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: cms@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 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. There are many potential configurations of such devices, so an important second goal (not addressed in this work) is to determine which configurations are best for each of a common suite of monitoring scenarios.

OBJECTIVES

1. Develop statistical methods for estimating the 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 (participants at these will be self-funded).

APPROACH AND WORK PLAN

Technical approach

In developing the statistical methods, we are building 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 Thomas and Martin (2006). We are developing methods to address these issues through a series of case studies, formulated as a set of linked tasks (see below). Our basic approach in each case is 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 most cases will require processing). In doing this, we are leveraging 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 will be analyzing specific datasets, our methods are designed to be general.

The case studies are as follows:

- estimation of beaked whale density at the Atlantic Undersea Test and Evaluation Center (AUTEC) range, Bahamas;

- estimation of minke whale density at the Pacific Missile Range Facility (PMRF), Hawai'i;
- estimation of sperm whale density at AUTEC;
- estimation of sperm whale density at AUTEC using single hydrophone data;
- if time allows, estimation of humpback whale density at PMRF.

Project investigators and roles

The research is being 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 are as follows:

- University of St. Andrews (UStA), St. Andrews, UK. Dr. *Len Thomas*, is project PI, and is collaborating 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 is performed by Dr. *Catriona Harris*.
- Space and Naval Warfare Systems Center (SSD), San Diego, CA. Mr. *Steve Martin* is overseeing the test cases based on data from PMRF. Martin was PI on the ONR-funded project to collect these data.
- Oregon State University (OSU), Newport, Oregon. Dr. *David Mellinger* is developing an automatic classifier for minke and humpback whales; he is also taking the lead on developing methods for estimating density from single fixed sensors, together with a post-doctoral research assistant to be employed from January 2009 at OSU.
- Naval Undersea Warfare Center (NUWC), Newport, RI. Mr. *David Moretti* is leading a team of engineers and acousticians, including Ms. *Jessica Ward*, Dr. *Ron Morrissey* and Ms. *Nancy DiMarzio*. They are using new detection algorithms developed under this project, together with the large collection of algorithms and hardware developed previously at NUWC (under the Marine Mammal Monitoring on Navy Ranges (M3R) program, funded by N45 and ONR) to extract data required for the case studies, as well as participating in developing and applying the new density estimation methods. They are also integrating data from animals fitted with acoustic tags with data collected on range hydrophones to estimate probability of detecting vocalizations, and other quantities required for density estimation.
- Woods Hole Oceanographic Institution (WHOI), Woods Hole, MA. Dr. *Peter Tyack* is, in collaboration with others at WHOI (including Dr. *Mark Johnson* and Ms. *Amanda Hansen*), providing 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 is also collaborating on analysis of tagged whale data.

In addition to the core team of investigators, there is a project steering group of acknowledged experts in the above fields, who provide annual feedback on progress and advice on future directions. The steering group is composed of 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

We plan to consolidate the excellent progress made in the first year of the project. We will finalize and submit a research paper on our analysis of beaked whale density at AUTEC, based on counting their echolocation clicks. The data used in this analysis will also be submitted to the OBIS-SEAMAP internet portal. We will continue development of an alternative approach for this case study, based on counting diving groups. We will complete our analysis of minke whale density at PRMF, which is in its initial stages, and begin work on sperm whales from multiple and single sensors at AUTEC. We also hope to write up and submit a research paper on the general framework developed for estimation of density from fixed passive acoustic data, presented already as a conference poster (Marques and Thomas 2008). Project progress will continue to be monitored through monthly telephone progress meetings, with review meetings every three months and a face-to-face annual progress meeting scheduled for September 2009. We also plan to hold two workshops open to all interested in density estimation from passive acoustics: the first on 16th July 2009 in San Diego, California, and the second on 13th September 2009 in Pavia, Italy. Outputs will continue to be uploaded to the DECAF project web site: http://www.creem.st-and.ac.uk/decaf/.

WORK COMPLETED

This was the first full year of the project, work having started in July 2007. During this time we have concentrated largely on the beaked whale case study, due to the perceived importance of this taxonomic group, and because of synergies with other projects being undertaken on beaked whales. We envisage two methods for estimating density in this case study. The first is based on “dive counting”, as outlined in last year’s progress report: a spatio-temporal smoother is used to determine the number of group dive initiations per unit time, and this is converted into an estimate of animal density using independent information about dive frequency and group size. The second is based on “cue counting”, where cues are individual echolocation clicks, and represents an extension of methods used to estimate density of other species. This second approach is the one we have largely pursued, as reported in Results, below.

We have also developed a draft general framework describing the possible methods for estimating density from fixed passive acoustic data, and this was presented as a poster paper (Marques and Thomas 2008) at the International Statistical Ecology Conference in July 2008.

The humpback whale case study was originally envisaged as the simplest of the studies (see project proposal), and was therefore planned to be undertaken in the first half of the project. This year, we undertook an evaluation of a set of test data that had been processed manually as part of a related effort (see Related projects, below). The data consisted of 14 10-minute samples from PMRF where discernable whale calls were detected, classified and localized where possible. We found that humpback whale calls mostly occurred far outside the range hydrophones, making their location hard to estimate accurately, and also violating an assumption of the simple analysis method we wanted to showcase with this case study (that animals are distributed at random with respect to hydrophone placement). Animals were also singing close together, making it difficult to distinguish individuals. We therefore decided (with the permission of the project sponsors) to postpone consideration of the humpback case study, and instead to switch to the estimation of minke whale density at PMRF. Minke whales produce distinct “boing” sounds, and these were found to occur within the hydrophone array, and also relatively widely spaced in time and space. We are currently developing automated detectors, classifiers and localizing algorithms for this species that can be applied on the test datasets, and then to the main study dataset. At the same time we are working on the required estimation framework. For the sperm whale case studies, we have identified the test dataset to use and made some initial investigations to confirm its suitability.

Our first annual progress meeting was held in July, 2008 in Paris, France. The second day was devoted to a workshop on methods for estimating density from passive acoustics that was attended by

18 invited participants (a list of talks presented is on the DECAF web site). This was highly successful, with many useful discussions, and has inspired us to plan two open workshops for the coming year.

RESULTS

We report results from the cue-count analysis of beaked whales at AUTEC. 4,961 minutes of sound recordings taken over a 6-day period in spring 2005 from 82 bottom-mounted hydrophones were analyzed using an automated detection and classification system, and a total of 2,940,521 beaked whale echolocation clicks were counted. Converting these into an estimate of average beaked whale density at AUTEC over this time period required estimation of three additional quantities: (1) click production rate; (2) probability of detecting a click; and (3) proportion of false positive detections (see Marques and Thomas (2008) for details of estimation framework). To obtain estimates of click production rate and detection probability, we used additional data from a tagging study of beaked whales at AUTEC undertaken in 2006 and 2007. Five beaked whales were fitted with tags that record sound production and movement, and were tracked over a total of 21 dives. Click production rate was estimated as the average number of clicks produced per second over each complete dive, which was 0.41 (coefficient of variation, CV 10%). To estimate probability of detection, we accurately determined the position of the whales' tracks for a subset of 13 dives for which this was possible, and associated clicks produced by these whales with clicks received on the AUTEC hydrophones. We used a regression framework to determine the proportion of clicks received on AUTEC hydrophones as a function of distance between whale and hydrophone, and orientation of the whale relative to the hydrophone. We found that the probability of detecting a click was strongly dependent on distance, declining to zero by 8km distance; probability of detection was also strongly dependent on the orientation of the whale, with clicks much more likely to be detected if the whale was pointing directly at a hydrophone (Figure 1). Average probability of detection of a click produced within 8km of a hydrophone was estimated to be 0.033 (CV 15%). False positive rate was estimated by manually examining a sample of 30 10-minute periods, and determining what proportion of clicks that passed the detection algorithm were determined to be beaked whale clicks by a human operator. The false positive rate was 0.44 or 0.49 (CV 2%), depending on whether a small number of ambiguous sounds were considered to be beaked whales or not. Putting these numbers together yielded a density estimate of 24.9 or 22.7 whales per 1000km^2 (CV 19%).

The methods used in this case study are widely applicable to other situations where distinct animal cues can be counted, and detection and cue rate information can be estimated from auxiliary data. This includes not only cetacean studies, but also terrestrial animals that are hard to count using visual methods, such as forest elephants and monkeys.

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.

TRANSITIONS

None at present.

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 will form the basis for a 'quasi ground truth' for evaluation of the minke whale and humpback studies.
- 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. This work will proceed in close collaboration with DECAF.

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 are available at the DECAF project web site: http://www.creem.st-and.ac.uk/decaf/

Marques, T. A. and L. Thomas. 2008. Estimating cetacean density from passive acoustic arrays. Poster presentation given at International Statistical Ecology Conference, July 9-11th 2008, St Andrews, Scotland.

Thomas, L. and S. Martin. 2006. Methods for estimating the density of cetaceans from fixed arrays of passive listening devices. White paper.

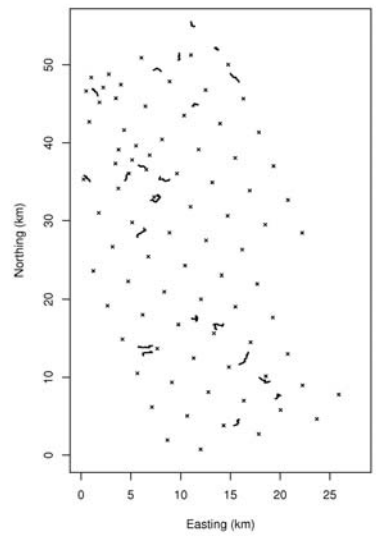

Figure 1. Spatial layout of the AUTEC hydrophones recording during collection of the beaked whale case study data. Also shown are tracks of the tagged whales during the vocal parts of their deep dives.

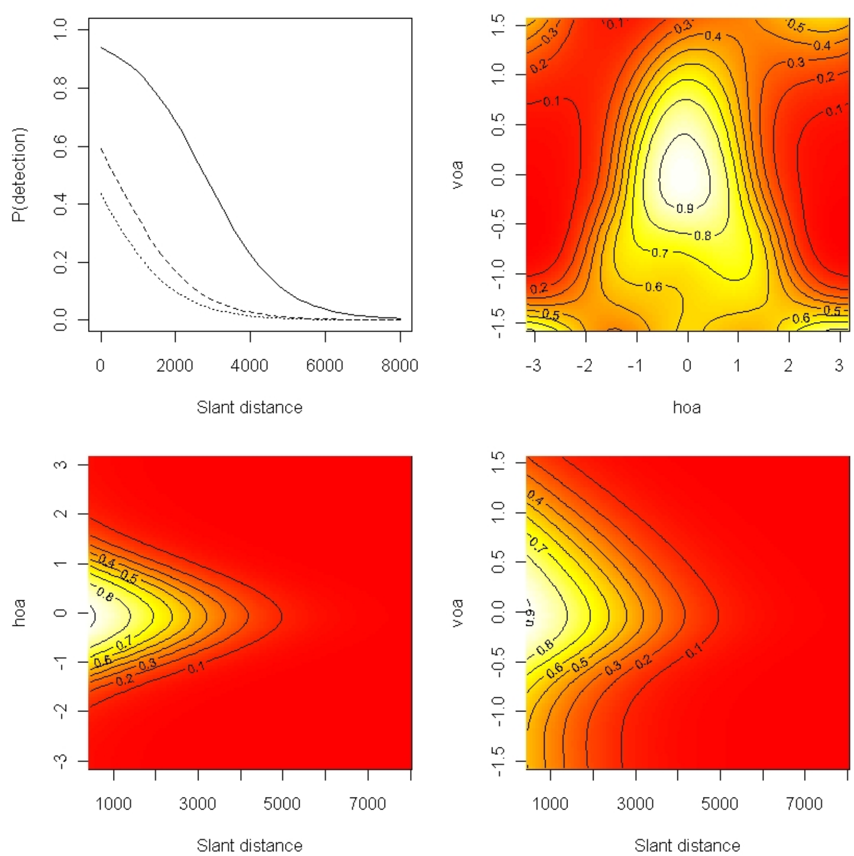

Figure 2. Estimated probability of detecting a beaked whale click given the distance between the whale and hydrophone (slant distance), and the whale-to-hydrophone angle (horizontal off-axis angle, hoa) and vertical off-axis angle (voa). Top left plot shows probability of detection against distance for off-axis angles of 0, 45 and 90 degrees. Remaining plots show probability of detection as contour lines, with two out of the three variables plotted against one another (hoa and voa given in radians), and the third set to zero.