PAM POWER: Methods for assessing the power to detect declines in cetacean density from Passive Acoustic Monitoring

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Aim: To provide an informative report on the AVADECAF tool, including an overview of the methods, and referencing the potential future applications of the tool.

Note: We hope to submit a peer-reviewed publication on power analysis using the AVADECAF tool next year, hence the Aquatic Noise publication is focused primarily on methods.

Key words: Animal Population Density Estimation, Passive Acoustic Monitoring, Power Analysis, Distance Sampling, Spatial Capture Recapture

Word limit: 13,000

# Abstract – max 200 words

Monitoring long-term trends of marine mammal populations is notoriously challenging, as density and abundance estimates are frequently characterised by high levels of uncertainty. Statistical power can be described as the ability to correctly detect a trend when one is present and is influenced by the uncertainty surrounding the input parameters. The ‘AVADECAF’ tool allows for the evaluation of the power of a fixed Passive Acoustic Array (PAM) to detect changes in animal density, via simulation. The simulations can be based on existing surveys or can be used to design speculative monitoring programs. The tool allows for population density estimation via distance sampling in scenarios where acoustic ranging of acoustic detections is possible, or Spatial Capture Recapture (SCR), when a vocalization of an animal’s sounds can potentially be detected on more than one of the acoustic sensors. Given that statistical power to detect population declines is typically low, the tool provides an opportunity to evaluate how power might be improved though the comparison of alternate survey designs. Improving statistical power increases the probability of detecting a change in the population and can reduce the required duration of a monitoring program. We provide a real-world example, applying the AVADECAF tool to simulated Blainville’s beaked whale clicks detected by hydrophones on the AUTEC (‘Atlantic Undersea Test and Evaluation Center’) range, and outline the potential future applications of this tool.

# Introduction

Monitoring marine mammal populations is notoriously challenging. Animals can occupy remote regions, at low densities over large areas, spend much of their time subsurface, and even at the surface can be difficult to observe. They are often monitored using visual surveys; however, this is a costly process, and such surveys are weather dependent (i.e., requiring periods of good visibility and calm conditions) and restricted to daylight conditions. Due to these challenges, standard visual surveys often result in considerable uncertainty in abundance estimates.

Many marine mammals produce sounds underwater as part of navigation, foraging and communication with conspecifics, making Passive Acoustic Monitoring (PAM) a viable method for monitoring them. Monitoring equipment can be deployed at or near the seabed, making data collection less susceptible to weather conditions, and can be deployed for up to six months prior to retrieval. Therefore, this approach is widely used around the world for long-term monitoring of marine mammals. The analysis of PAM data has been used for estimating spatial distribution of cetacean species, species identification, research into behaviour and communication, and mitigation of anthropogenic activity (Marques et al., 2012; Wisniewska et al., 2016; Curtis et al., 2020; Sarnocińska et al., 2020) In addition, there are now a range of methods by which cetacean density may be estimated using fixed passive acoustic devices; including plot sampling, distance sampling (DS), and Spatial Capture Recapture (SCR) (Marques et al., 2009; Moretti et al., 2010; Barlow et al., 2021; Oedekoven et al., 2022).

Statistical power is the probability of correctly rejecting the null hypothesis, but could also be described as correctly detecting a trend when one is present (Thomas and Juanes, 1996). While somewhat arbitrary, a value of 0.8 is considered to be an indication of a statistical test with reasonable power to detect a trend (Authier et al., 2020). In terms of population monitoring, statistical power can be described as the probability of correctly detecting a true change in animal abundance or density. Statistical power is affected by a combination of sample size, effect size and parameter variability, or sampling variance (Thomas and Juanes, 1996). Effect size relates to biological significance, and in the context of population monitoring is the quantitative population trend over time. Considering the potential effect and sample size prior to data collection can help define the survey design and methods required to accurately assess trend, and estimate the minimum detectable effect. Conducting a power analysis prior to commiting to a survey design can help ensure that the survey design is sufficiently robust to detect a specific change in the population. Therefore, to successfully monitor long term population trends (i.e., to determine if populations are stable, increasing or decreasing), consideration needs to given to both statistical power and biological significance, that is, the minimum effect size that is considered to be biologically important. This is crucial for the effective management and conservation of marine species.Given the challenges of long term monitoring of cetacean populations, it is unsurprising that between 1995 and 2018, only 20% of the marine mammal stock assessments published from NOAA ( National Oceanic and Atmospheric Administration) fisheries were associated with population trend analyses, and even well-studied stocks required annual estimates over at least 10 years to obtain sufficient power to detect current trends (White et al., 2022) . Similarly, Taylor et al. (2007) assessed power to detect trends in a range of marine mammal species, and reached comparable conclusions. For example, they predicted that from the reviewed stocks, 72% of precipitous declines in large whales would not be detected given current monitoring efforts. Likewise, Moretti (2019) determined that it would take 25-30 years of photo-ID data collection to detect an annual decline of 5% for Blainville’s beaked whales (*Mesoplodon densirostris*) on the U.S Navy range ‘Atlantic Undersea Test and Evaluation Center’ (AUTEC). The photo-ID monitoring program for Cuvier’s beaked whale (*Ziphius cavirostris*) on the Southern California Acoustic Range (SOAR) is considered to be a high intensity survey effort, however these efforts would not allow for detection of a 50% decline over the 11 years of survey effort (Curtis et al., 2020).

As the statistical power to detect a decline in marine mammals is often low, it is logical to consider how it might be increased. The original purpose of the AVADECAF project was to evaluate the utility of fixed PAM arrays for estimating cetacean density over the lifespan of ‘typical’ oil and gas fields. Booth et al. (2017) explored the importance of detection and classification methods, hydrophone array design, and evaluated the sensitivity of the statistical power to the input parameters required to estimate anmal density from PAM data. The tool was built with the capacity to estimate power given surveys from two different survey methods, distance-sampling and SCR. Here we provide an overview of the methods behind the AVADECAF tool, with a simulated example of distance sampling using PAM of Blainville’s beaked whales at the US Navy range AUTEC in the Bahamas (see Booth et al., 2017 for more details, and the associated available R code and helpfiles). Earlier literature provides thorough explanations of distance sampling and SCR (Buckland et al., 2001; Marques et al., 2013; Buckland et al., 2015). Here we present a broad overview of these methods, providing an initial step into density estimation from fixed PAM and the potential of the AVADECAF tool for guiding effective management and conservation activities.

# Methods

## Overview

The AVADECAF tool allows users to estimate statistical power to detect a decline in density using PAM – either using DS or SCR. Distance sampling with PAM data uses acoustic detections of animal cues, combined with a distance-based detection function derived from distances between the hydrophone and the cue producing animal to estimate animal density within a study area. In contrast, SCR does not rely on distance information, but requires that a proportion of the cues produced by the animals are detected by more than one hydrophone and that cues can be matched across hydrophones (Oedokoven et al., 2022). For SCR, having auxiliary information for each detected sound, namely received sound level, bearing angles or time of arrival can greatly increase performance (Borchers et al., 2015).

In either case, the tool simulates passive acoustic arrays in a hypothetical study area and detections made by the individual hydrophones. Within the tool, the DS package simulates a passive acoustic array that is suitable for applying distance sampling methods, i.e., allows for localisation of the detections and hence obtaining distances between the sensors and the localised detections. The utility of these respective methods relates to the characteristics of the particular vocalisations of the species of interest.

When designing a survey, DS or SECR, the spacing between the PAM sensors needs to be large enough that, with a given budget, nodes can be distributed throughout the study area. For SECR, however, the spacing also needs to be small enough that a proportion of calls can be detected by two or more detectors (e.g. Oedekoven et al. 2022). Furthermore, SECR requires that individual detections can be matched between detectors. Hence, detailed knowledge about the range and characteristics of the calls is necessary. DS methods require that at least for a representative proportion of the detections, distances to the detections can be obtained using the acoustic recorders from which a detection function can be estimated reliably.

Despite being a relatively recent addition to the statistical toolbox, SCR is considered to be a “standard” abundance and density estimation approach given its genesis from mark-recapture and distance sampling methods (Borchers, 2012; Borchers et al., 2015). SCR has also become a frequently-used tool for estimating vocalization density or abundance (Stevenson et al., 2015). In contrast to distance sampling, SCR does not require distances to the detections for estimating the detection function or call density. It does require, however, that call detections are matched between different detectors. This ‘recapturing’ of detected calls enables the detection probability of the sounds around the sensors to be estimated. In contrast to standard mark-recapture methods, for which abundance is strictly undefined, SCR allows the estimation of both density and abundance for a given area. Further, because the heterogeneity in detection probability is modelled as a function of the location, SCR methods deal directly with the unmodelled heterogeneity that poses a challenge to conventional CR (e.g., Link (2004)). SCR has been successfully applied to both visual (Pirotta et al., 2015) and passive acoustic data to estimate the abundance and density of marine mammals.

To determine the appropriate method for density estimation from PAM, it is important to identify the target species for the survey, whereby auxiliary information is required regarding the species of interest. The call frequencies, cue production rates, species behaviour and vocal detection ranges are all relevant considerations when selecting an appropriate method for density estimation using passive acoustic monitoring. This information will influence the array design, hydrophone elements, and sampling frequency. A sensitivity analysis using the original AVADECAF tool has been carried out (Booth et al., 2017) to determine the importance of each of these key input variables, including both the survey design and species-specific parameters. This report includes a brief overview of parameter sensitivity, however the original report (Booth et al., 2017) contains a comprehensive set of results and outputs.

## Implementation of models in the AVADECAF tool

The simulation workflow within the AVADECAF tool includes the creation of a study region, the generation of a survey design (the number of localising hydrophones and non-localising hydrophones) and the simulation of the species of interest derived from population specific parameters (Figure 1). The species information is incorporated to generate one surface of animal density throughout the study area and a buffer surrounding it per simulation . The parameters defining the survey design are used to generate an array of point transects distributed throughout the study area using a systematic design with a random starting point. Combining the density surface and the parameters describing the vocalization production rate of the animals, vocalizations are generated throughout the study area.

In DS, these vocalizations are then detected by each of the sensors according to a user-defined detection function . This can be either a hazard-rate or half normal detection function, with its parameters describing the decay in detection probability with increasing distance from the detector, and a probability of detection at distance zero. In the distance sampling package, distances from the sensors to the detections are provided; the proportion of these detections depends on the number of localising sensors that are deployed, and the number of detections that are available.

The subsequent step requires estimation of animal density using the ‘observed’ data, which is described in more detail below. These steps are undertaken for each survey year and season specified by the user, resulting in a time series of animal densities and associated density estimates. Lastly, a generalised linear model is fit to the estimated animal densities, to determine the power to detect a change. The AVADECAF simulation produces estimates of the power to detect a specified decline at a user-defined prespecified level (of significance, e.g. Alpha = 0.1, 0.05 or 0.01). A simulation includes 1000 iterations, and the percentage of iterations with p-values below the chosen level of significance estimates the power to detect the specified trend (for example a 1% annual decline over 50 years of monitoring).

### Density estimation equation (Distance Sampling)

The overall equation for estimating animal density from PAM using distance sampling is as follows

Where we observe a total number of cues (*nc*), detected on the cumulative number of hydrophones (*k*) over the time period of the acoustic recording (*T*). A proportion (*f)* of the detected cues may be false positives, meaning that the proportion of correctly detected cues is given by *1-f*. As it is difficult to identify individual animals using acoustic cues, the estimator includes ‘cue production rate’ to represent the average cue production rate (*c*). Estimating animal density requires information on survey area, where *𝜋𝑤2* represents the area monitored surrounding each sensor, multiplied by *k* to calculate the total survey area. This value is then multiplied by *p,* the average probability of detecting a cue within this region. The directionality of animal cues, combined with the depth and orientation of an individual can influence the probability of detection by an acoustic sensor, as such a perception bias parameter (*aperc*) is included to account for the proportion of missed detections.

Below we provide a case study with Blainville’s beaked whales for which DS was considered the most suitable survey method. Given vocalisations are medium-high in frequency, and very directional, and they are often not detected on multiple bottom mounted hydrophones, precluding the general use of SCR. In this context, SCR might be more suited to omnidirectional sources. SCR approaches are not discussed further here (see Booth et al 2017 and associated documents for more details).

## Case Study: Blainville’s beaked whale

As a deep-diving, visually elusive species group that use echolocation, beaked whale populations highlight the utility of acoustic monitoring for marine mammals. Conservation concern stems from stranding events of beaked whales that have been reported globally (D'Amico et al., 2009; Filadelfo et al., 2009) and have been associated with exposure to naval sonar use (Bernaldo de Quirós et al., 2019; Simonis et al., 2020). However, there are multiple beaked whale populations that are consistently exposed to sonar on navy training ranges, where local abundance is believed to be stable, and strandings have occurred apparently unrelated to sonar exercises (Curtis et al., 2020, Filadelfo et al., 2009). The uncertainty surrounding the effects of sonar on marine mammals has led to long term monitoring efforts on U.S Navy sonar ranges to determine the potential short- and long-term impacts at an individual and population level (Falcone et al., 2009; Falcone et al., 2017; Schorr et al., 2017; Jacobson et al., 2022).

The AVADECAF example provided below considers distance sampling, and is based on input parameters from the Blainville’s beaked whale population on the AUTEC navy range (Table 1). However, not all of the required metrics were available for this specific group of animals, and therefore some of the data have been taken from other Blainville’s beaked whale populations. This example therefore represents an imprecise estimation of the power to detect a decline in density from actual Blainville’s beaked whales at AUTEC using distance sampling but demonstrates the potential utility of the AVADECAF tool.

Table 1: the parameters for the simulations shown in figures 2 and 3, representing only a subset of the inputs required for the avadecaf tool

|  |  |  |
| --- | --- | --- |
| **Parameters** | **Value** | **Reference** |
| Array Dimensions | 1500km2 | Matsumoto (2013) |
| Hydrophones | 82 | Marques et al. (2009) |
| Initial population density estimate | 25.3/1000 km2 | Marques et al. (2009) |
| Cue Production Rate (cv) | 0.407 (0.098) | Marques et al. (2009) |
| False positive rate (cv) | 0.549 (0.0199) | Marques et al. (2009) |
| Perception bias (cv) | 0.07 (0.1) | Booth et al. (2017) |
| Density estimates per year | 1-2 | Not applicable |
| Annual decline | 1-3% | Not applicable |
| Number of localising hydrophones | 3-8 | Not applicable |

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figure 1: a visual representation of an example simulation. the black outline denotes the study area, the red/yellow surface represents a non-uniform animal density surface, green circles indicate a single hydrophone and blue circles represent a cluster of localising hydrophones.

By developing a range of scenarios, we obtain a better understanding of the potential power to detect a decline, given an increase in monitoring years and a variety of survey designs. In data-rich situations, it may be possible to increase the number of density estimates made per year, improving the power to detect a decline and reducing the number of monitoring years that are required to detect a population level change. In this scenario, doubling the number of estimates per year resulted in a reduction of approximately 7 monitoring years when the population was experiencing 1% annual declines (Figure 2). While this example demonstrates the change in statistical power when the number of density estimates is increased to two per year, providing there is sufficient information regarding detections, and seasonal changes in animal presence and cues, the number of density estimates per year could be increased further, with expected increases in power.

In addition to varying the number of estimates per year, the model allows for specification of the number of localising hydrophones within the array. These localisation clusters are more expensive to implement (as they require multiple hydrophones per node) but allow for multiple detection functions to be derived across the study area, which can address heterogeneity in detection probability. Increasing the number of localising hydrophones on the array allowed for the threshold for high power (0.8) to be reached 5 years earlier, when the population declined 1% per year (Figure 3). The reduction in the required number of monitoring years to detect a given trend will differ depending on the input parameters, but also depending on the heterogeneity of the environment. The required monitoring time will be species and region specific, and the proportion of localising hydrophones and the number of estimates per year are illustrative. The impact on power for several other parameters could also be evaluated within the simulations, for example, the influence of cue rate, false positive rates, and how environmental heterogeneity may impact power by increasing the variability of the detection probability. Monitoring scenarios that are extended over a longer time series allow us to determine the minimum number of survey years required to detect a specific decline, and the level of decline that we can realistically hope to detect with a given effort.

figure 2: the power to detect a decline in Blainville’s beaked whale based on input values derived from autec. simulations based on 1 or 2 density estimates per year, and 1 or 3 % annual declines. this simulation was based on an average of 5 localising hydrophones within the array, and alpha <0.05



Figure 3: the power to detect a decline in blainville’s beaked whale based on input values derived from autec, including a comparison in statistical power between arrays with different numbers of localising hydrophones. this scenario was based on one density estimate per year, while varying the number of localising hydrophones and the intensity of the annual decline, Alpha <0.05.

# Discussion

## Cue production rate

Booth et al. (2017) outlined the importance of cue production rate for PAM density estimation, where improved precision surrounding the estimate drastically improved the power to detect a decline. In addition to the importance of precise cue production rate estimation, note that cue production rate is not only species-specific but may vary with region/population, behavioural state, season, age and sex, and as a result of ambient noise levels (Warren et al., 2017; Thode et al., 2020; Blackwell et al., 2021). As such, integrating cue production rate data that is region-specific and temporally aligned with the acoustic datasets is imperative to ensure an accurate representation of local density over time (e.g., Marques et al. 2013), and is equally important to evaluate the power to detect a decline.

## False positives

The false positive rate is another important input for density estimation, representative of detections that have been wrongly associated with the species of interest. False positive rate is both species-specific and linked to the detection and classification system that is being used to process the acoustic cues; it is also spatially and temporally sensitive as other local sound sources can result in false positive detections. To identify infrequently detected species, the detector/classifier may be programmed to be sensitive (i.e. to not miss many detections), however this will likely lead to more false positives. Booth et al. (2017) determined that when high false positive detections were combined with variability in false positive estimates, the power to detect a decline was considerably reduced. This is also relevant where species with similar call frequencies and patterns co-exist. For example minke whale boing classifiers in Hawaiian waters have been found to be sensitive to humpback whale song (Ou et al., 2012), while humpback whales and bowhead whales also overlap in at least part of their vocal range (De Vreese et al., 2018).

## Survey design

Designing a survey requires careful consideration of logistics and budget available as this directly relates to the ability to detect and localize animals, a key component of density estimation via distance sampling. In AVADECAF, the user is able to specify if localisation occurs accurately or with error. In the latter case, error in localisation increases with distance between hydrophones, however it is important to be aware that the probability of detection may differ from the probability of localisation. As the frequency and source level of vocalisations influences propagation distance, the space between hydrophones on the array should be species-specific. Greater distances between hydrophones increases the magnitude of the acoustic time delay of multiple detections of the same sound, which reduces the time delay error. This suggests that greater aperture size (the distance between hydrophones) would be optimal for a localising hydrophone array. However, smaller distances between an animal and a hydrophone will increase the probability of detection. This is especially true for highly directional vocalisations. Therefore, selecting the array dimensions requires consideration of the species of interest, and an evaluation of these trade-offs.

The number of localising hydrophones depends on the study area and corresponding array dimensions, but also on the underlying density of animals (unknown), environmental conditions and local bathymetry. In a larger survey area, we might expect more variation in habitat conditions, which will influence the detection function for acoustic cues. In this case, it would be preferable to increase the number of localising hydrophones, to support the estimation of site-specific detection functions, or at the very least detection functions dependent on site-specific covariates, e.g., depth. Increasing the number of localising hydrophones allows for us to account for heterogeneity in the environment, which may improve the precision of the detection function model. However, estimating cetacean density using passive acoustic monitoring can be a costly process if the equipment is not already deployed. Booth et al (2017) evaluated the potential costs of the acoustic technology required for an array unit capable of localisation, estimating ~$20-30k per unit, extending this array to cover a large survey area would magnify these costs, with the distance between units (and therefore the number of units required) depending on the species of interest and their respective vocalisation characteristics. Conversely, initial investment in passive acoustic technology can support long-term monitoring efforts, allowing for a data collection duration of up to six months before retrieval and redeployment is required.

## Applications

The AVADECAF simulation tool presented here provides an opportunity to explore the statistical power of a monitoring program for PAM density estimation before deployment of equipment. For existing hydrophone arrays, it provides a means to assess the utility and scope of monitoring. To our knowledge this tool has been infrequently applied since its development, possibly due to lack of awareness and difficulty accessing the software. However, there is a need for PAM survey design associated with the fast-growing offshore wind sector where significant uncertainty around occurrence and response of marine mammals to construction noise remains. Baseline density and long-term monitoring at offshore wind farms could be explored using the AVADECAF tool, to determine the potential power of an array to detect cetacean density changes considered to be the result of windfarm development. The original AVADECAF report (Booth et al., 2017) contributed to the development of the [ACCURATE](https://accurate.st-andrews.ac.uk/) project, by identifying the sensitivity of cue rate as an input parameter in acoustic density estimation. The ACCURATE project was designed to evaluate the factors driving cue rates and their variability for a variety of marine mammals. As ACCURATE is currently ongoing, it is expected that within the next few years these outputs will be highly relevant to the AVADECAF tool by facilitating additional cue rate parameters, allowing for more realistic simulations.

The potential applications of the AVADECAF tool are numerous, including opportunities to evaluate existing passive acoustic monitoring programs. Distance sampling based density estimation from fixed PAM has been minimally explored for marine mammals, however these methods have been applied to North Pacific right whales, fin whales, and bowhead whales (Marques et al., 2011; Harris et al., 2013; Oedekoven et al., 2022). Navy training ranges represent regions where cetacean density estimation using PAM is possible using their cabled bottom-mounted hydrophones. In other locations, developing an array for the purpose of cetacean density estimation is also possible, however Booth et al. (2017) suggest that deploying a small-scale acoustic array as a trial would facilitate a better understanding of the required dimensions for detection and localisation for a range of species. The results of a carefully designed trial could directly contribute to the planning of acoustic arrays for the purpose of density estimation in the future.

The U.S Navy has already invested heavily in PAM to evaluate the impacts of sonar on marine mammals at both the individual and the population level. As the current literature demonstrates low power to detect declines from marine mammal visual surveys, statistical power of PAM surveys should also be evaluated to better understand the underlying trends that may be missed. Evaluating statistical power should be component of designing a monitoring program, facilitating the detection of less dramatic declines and allowing for earlier management of struggling populations. While a single data source monitoring method may not provide sufficient power to detect a moderate decline, initial power analysis offers a baseline value of statistical power that can be improved upon. Efforts to integrate multiple data streams have sucessfully demonstrated their capacity to reduce uncertainty in population estimates and improve the power to detect population level changes. Jacobson et al. (2020) determined that by combining multiple data sources, they were able to calculate biologically plausible estimates of population trends for cook inlet beluga whales, where this had previously not been possible. Boyd and Punt (2021) simulated data representative of a large whale population, and demonstrated that only an integrated population model (IPM) with the maximum combination of data sources (including environmental and demographic data) was capable of differentiating between a stable or heavily declining population. The AVADECAF software can provide an evaluation of statistical power for fixed passive acoustic monitoring, however if power remains low despite a range of monitoring scenarios, the next step could be to consider integrating data sources to improve monitoring power.

# Conclusion

The AVADECAF software tool is freely available [online](https://gisserver.intertek.com/JIP/DMS/Other/AVADECAF_TOOL.zip) and provides an opportunity to investigate the statistical power of an acoustic monitoring program, where density estimation of sound producing species like cetaceans is the desired outcome. The software is customisable to tailor the simulation to a region of interest and simulate a population trend for a specific species. The original development of the tool included a parameter sensitivity analysis that demonstrated the importance of certainty around input parameters including cue production rate and false positive rate. This tool is most applicable to species that are well-researched and supported with detailed information on vocalisations, notably this information should be population specific where possible. Current exploration of this tool has been limited, possibly due to lack of awareness, but given the frequent use of fixed PAM to monitor cetaceans there is scope to apply AVADECAF to a range of future research projects and species groups.

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