MOCHA - Multi-study OCean acoustics Human effects Analysis

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DURATION OF EFFORT: 36 months starting April 2012

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Project Summary

Behavioral response studies (BRSs) are experiments aimed at directly quantifying the relationship between potential anthropogenic disturbances and their effect on specific marine mammals. The US Navy is making a substantial investment in BRS studies, aimed at understanding the effect of active sonar on species of concern. Studying these species in ecologically valid settings often requires field experiments. BRS studies are difficult and expensive to conduct, and so sample sizes are necessarily small. Traditional statistical methods for analysis, based on null models and hypothesis testing, do not make best use of the available data, and make it hard to represent accurately the complexity of BRS experimental protocols. With traditional approaches, small sample sizes result in insufficient power for all but the most extreme effects. This creates a risk of biased reporting, where clear responses from the most sensitive species will be publishable, while responses (or lack of responses) from less sensitive species are harder to detect and results are more difficult to interpret and publish. There is therefore a need for analytical approaches where every outcome contributes equally to our understanding.

We propose to form a working group, supported by two full-time post-doctoral researchers, to develop and implement innovative methods for the analysis of the results from BRSs. The aim is to complement and enhance analyses already taking place as part of each current Navy-funded BRS project. One post-doc will focus on development of methods pertinent to individual studies, such as Bayesian hierarchical methods for dose-response analysis, as well as methods for quantifying response based on multiple behavioral measures. The other will focus on methods for pooling information across studies (meta-analysis), and hence predicting responses among populations and species not yet studied, as well as identifying data gaps and potentially improved experimental designs. However, their roles and taskings are flexible, depending on the outcome of working group meetings.

The working group will be composed of the chief scientists of existing BRS projects, together with other scientists working on BRS issues and statisticians who have expertise in the analysis of biological data of this kind. We will meet six times over a 3-year period, with the middle four workshops focusing on a functional/taxonomic group of marine mammals. A smaller steering committee, comprising the PIs on this project and the BRS PIs, will provide overall direction.

We anticipate that the outputs of this project will substantially enhance our ability to quantify the response of marine mammal species to navy sonar and other acoustic stimuli, make best use of available data, and provide guidance for future studies.

Statement of work

Rationale for work

Many marine mammals rely on sound for foraging, navigation, finding mates and avoiding predators. They may therefore be profoundly affected by the introduction of anthropogenic noise into the marine environment. Examples of potentially harmful noise sources include commercial shipping, seismic prospecting, whale-watching vessels and navy active sonar. Potential adverse effects range from masking, i.e., making it harder for an animal to detect or communicate important natural signals, to longer-term behavioral disturbance, which may exclude animals from important habitat, to stranding, which is the only known lethal

response. The US Navy has long recognized the need to quantify the impact of active sonar at the level of individual animal responses and also in terms of population consequences. It has therefore invested heavily in studies designed to quantify and mitigate impact. This proposal suggests a focused research effort to employ and further develop improved methods for quantifying impact using experimental data that is already being gathered by Navy-funded projects, and specifically from behavioral response studies (BRSs).

BRSs (also sometimes called controlled exposure experiments) are an important approach for studying the short-term response of animals to potential stressors. In a BRS, focal animals are identified and their behavior monitored using visual observations, passive acoustics and attachment of animal-borne tags. A sample of animals is exposed to a stimulus, such as a potentially disturbing sound sequence (see Table 1 for examples), and their response monitored. Various experimental protocols have been employed, such as escalating the dose until a response is observed, using various stimuli, exposing the same animal multiple times and varying the context of the experiment (such as the animal's behavior before the experiment or the path of the source vessel). Care is taken to ensure the experimental animals are not unduly stressed, for example by ceasing the stimulus as soon as a response is detected. Various measurements are recorded, including location (in 3D) through time, acoustic behavior, behavior at the surface, etc.

BRS experiments are extremely costly to undertake: large teams of researchers are required, as well as substantial amounts of ship time (unless the monitoring can be undertaken from shore), and the costs associated with deploying an acoustic source to project the stimulus. A single field season may cost many hundreds of thousands of dollars. Many species of interest occur at low density, or are hard to monitor (for example if they are visually cryptic and difficult to tag), and experiments can only take place in good weather conditions and when other interfering noise sources are not present. Because of these factors, the sample sizes associated with BRS experiments are usually very low: typically fewer than ten exposures per species per field season, and sometimes substantially fewer than this.

Despite the difficulties, BRSs are attractive because they offer a direct measure of the effect of sound on behavior. A literature review (summarized in Table 1) shows that 13 studies have been undertaken over the past 30 years. In the research proposed here, we will focus on studies funded by the US Navy to investigate the effect of mid-frequency active sonar[1]. These include the Sirena sonar trials on sperm whales, Bahamas BRS, SOCAL BRS, Norwegian 3S and 3S2, Cape Hatteras EK60 experiments and Cape Hatteras and Hawaiian killer whale BRS. We have omitted MED-09 from our focal studies because no controlled exposure experiments (CEEs) were carried out (D'Amico et al. 2010); however members of the steering group were involved in this BRS and therefore we will have the opportunity to evaluate important baseline data obtained during this study and in earlier tagging of beaked whales .

Many diverse analyses have been applied to data from each BRS, and we do not attempt to review them all in this proposal. Typically the first stage is to synthesize the observational data to determine whether there was a response or not (or the magnitude of any response) and at what level of dose. Secondly, results from individual exposures may be analyzed together

[1] We emphasize that the methods we propose to develop will be widely applicable to other BRS experiments, and we would be pleased to include other researchers undertaking BRSs as appropriate.

to estimate a (context-specific) dose-response function. Both stages are fraught with practical difficulties. At the first stage, it is not clear how best to combine the diverse input metrics (such as position, orientation, swim speed, dive time, social configuration and surfacing behavior) all measured through time, into a single measure of response, or indeed whether this is desirable. At both stages, analyses need to account for dependencies in the data, because many measurements are taken in close succession on the same subjects. The same subjects may also be exposed multiple times. While there are many measurements on each subject, there are few exposures in total, and often even fewer individual subject animals. Analysis approaches based on traditional statistical hypothesis testing and estimation have typically been employed; however these have restrictive assumptions and their statistical power is often very low. This has the undesirable effect that only studies on species showing the clearest responses are likely to provide statistically significant results that are easily publishable in top academic journals, because journals tend to be unwilling to publish studies showing "no effect". This can lead to a potential bias in published effect levels, such that animals are thought to be more sensitive on average than is actually the case.

Despite the complications, we believe that substantial progress can be made to enhance the inferences drawn from existing and future BRS data. We propose to achieve this by bringing together researchers undertaking BRS studies and statisticians specializing in the analysis of biological experiments of this kind in a working group format, with dedicated researcher effort between group meetings. We anticipate that progress can be made in four areas:
1. Improved methods for combining diverse behavioral measures into a response metric;
2. Better estimates of dose-response functions from individual studies through the use of cutting edge (hierarchical Bayesian) statistical techniques;
3. Predictions about taxa or contexts not yet studied by combining information across studies in a meta-analysis framework, informed by biological knowledge;
4. Sensitivity analyses to quantify where future experimental effort will most reduce uncertainty.

In summary, whilst each study has provided a wealth of information and is highly valuable as a stand-alone entity, we propose to look at the studies in combination in order to maximize the gain from each study. This will not only be through the development and application of sophisticated statistical methodologies but also through knowledge exchange between the members of each of the BRS project teams.

Objectives

The overall objective of this project is to develop and implement innovative statistical methodologies for the analysis of behavioral response study data. Our focus is on studies estimating the response to mid-frequency active sonar, but the methods developed will be widely applicable. We aim to maximize the inferences that can be drawn from current and ongoing studies as well as to provide advice on future studies. Advances will be made in close collaboration with those involved in existing BRS projects, using a working group format. This approach enables us to complement and enhance the analytical work already being undertaken, as well as to be flexible and incorporate new ideas as they arise in working group sessions.

The project has four specific objectives.

1. Improve methods for combining diverse behavioral measures into metrics of behavioral response. Consideration will be given to obtaining metrics that can be linked to biological consequences. We will consider the strengths and limitations of the various possible behavioral measures, and provide recommendations on appropriate behavioral measures and metrics for future studies.
2. Improve methods for estimating dose-response functions for individual studies. This involves both developing and applying cutting-edge statistical methods, as well as considering what contextual variables in addition to acoustic dose can be incorporated into the analysis. The output will be improved estimates of response curves (with uncertainty) for each study.
3. Combine information across studies and species ("meta-analysis"), making use of expert biological opinion, to make predictions about taxa and contexts not yet studied. Differences in methods/protocols between studies will need to be accounted for. A component of this objective is to quantify the similarity/dissimilarity between species, placed into functional groups.
4. Based on the above, determine where major uncertainties still lie, and hence suggest where future experimental effort might be applied most fruitfully (through sensitivity analyses).

Technical Approach

The first US Navy-funded BRS focusing on mid-frequency active sonar was conducted in 2007 and 2008 in the Bahamas with the aim of collecting baseline data on animal behavior, and conducting CEEs to measure responses to different sound stimuli. A major focus of the Bahamas work was beaked whales, which are thought to be some of the species most vulnerable to sounds from sonar exercises. The 3S project, which aimed to determine behavioral response of killer, sperm and pilot whales to different sonar frequencies, commenced in 2006 with funding from The Royal Norwegian and Dutch Navies, and in 2008 the additional US-Naval support allowed a significant expansion of the effort. This project was conducted in Norwegian waters and is now being followed by the $3S^2$ project (starting 2011), which plans to expand the range of species studied and investigate the effectiveness of ramp-up as a mitigation strategy. The SOCAL-BRS experiment conducted its first season of data collection in 2010. SOCAL-BRS is a five-year study in southern Californian waters, which aims to expand on the work conducted in the Bahamas by increasing the number of species studied and by integrating with other field efforts being conducted in the same region. Recently, funding has been secured to carry out CEEs on cetaceans off Cape Hatteras and Hawaii, in order to investigate their response to the sounds of potential predators that resemble the sounds of military sonar, specifically testing the influence of species-specific social structure on those responses.

All of the BRS experiments described above have relied on a range of existing data collection technologies/methodologies that have allowed a range of metrics to be compiled. Researchers have used these to try to determine whether or not exposed individuals have exhibited a behavioral response. The simplest metrics are derived from a range of visual protocols for the collection of data on position, orientation, social configuration, surfacing behavior and swim speed of individuals and groups before, during and after a CEE. These data are difficult to collect for the more cryptic and deep-diving species, but DTags have proven invaluable for this purpose. They are attached to cetaceans using suction cups and collect acoustic and

movement data for the duration of attachment. The deployment of these tags on unexposed animals has provided valuable baseline data on diving and foraging behavior. Their deployment during BRS experiments has allowed the behavior of exposed individuals to be tracked in fine detail before, during and after exposure. The acoustic sensor on the tags can also provide direct measurements of received sound levels.

Fixed hydrophone arrays on military ranges (AUTEC and SCORE) have been used during Bahamas BRS and SOCAL-BRS to identify and track individuals and groups of cetaceans. These hydrophones have been adapted to detect the sounds produced by marine mammals, and methods have been developed to track animals as they move and vocalize over the range. These hydrophone arrays are a permanent installation, allowing data to be collected during "quiet" times as well as during BRS experiments, providing an additional source of baseline data.

Whilst there has been considerable consistency in the technologies employed across all the BRSs there have also been a range of important differences that need to be understood if we are to collate and compare data across studies. The most obvious difference is geographical location, resulting in differences in bathymetry, distance to coastline, sound propagation properties and prey availability (i.e. motivation to remain in area). In addition, the species that have been used in CEEs have differed both within and across studies. The full spectrum of differences will need to be explored in detail within the working group meetings but is likely to include sound types, sound frequencies, exposure durations, position/direction/movement of source relative to animal and distance to animal.

Our approach to this potentially vast area of research will be flexible and responsive to the analytical requirements perceived by BRS researchers and discussed at working group meetings. We will also seek input from regulators and research sponsors. In preliminary discussions, we have formulated the four main objectives given in the previous section; we envisage each of these translating into a major module of research. As an example, we outline a possible approach to one of these objectives below.

Example: Bayesian hierarchical methods for estimating dose-response functions

The second objective, the development of improved methods for estimating dose-response functions, is an area in which we have done some preliminary investigative work based on the data on killer whale (*Orcinus orca*) from the 3S project, kindly supplied by Patrick Miller. Here, we provide a short summary of this work as an example of the type of research we intend to undertake. The model used here is solely intended as a preliminary illustration of what can be achieved with this approach.

The data we used consisted of 14 exposure events involving 4 individual killer whales. Exposure events consisted of either MFAS or LFAS sound sources. A behavioral response was observed in 11 out of 14 instances, and the associated dose was recorded. Following some exploratory analyses looking at response thresholds within and between individuals, we investigated the application of a Bayesian hierarchical model to the data. The model is hierarchical in the sense that it allows for variation in threshold between whales and between exposure sessions for each individual whale. Both of these are modeled as random effects. It also allows for an effect of prior exposure and sonar type. Lastly, it accounts for the fact that the actual level at which response occurred is not known precisely (indeed, for exposure sessions where no response was observed, all we have is a lower bound on the response threshold). We favor a Bayesian formulation for the model because it allows us much

flexibility in specifying the model, and also allows us to specify priors on model parameters based on *a priori* knowledge of reasonable bounds for these parameters.

For a first look we specified the components of the model as follows.

Process model: Let t_{ij} be the threshold of exposure that elicits a behavioural response for the *i*th whale on the *j*th exposure session. We assume that this threshold follows a normal distribution:

$$t_{ij} \sim N(\mu_{ij}, \sigma^2)$$

where μ_{ij} is the expected threshold for the *i*th whale in the *j*th exposure session and σ^2 is the within-animal between-session variance in threshold. We assume this variance is the same for all animals.

We assume that μ_{ij} depends upon the expected threshold for that whale, μ_i , as well as type of sonar used in the exposure session and whether or not the whale has been subject to previous exposure sessions:

$$\mu_{ij} = \mu_i + \beta_1 I(MFAS) + \beta_2 I(exposure)$$

where β_1 is a parameter governing the effect of MFAS relative to LFAS and I(MFAS) takes the value 1 if the exposure session used MFAS, 0 if LFAS, β_2 is a parameter governing the effect of previous exposure on threshold, *I* (exposure) is an indicator variable that takes the value 1 if the whale has had prior exposure, 0 otherwise. We note that there are many other possible formulations: for example, animals could become increasingly sensitive or desensitize according to the number of exposures, not just whether or not they had been exposed previously; also if animals are more sensitive to MFAS then previous exposure to MFAS may have more of an effect than previous exposure to LFAS. Such issues could be investigated through different models, and evidence for them weighed via Bayesian model selection.

Lastly, we assume that the expected threshold for each whale follows a normal distribution:

$$\mu_i \sim N(\mu, \phi^2)$$

where μ is the mean threshold for whales, and ϕ^2 is the between-whale variance in threshold.

Observation model: In each exposure session, we obtain measurements of the lower and upper bounds on the exposure threshold, which we will denote L_{ij} and U_{ij}. The lower bound is given by the last level of exposure measured just before there was a response (or, in the case of no response, just before the experiment was stopped). The upper bound is given by the level of exposure measured just after there was a behavioral response (or, in the case of no response, it is the level at which we are sure a response would have occurred). We assume that any value within this range is equally likely to be the threshold for that whale and exposure session:

$$t_{ij} \sim U(L_{ij}, U_{ij})$$

Note that the model given here assumes measurements in units of sound pressure level; a useful alternative would be to use the accumulated sound exposure level.

Priors: We specify the following priors. Note that these were largely created in the absence of much biological knowledge and need to be refined following discussion with 3S researchers. Priors on the random effects variance parameters, in particular, have an important effect on inference (for brevity, these results are not shown here).

- $\mu \sim U(80,200)$ – i.e., the threshold of an average whale that has not been exposed before, and for an experiment involving LFAS, could take any value between 80dB and 200dB with equal probability
- $\phi \sim U(0.001,30)$ – i.e., that the between-whale standard deviation in threshold could take any value between 0.001 and 30dB with equal probability
- $\sigma \sim U(0.001,30)$ – i.e., that the within-whale between-exposure session standard deviation in threshold could take any value between 0.001 and 30dB with equal probability
- $\beta_1 \sim N(0,100)$ – i.e., that the effect of exposure follows a normal distribution centred on 0 and with a very large variance
- $\beta_2 \sim N(0,100)$ – i.e., that the effect of MFAS on exposure, relative to LFAS, follows a normal distribution centred on 0 and with a very large variance

Results: The data suggest that there is considerable within-whale between-exposure variation in threshold (posterior mean for $\sigma = 25.2$, 95%CI 17.5 - 29.8). There may also be moderate between-whale variation ($\phi = 15.5$, 95%CI 0.9 - 29.1), although the lower bound of the credible interval is close to zero. Note that in both cases the upper bounds of the credible intervals are close to the boundary set by the prior, indicating that the data may suggest even more variability is present. By contrast, there is no evidence for a systematic effect of MFAS vs LFAS ($\beta_1 = -4.9$, 95%CI -22.4 – 12.7) or previous exposure ($\beta_1 = 1.9$, 95%CI -15.7 – 19.4). The estimated dose-response function is shown in Figure 1. From this, 50% of animals are estimated to respond at a dose of 141dB or lower, but uncertainty on this value is high (95%CI 113 – 170dB).

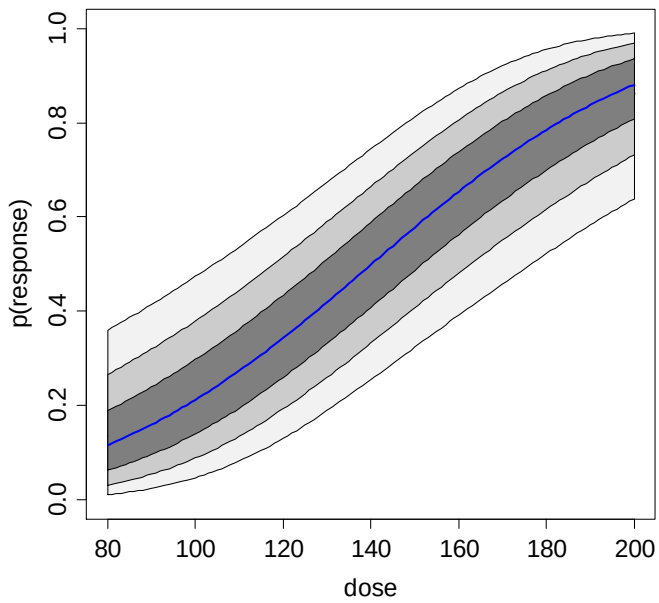

Figure 1. *Estimated dose-response function for killer whales from 3S data using a hierarchical Bayesian model. Solid blue line shows posterior mean estimate for an LFAS exposure and first exposure session; lines for MFAS or subsequent exposures are similar. Shading indicates (from inner to outer) 50%, 80% and 95% CIs on the estimated dose-response function, accounting for both between-whale and within-whale variation in response.*

Although more work can clearly be done to refine the model and priors, it appears that there is considerable variation in sensitivity to sonar in the study animals, even between exposure session within animal, and that this appears to depend upon factors other than the type of sonar or previous exposure. This highlights the importance of considering other measurable contextual variables (behavioral state, relative orientation, environmental conditions, etc.) that could help account for this variation.

Synergies with MMB program objectives and current Navy research

This project aims to significantly enhance the Controlled Exposure Experiments component of the Marine Mammals and Biology Program, and it will also address broader commitments of the Navy for environmental compliance. As part of rule making under the US Marine Mammal Protection Act, the Navy has committed to an Integrated Comprehensive Monitoring Program with the following objectives: Monitor and assess the effects of Navy activities on protected marine species; Ensure that data collected at multiple locations is collected in a manner that allows comparison between and among different geographic locations; Assess the efficacy and practicality of the monitoring and mitigation techniques; Add to the overall knowledge base of protected marine species and the effects of Navy activities on these species (Stone 2009). As part of its environmental compliance, the Navy must attempt to quantify the effect of sonar operations on marine mammals in all of its operating areas. This requires methods to estimate the relationship between acoustic dosage and other factors with behavioral responses. Here we propose to develop a framework to pool data across studies and areas to develop more systematic models to quantify these effects.

The focus of this research will be BRSs that have been funded by the US Navy and SERDP. We hope to maximize the gain from each BRS by combining the expertise, knowledge and data from these studies. All BRS studies collected some baseline and control data, but we also propose to include as much baseline data from other studies as will strengthen the development of our models.

Additionally, this project can build upon the large amount of ancillary research that has been conducted in relation to the behavioral response of marine mammals to sounds, much of which has been funded by the US Navy. For example, the M3R project is providing important opportunistic data on the movements of vocalizing beaked whales within the AUTEC range during periods with and without sonar activity. Additional data on ship movement and source location relative to whales will provide the context-specific information that is likely to be an important determinant of variability in responses and thresholds.

The personnel involved in this project will be representing many US Navy-funded projects beyond those listed above (e.g. IQOE, LATTE, PCAD, BBES) and we propose to maximize opportunities to transfer knowledge, expertise and research developments between all of these projects and this proposed project. The list of personnel and their relevance to this project can be found below.

Project schedule and milestones

Year:	**2012**								**2013**												**2014**												**2015**		
Quarter:	**Q2**			**Q3**			**Q4**			**Q1**			**Q2**			**Q3**			**Q4**			**Q1**			**Q2**			**Q3**			**Q4**			**Q1**	
Month:	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**	**J**	**F**	**M**
Financial Year:	**FY2012**						**FY2013**												**FY2014**												**FY2015**					
Workshop 1	x																																			
Workshop 2						x																														
Workshop 3											x																									
Workshop 4																		x																		
Workshop 5																							x													
Workshop 6																														x						
Post-doc 1 - biologist																																				
Individual project support	x	x				x	x				x	x						x	x				x	x						x	x					
Meta-analysis		x	x	x	x		x	x	x	x		x	x	x	x	x	x		x	x	x	x		x	x	x	x	x	x		x					
Attend BRS project meetings	x					x						x						x						x						x						
Refining analyses and writing publications														x	x	x															x	x	x	x	x	x
Post-doc 2 - statistician																																				
Individual project support	x	x				x	x				x	x						x	x				x	x						x	x					
Behavioural metric development		x	x	x	x		x	x	x	x		x	x	x	x	x	x		x	x	x	x		x	x	x	x	x	x							
Dose-response methodology development		x	x	x	x		x	x	x	x		x	x	x	x	x	x		x	x	x	x		x	x	x	x	x	x							
Attend BRS project meetings	x					x						x						x						x						x						
Refining analyses and writing publications														x	x	x															x	x	x	x	x	x
Catriona Harris																																				
Data management		x	x	x	x		x	x	x	x		x	x	x	x	x	x		x	x	x	x		x	x	x	x	x	x		x	x	x	x	x	x
Post-doc management/project support	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Workshop organisation	x				x					x							x					x							x							
Project Management																																				
Progress meetings	x			x			x			x			x			x			x			x			x			x			x			x		
Annual reports							x												x												x					
Final report																																				x

Deliverables

1. Final report, detailing all findings as well as the datasets used and algorithms developed. In cases where this information is already contained in a peer-reviewed publication (see below), reference to that publication will be sufficient. March 2015.
2. Annual progress reports describing progress to date: October 2012, October 2013, October 2014.
3. At least three manuscripts submitted to peer-reviewed journals. March 2015.
4. Datasets used archived wherever possible. March 2015.

Management approach

We propose to follow the successful format adopted by the PCAD project (Fleishman, 2010) where a series of workshops have brought together participants to exchange knowledge and to discuss options to model the available datasets. Following each workshop, a small number

of post-doctoral researchers have carried out model development and analysis at their home institutions. Each PCAD workshop focused on one model species. In this project we anticipate a series of workshops, each focusing on a functional/taxonomic group of marine mammals (deep divers, pilot whales, baleen whales, other odontocetes). We have chosen these focal groups and in this order because for a number of reasons: We will begin with deep divers (beaked whales and sperm whales) because this group contains species of concern, there are data for these species across multiple BRS projects and the metrics measured are fairly well defined and the social complexities are minimized. We will then focus on pilot whales for which there is data from most BRSs but focusing on this species will provide an opportunity to investigate the additional complexities associated with a social species whose vocal behavior is poorly understood. The 3rd and 4th workshops will focus on baleen whales and other odontocetes respectively – one motivation for focusing on these groups later in the project is because data collection is ongoing and we anticipate additional data being obtained for these groups particularly over the first year of the project (2012).

Proposal development was greatly facilitated by an initial scoping meeting held in The Hague on 9th September 2011 in association with the Effect of Sound on Marine Mammals (ESOMM) meeting in Amsterdam, 5-9th September 2011. There is an opportunity for further planning and project development at the Biennial Society for Marine Mammalogy conference in Tampa, Florida, 26th November-2nd December 2011, particularly in association with the BRS workshop being held on the 26th November. We acknowledge that these will take place before the formal start of the project, and we will not apply for financial support for them; however, they provide a valuable opportunity to engage with the majority of the named investigators at the planning stage and will hopefully result in an effective project start-up in April 2012.

We plan to hold five workshops within the first 24 months of the project, following appointment of the post-doctoral researchers in Spring 2012. The initial workshop will involve all parties and will include an overview of each BRS project, with a focus on protocols used and metrics measured and then discussion of how to integrate data and results across studies (objective 3, above). Thereafter, we propose holding workshops that will each focus on a functional/taxonomic group of marine mammals – namely deep divers (beaked whales and sperm whales), pilot whales, baleen whales and other odontocetes. This will enable us to restrict the number of attendees at these four workshops to a productive level, and also to deal with the peculiarities of each group in turn. We emphasize, however, that we will invite the core working group to all meetings, and will address progress on synthesizing results across studies and species at each meeting. We will hold one final workshop in the final 12 months of the project, which will allow for reporting and final analysis improvement. To minimize travel by participants, we will, whenever possible, schedule the workshops to coincide with existing BRS project meetings, for example cruise planning meetings or analysis meetings.

In the periods between face-to-face workshops, we will hold regular (at least one per month) conference calls to discuss technical aspects of the project with small sub-sets of the working group, and every two months we will hold a progress meeting via conference call with the entire working group. This format of separating conference call meetings into small technical meetings and larger progress meetings has worked very well within other projects coordinated by the PIs (such as the NOPP-funded DECAF project and the ONR-funded LATTE project). Many members of the working group are based in St Andrews, and others visit regularly, so it is envisaged that many of the technical meetings may be largely held

face-to-face in St Andrews. The close proximity of many of the researchers will lead to strong interactions and rapid progress; however we are acutely aware that several key collaborators are at other locations and will make strong efforts to engage a diversity of modeling approaches and to keep everybody included in the work.

Two post-doctoral researchers will conduct the majority of the research and model development over the course of the project under the supervision of Harris and Thomas, with frequent inputs from other project partners as required. These positions will be based within CREEM at the University of St Andrews where they will have access to a range of statistical expertise, primarily provided by those CREEM personnel included in the working group. The researchers will also have frequent contact with Co-PIs based at the Sea Mammal Research Unit (SMRU). One post-doc will have a strong background in mathematics and statistics and will focus on development of methods pertinent to individual studies, such as Bayesian hierarchical methods for dose-response analysis. The other will have more of a biological background (although with strong experience in quantitative methodologies) and will focus on methods for pooling information across studies (meta-analysis), and hence predicting response among species not yet studied, as well as identifying data gaps and potentially improved experimental designs. However, our staff skill requirements are flexible, depending on the strengths of applicants, and their roles and tasks are flexible, depending on the outcome of working group meetings.

Role of personnel associated with the project

Principal Investigators

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Peter Tyack	SMRU	ptyack@whoi.edu

Working Group (Co-Investigators)

John Calambokidis	CRC	calambokidis@cascadiaresearch.org
John Harwood	CREEM/SMRU	jh17@st-andrews.ac.uk
Ruth King	CREEM	ruth@mcs.st-and.ac.uk
Petter Kvadsheim	FFI	phk@ffi.no
Frans-Peter Lam	TNO	frans-peter.lam@nto.nl
Monique MacKenzie	CREEM	monique@mcs.st-and.ac.uk
Jason Matthiopoulos	SMRU/CREEM	jm37@st-andrews.ac.uk
David Moretti	NUWC	david.moretti@navy.mil
Doug Nowacek	DUML	doug.nowacek@duke.edu
John O'Quigley	UPMC	john.oquigley@upmc.fr

Those included within the steering group and working group will act as representatives of their respective research group and it is anticipated that other members of these groups will be invited to working group meetings when relevant and at the discretion of the co-investigators and largely self-funded. Suggested additional participants include:

Michael Ainslie (TNO), Ana Catarine Alves (SMRU), Ricardo Antunes (SMRU), Robin Baird (CRC), Diane Claridge (BMMRO), Charlotte Cure (SMRU), Volker Deeke (SMRU), Nancy DiMarzio (NUWC), Lise Doksaeter (IMR), Carl Donovan (CREEM), Dorian Houser (NMMF), Ron Kastelein (SEAMARCO), Lars Kleivane (FFI), Sanna Kuningas (SMRU), Mike Longergan (SMRU), Filipa Samarra (SMRU), Fleur Visser (KMR), Paul Wensveen (SMRU)

Institutional addresses

BMMRO	Bahamas Marine Mammal Research Organisation, P.O. Box AB-20714 Marsh Harbour, Abaco, Bahamas
CRC	Cascadia Research Collective, 218 1/2 W 4th Ave., Olympia, WA 98501 USA
CREEM	Centre for Research into Ecological and Environmental Modelling, University of St Andrews, St Andrews KY16 9LZ, UK.
DUML	Duke University Marine Lab, 135 Duke Marine Lab Rd Beaufort, NC 28516, USA
FFI	Maritime Systems Division, Norwegian Defence Research Establishment (FFI), NO-3191 Horten, Norway
IMR	Institute of Marine Research, Nordnesgaten 50, 5005 Bergen, Norway
KMR	Kelp Marine Research, Amsterdam, The Netherlands
NMMF	National Marine Mammal Foundation, 1220 Rosecrans st. #284, San Diego, CA 92106, USA
NUWC	Navy Undersea Warfare Center, Newport, R.I. USA
SEA	Southall Environmental Associates, Inc., 9099 Soquel Drive, Suite 8 Aptos, CA 95003, USA
SMRU	Sea Mammal Research Unit, Scottish Oceans Institute, University of St Andrews, St Andrews KY16 8LB, UK
SEAMARCO	Sea Mammal Research Company, Julianalaan 46, 3843 CC Harderwijk, The Netherlands.
TNO	Observation Systems, TNO, Defence, Security and Safety, The Hague, The Netherlands
UPMC	Université Pierre et Marie Curie, Paris

Role of PIs

Dr Catriona Harris (CREEM)

Harris will manage the overall project and will coordinate the workshops and the research being carried out by the post-doctoral researchers, and will help guide the science to ensure it meets the objectives outlined above.

Dr Len Thomas (CREEM)

Thomas will lead the development of the required mathematical and statistical framework. This work will be undertaken in close collaboration with the post-doctoral researchers who will have these tasks as their full-time assignment.

Role of Steering group members
Ian Boyd (SMRU)
As one of Principal Investigators of the Bahamas BRS experiment Boyd has direct experience of the data collected on the AUTEC range and has an overview of all the analytical efforts that have been applied to these data thus far. His input will be invaluable in guiding the project to meet the general objectives of investigating the behavioral responses of cetaceans to sonars.

Patrick Miller (SMRU)
Miller is Principal Investigator of the 3S and $3S^2$ experiment and, as such, will provide an overview of the experimental approach, the data and analysis associated with this project. Miller will be responsible for representing the work carried out during the 3S and $3S^2$ experiments and for involving relevant co-investigators and researchers where appropriate.

Andy Read (DUML)
Read is a leading expert in odontocete cetaceans and is currently PI on a recently funded SERDP project to look at the behavioral response of odontocetes to threatening and non-threatening sympatric species using CEEs. He will be responsible for representing the work carried out under this project and ensuring relevant personnel are involved where appropriate.

Brandon Southall (SEA)
Southall is Principal Investigator of the SOCAL experiment and, as such, will provide an overview of the experimental approach, the data and analysis associated with this project. Southall will be responsible for representing the work carried out during the SOCAL experiments and for involving relevant co-investigators and researchers where appropriate.

Peter Tyack (SMRU)
Tyack has been involved in all three BRS experiments that are the focus of this proposal and therefore his involvement is crucial in bringing together an overview of all the experimental work that has been conducted and is planned, and in communicating the important differences and similarities across the projects. In addition, Tyack will provide expertise on the deployment of DTAGs and the analysis of the data collected by these devices. We propose that Tyack will chair at least one of the workshops.

Role of working group members
John Calambokidis (CRC)
Calambokidis is a senior research biologist with Cascadia Research, which is a leading participant in the SOCAL BRS project. He will be responsible for providing an overview of the experimental approach, the data and analysis associated with this project and will represent the work carried out by CRC. Calambokidis will ensure that other researchers are involved in this project where appropriate.

John Harwood (CREEM/SMRU)
Harwood has been heavily involved with the ONR working group on the development of models of the Population Consequences of Acoustic Disturbance. He will therefore help

ensure that some of the outputs from BRS experiments are relevant to the energetics models that will form part of the PCAD approach.

Ruth King (CREEM)
King is a statistical ecologist with expertise in Bayesian statistics and state-space modeling, statistical methods which are likely to be integral in the proposed analyses. King will provide guidance during workshops and to the post-doctoral researchers on the applicability and implementation of these methods to the BRS data sets.

Petter Kvadsheim (FFI)
Kvadsheim is the chief scientist and manager of the 3S and $3S^2$ projects and as such will bring a wealth of knowledge relating to the practicalities of conducting BRS experiments, which will be invaluable in future experimental design.

Frans-Peter Lam (TNO)
Lam was responsible for the recording and detection of marine mammal sounds using an advanced towed array hydrophone system during the 3S and $3S^2$ projects. He will provide expertise on the use of towed arrays for data collection during BRS experiments and will represent the work carried out by TNO, ensuring that other researchers are involved in this project where relevant.

Monique MacKenzie (CREEM)
MacKenzie is a statistical ecologist with expertise in methods dealing with repeated measure of individuals over time and spatially and temporally autocorrelated data, all issues which are relevant to the BRS data sets. She has also been involved in statistical analyses of the Bahamas BRS dataset looking at whether animal movement, specifically dive shape, demonstrates an effect of sound exposure. MacKenzie will represent the work carried out by herself and colleagues in this area and will provide guidance on the use of these methods in relation to BRS datasets.

Jason Matthiopoulos (SMRU)
Matthiopoulos is a quantitative ecologist specializing primarily in marine mammal habitat preferences and individual movement and has expertise in analysis of spatial data, telemetry data and the fitting of state-space models. He will provide guidance to the working group and the post-doctoral researchers on the appropriate use of different statistical methodologies to the BRS data sets.

David Moretti (NUWC)
The Bahamas BRS experiment was conducted on the AUTEC range and relied heavily on data collected on the fixed hydrophone array. Moretti has directed the collection and analysis of these data at NUWC and will provide expertise on the use of fixed hydrophone arrays as a data collection tool for BRS experiments. He will be integral in ensuring the work carried out by NUWC is represented and that personnel from the NUWC research group are involved where relevant.

Doug Nowacek (DUML)
Nowacek has been involved in a number of projects that have conducted controlled exposure experiments using a wide array of different stimuli and will therefore be able to represent the findings of a range of projects. In addition he has expert knowledge of diving and foraging behavior of some of the species of interest in some key locations. He is Co-PI on a recently

funded SERDP project to carry out further CEEs on odontocete species and he will ensure that this project and the personnel involved are represented.

John O'Quigley (UPMC)
O'Quigley has extensive theoretical and applied experience in the use of methods for identifying a target dose (maximum tolerated dose) in Phase I and Phase I/II clinical trials. Originator of the Continual Reassessment Method which has had great success in finding the MTD (viewed as a percentile from some unknown dose-toxicity curve) on the basis of small samples. He is a recipient of grants from the US National Institute of Health to develop and apply this methodology in the clinical setting as well as a co-PI recipient of one of President Obama's highly competitive stimulus grants partly based on this methodology. The use of this methodology in the field of this current proposal is entirely new and O'Quigley will be focused on providing expertise on the mathematical and statistical aspects of dose finding algorithms.

Current and pending project and proposal submissions

There is one pending proposal that is relevant to the work being proposed here. We are proposing to investigate historical BRSs such as the SURTASS LFA and Malme et al. (1984) studies. We would also like to consider the data being collected from seismic BRSs such as those being conducted by the BRAHSS project in Australia. Consideration of these additional BRSs would complement the work outlined here but is beyond the scope of this proposal and will require additional funding. We propose to approach industry, for example through the Joint Industry Program, to allow this additional work to occur alongside the work proposed here.

St Andrews Projects
Projects at St Andrews for which Thomas is PI or Co-PI and that have research overlap with the work proposed here:

The technical contact for all projects, unless otherwise stated is Len Thomas, and the business contact is John McAleese. Contact details for both are on the front cover of this proposal. Time allocations (person-months per year) are for Thomas only. All projects are based in St Andrews, and the prime offeror is University of St Andrews unless otherwise noted.

Project/Proposal Title:	DECAF: Density Estimation for Cetaceans from Acoustic Fixed Sensors
Status:	Ended
Source of Support:	National Fish and Wildlife Foundation (funded under NOPP; funds from Ocean Acoustics Program of the US National Marine Fisheries Service Office of Protected Resources and the Joint Industry Program of the International Association of Oil and Gas Producers)
Total Award Amount:	US$1,525,859.63
Award Number:	2007-0145-002
Total Award Period:	1 June 2007 - 28 February 2011
Person-months per FY:	1.5, 1.0, 5.5, 2.0

Summary: This project was three-year multi-institution project to develop methods for estimating cetacean density from fixed passive acoustics.

Project/Proposal Title: PhD Studentship: Estimating the abundance of whales using information from sparse arrays of seabed-mounted hydrophones
Status: Ending
Source of Support: National Fish and Wildlife Foundation (funded under NOPP; funds from Ocean Acoustics Program of the US National Marine Fisheries Service Office of Protected Resources and the Joint Industry Program of the International Association of Oil and Gas Producers)
Total Award Amount: UK£58,773.00
Award Number: RD034-014166
Total Award Period: Oct 1 2007 – 30 Sept 2010
Person-months per FY: Nominal
Summary: Studentship that funded Danielle Harris to work on methods for estimating density from fixed acoustics.

Project/Proposal Title: Latte
Status: Current
Source of Support: ONR
Total Award Amount: US$1,170,652
Award Number: N000141010382 / 1058479
Total Award Period: April 1 2010 – March 31 2013
Person-months: 0.75mo, 3mo, 2mo, 0.75mo
Summary: This three year project will develop and implement statistical models that integrate passive acoustic monitoring data and animal-borne tag data to estimate the effect of Mid Frequency Active (MFA) sonar on beaked whales at AUTEC.

Project/Proposal Title: Cheap DECAF
Status: Current
Source of Support: ONR
Total Award Amount: US$317,536
Award Number: N000141110615 / 1065646
Total Award Period: April 1 2011 – March 31 2013
Person-months: 3 mo over 2 project years
Summary: This is a two year project to extend the work carried out under the DECAF project to develop and demonstrate density estimation methods using sparse arrays of inexpensive sensors.

Project/Proposal Title: Extending our capability to determine distribution and abundance of marine mammals from line transect data
Status: Current
Source of Support: Naval Postgraduate School (funds from U.S. Navy Environmental Readiness Division (N45))
Total Award Amount: US$774,553.60
Award Number: N000244-10-1-005
Total Award Period: July 1 2010 – June 30 2013
Person-months per FY: 2.5mo, 3.5mo, 2.5mo
Summary: A three year project to develop methods and software to extend line transect methods for estimating density.

Project/Proposal Title:	SAMBAH – Static Acoustic Monitoring of the Baltic harbour porpoise
Status:	Current
Source of Support:	Half funded from European Union Life+, half funded by EU member states
Prime Offeror:	Kolmardens Djurpark AB
Technical Contact:	Mats Amundin, Research Director, Molmardens Djurpark, Kolmarden Sweden 61892
Administrative Contact:	Julia Carlström, address as above.
Total Award Amount:	EU€5,153,596; approx EU€200,000 to St Andrews
Award Number:	LIFE08 NAT/ S/ 261
Total Award Period:	January 1 2010 – December 31 2014
Person-months:	5mo over life of project

Summary: A five year project to estimate Baltic harbour porpoise density via fixed passive acoustic sensors.

Project/Proposal Title:	The ecology and acoustic behavior of minke whales in the Hawaiian and Pacific Islands: A study to assess the distribution, abundance, acoustic behaviors, and the effects of noise on an elusive but acoustically active species.
Status:	Current
Source of Support:	ONR
Prime Offeror:	BioWaves, Inc.
Technical Contact:	Tom Norris, Bio-Waves Inc., 517 Cornish Dr., Encinitas, CA 92024. thomas.f.norris@cox.net
Administrative Contact:	As above.
Total Award Amount:	US$696,566
Award Number:	N000140910489
Total Award Period:	February 15 2009 – February 14 2011
Person-months:	1mo

Summary: A study that provides vital background information on the acoustic ecology of minke whales in Hawaii, including first estimates of vocalization rates and density.

Project/Proposal Title:	Multi-year minke whale densities at the Pacific Missile Range Facility in Hawaii.
Status:	Proposed
Source of Support:	ONR
Prime Offeror:	SPAWAR Systems Center Pacific.
Technical Contact:	Stephen W. Martin, SPAWAR Systems Center Pacific, San Diego, CA
Administrative Contact:	Unknown.
Total Award Amount:	Approx US$430,000
Total Award Period:	October 1 2010 – September 30 2012
Person-months:	1.5mo

Summary: Two year effort to provide estimates of spatial and temporal variation in Minke whale boing density, as well as develop better methods for estimating this and animal density, and more automated procedures for processing the acoustic data.

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Table 1: Overview of past and ongoing cetacean behavioral response studies.

Name	Location	Years	Number of trials	Type of stimuli	Target species	Species tagged	Number of tags deployed	Monitoring/obs methods	PI	Funder	References
Petroleum activity and Grey whale migration	Monterey, California	1983-1984		Playbacks of drilling platform, drillship, production platform, drilling rig, helicopter, single airgun, killer whale calls	Grey whales (migrating)	N/A	N/A	Shore-based obs	Charles Malme	Minerals Management Service	Malme et al. 1984
ATOC MMRP	Hawaii and California	1995-1999?		Playbacks of ATOC-like sounds and response to ATOC itself	Humpback whales, elephant seals	Elephant seals		Sat tags, aerial surveys		US Navy	Au et al. 1997 Frankel and Clark 2000
SURTASS LFA SRP	Hawaii and California	1997-1998	~40	Playbacks of SURTASS LFA sonar	Blue, fin, gray, humpback whales	N/A	N/A	Visual observations, passive acoustic monitoring	Chris Clark, Peter Tyack	US Navy	Miller et al. 2000; Croll et al. 2001
Right whales and shipping	Bay of Fundy	2001?	20	Ship noise, conspecifics, alert noise	North Atlantic right whales	North Atlantic right whales	10	D-Tags, visual		NOAA Fisheries	Nowacek et al. 2004
SWSS	Gulf of Mexico	2001-2003	8	Full commercial airgun array	Sperm Whales	Sperm Whales	?	Dtags Visual observations, passive acoustic monitoring	Peter Tyack	MMS	Miller et al. 2008
3S project	Norway	2006		Experimental sonar	Killer whales,				Patrick Miller	Norwegian Navy and Netherlands Navy	Kvadsheim et al., 2007
Bahamas BRS	Bahamas	2007-2008	9 individuals exposed	Simulated military mid-freq sonar, killer whale calls, “control” noise	Beaked whales, pilot whales, false killer whales, melonheaded whales	Beaked whales, pilot whales, false killer whales, melonheaded whales	16	D-Tags Range hydrophones Visual	Ian Boyd	ONR	Southall et al. 2008

Norwegian 3S	Norway	2008-2010	14 individuals exposed	Experimental sonar at 2 frequencies (1-2kHz and 6-7kHz), killer whale calls	Killer whales	Killer whales, longfinned pilot whales, sperm whales	14	D-Tags, towed hydrophone array, visual	Patrick Miller	ONR Norwegian Navy and Netherlands Navy	Kvadsheim et al. 2009
Sirena 00-08; MED-09-11	Mediterranean	2000-2011	3	mid-freq sonar, *Ziphius*	sperm whale, ship noise	sperm whale, pilot whale, *Ziphius*	~12 sperm whale ~12 pilot whale; ~6 baseline Ziphius	Dtag, visual observation, passive acoustic monitoring, sonar tests on sperm whales	Angela D'Amico, Peter Tyack, Brandon Southall	ONR, NURC, SERDP	Baird et al. 2002; Zimmer et al. 2003, 2005abc, 2008
Acoustic Deterrent Devices and seals	Captive and wild experiments, Scotland	2009?		Acoustic deterrent devices and control noises	Grey seals and harbour seals			Captive experiment and visual obs in wild experiment	Vincent Janik		Gotz et al. 2010
SOCAL BRS	Southern California Bight	2010 - 2015	28	Simulated military sonar, control noise	16 focal species including 3 beaked whale species	Blue, fin, sperm, Baird's beaked whale, sei/fin hybrid, bottlenose dolphin, risso's dolphin, killer whale, cuvier's beaked whale	63 tags on 44 individuals of 9 species	D-Tags, range hydrophone, visual, MK-10, Bprobe, Sat tag, Acousonde	Brandon Southall	ONR	Southall et al. 2011
BRAHSS	East coast Australia	2010-2013	55?	Single air gun	Humpback whales	Humpback whales		D-Tags, theodolite stations, hydrophone array	Doug Cato et al	JIP E&P Sound & Marine Life and Bureau of Ocean Energy Management, Regulation and Enforcement	Cato et al. 2010
Norwegian 3S2	Norway	2011-2013		Experimental sonar at 2 frequencies (1-2kHz and 6-7kHz), killer whale calls, ramp up	Northern bottlenose whale, minke whale, humpback whale				Patrick Miller	ONR Norwegian Navy and Netherlands Navy	

Cape Hatteras EK-60 experiment	Cape Hatteras	2011		SIMRAD EK-60 echosounder system	Short-finned pilot whales			D-tags	Andy Read	NAVFAC Atlantic	
Cape Hatteras and Hawaii killer whale BRS	Cape Hatteras and Hawaii	2011-2014		Playbacks of killer whale calls, and sounds from non-threatening sympatric species (humpback whales)	Short-finned pilot whales, bottlenose dolphins, common dolphins, Cuvier's beaked whales			D-tags	Andy Read	SERDP	

Curriculum Vitae

Resumes for the principle investigators appear on the following pages, in alphabetic order by surname.

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University of St Andrews
Centre for Research in Ecological and Environmental Modelling
The Observatory, Buchanan Gardens, St Andrews, Scotland KY16 9LZ
Tel: (0)1334 461831 Email: catriona@mcs.st-and.ac.uk

Career Summary

2005 – present	**Post-doctoral Research Fellow**, Centre for Research into Ecological and Environmental Modelling, University of St Andrews
2004 – 2005	**Post-Doctoral Research Associate (NERC),** Sea Mammal Research Unit, University of St Andrews
2003 – 2004	**Post-Doctoral Research Associate (SHEFC),** Centre for Conservation Science, University of Stirling

Degrees

1999 – 2003 PhD: *Factors affecting the distribution and abundance of grey seals (Halichoerus grypus) around the UK.* Sea Mammal Research Unit, University of St Andrews

1995 – 1999 Bsc (Hons) Zoology (Marine and Fisheries) – First Class, University of Aberdeen

Research Interests

- Landscape, population and spatial ecology within the disciplines of marine mammal ecology, invasive species ecology and epidemiology.
- Impact of anthropogenic noise on marine mammals and the development of methods for modelling the distribution of marine mammals across space for risk mitigation purposes, for quantitatively assessing cumulative risk associated with noise exposure, and for analysing animal responses to controlled exposure experiments.
- Development of spatially-explicit models for the prediction of spread of invasive species and diseases.

Funding as Principal or Co-Investigator (includes consultancy income)

- Firth and Tay Offshore Wind Developers Group Seal project. SMRU Ltd. July – December 2011.
- Data Gateway Project. SMRU Ltd. July 2010 – April 2011
- Study of the epidemiology of *Phytophthora ramorum* and *Phytophthora Kernoviae* in managed gardens and heathland in Scotland. Scottish Government. August 2009 - July 2012
- Integrating ecological and epidemiological approaches to risk-assessment: The role of *Rhododendron ponticum* as a reservoir for non-native plant pathogens. UKPopNet Early Career Grant. 2008
- Assessing the risks to marine mammals associated with sonar based surveys off Libya. SMRU Ltd. August 2008
- Data Gateway Project. SMRU Ltd. July 2008 – December 2009
- Marine Mammal Awareness and Alert Response System. BAE System Avionics Ltd. August 2007 - July 2010
- Development of a landscape model for the control of *Rhododendron ponticum*. Carnegie Trust for the Universities of Scotland, Larger Grants Scheme. 2007-2009

Publications

Travis, J. M., **Harris, C. M.**, Park, K. J., & Bullock, J. M. (2011). Improving prediction and management of range expansions by combining analytical and individual-based modelling approaches. *Methods in Ecology and Evolution*. doi: 10.1111/j.2041-210X.2011.00104.x

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The Observatory, Buchanan Gardens, St Andrews, Scotland KY16 9LZ
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PROFILE:

- A research-active academic working at the interface between statistics, computing and ecology.
- Eighteen years' experience in applied statistics, specializing in:
  - design and analysis of ecological survey data, particularly distance sampling
  - trend estimation and monitoring wildlife populations
  - fitting data to nonlinear, stochastic models of wildlife population dynamics
- Committed to promoting the application of latest statistical research in ecology through provision of user-friendly software, training workshops and accessible books
- Coordinator of the ongoing Distance software development project at St Andrews. Distance is the industry standard software for design and analysis of distance sampling surveys of wildlife abundance.
- Principal investigator, co-investigator or contractor on numerous research projects totalling >UK£4.5million since 2005 Recent projects include:
  - DECAF: Density estimation for Cetaceans from Acoustic Fixed Sensors. 2007-2010. (http://www.creem.st-and.ac.uk/decaf/). Follow-up Cheap DECAF 2011-2013.
  - Estimation of cetacean distribution and trends through analysis of data from Joint Cetacean Protocol. 2008-2011.
  - PCAD tools: New statistical tools for fitting models of the Population Consequences of Acoustic Disturbance to data from marine mammal populations. 2010-2013.
  - LATTE: Linking Acoustic Tests and Tagging using statistical Estimation: Modeling the Behavior of Beaked Whales in Response to Medium Frequency Active Sonar. 2010-2013
  - SAMBAH: Static Acoustic Monitoring of the Baltic Harbour Porpoise. 2010-2014
  - Determining US Navy lookout effectiveness in detecting marine mammals . 2010-2011.
  - Extending our capability to determine distribution and abundance of marine mammals from line transect data. 2010-2013

CAREER HISTORY:

2010-present	**University of St Andrews, Scotland** Reader in Statistics
2005-2010	**University of St Andrews, Scotland** UK Research Council Academic Fellow in Mathematics and Statistics
1997 - 2005	**University of St Andrews, Scotland** Post-doctoral Research Fellow in Mathematics and Statistics

EDUCATION:

1997	**PhD in Conservation Biology**, University of British Columbia, Canada. Thesis entitled 'Evaluation of statistical methods for estimating long-term population change from extensive wildlife surveys'.
1991	**MSc (Distinction) in Biological Computation**, University of York, U.K.**.**
1990	**BSc (Hons.) in Animal and Plant Sciences**, Class 2:1, University of Sheffield, U.K.

RESEARCH OUTPUTS:

37 papers in peer-reviewed journals; 2 books (one an edited volume); 46 other publications and technical reports; >50 external seminars and conference talks since 2001. Selected publications:

Durant, S., M. Craft, R. Hilborn, S. Bashir, J. Hando and L. Thomas. In press. Long term trends in carnivore abundance using distance sampling in Serengeti national park, Tanzania. J. Appl. Ecol.

Küsel, E.T., D.K. Mellinger, L. Thomas, T.A. Marques, D.J. Moretti, and J. Ward. In press. Cetacean population density from single fixed sensors using passive acoustics. J. Acoust. Soc. Am.

McCarthy, E., D. Moretti, L. Thomas, N. DiMarzio, R. Morrissey, S. Jarvis, J. Ward, A. Izzi, In press. 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.

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

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

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

Buckland, S.T., A.J. Plumptre, L. Thomas and E.A. Rexstad. 2010. Design and analysis of line transect surveys for primates. International Journal of Primatology 31: 833-847.

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.

Savage, A., L. Thomas, K.A. Leighty, L.H. Soto and Felix S. Medina. 2010. Novel survey method finds dramatic decline of wild cotton-top tamarin population. Nature communications 1:30. doi: 10.1038/ncomms1030

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

Fewster, R.M., S.T. Buckland, K.P. Burnham, D.L. Borchers, P.E. Jupp, J.L. Laake and L. Thomas. 2009. Estimating the encounter rate variance in distance sampling. Biometrics 65: 225-236.

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. J. Acoust. Soc. Am. 125: 1982-1994.

Newman, K.B., C. Fernández, S.T. Buckland and L. Thomas. 2009. Monte Carlo inference for state-space models of wild animal populations. Biometrics 65: 572-583.

Thomas, L. 2009. Grey seals red in tooth and claw: how Darwin helps model their population. Significance 6(3):108-112

Patterson, T.A., L. Thomas, C. Wilcox, O. Ovaskainen and J. Matthiopoulos. 2008. State-space models of individual animal movement. Trends in Ecology and Evolution 23: 87-94.

Thomas, L., R. Williams and D. Sandilands. 2007. Designing line transect surveys for complex survey regions. Journal of Cetacean Research and Management 9: 1-13.

Thomas, L., S.T. Buckland, K.B. Newman & J. Harwood. 2005. A unified framework for modelling wildlife population dynamics. *Australian and New Zealand Journal of Statistics* 47: 19-34.

Buckland, S.T., D.R. Anderson, K.P. Burnham, J.L. Laake, D.L. Borchers & L. Thomas (Eds.), 2004. Advanced Distance Sampling. Oxford University Press.

Buckland, S.T., D.R. Anderson, K.P. Burnham, J.L. Laake, D.L. Borchers & L. Thomas. 2001. Introduction to Distance Sampling. Oxford University Press.