be problematic. By contrast, estimation of  $p$  is non-trivial. In the study of Marques et al. [9], this was heavily dependent on the use of data obtained from Woods Hole Oceanographic Institution (WHOI) digital recording tags (DTags) [14]. The tag recorded the clicks produced by the animal. These clicks were directly compared to clicks detected on the surrounding hydrophones to determine the probability of detection at a known range for that individual animal. Obtaining the range from the animal to the hydrophone demanded that the position of the animal be precisely calculated. This was done by combining the outgoing clicks recorded on the tag with those detected on the surrounding hydrophones. The Time Difference Of Arrivals (TDOAs) were measured, and the animal position calculated using a hyperbolic tracking algorithm. Once probability of detection at known distances was estimated, the average detection probability ( $p$ ) could be estimated by integrating appropriately over distance [9]. The tags also provided a direct measure of the click production rate ( $r$ ). Note that the tag data were not obtained at the same time as the main dataset of clicks used to estimate density—something that we return to in the discussion.

As the variables required for click counting are a function of location, time, algorithm type, and threshold levels, accurate measurement of animal density requires a determination of these variables for each site. Because of these limitations, an alternate method of density estimation is proposed which involves cue counting based on dive starts as opposed to clicks.

### 2.3. Dive counting

#### 2.3.1. Density estimation equation

Blainville's beaked whales are known to associate in groups [15] and to exhibit metronomic dive behavior [5,16]. Within a dense field of sensors where dives are certain to be detected, this dive rate coupled with the average group size can be used as a measure of animal abundance ( $N$ ). This relationship is given by:

$$N = \frac{n_d s}{r_d T} \quad (3)$$

where  $n_d$  = total number of dive starts;  $s$  = average group size;  $r_d$  = dive rate (dives/unit time);  $T$  = time period over which the measurement was made

Note this is a direct extension of Eq. (1) once we assume that there are no false positives and the probability of detecting a

dive is 1. Density ( $D$ ) is obtained by dividing the abundance ( $N$ ) by the total area ( $A$ ) over which the measurement was made, giving

$$D = \frac{n_d s}{r_d T A} \quad (4)$$

where  $A$  = measurement area.

This methodology is less dependent on detection algorithm performance and less sensitive to detection thresholds and acoustic propagation effects. The method assumes that all groups of animals diving within the field of sensors are detected. This requires a sensor layout that, when coupled with the detection algorithm, guarantees detection. Lacking this, the probability of detecting a group vocal period must also be measured and included in the denominator of the above equation. (Strictly, it is the probability of detecting a dive start that must be quantified, but if  $T$  is commonly large compared with  $1/r_d$  then probability of detecting a dive is sufficient.) The method also assumes no false positives. For the case described below, data were screened to verify this assumption. This could however be included in the formulation if required.

As with click counting, variance can be estimated using the delta method. Assuming that  $s$  is measured without error, and that  $s$  and  $r_d$  are estimated independently of one another, then

$$\text{var}(\hat{D}) \approx \hat{D}^2 (CV(\hat{s})^2 + CV(\hat{r}_d)^2) \quad (5)$$

Again, as with click counting, confidence limits on  $D$  can be obtained by assuming that  $D$  follows a log-normal distribution.

### 2.3.2. Group size ( $s$ )

Based on visual observations, Blainville's beaked whales are known to associate and dive in small groups. Within the Northern Bahamas, an average group size of 4.1 animals has been measured ( $n = 111$ ,  $SD = 1.9$ ) [15]. The average group size of Blainville's beaked whales off the Big Island in Hawaii has been reported as 3.6 animals ( $n = 11$ ,  $SD = 3.0$ ) [17].

### 2.3.3. Dive starts ( $n_s$ )

Blainville's beaked whales produce echolocation clicks during deep foraging dives. Therefore, the dive start ( $n_s$ ) is the start of a vocal period during a foraging dive for a group of animals, where the vocal period is determined from echolocation click detections. This method assumes that groups and hence dive starts are separable, and that groups dive synchronously. Dive starts for groups in close spatial and temporal proximity must be determined.

### 2.3.4. Dive rate ( $r_d$ )

The dive rate is a measure of the average number of deep foraging dive starts per hour (which is the same as the average number of dives per hour over a long measurement period). For Blainville's beaked whale, the dive rate for deep foraging dives (>800 m) has been found to be similar throughout the day and night with little diel variation [16]. Echolocation clicks are produced when the group is in a deep foraging dive. Therefore, detected clicks represent a group of animals. Dive rate ( $r_d$ ) is primarily derived from dive profiles as measured by tags attached to animals. The dive rate for Blainville's beaked whale derived from animals in the Mediterranean is 0.44 dives/h (16 dives over 36.7 h for three animals) as reported by Tyack et al. [5] and 0.42 dives/h if day and night rates reported by Baird et al. [16] are averaged for animals off the coast of the Big Island in Hawaii.

## 3. Case study: multi-ship active sonar exercise

### 3.1. Dive counting

#### 3.1.1. Overview

The dive counting methodology was applied to a multi-ship sonar exercise that took place over 3 days in May 2008 at AUTEK. Hydrophone detection data were archived approximately 65 h before, 68 h during, and 108 h after the operation. The period after active operations was further divided into the 65 h period immediately after the cessation of active operations and the 43 h remaining.

#### 3.1.2. Group size ( $s$ )

A mean group size ( $s$ ) of 2.62 animals/group ( $n = 73$ ,  $SE = 0.14$ ,  $CV = 5.46\%$ ) has been measured for Blainville's beaked whale groups observed on the AUTEK range by Claridge [1] and was used in the analysis for this case study. This number was derived from tests conducted on the AUTEK range in which visual observers were directed to beaked whales using passive acoustic monitoring of the hydrophone field.

#### 3.1.3. Dive starts ( $n_d$ )

Dive starts were first isolated from detection archives. These archives consist of detection records generated from a Fast Fourier Transform (FFT) based detector. They contain the time of detection and the frequency bins in the FFT that were reported with energy above an adaptive bin threshold. A simple exponential average is used as the threshold. A 2048 point FFT with 50% overlap at a sample rate of 96 kHz is executed. This provides a bandwidth resolution of 46.875 Hz [8].

Using detection archives, the analyst separated groups by considering group vocal period length, maximum detection range, inter-click interval (ICI) and click structure. Detection reports were first screened for interferers. Clicks with frequencies between 24 and 48 kHz at an ICI between 0.26 and 0.40 s were classified as Blainville's beaked whale. Group separation was based on temporal and spatial limits on the group vocal period, as follows. The average group vocal period for a given dive is approximately 31 min [18]. Second, a maximum 6.5 km detection range has been measured for the FFT based detector on the bottom-mounted AUTEK sensors [8]. At AUTEK the baseline between hydrophones is approximately 3.8 km [2]. For a given vocal period, a group was generally considered to encompass all hydrophones within one baseline of the hydrophone with the most click detections, although in some instances additional hydrophones were included with the group. Typically, hydrophones are arranged in hexagonal arrays with a center phone. Given this criteria, up to seven hydrophones could generally be assigned to the same group.

In instances when there were overlapping groups of vocalizing animals, an analyst compared the arrival times of distinguishable groups of clicks on adjacent hydrophones and took into account other parameters such as detection range and duration of click trains. This allowed for a separation of overlapping vocal groups and a determination of the duration of their vocal periods.

The occurrence of overlapping groups was measured and is presented in Table 1. Of the total number of groups detected before

**Table 1**  
Occurrence of overlapping group vocal periods.

Measurement period	Total # of groups	# of overlapping groups	%
65 h before sonar	263	49	18.63
68 h during	93	11	11.83
365 h after sonar	365	70	19.18

**Table 2**

Dive rates as measured from five tagged animals at AUTEK. Mean is weighted by number of dives recorded per animal.

Tag deployment	Foraging dives	Record length (h)	Dives/h
md06_296a	6	17.7	0.34
md07_227a	7	15.94	0.44
md07_248a	5	12.85	0.39
md07_248b	4	16.52	0.24
md08_271a	1	1.6	0.63
		Weighted mean	0.36
		Weighted standard error	0.04
		Coefficient of variation (%)	10.6

and after sonar operations, ~19% were derived by applying these overlap criteria. During sonar, significantly fewer dive starts were detected with ~12% derived from overlapped conditions.

### 3.1.4. Dive rate ( $r_d$ )

Data from five tagged Blainville's beaked whales at AUTEK were used to estimate the dive rate. As the process of tagging the animal may illicit a response, the measurement period was started at the end of the first foraging dive. A total of 64.6 h of tag data and 23 dives were included from five tags. To aid precision, we calculated mean dive rate, weighted by the record length in hours, so that animals for which we had more data were weighted more heavily in the calculation. Variance for this weighted mean was calculated using Cochran's method [19]. The weighted mean dive rate was 0.36 dives/h with a weighted standard error of 0.04 and CV of 10.6% (Table 2). Note these results are somewhat lower than those from Tyack (0.44 dives/h) for animals in the Mediterranean and Baird (0.42 dives/h) for animals in Hawaii as cited above.

### 3.1.5. Measurement area (A)

It is assumed that isolated Blainville's beaked whale groups are within a bounded area. Given the measured performance of the FFT based detection algorithm, a maximum detection range of 6.5 km was used. First the outer most hydrophones (edge phones) were identified. A boundary was established based on a 6.5 km radius from the first inner hydrophones (Fig. 1) and a total measurement area (A) of 1291 km was obtained.

If a group of foraging animals was within this boundary, vocalizations would be detected on both the edge and inner row hydrophones. If detections were made only on edge hydrophones, the group was assumed to be outside the measurement area (A) and the associated dive start was discounted.

### 3.1.6. Dive counting results

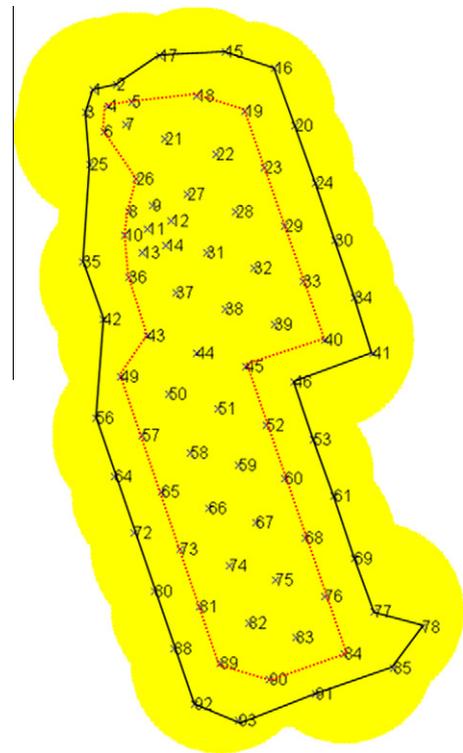
Over the entire test period, 721 group vocal periods were detected over all range hydrophones. Of these, 538 group vocal periods and associated dive starts were isolated on the range hydrophones using the criteria described in Section 3.1.3. One hundred and ninety-four periods were isolated for the 65 h period before, 57 for the 68 h period during, 99 for the 65 h after, and 188 for the final 43 h period after sonar.

These data were combined with the dive rate ( $r_d$ ) of 0.39 dives/h, average group size ( $s$ ) of 2.62 animals/group, and the respective time ( $T$ ) for each of the four measurement periods to estimate animal abundance and density. These results are summarized in Table 3.

## 3.2. Click counting

### 3.2.1. Overview

To compare density estimation methods click counting was applied to the 65 h period before the MFA multi-ship sonar opera-



**Fig. 1.** Range sensor layout with measurement area in yellow and edge hydrophones (black line). The dashed red line indicates the inner phones used to calculate the measurement area (A). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

tions. The same detection archives as used for the dive counting were analyzed. All clicks that were characterized as Blainville's beaked whale were extracted and click count sums were calculated for all 82 range hydrophones.

Click counting was not attempted during the sonar exercise as the level and complexity of background noise is significant. The statistics including the probability of detection, false positive rate, the effective circular area of coverage are sure to change. Given the data currently available, it is not possible to calculate these statistics for this period. By contrast, given the animal's source level, the dive counting assumption that dives are not missed is maintained.

The number of clicks detected over the 82 hydrophones and 3801 min was 1,266,437.

Variance was calculated using the standard formula for variance of a sum of independent quantities (see Marques et al. [9], p. 1984), which gave a SE of 85,827 and CV 6.78%.

### 3.2.2. False positive proportion (c)

To determine the false positive proportion, twenty 10 min samples were extracted from the data archives. The samples were uniformly spaced with a random start time. The samples were manually scanned to determine if they contained Blainville's beaked whale clicks. The 20 samples contained 68,586 detections classified as beaked whale of which 17,578 were interferer signals. This corresponds to a false positive proportion (c) of 0.257, with its complement ( $1 - c$ ) being 0.744. Variance was calculated following the methods of Marques et al. [9], which treats each of the 20 samples as an independent sample of false positive rate; hence c is the mean false positive rate from the 20 samples, weighted by the number of detections in each sample, and the variance can be calculated using Cochran's method [19]. This gave an SE for ( $1 - c$ ) of 0.060, and CV of 8.09%.

**Table 3**  
Estimated abundance and density based on dive counting, with corresponding coefficient of variation (CV). Values in brackets after the estimates are 95% confidence limits.

Time period	Abundance	Density (whales/1000 km <sup>2</sup> )	CV (%)
Before sonar (65 h prior to initial transmission)	22 (17–28)	16.99 (13.47–21.43)	11.89
During sonar (68.13 h of transmission)	6 (4–8)	4.76 (3.78–6.01)	11.89
After sonar (65 h after last transmission)	11 (8–14)	8.67 (6.87–10.94)	11.89
>65 h after sonar (43.23 h)	32 (25–40)	24.76 (19.63–31.23)	11.89

### 3.2.3. Average detection probability ( $p$ )

We used the values given by Marques et al. [9], which were based on an analysis of 13 dives from four tagged whales (all of those from Table 2 except Md271). For a truncation distance of  $w = 8$  km they estimated  $\hat{p} = 0.032$  with an associated CV of 15.9%.

### 3.2.4. Click rate ( $r$ )

Again, we used the values from [9], which were based on an analysis of 21 dives from five whales (all of those from Table 2 except Md271, but with the addition of whale Md245; see [9] for details). Click rate was estimated as a weighted mean of the click rate per dive, weighted by dive time. The resulting value was 0.407 clicks/s, with SE 0.040 and CV of 9.8%.

### 3.2.5. Density estimation

Substituting the above estimates into Eq. (1), gave a density estimate for the “pre-exercise” time period of 19.23 whales/1000 km<sup>2</sup>. Using Eq. (2), the corresponding variance was 16.99, giving a CV of 21.43%, with 95% confidence limits on  $D$  of 12.69–29.13.

## 4. Discussion

### 4.1. Comparison of dive counting and click counting estimates

The dive counting density estimation method presented provides a means of estimating the abundance and density of Blainville's beaked whales from a field of hydrophones. For this example, dive starts were extracted in a semi-automated fashion that required an analyst to verify the presence of beaked whales. It also requires an estimate of average group size ( $s$ ) and dive rate ( $r_d$ ) for the bounded measurement area ( $A$ ).

For comparison, the 65 h period ahead of the multi-ship sonar operation was analyzed using the click counting density estimation method [9]. The click count method estimated a Blainville's beaked whale density of 19.23 animals/1000 km<sup>2</sup> (95% CI 12.69–29) as opposed to an estimate from dive counting of 16.99 animals/1000 km<sup>2</sup> (95% CI 13.47–21.43). Thus the click counting estimate was 13% higher than that from dive counting, although confidence limits from each method easily includes the other method's point estimate. We do not go so far as to say they are statistically indistinguishable because they are not independent, being based on the same hydrophone and almost the same tag data. Note the coefficient of variance for dive counting was 11.89% versus 21.43% for click counting.

### 4.2. Comparison of assumptions and external data requirements

Both methods rely on a set of externally estimated factors or “multipliers” to scale the measured quantity (dive starts or detected clicks) to an estimate of density. These can be broadly divided into two varieties: (1) multipliers that account for the imperfect detection process, i.e., false positives and false negatives; and (2) multipliers that account for the fact that counts are not of individual animals, but of cues assumed linearly related to animal numbers. Dive counting has stronger assumptions about the detection process (that dive starts will be detected with certainty and

that there are no false positives) and hence has no detection-related multipliers. There are, however, two cue-related multipliers: group size ( $s$ ) and dive rate ( $r_d$ ). Click counting does not require perfect detection, but therefore requires multipliers to account for false positives ( $c$ ) and false negatives ( $p$ ). There is only one cue-related multiplier, click rate ( $r$ ). Which method is preferred will depend on how well the assumptions of the methods can be met and how reliably the required multipliers can be estimated. Since many of the multipliers must often be derived from data obtained at different times and even places than the time and place where the density estimate is required, it will be important to consider whether these are valid for the application used.

Dive counting relies on estimates of mean group size ( $s$ ), and for many species these can be obtained from visual data. Based on preliminary analysis, there was no indication of systematic changes in mean group size over the period our group data was collected. Dive counting also requires an estimate of dive rate, which we obtained from tag data collected from five animals tagged between 2006 and 2008. Sample size will always be a limitation for tagging studies; nevertheless, our values agree reasonably well with those from tagging studies on the same species in other locations and hence it appears for this species that dive rates may be relatively stable across time and space. It may be possible to obtain dive rate data from visual studies, but like tagging this will be difficult, costly and very labor-intensive. One consideration is that the acoustic disturbance associated with the sonar exercise caused animals to change their diving behavior; hence it would be desirable to have measurements of dive times of animals under such conditions to confirm that the estimated changes in density are not due to changes in dive rates.

Click counting requires an estimate of the proportion of false positives ( $c$ ), and this is the one multiplier that is relatively straightforward to obtain. Part of the analysis for the click counting method included recalculation of the proportion of false positives ( $c$ ). This rate was measured as 0.257 as compared to 0.451 or 0.511 (depending on assumptions about ambiguous detections) as reported by [9] for a 6-day period in the spring of 2005. Both AUTECH data sets were collected from periods in the spring of the year; however the current case study data were collected during a period of high range activity. The 65 h ahead of the multi-ship sonar exercise should not be used for a comparison with baseline beaked whale activity. Although there was little or no active sonar present, there was significant range activity. In [9], interferers consisted predominantly of vocalizations from delphinid species. In the current study false positives were attributed by the analyst to other sources of anthropogenic noise including acoustic communications, pingers, and boat noise. Few delphinid vocalizations were detected in the data. This difference illustrates the sensitivity of the method to changes in local acoustic conditions.

Click counting also requires an estimate of average detection probability ( $p$ ) within some distance  $w$ . As discussed by [9], there are several ways that this statistic could be obtained, for example using recorded distances to detected cues along with an assumption about animal distribution. In general, methods that allow estimation at the same time and place as the time and place for which density is to be estimated are to be preferred. In this study, we used tag data from another time, and it is quite possible that our

estimate of  $p$  is incorrect due to differences in acoustic conditions. One obvious consideration is changes in detectability due to changes in ambient noise, and this is the subject of a current investigation. The truncation distance,  $w$ , used in a click counting analysis is not critical, and we used the same value (8 km) used in [9]. Had we used a value of 6.5 km, as was used for the dive counting method, we would have had to re-calculate the  $\hat{p}$  this new value would have been higher and the product  $w^2\hat{p}$  would have remained approximately the same, producing approximately the same density estimate. The quantity  $w^2p$  is referred to as the effective detection radius in the distance sampling literature, e.g. [11].

Lastly, click counting requires an estimate of average click rate,  $r$ . As with dive rate, it appears that the average click rate over reasonably long time periods is quite stable; however it is also possible that the acoustic disturbance associated with the sonar exercise caused animals to alter their clicking behavior.

Comparing the two methods, one key difference is the requirement to accurately quantify detector performance for click counting, whereas for dive counting it is just required that sensors are close enough together that diving groups can be detected with certainty and accurately separated, and that the area surveyed,  $A$ , is known. Click counting, the way it is implemented here and in [9], does not require dives to be detectable on multiple hydrophones, and hence can be applied using an array of very widely separated hydrophones; dive counting, by contrast, requires a dense array. Hence we are trading off more effort in hydrophone placement against a milder requirement for detector characterization. The best method will, therefore, depend on the resources available and the acoustic biology of the study species, as well as what is known about this.

Dive counting is less sensitive than click counting to detector performance. However, the calculation of the bounded measurement area ( $A$ ) was based on the detection range and so in practice is not known with certainty. Given the size of the censused area, the sensitivity to the chosen maximum detection range is relatively small. For click counting, every detected click is a cue versus the start of the dive for dive counting. Consequently, the click counting algorithm is particularly dependent on the probability of detection.

For species that produce omni-directional sounds, a more robust dive counting algorithm would be one that discarded all dives where the number of sounds recorded on the outer set of hydrophones was greater than those recorded on the first set of inner phones. The area surveyed,  $A$ , is then the polygon formed by joining lines that run half way between the outer and first inner phones. In our case, because calls from beaked whales are highly directional, we could not use the relative number of calls received at adjacent hydrophones as an indicator of which was closer to the diving animals. Hence, we implemented the area-bounding method described above, which relies on knowing the maximum detection distance, and assuming all calls within this distance area heard. If, in practice, the true maximum detection distance is larger but some calls are missed within the maximum distance used, then the two will approximately balance out. The distance used is then better referred to as the effective detection distance.

Both click and dive counting required direct data processing by a trained analyst, but it is highly likely that in the future the methods can be automated thus significantly reducing the required analysis.

#### 4.3. Comparison of variances

When comparing methods, we have emphasized the importance of assessing reliability of assumptions and required multipliers. One less important consideration is the expected variance associated with estimators from each method. Because with dive counting we assume all dives are counted with certainty, there is

no component of variation due to spatial variation in counts between hydrophones. There is also no detection probability to estimate, or false positive rate to quantify. Although the amount of variance contributed by these components will vary from study to study, it may nonetheless be expected that dive counting will, in general, give a lower variance than click counting, as we found in this study.

## 5. Conclusions

The prototype dive counting method presented provides a means of estimating the density of Blainville's beaked whales using a field of acoustic sensors. This ability to estimate density of deep diving beaked whale species is a critically important part of ongoing opportunistic studies of the effect of sonar and anthropogenic activities on these animals.

This is illustrated in the case study which measured the number of animals present before, during, and after sonar operations on the AUTC range. These numbers suggest a possible avoidance reaction to sonar and other range activities.

The Blainville's beaked whale density estimated (24.76 animals/1000 km<sup>2</sup>) in the final 43 h period is similar to those measured from separate data without sonar using alternate click (22.5–25.3 animals/1000 km<sup>2</sup>) [9] and group localization (21.97 animals/1000 km<sup>2</sup>) methods [20].

As Blainville's beaked whales are deep diving cetacean and spend little time on the surface, traditional visual line transect survey methods are extremely difficult to apply. For areas of repeated navy operations, long-term monitoring may be required to meet environmental compliance guidelines. Blainville's beaked whales are readily detected on bottom-mounted sensors and groups of animals are generally recognizable. Therefore, passive acoustic density estimation offers a viable means of assessing trends in beaked whale populations.

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