The Effects of Behavioral Change in Response to Acoustic Disturbance on the Health of the Population of Blainville's Beaked Whales (Mesoplodon densirostris) in the Tongue of the Ocean

David Moretti
Navy Undersea Warfare Center (NUWC)
Newport, RI
phone: (401) 832-5749   email: David.moretti@navy.mil

Len Thomas & John Harwood
Centre for Research into Ecological and Environmental Modelling (CREEM)
University of St Andrews
St Andrews, UK

Diane Claridge
Bahamas Marine Mammal Research Organization (BMMRO)
Marsh Harbour
Abaco, Bahamas

Award Number: N0001412WX20964

LONG-TERM GOALS

The objective of this effort is to provide a model framework and initial estimate of the population level effect of sonar on Blainville's beaked whales (*Mesoplodon densirostris*) hereafter *Md*, in the Bahamas**.** It builds on the results from ongoing programs including the Marine Mammal Monitoring on Navy Ranges (M3R), the Behavioral Response Study (BRS), Density Estimation for Cetaceans (DECAF), Bahamas Beaked Whale Ecology Study (BBES), Linking Acoustic Tests and Tagging using statistical Estimation (LATTE), and will adapt the methodology developed by the Marine Mammal Commission (New, Moretti, David J., Hooker, Sascha K., & Simmons, Samantha E.) in coordination with the ONR Population Consequences of Acoustic Disturbance (PCAD) Working Group.

OBJECTIVES

Same as the long-term goals.

APPROACH

A *Md* specific model will be derived from the general PCAD model. The model will use an energetics approach with an estimate of foraging dives lost due to sonar as a proxy for overall energy loss. It will be applied to a population of sonar-exposed animals found on the Atlantic Test and Evaluation Center (AUTEC) weapons range. As a means of comparison, a second estimate will be derived for what is believed to be a separate population of animals in the Northwest Providence Channel (NWPC) off Abaco that are rarely exposed to sonar.

To estimate the cumulative effect of sonar, M3R passive acoustic data for *Md* are being accumulated over an entire year. The spatial and temporal distribution of groups of *Md* are being documented. Tracks of active sonar are being obtained from AUTEC. These data are being combined to estimate the probability of disturbance as defined as the cessation of foraging dives. From this, a *Md* risk curve which predicts the probability of disturbance for a give sonar exposure level can be obtained. This function can then be applied for each documented operation that occurs over a year to obtain the cumulative energy loss as measured by the loss of foraging dives. These data will then be combined with observational data that provides necessary biological parameters such as group size, gestational period, time to weaning, etc. and used in the energetics based PCAD model.

WORK COMPLETED

A risk function that predicts the probability of dive disruption at a given Root Mean Squared (RMS) exposure level to sonar was derived.

Groups of vocalizing animals on the AUTEC range were isolated using M3R detection archives which are composed of detection reports from a hard-limited Fast Fourier Transform (FFT) based transient detector. The reports contain the precise time of detection (< 10 milliseconds) and the binary frequency output bins of a 2048 point FFT indicating if energy in the specified bin exceeded a Noise-Variable-Threshold (NVT). The report also provides the bin with the highest energy and its value prior to thresholding. The reports were used to create hard-limited 2D spectrograms for monitoring of selected hydrophones which were then used to isolate *Md* active hydrophones and Mid-Frequency Active (MFA) sonar.

To examine the effects of sonar on *Md* foraging, data were collected before, during, and after a three day, multi-ship Mid-Frequency Active (MFA) sonar exercise starting 19 hours before and ending 12 hours after the operation. Within the three day operation, six distinct periods of active sonar, dubbed scenarios, were noted (Table 1). During these periods, three ships operated MFA sonar throughout the range.

From the FFT data archives, the start and stop times of sonar transmissions were determined by visual inspection of the 2D spectrograms. The sonar type, frequency, ping repetition rate, and frequency were isolated. Precise ship tracks were obtained from AUTEC. These were combined with the sonar data to determine where and when each ship was transmitting. The Navy Acoustic Effects Model (NAEMO) was then used to estimate the time-varying sound field across the entire range. Once per second, the sound level received at every hydrophone at depths of 10, 100, 500, 1,000, 1,500, and 2,000 meters was estimated.

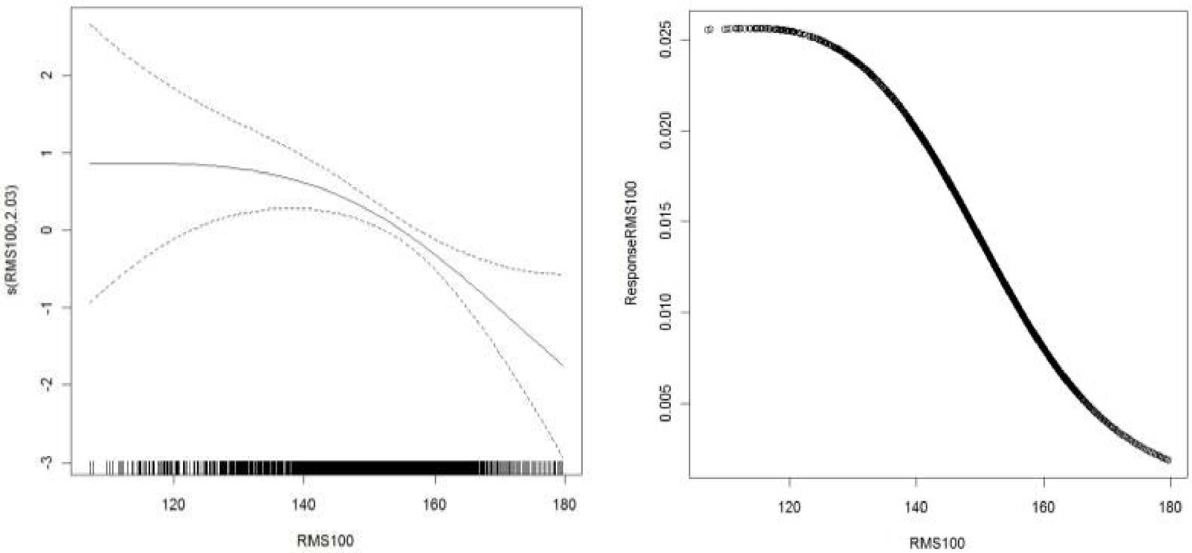
The data were divided into 30 minute segments. The maximum RMS receive level within the period was obtained for each hydrophone on the range at each of the five depths. This analysis focused on the probability of an animal dive within the period. Since the animal spends most of its time in within 200 meters of the surface, the risk curve was based on receive level data at 100 m.

Table 1. Six sonar scenarios (indicated in color) Start and Stop times

Start and Stops		Analysis Window
	Gap	Time Begin to End
5/13/2009 (133)		
15:12 Start Time Before	NA	19:35
5/14/2009 (134)		
1047-1956		9:09
	4:21	
5/15/2009 (135)		
0017-0935		9:18
	2:37	
1212-2102		9:50
	3:39	
5/16/2009 (136)		
0041-0725		6:44
	6:37	
1402-2157		7:55
	4:03	
5/17/2009 (137)		
0200-1044		8:44
137 23:18		12:34

Md vocalizations were isolated on all hydrophones. Click chains were established and the start and stop times noted. These were then associated with a single Group Vocal Period (GVP). To estimate the location of the group, the geometric group mean was calculated based on the number of clicks present on each hydrophone and the closest hydrophone was assigned as the group center. The earliest start of the click trains assigned to a GVP was designated as the GVP start. The total number of GVP starts within a time period was calculated for every range hydrophone.

A Generalized Additive Model (GAM) model was used to fit the GVP start as a function of RMS receive levels (Figure 1a) on the center hydrophone for each 30 minute period using a binomial distribution with a logit link function for each reported depth (10, 100, 500, 1,000, 1,500, 2,000 meters).



a. **b.**

Figure 1: GVP starts as a function of max RMS level in a 30 minute period on a given hydrophone. (a) Binomial GAM fit and response (p) on the logit scale, from model for a depth of 100 meters. (b) Fit back-transformed to the scale of the response.

The GAM output was converted from the logit to the response scale (Figure 1a) to give the probability of a GVP start (P_S) on a hydrophone in a 30 minute period (Figure 1b).

A baseline probability P_B of GVP starts with no sonar using the data which spanned the 19 hour period ahead of the operation was calculated. The probability of a change or disturbance (P_D) was calculated as:

$$P_D = (P_B - P_S) / P_B \qquad \text{(Equation 1)}$$

The change to the baseline GVP start rate (P_D) is given as P_B minus the probability of a GVP start (P_S) at each level (RMS) divided by the baseline (P_B).

The data from before the start of the MFA active scenarios spans 39 full 30 minute periods. The baseline probability of a GVP start on any phone without sonar present within a period (P_B=.0290) is given as the total number of periods containing GVP starts (S_t) divided by the number of periods (P_t = 39) times the total number of hydrophones (H_t = 93):

$$P_B = S_t / (P_t * H_t) = 105/(39*93) = 0.0289$$

The probability of disturbance as calculated at all 5 depths is shown in Figure 2.

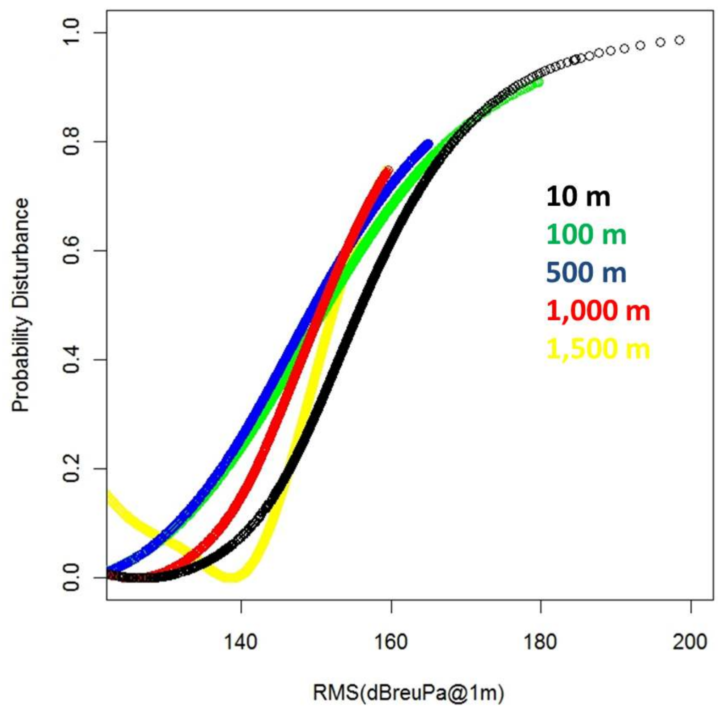


Figure 2. Probability of Disturbance at depth of 10, 100, 500, 1,500, and 2,000 meters

As stated above, since the animals are likely to make the decision to dive within the upper 200m, the 100m curve was considered for the test case. The probability of disturbance base on the sonar levels received at 100 m can be compared to the historic navy risk function.

The navy risk function is calculated as:

$R(L)=(1-(((L-B)/K)^{A}))/(1-((L-B)/K)^{(-2*A)})$

Where:

R(L)=Probability of response
L=receive level

A, B & K Shape Parameters B=basement parameter
B=100
K=88
A=7

A plot of the historic risk curve used for compliance modeling plotted against the calculated risk curve at 100m is presented in Figure 3a.

This measured risk function was fit to a sigmoidal function. A GLM model with a probit link function was applied. This provides a mathematical expression that can be applied for cases from ambient to high levels of exposure (3b). Note the tail below 125 dB which levels off at approximately a probability of 0.17 is a function of the input data as provided in the histogram below.

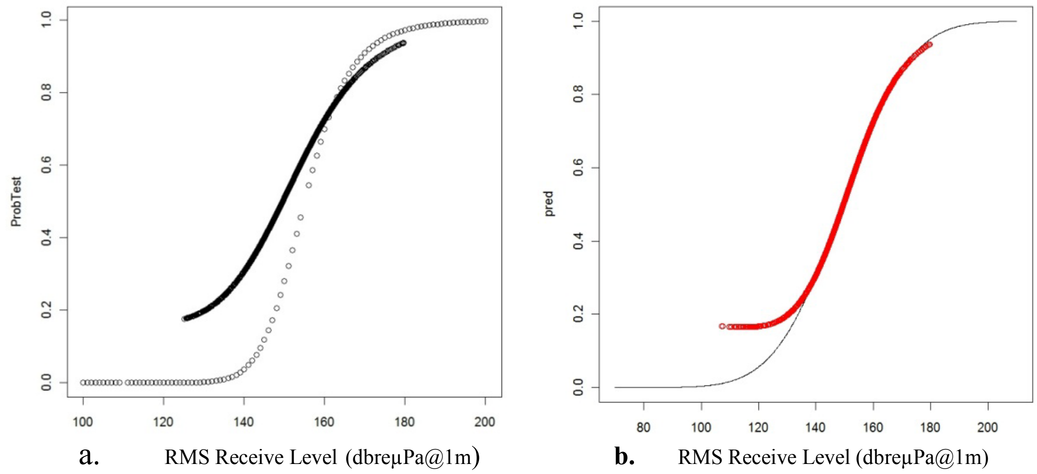


Figure 3. (a) Historic navy risk function (dotted) vs. the measured risk function (black) based on actual Md dive data and MFA sonar operational data. (b)GLM fit of Probability of Disturbance vs. Exposure level (black) along withmeasured probability of disturbance (red)

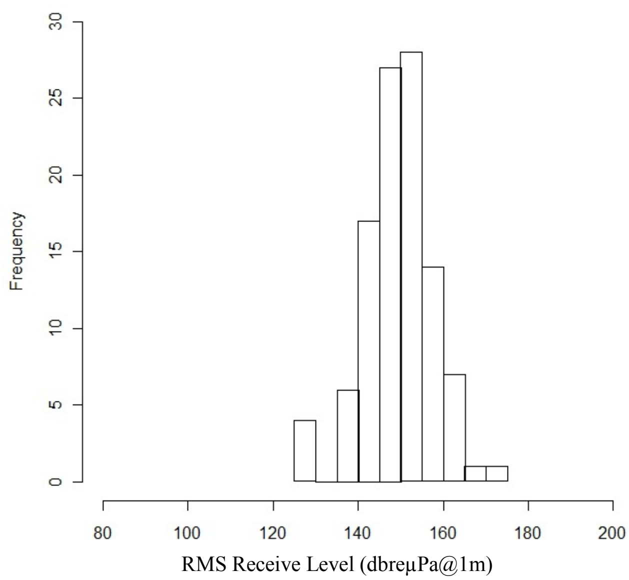


Figure 4. Histogram of dive starts as a function of sonar level (dBreµPa@1m) at a depth of 100m

Uncertainty in the estimated probability of disturbance was quantified using a bootstrap procedure, as follows. From equation (1), it can be seen that the probability of disturbance P_D is computed from two estimated quantities: probability of GVP in the baseline, P_B, and probability of GVP during exposure, P_S. For the former, a nonparametric bootstrap was used to generate 10,000 random realizations of P_B, by resampling with replacement from the 39 full 30 minute intervals on each hydrophone in the baseline period and re-computing P_B in each resample dataset. For P_S, a parametric bootstrap was used, where 10,000 random realizations were generated from the fitted GAM using a multivariate normal distribution to generate new parameter estimates for the smooth basis functions, based on the estimated values and variance-covariance matrix. The 10,000 values of P_B and P_S were then combined according to equation 1 to yield 10,000 bootstrap resample estimates of P_D. Confidence intervals on P_D were then computed by taking the 2.5th and 97.5th percentiles (the so-called "percentile method"). In figure 4 below, the mean value for the probability of disturbance from the bootstrap(red) and the sigmoidal fit to the original GAM (black solid) are plotted along with the confidence intervals (dotted). The RMS level (100m) at which a 50% probability of disturbance is estimated is indicated by the blue lines.

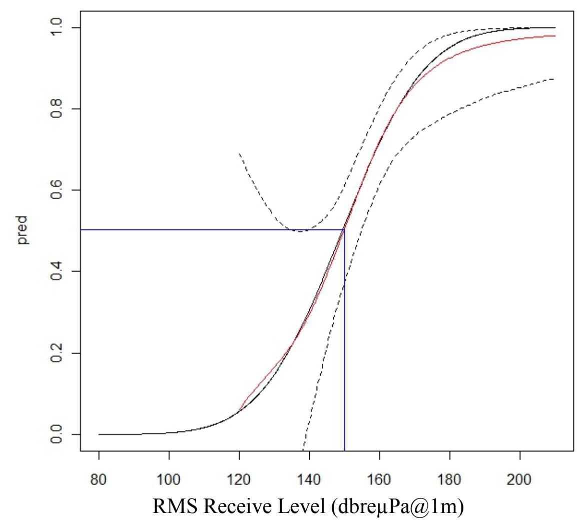


Figure 5. Probability of disturbance as a function of RMS level @ 100m with the mean of bootstrap (red), sigmoidal fit to original GAM (blue), and the 97.5 and 2.5 quintiles (dotted). The 50% probability of disturbance as a function of RMS @ 100m is indicated in blue.

Continuing Effort

With the development of a risk function, the probability of disturbance can be applied to exercises over an entire year. A general analysis framework for determining the number of dives lost for groups of *Md* is shown in 8.

First, the number of groups on range for each event must be estimated using data available from past density estimates (Marques, Thomas, Ward, DiMarzio, & Tyack, 2009; Moretti, et al., 2010). For each exercise type such as dipping helicopter or DICASS sonobouy sonar, the sound field will be estimated using CASS/GRAB. The receive level for each group on range will be calculated and the risk curve applied to determine whether or not the group was disturbed. The number of dives lost for each exercise will be tallied.

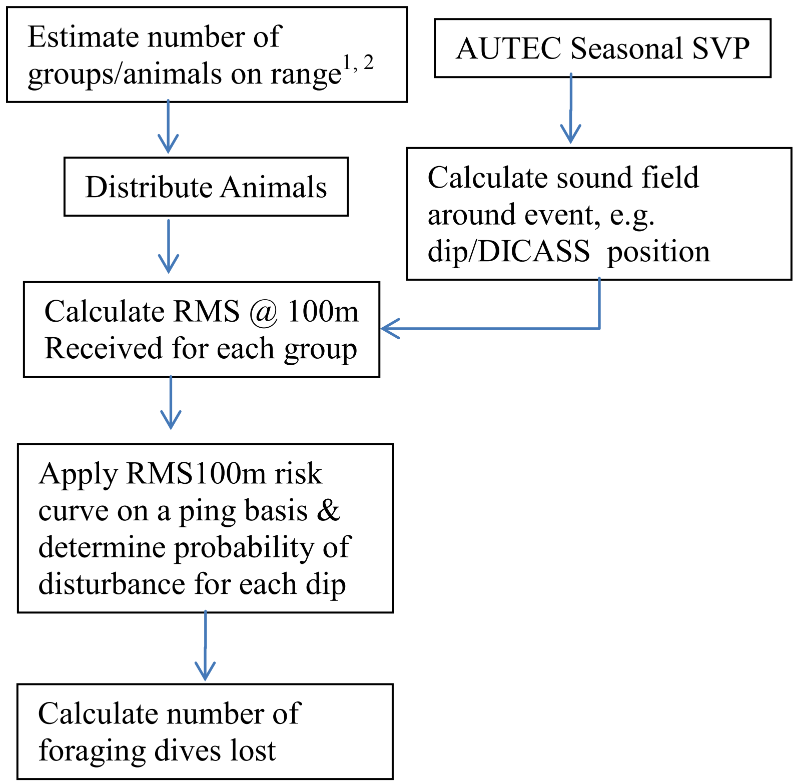


Figure 6. General framework for analysis for Md dives lost due to sonar exposure at AUTEC.

Each dive represents a portion of the daily energy lost. A measure of dives lost when disturbed by sonar is being obtained through the use of mid-term satellite tags. Tagging of animals is included in an on-going series of species verification tests at AUTEC funded by CNO N45. Observers led by the Bahamas Marine Mammal Research Organization (BMMRO) and the NOAA Southwest Fisheries Service are vectored to vocalizing animals based on M3R passive acoustic observations on the AUTEC hydrophones. The tests provide a means of locating beaked whales as well as other species, collecting individual-based data (photo-identification/biopsy), and attaching depth telemetry satellite tags. From these tags, a dive record for sonar disturbed animals is being obtained.

This year, two tags were attached on *Md* at AUTEC in May and remained active through an SCC multi-sonar exercise. An additional two tags were attached in July and transmitted data through a period of no sonar exercises. Data from these tags is being analyzed. It is anticipated that data from the May exercise will provide insight into the foraging behavior of these animals in reaction to MFA operations. These data are critical to the overall population model. The derived risk function provides a means of predicting if an animal ceases foraging. However, it is critical to obtain a measure of the length of disturbance as well as the animal's movement patterns in response to exposure. These tag data will begin to fill this knowledge gap.

The number of animals disturbed, based on the risk function, and the total number of dives lost, based on tag data, will provide input to an energetics model. This model will be an adaptation of the L. New *et al*. model. The model focuses along maternal lines. If the there is a deleterious cumulative effect due to repeat sonar exposure, it should be reflected in the ratio of adult animals to juveniles. These data are being obtained through visual observation and photo-ID work being carried out by the Bahamas Marine Mammal Research Organization as part of the species verification tests described above.

The results obtained at AUTEC will be compared to those obtained for animals at the BMMRO site off the southwest tip of Abaco. To date, no movements between these sites have been documented through satellite telemetry, or by comparing photo-identification catalogues. Analyses of photo-identifications and chemical tracers suggest these are separate sub-populations, exhibiting high site fidelity, with low rates of emigration and re-immigration. As compared to AUTEC, animals at the Abaco site are rarely exposed to MFA sonar. It should be noted that a direct comparison must consider other factors most notably the availability of prey. Extended prey mapping at both sites would be advised in the coming years to assure the validity of such comparisons.

RESULTS

For the first time, a risk function for *Md* has been derived using in-situ animal data and receive levels calculated using actual multi-ship MFA sonar tracks obtained from AUTEC. The risk function predicts the probability of disturbance as functions of the RMS receive level (dBreµPa@ 1 m) where disturbance is defined as the failure to initiate foraging dives. Tags attached at AUTEC will help determine the strength of this reaction as measured in dives lost.

Data for one year of operations have been obtained from AUTEC. These data include ship-based sonar operations as well as an array of lower level sources mainly dipping helo sonar and DICASS sonobuoys.

The New *et al*. energetics model will be used as a basis for development of a *Md* population level model. To determine the cumulative effect of sonar operations, the data for the year will be applied to predict population health.

IMPACT/APPLICATIONS

This effort is focused on developing a means of estimating the population health of *Md* in the TOTO. The long-term monitoring of cetaceans in areas of repeated sonar use is a mandated component of the Navy's environmental compliance requirements. If successful with *Md*, this methodology can be adapted to other Navy ranges and sonar-sensitive beaked whale species including Cuvier's (*Ziphius cavirostris*) beaked whales at SCORE.

RELATED PROJECTS

Marine Mammal Monitoring on Navy Ranges (M3R)

The basic opportunistic passive acoustic data with and without MFA sonar present for vocalizing groups of *Md* are being collected through the M3R program. Two major multi-ship sonar exercises per year at AUTEC will be monitored. The program is also providing the basic signal processing infrastructure and algorithms which make the collection and analysis of these data possible. This includes isolation of the sources present, their location, and transmission durations. These data are then being integrated with precise AUTEC vehicle track which allow an understanding of the interaction of active sources with ship movements relative to vocalizing and tagged animals. This attention to context is extremely important and is often overlooked in the discussion of interaction of sonar and marine mammals.

The ability to obtain precise ship track and at the same time extract precise detail as to the use of MFA sonar is unprecedented. Depending on the circumstances, some data may be classified. M3R is providing the necessary processes to handle these data in the appropriate manner and providing the final outputs via the specified Navy release chain.

M3R is providing in-kind support in excess of $200K per year. These data are also being used as part of the LATTE program the results of which will be incorporated into this program.

The ONR PCAD Working Group

ONR has funded the University of California, Santa Barbara (led by Erica Fleishman) to convene a collaborative Working Group of researchers (including two of the PIs on this proposal) who will cooperate and meet regularly to examine the population-level effects of sound exposure on marine mammals. The objectives of that group include, but are not limited to:

- Explore how the conceptual model developed by the NRC committee might be translated into a formal mathematical structure
- Consider how the above model might be parameterized with existing or emerging data on the responses of large vertebrates to disturbance
- Define conceptual approaches for investigating transfer functions (e.g., time-energy budgets, trait-mediated responses)
- Expand work by the NRC to include sensitivity analyses on different transfer functions
- Outline exploratory models that might be used to model transfer functions, synthesize existing knowledge, examine potential mechanisms, or inform research and management efforts

The Working Group meets at 6-monthly intervals and has already developed PCAD-style models for elephant seals and coastal bottlenose dolphins, and will begin the development of a similar model for beaked whales at its spring 2011 meeting. The mathematical structure developed by the Working Group will be applied as part of this program. Two of the PIs associated with this proposal are members of the Working Group and they will ensure that the project's outputs are harmonized with the needs of the Working Group.

Density Estimation for Cetaceans from Acoustic Fixed sensors (DECAF)

One required input for the proposed project is an estimate of the number of animals present within the AUTEC range under different circumstances (for example, before, during and after exercises). Methods for estimating absolute animal density from fixed hydrophone data have been developed under the above project, and applied to estimate beaked whale density (and hence numbers) at AUTEC. This project, which will finish in May 2010, was co-funded under the National Oceanographic Partnership Program by the Joint Industry Program of the Association of Oil and Gas Producers and by the National Oceanographic and Atmospheric Administration; the project budget is US$1,500K.

Linking Acoustic Tests and Tagging using statistical Estimation: Modeling the Behavior of Beaked Whales in Response to Medium Frequency Active Sonar (LATTE)

Another essential input is an estimate of the behavioral response of beaked whales at AUTEC, in terms of their change in diving behavior and location. Methods to estimate this using combined tag and passive acoustic data are being developed in the LATTE project, which runs from April 2010 to March 2013. The output will be a statistical description of the animal behavioral response, produced using all available relevant data. The framework used to produce the parameterized model can be used in the project proposed here to further refine the parameter estimates as new data are produced. The LATTE project is funded by ONR and has a budget of US$1,250K.

The Way They Move

The LATTE project is leveraged on parallel work taking place at the University of St Andrews to develop statistical methods for fitting movement models to tag data from mammals. This project is funded from September 2008 to August 2011 by the UK Engineering and Physical Science Research Council, with a budget of approximately US$650K

REFERENCES

1. Marques, T., Thomas, L., Ward, J., DiMarzio, N., & Tyack, P. (2009, April). Estimating cetacean population density using fixed passive acoustic sensors: an example with Blainville's beaked whales. *Journal of the Acoustical Society of America , 125(4)* , 1982-94.

2. Moretti, D., Marques, T., Thomas, L., DiMarzio, N., Dilley, A., Morrissey, R., et al. (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(11)* , 1036-1042.

3. New, L. F., Moretti, David J., Hooker, Sascha K., & Simmons, Samantha E. (n.d.). Using energetic models to investigate the survival and reproduction of beaked whales (family Ziphiidae). *In process* .