DECAF – Density Estimation for Cetaceans from passive Acoustic Fixed sensors

Len Thomas
CREEM, University of St Andrews, St Andrews, Fife, Scotland, UK. KY16 9RR
Phone: (+44) 1334-461801 FAX: (+44) 1334-461800 E-mail: len@mcs.st-and.ac.uk

Tiago Marques
CREEM, University of St Andrews, St Andrews, Fife, Scotland, UK. KY16 9RR
Phone: (+44) 1334-461801 FAX: (+44) 1334-461800 E-mail: tiago@mcs.st-and.ac.uk

David Borchers
CREEM, University of St Andrews, St Andrews, Fife, Scotland, UK. KY16 9RR
Phone: (+44) 1334-461843 FAX: (+44) 1334-461800 E-mail: dlb@mcs.st-and.ac.uk

Catriona Harris
CREEM, University of St Andrews, St Andrews, Fife, Scotland, UK. KY16 9RR
Phone: (+44) 1334-461831 FAX: (+44) 1334-461800 E-mail: catriona@mcs.st-and.ac.uk

David Moretti
NUWC, Code 74, Bldg. 1351, 1176 Howell St., Newport, R.I. 02841-1708
Phone: (401) 832-5749 FAX: (401) 832-4441 E-mail: david.moretti@navy.mil

Ronald Morrissey
NUWC, Code 74, Bldg. 1351, 1176 Howell St., Newport, R.I. 02841-1708
Phone: (401) 832-5600 FAX: (401) 832-4441 E-mail: ronald.morrissey@navy.mil

Nancy DiMarzio
NUWC, Code 74, Bldg. 1351, 1176 Howell St., Newport, R.I. 02841-1708
Phone: (401) 832-3872 FAX : (401) 832-4441 E-mail: nancy.dimarzio@navy.mil

Jessica Ward
NUWC, Code 74, Bldg. 1351, 1176 Howell St., Newport, R.I. 02841-1708
Phone: (401) 832-5317 FAX: (401) 832-4441 E-mail: jessica.ward@navy.mil

David Mellinger
CIMRS, Oregon State University, 2030 SE Marine Science Drive, Newport, OR 97365
Phone: (541) 867-0372 FAX: (541) 867-3907 E-mail: david.k.mellinger@noaa.gov

Steve Martin
SPAWAR Systems Center San Diego, Code 2374, 53560 Hull Street, San Diego, CA 92152-5001
Phone: (619) 553-9882 FAX: (619) 553-2726 E-mail: steve.w.martin@navy.mil

Peter Tyack
Biology Department, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543
Phone: (508) 457-2041 FAX: (508) 289-2818 E-mail: ptyack@whoi.edu

Grant Number: NFWF 2007-0145-002
http://www.creem.st-and.ac.uk/decaf/

LONG-TERM GOALS

Determining the spatial density and distribution of cetacean (whale and dolphin) species is fundamental to understanding their basic biology, and also to monitoring and mitigating the effect of man-made impacts on their populations. However, this task is difficult because most cetacean species occur at low density and over enormous areas, and because they spend relatively little time at the surface where they can be seen using standard, visual surveys. Our primary long-term goal is to develop and test methods for estimating cetacean density based on detecting the sounds cetaceans make underwater, using fixed hydrophones.

OBJECTIVES

1. Develop statistical methods for estimating the spatial density of cetacean species from fixed passive acoustic devices. Methods should be applicable to a wide range of scenarios, including dense and sparse arrays of permanent, bottom-mounted sensors and single bottom-mounted or floating sensors.

2. Demonstrate the utility and generality of the methods by implementing them in a set of key test case studies. These test cases will also focus the methodological development to ensure their relevance to real-world applications. We aim as far as possible to leverage data that have already been collected, and acoustic detection, classification and localization methods that have already been developed.

3. Promote adoption of the new methods in the marine mammal research community by (a) publishing results in the peer-reviewed literature, (b) archiving data and results in publicly available electronic storehouses (e.g., the Ocean Biogeographic Information System, OBIS SEAMAP), (c) holding one or more workshops open to all interested researchers.

APPROACH AND WORK PLAN

The project was originally due to end in May 2010, but due to the volume of results, we have obtained a no-cost extension until February 2011 to enable us to write up the last few papers, and shepherd those already submitted through the review process.

Technical approach

In developing the statistical methods, we have built upon the existing substantial body of work on distance sampling survey methods (e.g., Buckland et al. 2001, 2004). Fixed passive devices are conceptually most similar to a type of distance sampling called point transect sampling. However, there are several important issues that prevent a straight application of existing methods, as described in the project proposal and in Marques et al. (2009). We have developed methods to address these issues through a series of case studies. Our basic approach in each case has been to develop the new statistical methods required for the situation and to apply the methods using acoustic data that has already been collected (but in all cases required further processing). In doing this, we leveraged the very significant efforts already expended in data collection, and also in the development of methods for data processing and analysis. We stress that although we analyzed specific datasets, our methods are designed to be general. We are currently synthesizing this work into a comprehensive review paper.

The case studies were as follows.

- *Estimation of beaked whale density at the Atlantic Undersea Test and Evaluation Center (AUTEC) range, Bahamas.* Beaked whales are deep-diving animals that produce echolocation clicks to

locate prey at depth (like bats do in air). These clicks are received at a widely-spaced (4km) array of 82 bottom-mounted hydrophones at AUTEC, and a great deal of previous work has gone into developing a system to process the sounds and quantify the number of clicks received. Because the sounds are highly directional, each is usually received less than three hydrophones, making it difficult to pinpoint the location of the animal producing the sound. Instead, we used information from tagged whales to turn the number of clicks into estimates of animal density.

- *Estimation of minke whale density at the Pacific Missile Range Facility (PMRF), Hawai'i.* Minke whales are very cryptic to visual observers in the waters around Hawai'i, but they can be heard in late winter, when they call with a characteristic "boing" sound. The function of this sound is not known, but it may be a male display. A single boing can be heard on multiple hydrophones at the PMRF facility, which, together with the shallow-diving behavior of minke whales, made this a contrasting case study to the previous one. We used an array of about 20 bottom-mounted hydrophones spaced approximately 8 km apart to estimate density.
- *Estimation of sperm whale density at AUTEC.* Sperm whales produce very loud echolocation clicks. In contrast to beaked whales, these sounds are loud enough to produce significant bottom and surface echoes, and also to enable successive clicks from the same individual to be picked up on multiple hydrophones. We developed methods that allow filtering out of echoes, as well as association of successive clicks into "trains", thereby allowing estimation of the number of diving animals in a group, and hence (assuming all groups are heard at AUTEC) animal density.
- *Estimation of beaked and sperm whale density at AUTEC using single hydrophone data*. With a single hydrophone, many of the previous methods are not feasible. We investigate the estimation of detection radius around single sensors using models of source sound levels, acoustic propagation and detector characteristics.

Project investigators and roles

The research has been undertaken by an internationally-leading, multi-disciplinary team of statisticians, acousticians, cetacean survey specialists and biologists, drawn from academia and the US military. In summary, our major roles were as follows:

- University of St. Andrews (UStA), St. Andrews, UK. Dr. *Len Thomas*, was project PI, and collaborated with Dr. *Tiago Marques* and Dr. *David Borchers* on development of the new statistical methods and testing by simulation. Overall project management and coordination across all institutions was performed by Dr. *Catriona Harris*, with Ms. *Danielle Harris* covering for Catriona while she was on maternity leave.
- Space and Naval Warfare Systems Center (SSD), San Diego, CA. Mr. *Steve Martin* oversaw the test cases based on data from PMRF. Martin was previously the PI on the ONR-funded project to collect these data.
- Oregon State University (OSU), Newport, Oregon. Dr. *David Mellinger* developed an automatic classifier for minke and humpback whales; he also took the lead on developing methods for estimating density from single fixed sensors, together with post-doctoral research assistant Dr. *Elizabeth Küsel*.
- Naval Undersea Warfare Center (NUWC), Newport, RI. Mr. *David Moretti* led a team of engineers and acousticians, including Ms. *Jessica Ward*, Dr. *Ronald Morrissey*, Ms. *Nancy DiMarzio*, Ms. *Susan Jarvis*, and Dr. *Paul Baggenstoss*. They used new detection algorithms developed under this project, and capability previously developed under the Marine Mammal Monitoring on Navy Ranges (M3R) program, to extract and process data required for the case studies. They also integrated data from animals fitted with acoustic tags with data collected on

range hydrophones to estimate probability of detecting vocalizations, and other quantities, as well as participating in development of methods for density estimation.
- Woods Hole Oceanographic Institution (WHOI), Woods Hole, MA. Dr. *Peter Tyack* provided estimates of vocalization behavior and movement data for sperm whales and beaked whale species required to convert estimates of click density to estimates of animal density. He also collaborated on analysis of tagged whale data.

In addition to the core team of investigators, there was a project steering group of acknowledged experts in the above fields, who provided annual feedback on progress and advice on future directions. The steering group was Dr. *Jay Barlow* (NOAA Southwest Fisheries Science Centre), Prof. *Stephen Buckland* (University of St. Andrews) and Dr. *Walter Zimmer* (NATO Undersea Research Centre).

Work plan for coming year

The main bulk of the project is now complete; our main focus until February 2011 will be to synthesize our findings from the case studies into a comprehensive review paper on animal density estimation from fixed passive acoustics, to be submitted to a high profile journal. We are also planning a forth open research meeting, and a one day training workshop, both to be held in conjunction with the next Detection, Classification, Localization and Density Estimation meeting in Mount Hood, Oregon 22nd-25th August, 2011. The methods developed under this project are now being put to use in a variety of new projects (see Transitions, and Related Projects, below), and many of us are working as part of these.

WORK COMPLETED

A comprehensive overview of the accomplishments of the project is given in our Final Programmatic Report, available at the project web site http://www.creem.st-and.ac.uk/decaf/. In summary, the project has been an outstanding success: we have met or exceeded our project milestones in each year of the project. We have successfully developed methods for estimating cetacean population density from fixed passive acoustic sensors, and applied them in four case studies. We have given 20 presentations on our work, held 4 public research workshops, submitted 12 papers of which 6 have been accepted to date, and have another 4 in preparation.

RESULTS

Beaked whale case study. Earlier in the project, we published a method for density estimation for this case study that involved determining detectability of beaked whale echolocation clicks using tagged animals (Marques et al. 2009). However, tags can only be applied in calm seas, while density estimates are required for all sea conditions. We therefore undertook an investigation of the effect of additional ambient noise on detectability, by characterizing ambient noise and then adding synthetic noise to our recordings and re-analyzing them. We found that for deep hydrophones and high frequency vocalizations, such as those in this case study, the effect was not large (Ward et al. in revision, Marques et al. in prep.). This is re-assuring, and increases the applicability of the method. Separately, we have also published our study on the effect of a Navy training exercise on animal density, providing valuable insight into possible avoidance behavior (McCarthy et al. in press).

Minke whale case study. Our novel detection algorithm has been written up and submitted for publication (Mellinger et al. submitted). We used this algorithm to detect calls on the PMRF range, and then associated calls across hydrophones and used the spatially-explicit capture-recapture (SECR)

method (as mentioned in last year's report) to estimate the probability of detecting a call as a function of range (Figure 1). A simulation study comparing two methods of doing this has now been accepted for publication (Marques et al. in press a), and we are preparing a manuscript that estimates density for a longer sample of data (Martin et al. in prep.). We have developed a unifying framework that combines distance sampling and SECR studies, potentially allowing a host of novel applications, and are writing this up for publication (Borchers et al. in prep.).

Sperm whale case study. The algorithms we developed for grouping clicks into trains, and for associating trains across multiple hydrophones to allow localization and tracking have been submitted as two papers (Baggenstoss submitted a, b). We then used these methods to demonstrate density estimation, effectively by counting all animals within the AUTEC range at a sample of time periods over 30 days. This work was written up as a paper and submitted, but was rejected and is now in revision.

Single hydrophone case studies. We have developed a framework for estimating density from counts of received sounds coupled with assumptions about animal distribution, source levels, directionality, propagation and detector characteristics. We have applied this to estimate beaked whale density from a single hydrophone (Küsel et al. submitted), obtaining results not too far from those derived in the first case study, above (see Marques et al. 2009). We are using similar methods to estimate sperm whale density at AUTEC, this time using more hydrophones but treating them as a non-linked array. These sound propagation model based methods have the potential to provide density estimates at far lower costs than the previous methods, which require either expensive additional data from tags deployed alongside the hydrophones, or an extensive array of linked sensors.

Other activities. Using methods developed during the DECAF project and in collaboration with researchers at Scripps Institution of Oceanography, we derived a preliminary estimate of the density of the highly endangered north Pacific right whale (Marques et al. in press b). Also, as part of our work on SECR, we published a correction to some previous research in this area (Marques et al. in press c). Our results and findings are described in detail in the Outputs section of the DECAF web site http://www.creem.st-and.ac.uk/decaf/outpus.

IMPACT AND APPLICATIONS

National Security

The US Navy is committed to marine mammal risk mitigation, both on testing ranges and exercises outside of these areas. Methods developed under this project will contribute substantially to risk mitigation capabilities, both in enabling more effective planning of testing and training for times and places that minimize exposure of marine mammals to underwater sound, and also potentially in real-time monitoring of marine mammal presence.

Economic Development

There is increasing recognition that noise in the marine environment can potentially impact cetacean populations. Important sources of noise are from shipping and from oil and gas industry seismic exploration and production. Just as for national security applications, methods developed under this project can contribute substantially to risk mitigation in industry.

Quality of Life

Cetaceans are an iconic part of the world's biodiversity; the project will enable us to better monitor their numbers and so conserve them for future generations.

Science Education and Communication

One of the most important questions we can ask about a wild animal population is "how many are there?" Our methods enable this question to be answered by listening for the sounds produced by animals that are, in many cases, almost impossible to see and yet are highly charismatic and of strong conservation concern. Hence the methods and findings are of high potential interest to the public, and can readily be used for education and communication.

TRANSITIONS

National Security

Methods and density estimates are now being used in two major Navy testing ranges (AUTEC and PMRF), and there is high potential for their use in other areas of Navy operation.

Quality of Life

Methods developed under this project are being applied to determine abundance of the endangered Baltic Sea harbor porpoise subpopulation (SAMBAH project – see below), and have been used to provide a preliminary density estimate for the highly endangered north Pacific right whale.

RELATED PROJECTS

- The N45 and ONR-funded Marine Mammal Monitoring on Navy Ranges (M3R) program has developed tools capable of detecting and tracking marine mammals in real time on Navy ranges (see proposal). Archival and new data from this program is being used to provide much of the input data for the current project.
- US Navy Pacific Fleet and Office of Naval Research have funded PMRF data collection and analysis, including a manual analysis of acoustic snapshots of data that forms the basis for a 'quasi ground truth' for evaluation of the minke whale and humpback studies.
- Office of Naval Research funds a project, led by Mr. Tom Norris, to investigate the vocal behavior of minke whales in Hawai'i.
- The UK Defense Science Technology Laboratory (DSTL) is funding a PhD student based at UStA from 2007-2010, co-supervised by Thomas, John Harwood (UStA) and Chris Clarke (Cornell), to work on estimation of cetacean density from sparse arrays of hydrophones, such as those of the IUSS SOSUS array.
- The European Union Life+ program has funded a project, SAMBAH, to determine abundance of the endangered Baltic Sea harbor porpoise, using methods developed by this project.

REFERENCES

Buckland, S. T., Anderson, D. R., Burnham, K. P., Laake, J. L., Borchers, D. L., and Thomas, L. 2001. *Introduction to distance sampling - Estimating abundance of biological populations*. Oxford University Press, Oxford.

Buckland, S. T., Anderson, D. R., Burnham, K. P., Laake, J. L., Borchers, D., and Thomas, L. 2004. *Advanced Distance Sampling*. Oxford University Press, Oxford.

PUBLICATIONS

Please note that all project outputs (including talk slides, papers and technical reports) are available at the DECAF project web site: http://www.creem.st-and.ac.uk/decaf/

Published

Marques, T.A., L. Thomas, J. Ward, N. DiMarzio, P. L. Tyack. 2009. Estimating cetacean population density using fixed passive acoustic sensors: an example with beaked whales. *Journal of the Acoustical Society of America* 125: 1982-1994.

Moretti, D., T.A. Marques, L. Thomas, N. DiMarzio, A. Dilley, R. Morrissey, E. McCarthy, J. Ward and S. Jarvis. 2010. 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. Applied Acoustics 71: 1036-1042.

In press

Marques, T. A., Thomas, L., Martin, S. W., Mellinger, D. K., Jarvis, S., Morrissey, R. P., Ciminello, C., DiMarzio, N. In press a. Spatially explicit capture recapture methods to estimate minke whale abundance from data collected at bottom mounted hydrophones. Journal of Ornithology. DOI: 10.1007/s10336-010-0535-7

Marques, T.A., L. Thomas, L. Munger, S. Wiggins and J.A. Hildebrand. In press b. Estimating North Pacific right whale (*Eubalaena japonica*) density using passive acoustic cue counting. Endangered Species Research. DOI: 10.3354/esr00325

Marques, T. A., Thomas, L., and J. A. Royle. In press c. A hierarchical model for spatial capture-recapture data: comment. Ecology. DOI: 10.1890/10-1440.1

McCarthy, E., D. Moretti, L. Thomas, N. DiMarzio, R. Morrissey, S. Jarvis, J. Ward, A. Izzi, A. Dilley. Changes in spatial and temporal distribution and vocal behavior of Blainville's beaked whales (*Mesoplodon densirostris*) during multi-ship exercises with mid-frequency sonar. Marine Mammal Science.

Submitted

Baggenstoss, P.M. submitted a. Separation of Sperm Whale Click Trains for Multipath Rejection.

Baggenstoss, P.M. submitted b. An Algorithm for the Localization of Multiple Interfering Sperm Whales Using Multi-Sensor Time Difference of Arrival.

Mellinger, D.K., S.W. Martin, R.P. Morrissey, L. Thomas and J.J. Yosco. Submitted. A method for detecting whistles, moans and other frequency contour sounds. Submited to Journal of the Acoustical Sociey of America.

Küsel, E.T., D.K. Mellinger, L. Thomas, T.A. Marques, D.J. Moretti, and J. Ward. Submitted. Method for cetacean density estimation from single fixed sensors using passive acoustics. Submited to Journal of the Acoustical Sociey of America.

Ward, J., Jarvis, S., Moretti, D., Morrissey, R., DiMarzio, N., Thomas, L. and Marques, T. Beaked whale (*Mesoplodon densirostris*) passive acoustic detection with increasing ambient noise.

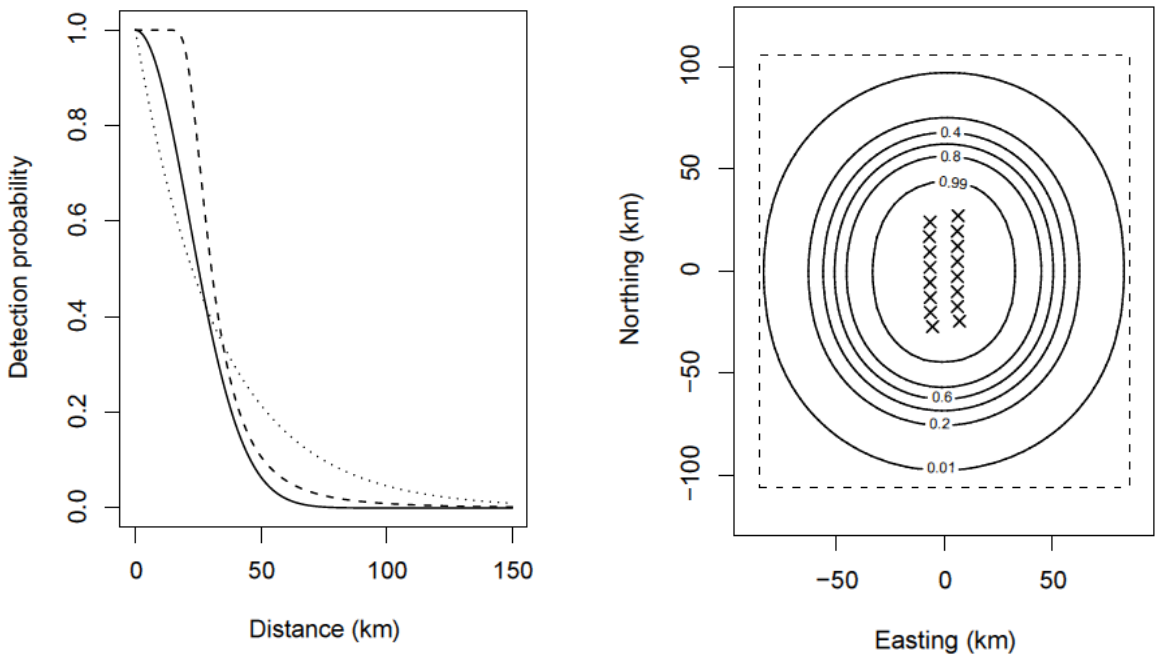

Figure 1. Left plot: Probability of detecting a minke whale "boing" sound as a function of distance from one of the bottom-mounted hydrophones at the PMRF range, Hawaii, estimated using three different models (the three lines) using spatially-explicit capture recapture (SECR) methods. Right plot: layout of the hydrophones in this analysis (crosses), with solid contour lines showing probability of detecting a "boing" at one or more hydophone on the range using the detection function shown as a solid line on the right plot. Such information allows us to calculate the area sampled by the hydrophone array, and hence convert the number of "boing" sounds heard into a boing density (number per unit area). Given a estimated boing rate, one can then calculate animal density.