Double MOCHA: Phase II Multi-study Ocean acoustic Human effects Analysis

RESEARCH PROPOSAL SUBMITTED TO US OFFICE OF NAVAL RESEARCH
MARINE MAMMALS AND BIOLOGICAL OCEANOGRAPHY PROGRAM
BAA Number: N00014-18-S-B001

Technical Proposal

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PERIOD OF PERFORMANCE:

Base period: 1 September 2018 – 31 December 2021 (40 months)
Option 1: 1 May 2019 – 30 April 2021 (24 months)

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Project summary

The overall objective of this project is to develop new quantitative models and analytical methods for inferring behavioral response of marine mammal species to Navy sonar. The results will be directly applicable to current Behavioral Response Studies (BRSs) operating on multiple species in multiple oceans and will support future Navy Behavioral Response Criterion development. Three specific objectives are as follows.

1. Develop analytical methods for estimation of behavioral response and subsequent recovery from controlled exposure experiments (CEEs) that allow fusion of multiple input datasets collected across a range of spatial and temporal scales. A particular emphasis will be on the multi-scale Atlantic BRS study.

2. Develop recommendations for effects analysis of long-term passive acoustic data. The work will support effects analysis of vocal marine mammals by both Atlantic and Pacific fleets, as well as BRS studies that deploy long-term passive acoustic sensors.

3. Develop next-generation models for behavioral response based on our understanding of marine mammal signal detection and the evolutionary drivers of response. This will have longer-term impact on exposure-impact modelling and future BRS design.

We also list a further objective as an option.

Option 1. Develop flexible and practical methods for dose-response modeling that allow data from multiple species to be combined and different functional forms of the dose-response function to be fit. This will facilitate development of improved noise exposure criteria, and hence support future Navy Behavioral Response Criterion development.

Technical Approach and Justification

Background

Behavioral Response Studies (BRSs) aim to directly quantify the relationship between potential anthropogenic disturbance and their effect on marine mammals. The US Navy is making a substantial investment in BRSs, aimed at understanding the effect of active sonar on species of concern. BRSs can be broadly divided into those that rely on a formal experimental design (Controlled Exposure Experiments, CEEs), and those that make opportunistic use of real-world naval activities (observational studies). CEEs on wild swimming animals are difficult and costly to perform: they typically involve attaching a data recording tag to a free-swimming animal, maneuvering a sonar source vessel along a specified trajectory relative to the animal, and recording the animal's behavioral response to the source – both visually and via data collected by the tag. Sample sizes are necessarily small, and the resulting multivariate datasets are complex to analyze. These and other issues led to the formation of a Navy-funded working group, MOCHA (for Multi-study Ocean acoustic Human effects Analysis, ONR award number N000141210204), led by PIs Thomas and Harris in 2012. This working group involved members from all Navy-funded BRS projects and had as its goal the development and implementation of analysis methods that made most effective use of the available data. The project, which ended in 2016, was an outstanding success, with MOCHA PIs and post-docs contributing to 26 publications to date (Thomas and Harris 2016; see also https://synergy.st-andrews.ac.uk/mocha/). A suite of methods is now available to the BRS community for characterizing marine mammal behavior, identifying behavioral change-points caused by exposure and relating behavioral responses to dose metrics such as received level and range. Further, by working with the BRS teams, team members now have experience of and skills in using these advanced methods. The outputs of the MOCHA project have substantially enhanced our ability to quantify the response of marine mammal species to Navy sonar and other acoustic stimuli. However, as the BRS field studies have evolved so have the analytical requirements.

A recent Navy funded program (BRREW project, ONR award number N000141512664) reviewed the current state of knowledge on marine mammal behavioral response to sonar. The goals were to evaluate the return on investment of current US Navy funded programs, identify the data needs and the contributions of current research programs to meeting data needs, and evaluate the ability to meet outstanding data needs given the current state of technology. Results appeared as a report (Harris & Thomas 2015) and a review paper (Harris et al. 2018). BBREW recommended that "BRS research be continued and extended to increase sample sizes and experimental replication, and temporal duration and spatial scale…. It was noted that future investigations would benefit from combining experimentation and observation to enable linkage of short-term behavioral response to long-term fitness consequences of repeated exposure. The importance of baseline studies and longer-term monitoring of animals before and after exposure is emphasized throughout." (Harris & Thomas 2015). Some of these recommendations have been acted upon by the most recent experimental BRS efforts, e.g., the Atlantic BRS study (Southall et al. 2018) and the most recent 3S project trials (Lam et al. 2016). For example, the Atlantic BRS is using a combination of animal-borne tags (short-duration high-fidelity DTAGs and longer-duration lower-fidelity satellite tags), and passive acoustic monitoring (PAM). The most recent 3S project experiments have added PAM from static autonomous sensors to their protocol. The collection of data across multiple spatial and temporal scales from a variety of different platforms presents new analytical challenges that were not addressed explicitly by the MOCHA project. In addition, these recent BRS efforts are aiming to address some of the outstanding questions from the early BRS studies, such as the relative importance of range and received level and the duration of response. As such the integration of data from across scales and sources will be required to adequately answer these questions. The need to deal with data from multiple spatial and temporal scales is the main motivation behind our first objective.

Passive acoustic data is an important modality for inferring behavioral response. As noted above, PAM is a component of some CEE protocols. Passive acoustic tracking from dense hydrophone arrays can also potentially provide an alternative to inferring behavioral response from tags (for example using Navy instrumented testing ranges). Lastly, long-term sparse-array PAM studies can be used in an observational context to examine whether there is a relationship between detection rates of marine mammal vocalizations and Navy sonar. Observational studies cannot be used to infer causation, but these long-term PAM studies can play a crucial and complementary role to the CEEs in two respects. First, being relatively inexpensive (especially when based on existing data, or data collected for other purposes) they may be used as a "triage", i.e., to find species and circumstances where a strong relation between detection rate and sonar is found. These may then be the target for experimental studies. Second, they provide a population-level context to interpret findings of CEEs, which focus on the individual. Analysis methods for inferring behavioral response from long-term PAM data have been developed and demonstrated under funding both from the Atlantic fleet (Oswald et al. 2015, 2016) and Pacific fleet (Bauman-Pickering 2018). Two statistical approaches have been developed, one using Generalized Estimating Equations (GEEs) and the other Hidden Markov Models (HMMs). Both approaches have merits and downsides, and a major recommendation of Oswald et al. (2016) was to undertake a simulation study to quantify these, so that the most suitable approach can be selected. In addition, methodological advancements are required to deal with the considerable size of many long-term datasets, the need to account for between site differences (using random effects models), and the richness of the suite of possible explanatory variables (both environmental and sonar-related). Such developments will be of utility not just to the long-term observational datasets, but also to BRSs such as the 3S project that deploy single acoustic sensors as part of the experimental setup. These needs are the basis of our second objective in this proposal.

To date, much of the emphasis in BRSs has been on the empirical quantification of probability of behavioral response to sonar, severity of response, and the factors affecting these (Harris and Thomas 2015, Harris et al. 2018). These empirical studies have been linked to what is understood about animal biology to varying degrees. For example, the Bayesian dose-response function of Miller et al. (2014) used as one measure of acoustic dose the sensation level, which depended on a frequency-specific hearing threshold for the subject species; conversely within- and between-individual variation in response was assumed to follow a normal distribution, for want of better information. (This was subsequently extended to a mixture of two normal distributions by Department of the Navy (2017), based on biological considerations elucidated by Ellison et al. (2011).) Whether and how an animal responds to sonar depends on many factors – whether the animal detects the sound, how it perceives the sound, what it is currently doing and its options for response. We believe that integrating recent research studies on these topics will lead to more accurate dose-response functions, and this is the basis for our third objective.

A general issue in developing response criteria applicable to all species of Navy interest is that for many species there are still no empirical data to parameterize dose-response functions. Therefore, in lieu of data, species groupings must be established, to allow responsiveness to be predicted for, as yet, unstudied species based on common characteristics. Multi-species dose-response modelling is one approach to objectively select species groupings based on observed thresholds for behavioral response and using model selection methods. Such an approach has been trialed under a Bayesian hierarchical dose-response framework developed during the MOCHA project and applied to a range of single species (e.g., Antunes et al. 2014, Miller et al. 2014, Wensveen 2016). However, the method used for model selection is computationally intensive and becomes infeasible for selection of species groupings given the number of species of interest to the Navy. This framework was used as a basis for the dose-response modelling performed by the Navy Marine Mammal Program Compliance Team in the most recent round of Navy Behavioral Response Criterion development (Department of the Navy 2017) – there *ad hoc* species groupings were used. To give the option of using objective groupings, we propose development and implementation of a more computationally-feasible method for model selection, as well as other improvements to the modelling framework, as a project option.

<u>Objectives</u>

The overall aim of this project is to develop new quantitative models and analytical methods for inferring behavioral response of marine mammal species to Navy sonar. Our focus is on studies estimating the response to mid-frequency active sonar, but the methods developed will be widely applicable. We aim to build upon the work of the previous MOCHA project to address outstanding and new statistical challenges. The results will be directly applicable to current Behavioral Response Studies (BRSs) operating on multiple species in multiple oceans and will support future Navy Behavioral Response Criterion development.

Three specific objectives are proposed. Each will form a task of the Double MOCHA project.

1. Develop analytical methods for estimation of behavioral response and subsequent recovery from controlled exposure experiments (CEEs) that allow fusion of multiple input datasets collected across a range of spatial and temporal scales. A particular emphasis will be on the multi-scale Atlantic BRS study.

2. Develop recommendations for effects analysis of long-term passive acoustic data. The work will support effects analysis of vocal marine mammals by both Atlantic and Pacific fleets, as well as BRS studies that deploy long-term passive acoustic sensors.

3. Develop next-generation models for behavioral response based on our understanding of marine mammal signal detection and the evolutionary drivers of response. This will have longer-term impact on exposure-impact modelling and future BRS design.

We also list a further objective as an option.

Option 1. Develop flexible and practical methods for dose-response modeling that allow data from multiple species to be combined and different functional forms of the dose-response function to be fit. This will facilitate development of improved noise exposure criteria, and hence support future Navy Behavioral Response Criterion development.

Task descriptions

Task 1. Develop analytical methods for estimation of behavioral response and subsequent recovery from CEEs: multi-scale and data fusion.

Until recently, CEEs primarily collected data at a high temporal resolution using a combination of visual observations and high-resolution animal-borne kinematic and acoustic recording tags (Harris and Thomas 2015). The MOCHA project focused on development of analytical tools for such situations. A limitation of these tags is that the observation period over which animals were monitored before and after exposures is generally limited (typically < 1 day), largely because of the tag technology. This, and other factors, has stimulated the increased use of longer-term satellite telemetry tags that typically transmit horizontal position intermittently and only a few times a day, with sometimes considerable measurement error, and depth records sampled at higher temporal resolution. This raises many analytical challenges: inferring location in the face of measurement error; dealing with the intermittent time series; reconciling the mixed resolution of horizontal and vertical data. In addition, rather than modelling each tag deployment separately, there is often the desire to make joint inferences across multiple deployments – borrowing strength to increase the power to detect effects, and also moving from individual to population-level inference. Such "random effects" models represent a further level of complication. In addition, multiple data streams are often available, with the desire to analyze them jointly. Indeed, making inferences across multiple scales is the stated aim of the Atlantic BRS project, where high-resolution DTags and satellite tags are to be deployed on the same groups and, if possible, the same individuals. A further source of data comes from statistic acoustic recorders, deployed around the same time and location as the CEEs. This gives population- (rather than individual-) level data about acoustic activity of animals that could potentially supplement the individual-level analyses from tag and visual data. Lastly, a recent output of the ONR MMB Sensor and Tag Development topic is development of longer term tags (SMRT tags) capable of recording long-term acoustic and accelerometry data. It is therefore important that analytical tool development considers both current forms of data acquisition and new methods that are anticipated to be available in the relatively near future.

The current state of the art in animal movement modelling relevant to the CEE scenarios described above involves compromises. One broad categorization of movement models is into discrete time vs continuous time models (McClintock et al. 2014). Discrete time models are generally easier to fit to data, and a rich array of models and fitting approaches exist to deal with complications such as measurement error, multiple underlying behavioral states, multiple individuals, etc. (Hooten et al. 2017) – although in practice fitting models that include all these features is still challenging. However, the major problem with discrete time models is that they do not deal well with intermittent data streams or data at multiple temporal scales. Continuous time models, by contrast, naturally accommodate multi (temporal) scale data, but represent a harder analytical challenge and cannot currently deal with all of the complications outlined above. One pragmatic suggestion (McClintock et al. 2017) is to take a 2-stage approach: first fitting a simple continuous-time model (e.g., Johnson 2016) to data to accommodate the measurement error, and then secondly use multiple tracks imputed from this model at regular time steps in a discrete-time model that contains the other desired features. However, model selection and uncertainty estimation is difficult with such an approach.

We propose to address these challenges by developing a continuous time movement model that is capable of simultaneously handling data from multiple temporal resolutions, measurement error, intermittent observations and random effects arising from multiple individuals. This model will include estimation of behavioral state, and so be capable of inferring behavioral response as well as recovery to baseline conditions, given adequate data. This represents an ambitious goal, and we propose to address it in stages and through multiple routes. One initial focus will be on improved inference from satellite tag data, where it may be possible to generalize the computationally-efficient methods developed by project co-PI Glennie (2018). A second will be on the application of Bayesian data fusion concepts (e.g., Gelfand et al. 2012) to joint inference on animal movement from multiple data streams. We will hold a technical workshop focused on this task early in the project (approx. April 2019). Subsequent to that (likely towards the end of the project), we will investigate the generalization from individual to population level (using random effects modeling), allowing incorporation of acoustic data and potential pooling across species.

Subtasks:

1.1. Improve methods for inferring behavioral response from long-term low-fidelity data such as from satellite tags. Align with Atlantic BRS efforts.
1.2. Investigate methods for integrating multiple disparate data streams (e.g., satellite, DTag and potentially SMRT tag data) to infer behavioral response and return to baseline behavior.
1.3. Hold workshop focused on multi-scale movement modeling and inference on behavioral response.
1.4. Investigate methods for including PAM data from widely-spaced recorders such as those deployed by the 3S and Atlantic BRS teams.
1.5. Investigate methods for pooling across species and CEEs to borrow strength and improve inference.

Task 2. Develop recommendations for effects analysis for long-term passive acoustic data.

As noted previously, long term PAM studies have important roles to play in inferring behavioral response: (1) enabling an initial assessment of whether poorly-studied species (or well-studied species within particular regions and/or seasons) show an acoustic response, and (2) giving a wider, population-level context for the results of CEEs which are, by their nature, focused on response of individuals. Two statistical approaches have been developed to relate detection parameters such as detection rate to explanatory variables such as presence and type of sonar. One approach was based on a linear modeling framework, using Generalized Estimating Equations (GEEs) to allow for smooth relationships between response (detection rate) and explanatory variables, while simultaneously dealing with the temporal correlation inherent in this time series data. The second approach was based on stochastic temporal modelling, using Hidden Markov Models (HMMs) to model switching in time between periods of high and low vocal detections, and how explanatory variables such as sonar affect the probability of switching. As noted earlier, it is unclear as to which method is better in this context. We therefore propose to undertake a simulation study to investigate the utility of the two approaches. We will also need to develop strategies to cope with the very large amount of data that is potentially available from some historical studies.

Subtasks:

2.1. Undertake simulation study comparing HMMs and GEEs in the context of long-term dispersed sensor behavioral response studies.
2.2. Develop methods that are computationally feasible given the size of datasets available from Atlantic and Pacific PAM projects.

Note that task has some overlap with Task 1, where PAM data is being considered for incorporation into CEE analyses. Therefore, this task will be under consideration also during the Task 1 workshop planned for spring 2019.

Task 3. Develop next-generation, biologically-driven models for behavioral response.

This task is focused on synthesizing knowledge generated from studies of animal audition, perception, energetics and population consequence of disturbance with the ultimate goal of creating more biologically-based models for behavioral and physiological response of marine mammals to Navy sonar. The ultimate goal is very ambitious, so we propose to proceed through a series of linked stages. First, we will undertake a review of the potential factors ("contextual variables") affecting behavioral and physiological response, and the potential for the statistical distribution of these factors to be predicted in advance so that they can be used in Navy planning. Second, we will hold a workshop (approx. March 2020) bringing together experts from the fields of marine mammal hearing, attention, stress physiology, energetics and behavioral ecology, together with quantitative scientists to consider the potential for creation of a quantitative, mechanistic model for behavioral response. We anticipate the workshop output will be a model framework, and so the next stage will be to develop mathematical models that build on this framework to enable quantitative exploration of how inputs (contextual variables) relate to outputs (responses). One potentially useful technique is the use of stochastic dynamic programming (Mangel and Clark 1989, Pirotta et al. 2018) to determine the optimal strategy for animal response given its context. We next propose to explore the sensitivity of the mathematical model outputs to input parameters, especially considering the contextual variables that can potentially be used in Navy planning. This will enable us to provide guidance regarding priorities for future data collection. Finally, we will explore the potential for developing statistical models, based on the underlying mathematical models, that can be fit to diverse contextual data collected during BRS studies. Techniques based around Bayesian hidden state (also called state-space) modelling (e.g., Durban and Koopman 2012) will likely be applicable here.

Subtasks:

3.1. Review potential contextual variables affecting behavioral and physiological response, and their potential for inclusion in future Navy effects analysis.
3.2. Hold inter-disciplinary workshop focused on development of framework for a quantitative mechanistic model for behavioral response.
3.3. Develop mathematical models based on framework from 3.2.
3.4. Determine sensitivity of models to input parameters, especially variables flagged in 3.1.
3.5. Develop statistical (i.e., data-based) models based on mathematical models from 3.2 that can potentially be used to predict response.

Option 1. Develop an enhanced dose-response modelling framework.

This proposed work will build upon research successfully completed within the MOCHA project. There, Bayesian hierarchical models were developed for estimating behavioral response functions (with uncertainty) across acoustic dose and accounting for contextual variables (Miller et al. 2014, Antunes et al. 2015, Wensveen 2016). In addition, two extensions were initiated: (1) multi-species functions; (2) biphasic functions. Here, we propose to complete model development in both these areas (with the second being classed under the label of "model extensions"), as outlined below.

Multi-species functions. The current models are implemented in the Bayesian analysis software JAGS (Plummer 2012), and use the Gibbs Variable Selection technique (Ohara and Sillanpaa 2009) for model selection – i.e., to estimate which species belongs in which group. This is computationally infeasible for anything but a few species or covariates. We propose to implement new models using reversible-jump Markov chain Monte Carlo methods (RJMCMC, Green 1995) using custom-written code. RJMCMC is well suited to high-dimensional variable selection problems, and should therefore allow inclusion of many more species and explanatory variables in the model selection step. This is a critical development to maximize the potential and application of the Bayesian hierarchical model framework. We have obtained permission from all BRS project teams to use data from 10 species for the proposed project, and will perform a complete analysis of these data, producing recommended groupings, as part of this task.

Model extensions. We propose to extend the biphasic approach developed previously to include an element of model selection – i.e., determining if the data give evidence for a biphasic function over the monophasic function used by, e.g., Miller et al. 2014. In addition, we propose to extend the suite of currently-available dose-response functions to incorporate concepts from survival analyses. Survival analysis is an approach commonly used to model risk-of-event data (Cox and Oakes 1984, Ibrahim *et al.* 2001), and one that was not investigated within the Bayesian framework during the MOCHA project due to time constraints. It may, for example, offer a better approach for dealing with right and left censored data which occurs when no response is detected in a dose-escalation experiment (right censoring) or when a response is detected in a fixed-dose experiment (left censoring).

Subtasks:

- Option 1.1. Develop methods and accessible software for assessment of multi-species behavioral results functions.
- Option 1.2. Extend current marine mammal dose-response functions to allow for model selection and alternative approaches to right- and left- censoring.

Future Naval Relevance

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 research to enhance our understanding of the behavioral responses of marine mammals to sonar exposure and to allow the estimation of the relationship between acoustic dosage and other factors with behavioral responses.

A recent Navy funded program (BRREW project) reviewed the current state of knowledge in this subject area in order to evaluate the return on investment of current US Navy funded programs, identify the data needs and the contributions of current research programs to meeting data needs, and the ability to meet outstanding data needs given the current state of technology. In summary it was recommended that "BRS research be continued and extended to increase sample sizes and experimental replication, and temporal duration and spatial scale…...It was noted that future investigations would benefit from combining experimentation and observation to enable linkage of short-term behavioral response to long-term fitness consequences of repeated exposure. Beaked whales were the species group ranked highest in terms of research priority. The importance of baseline studies and longer-term monitoring of animals before and after exposure is emphasized throughout." (Harris & Thomas 2015). The development of methods to analyze longer term, lower resolution data, and to integrate data across different spatio-temporal scales and from different platforms satisfies many of these BRREW recommendations and will enhance the analysis of data being collected by current BRS efforts. The analysis of longer term data using these methods will result in a step increase in the understanding of the effect of navy sonar on cetacean species and provide support to monitoring programs. In addition, we will facilitate communications to maximize the likelihood of applicability to the proposed new tags the Navy is supporting the development of (e.g. SMRT tags).

Our proposed work to develop the next generation of predictive models of behavioral models has the potential to significantly increase the accuracy of future take calculations. In addition, if appropriate information about marine mammals can be gathered just before or during Naval operations, and there is operational flexibility for appropriate mitigation actions, then model predictions may allow reductions in behavioral disturbance.

We anticipate that the outputs of the optional task on dose-response modelling will be of direct relevance to the next round of Navy Behavioral Response Criterion development. We plan to work closely with Navy stakeholders to maximize the utility of our research and the chance that both the outputs based on current data will be used by the environmental compliance community, and that the analytical methods will be used in future iterations as data on more species becomes available. As well as suggesting species groupings, the proposed work will also address the need to understand the relationship between responsiveness and dose metrics other than those related to received sound level. We will use the Bayesian hierarchical dose-response model to fit a relationship between whale-vessel range and probability of response based on currently available data, and determine the form of this relationship and the level of variability within and between species. This work could help identify data gaps that could be addressed by future behavioral response studies.

Overall, this research effort will build upon many relevant US Navy-funded projects and involve personnel from many of these projects.

Project schedule and milestones

Year:	**2018**				**2019**												**2020**												**2021**											
Quarter:	**Q3**	**Q4**			**Q1**			**Q2**			**Q3**			**Q4**			**Q1**			**Q2**			**Q3**			**Q4**			**Q1**			**Q2**			**Q3**			**Q4**		
Month:	**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**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**
Financial Year:		**FY2019**												**FY2020**												**FY2021**												**FY2022**		
Workshop 1 - Start up	x																																							
Task 1					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
Task 2														x	x	x	x	x	x																					
Workshop 2								x																																
Task 3																	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 3																			x																					
Workshop 4 - wrap up																																					x			
Project Management																																								
PDRA 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	x	x	x	x
Workshop organisation	x					x	x										x	x																	x	x				
Progress meetings		x		x		x		x		x		x		x		x		x		x		x		x		x		x		x		x		x		x		x		x
Annual reports										x												x												x						
Final report																																								x
Option 1									x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x								

Reports and deliverables

1. Annual progress reports describing progress to date: June 2019, June 2020, June 2021.
2. 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. December 2021.
3. Public reports summarizing the discussions and outcomes of each workshop. These will be available on the project website.
4. At least four manuscripts submitted to peer-reviewed journals. December 2021.
5. Presentations at four or more scientific/statistical conferences. Relevant opportunities include the Society for Marine Mammalogy biennial conference in December 2019 and December 2021, the International Statistical Ecology Conference in June 2020, and the Effects of Noise on Aquatic Life conference in July 2019.
6. Datasets used archived wherever possible. December 2021.
7. If Option 1 is exercised, at least one additional manuscript submitted to a peer-reviewed journal. April 2021.

Management approach

The project will build upon the success of the MOCHA project (https://synergy.st-andrews.ac.uk/mocha/), where a series of workshops brought together participants to exchange knowledge and to discuss statistical solutions to analytical challenges, backed by post-doctoral researchers carrying out methodological development during the entire course of the project. For Double MOCHA, the project will be led by the University of St Andrews, with co-PIs at Duke University and post-doctoral researchers at both institutions. As with the MOCHA project, we propose a steering committee made up of representatives of all current and recent Navy-funded Behavioral Response Studies. Invited workshop participants will depend on the workshop focus (see below), but will generally include researchers involved in analysis for the Navy BRS projects, plus external experts in the workshop topic.

We plan to hold four workshops over the course of the project. The fine-scale definition of the research challenges will be facilitated by a start-up workshop held in The Hague immediately following the Effect of Sound on Marine Mammals (ESOMM) meeting, 9-14th September 2018. The cost of this workshop will be low due to high attendance of workshop participants at the preceding meeting. We will then hold a further three workshops, one per year, following appointment of the post-doctoral researchers in January 2019. These workshops will allow for general progress updates and discussion, but additionally will have a unique focus. The second workshop will focus on Tasks 1 and 2, the third workshop will focus on Task 3 and Option 1, and the final workshop will allow for reporting and final analysis improvement. The focus of the second and third workshops will enable us to restrict the number of attendees to a productive level, and to deal with the peculiarities of each challenge in turn. Note that we will consider Option 1 at the third workshop whether it is exercised or not; our main focus will be on Task 3, but the additional cost of considering Option 1 will be small, and the information gathered will be included in our workshop report to help facilitate future work in this area. 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 the PIs and PDRAs, and every six months we will hold a progress meeting via conference call with the steering committee. 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, the ONR-funded LATTE project, the ONR-funded MOCHA project and currently the LMR-funded DenMod project).

Two post-doctoral researchers (PDRAs) will conduct the majority of the research and model development over the course of the project. One PDRA will be based in St Andrews and will be supervised by Thomas, Harris and Glennie. The other will be based at Duke University under the supervision of Gelfand and Schick. However, there will be frequent communication to ensure both PDRAs receive input from all supervisors as well as other expertise as required. Both researchers will also have frequent contact with colleagues based at the Sea Mammal Research Unit (SMRU) and at the Duke Marine Lab who have extensive experience with the species, experimental protocols and data. Both PDRAs will have a strong background in mathematics and statistics. We have included additional expertise where required, as follows. Dr Nicola Quick will provide an advisory role with regards data and biological interpretation, particularly on Task 1. Quick is a research scientist at Duke Marine Lab and has been involved with projects concerning acoustic behavior of marine mammals and the effects of anthropogenic noise on cetaceans. Most recently she has been one of the lead analysts for the Atlantic BRS efforts. Dr. Cornelia Oedekoven will lead on the statistical development of the RJMCMC method for the model selection for the Bayesian dose-response modelling (Option 1). Oedekoven has been a post-doctoral research fellow at CREEM) since October 2012. As part of her PhD program at CREEM she developed hierarchical models and RJMCMC methods for distance sampling and other count data.

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