ONR
Marine Mammal & Biology Program Review

16-19 April 2012

Abstracts

AGENDA

Day 1: Monday 16 April 2012					
Time	**Funding**	**Lastname**	**Institution**	**Title**	**Award #**
830		Weise	ONR	Welcome: Overview and Update MMB Program	
BIOLOGICAL OCEANOGRAPHY					
900	6.1	Hanlon	MBL	Advances in camouflage quantification, breaking and prediction	N000140610202
920	6.1	Donaghay / Rines /	URI / NOAA-ESRL	In situ quantification of the impact of episodic enhanced turbulent events on large phytoplankton	N000140910492
940	6.1	Huettel	FSU	Transport of gas and solutes in permeable estuarine sediments	N000140810360
1000	6.1	Latz / Hyman	SIO / NSWC	Developing a predictive capability for bioluminescence signatures	N000140910495
1020	Coffee Break				
1040	6.1	Lavery	WHOI	Field demonstration of a high-frequency, broadband acoustic backscattering system for imaging, classification and quantification of water-column scatterers from an autonomous vehicle (REMUS-100)	N000140810090
1100	6.1	Moline / Shulman	CPSU / NRL-SSC	Dynamic modeling of marine bioluminescence and night time leaving radiance	N0001411WX20051
1120	6.1	Holliday / Rines	URI	Photosynthesis as a possible source of gas bubbles in shallow sandy coastal sediments	N000140910491
1140	6.1	Menden-Deuer		Drivers of plankton patch formation, persistence and decline in East Sound, Orcas Island, Washington	N000141010124
1200	Lunch				
1300	6.1	Banse	UW	Plankton production biology	N000141010044
1320	Discussion - BIOLOGICAL OCEANOGRAPHY				
INTEGRATED ECOSYSTEM RESEARCH					
1340	6.2	Costa / Block	UCSC / SU	Use of electronic tag data and associated analytical tools to identify and predict habitat utilization of marine predators	N000140811195 / N000140811196
1400	6.1	Claridge	BMMRO	Distribution, abundance and population structuring of beaked whales in the Great Bahama Canyon	N000140710120
1420	6.1	Cowles / Benoit-Bird	OSU	Factors influencing the acoustic behavior and nearshore residence of the gray whale (*Eschrichtius robustus*) along their migration route	N000140910475
1440	Coffee Break				
1500	6.2	Benoit-Bird / McManus	OSU / UH	Importance of thin plankton layers in Hawaiian food web interactions: research spanning from physical circulation to spinner dolphins	N000140811210 / N000140811212
1520	6.2	Miksis-Olds / Nysteun	PSU-ARL / UW-APL	Using acoustics to understand ecosystem dynamics in the Bering Sea	N000140810391 / N000140810394
1540	6.1	Nowacek	Duke	Prey fields and habitats of deep diving odontocetes: 3D characterization and modeling of beaked and sperm whale foraging areas in the Tongue of the Ocean	N000140811162
1600	6.1	Warren	SUNYSB	Fine-scale survey of right and humpback whale prey abundance and distribution	N000140910484
1620	6.1	Wilcock	UW-Oceanography	Continuing investigations of the relationship between fin whales, zooplankton concentrations and hydrothermal venting on the Juan de Fuca Ridge	N000140810523
1640	6.2	Azzellino	Politecnico di Milano	Habitat modeling of marine mammals as function of oceanographic characteristics: Development of predictive tools for assessing and managing the risks and the impacts due to sound emissions	N000141010533
1700	Adjourn				

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INTEGRATED ECOSYSTEM RESEARCH - CON'T					
830	6.2	Baumgartner	WHOI	Right whale diving and foraging behavior in the southwestern Gulf of Maine	N000141110534
INTEGRATED ECOSYSTEM RESEARCH - SENSOR & TAG DEVELOPMENT					
850	6.2	Andrews	ASLC	Improving attachments of remotely-deployed dorsal fin-mounted tags: tissue structure, hydrodynamics, in situ performance, and tagged animal follow-up	N000141010686
910	6.2	Burgess / Ware	Greeneridge / UNH	Tools to compare diving-animal kinematics with acoustic behavior and exposure	N0001409C0406 / N000140910601
930	6.2	Mate	OSU	Improved satellite-monitored radio tags for large whales: Dependable ARGOS location-only tags and a GPS-linked ARGOS to reveal 3-dimensional body orientation and surface movements	N000140910453
950	6.2	Woodward	UM	Development of a peduncle belt as a medium to long-term tag attachment platform for cetacean studies	N000141010571
1010	6.2	Bocconcelli / Tyack	WHOI	Development of a pneumatic launcher delivery system for the new digital recording tag, DTAG3	N000141010380
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1050	Discussion - INTEGRATED ECOSYSTEM RESEARCH				
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1120	6.1	Houser	SPAWAR	Behavioral response of dolphins and sea lions to signals simulating mid-freqeusncy sonar	N0001410WX20090
1140	6.2	Calambokidis / Oleson	SIO	Blue whale behavioral response study & field testing of the new bioacoustic probe	N000140811221
1200	Lunch				
1300	6.2	Miller	SMRU	Cetaceans and naval sonar: Behavioral response as a function of sonar frequency	N000140810984 / N000141010355
1320	6.2	Tyack	WHOI	Behavioral responses of odontocetes to playback of anthropogenic nad natural sounds / 3S2 - Behavioral response studies of cetaceans to naval sonar signals in Norwegian waters	N000140710988 / N000140810661
1340	6.2	Calambokidis	CRC	SOCAL Behavioral Response Study	N000141110565
1400	6.1	Kyburg / Carlson	SPAWAR	Observation logging and decision support using SSC Pacific developed software, Whale Identification, Logging and Display (WILD)	N0001410WX21320
1420	6.1	Tyack / Canadas	UStA / ALNILAM	Tagging and playback studies to toothed whales / Beaked whales and pilot whales in the Alboran Sea (SW Mediterranean)	N000140910528 / N000141010709
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1500	6.2	Thomas / Moretti	UStA / NUWC	LATTE - Linking acoustic tests and tagging using statistical estimation: Modeling the behavior of beaked whales in response to medium frequency active sonar	N000141010382
MODELS AND DATABASES					
1520	6.2	Mountain	BU	The ESME workbench version 3.0	N000140910487
1540	6.2	Ketten	WHOI	Database development for ocean impacts: Imaging, outreach and response	N000140811231
1600	Adjourn				
1630-1830	**WELCOME RECEPTION - POSTER SESSION**				

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830	6.2	Nachtigall	UH	Marine mammals: Hearing and echolocation at Coconut Island	N000140811160
850	6.2	Reichmuth	UCSC	Pinniped hearing in complex acoustic environments	N000140610295
910	6.2	Branstetter	NMMF	Dolphins use multiple auditory mechanisms for detecting tonal signals in natural and anthropogenic noise	N000141010500
930	6.1	Cranford / Krysl	QMCC	Virtual experiments in marine bioacoustics: whales, fish, and anthropogenic sound	N000140910611
950	6.1	Rogers	GT	In vivo determination of the complex elastic moduli of cetacean head tissue	N000140811158
EFFECTS OF SOUND - PHYSIOLOGY					
1010	6.2	Holt / Noren / Williams	NOAA-NWFSC /	The metabolic costs of sound production in odontocete cetaceans	N0001411IP20017
1030	Coffee Break				
1050	6.1	Fahlman /	WHOI	Imaging the lung under pressure	N000141010059
1110	6.2	Fahlman / Tyack	Texas A&M-CC	Physiological monitoring in diving mammals	N000141010791
1130	6.2	Ponganis / McDonald	SIO	Blood oxygen depletion in diving California sea lions: How close to the limit?	N000141010514
1150	6.2	Williams	UCSC	Predicting natural neuroprotection in marine mamamals: environmental and biological factors affecting vulnerability to acoustically mediated tissue trauma in marine species	N000140811273
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1330	6.1	Fleishman	UCSB	Population-level effects of disturbance on marine mammals	N000140910896
1350	6.2	Costa	UCSC	Environmental perturbations, behavioral change, and population response in a long-term northern elephant seal study	N000141010356
1410	6.2	Clark / Schick	Duke	Fitting models of the population consequences of acoustic disturbance to data from marine mammal populations	N000141010516
1430	6.2	Kraus	NEAQ	Defining the transfer functions of the PCAD model in North Atlantic right whales (*Eubalaena glacialis*): Retrospective analyses of existing data	N000141010614
1450	Coffee Break				
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MONITORING & DETECTION					
1540	6.2	Bogue / Luby	UW/APL	Passive autonomous acoustic monitoring using Seaglider	N000140810309 / N000141010515
1600	6.2	Mellinger	OSU	Real-time acoustic cetacean detection with the Seaglider	N000140811082
1620	6.2	Abbot	OASIS	Passive autonomous acoustic monitoring of marine mammals (PAAM): Proof-of-concept demonstration	N0001407C0771
1640	6.2	Hildebrand	SIO	Glider-based passive acoustic monitoring techniques	N000140811124
1700	Adjourn				

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830	6.2	Hurst /	WHOI	Beta testing of persistent passive acoustic monitors	N000141010381
850	6.1	Au	UH	Remote monitoring of dolphins and whales in the high naval activity areas in Hawaiian waters	N000140810903
910	6.2	Au	UH	Utilizing pro-bono commercial assets for marine mammal surveys in high naval activity area in hawaiian waters	N000140911111
930	6.2	Hildebrand	SIO	Beaked whale presence, habitat, and sound production in the North Pacific	N000140910489
950	6.2	Norris / Janik / Martin	Biowaves / UStA / SPAWAR	The acoustic ecology and behavior of minke whales in the sub-tropical North Pacific: Localization, abundance and characteristics of minke whale "boings"	N000141010429 / N000140910534
1010	6.2	Nosal	UH	Passive acoustic methods for tracking marine mammals	N000140811142
1030	Coffee Break				
1050	6.2	Roch	SDSU	Passive acoustic monitoring for the detection and classification of marine mammals	N000140811199
1110	6.2	Mellinger	OSU	Next-generation bioacoustic software	N000141010534
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1200	Wrap-up - Final Discussion				
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Day 1: Monday April 16, 2012

2012 ONR
Marine Mammal & Biology
Program Review

ADVANCES IN CAMOUFLAGE QUANTIFICATION, BREAKING AND PREDICTION

Roger T. Hanlon, Charles Chubb, Liese Siemann, Derya Akkaynak, C-C. Chiao
Marine Biological Laboratory, Woods Hole, MA
rhanlon@mbl.edu(508) 274-3633

Background

Camouflage has obvious application to a wide range of naval activities above, on or below the ocean surface. The visual principles upon which effective camouflage patterning depends are not well studied or understood. We are deciphering these principles by acquiring extensive digital image libraries and analyzing them in multiple ways, including novel computational approaches that can begin to address key subjects such as camouflage breaking and prediction of what camouflage pattern will be effective on any given background.

Objectives

The central question is: what optical principles are used by opaque organisms to achieve crypsis in shallow, nearshore marine habitats? (1) Acquire imagery of camouflaged animals and their backgrounds in coral reef and temperate rock reef environments; (2) collect corresponding *in situ* irradiance and reflectance data from the animal and background; (3) develop a suite of image analysis methods to quantify the type and degree of crypsis; (4) Construct a comparative digital photographic and video library of shallow-water marine animals in the camouflage categories of Uniform, Mottle and Disruptive.

Methods

We use high-resolution still and video cameras to document natural behavior of cephalopods and fishes under natural lighting conditions in a variety of marine habitats (coral reef, kelp forest, seagrass, temperate rock reef, etc.). In the lab, we used HyperSpectral Imager (HSI) to view underwater camouflaged cuttlefish “in the eyes of the beholder” such as teleost fish. We use a wide variety of image analysis methods, and have developed new ones, to quantify camouflaged animals compared to their backgrounds.

Results

The most noteworthy achievements are with camouflage breaking and prediction. Fig. 1 shows a novel method of camouflage breaking in which a RGB image of a cuttlefish can be strongly enhanced. Fig. 1B is a far more difficult image to find – one that humans cannot detect at all – but the algorithm searches and finds it. The new methodology can analyze grayscale, RGB or HSI imagery.

Prediction of camouflage has also been developed in the past 6 months (Fig. 2). That is, given a natural substrate, we can analyze the surrounding visual background in a manner similar to cuttlefish, and construct a tailored cuttlefish camouflage pattern for that visual microhabitat. We then compare that to the cuttlefish’s actual pattern (which is held blindly from the researcher).

Both new sets of algorithms – derived from biological imagery on this grant - hold great promise for their contributions to vision research as well as practical application by ONR.

For spectral as well as spatial quantification of camouflage, we have used hand-held spectrometers in the field and HSI in the lab to quantitatively measure color matching between animal and background. The newest HSI technology, which we recently acquired, will allow convenient and unprecedented field sampling and analysis of light fields and patterning (both for signaling and camouflage) under natural lighting changes.

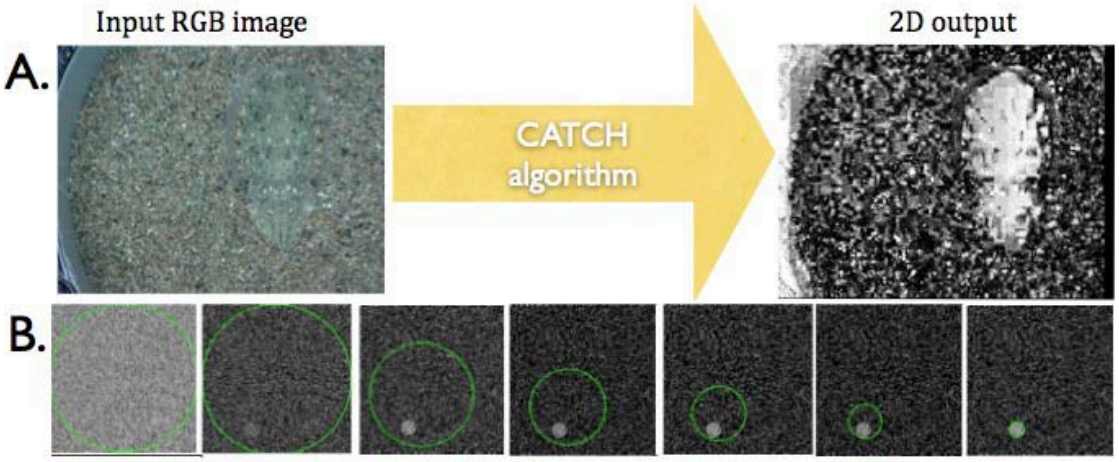

Fig. 1. Breaking crypsis. A) Example enhancement.
B) Sequence of edge localization search pattern.

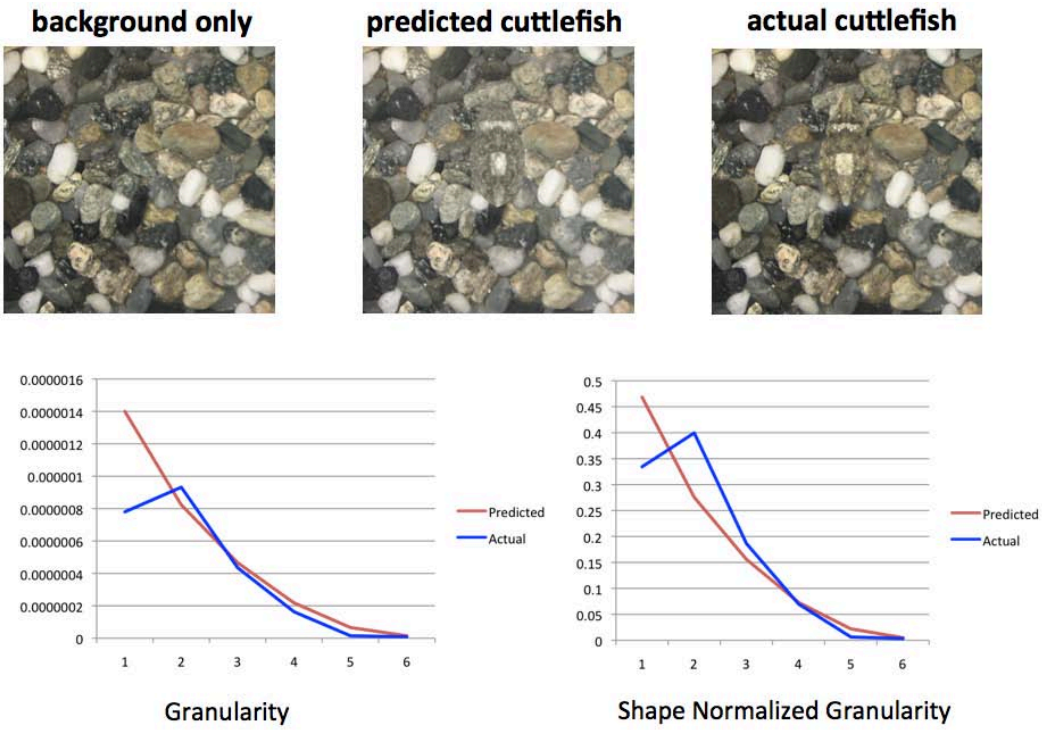

Fig. 2. Researcher is presented with background only, and algorithms calculate the camouflage pattern based on those background statistics; actual cuttlefish photo is in top right, and comparisons of the 2 body patterns are graphed below.

IN SITU QUANTIFICATION OF THE IMPACT OF EPISODIC ENHANCED TURBULENT EVENTS ON LARGE PHYTOPLANKTON

Dr. Percy L. Donaghay, Dr. Jan Rines and Dr. James Sullivan
Graduate School of Oceanography University of Rhode Island
donaghay@gso.uri.edu 401-874-6944

Background

Diatoms are one of the most widespread and ecologically important groups of phytoplankton, frequently dominating blooms in coastal and upwelling environments. For example, blooms of large diatoms provide the base of highly efficient food chains that support high concentrations of some species of marine mammals. Most cells range from 5 to 500 µm in size, but many species form multicellular colonies, which can reach millimeters, or even centimeters in length. Although scientists have speculated on the role, or 'purpose' of such elaborate morphology for more than a century, little progress was made toward elucidating the relationships between form and function. However, recent technological advances have provided evidence that interactions between turbulence and the size and morphology of these species can affect the growth, morphology and mortality of large colonial diatoms. These species-specific effects are important since they can affect not only the efficiency of food chains, but also because they can lead to the dominance of toxic diatom species that can alter the behavior or even kill marine mammals. Moreover, since phytoplankton absorb and scatter light, their species-specific properties and patterns of distribution can affect *in situ* and remotely sensed ocean optics, thus impacting the performance of DoD sensor systems.

Objectives

Our objective during this grant period was to focus on field-testing the scanning flow cytometery and autonomous profiling techniques needed to quantify *in situ* the effects of episodic enhanced turbulent events on large chain-forming phytoplankton and the bulk inherent optical properties of the water column. We were particularly interested in refining those techniques needed to field test our lab-based models which predict that brief exposure to high turbulence levels (such as those occurring during episodic wind events) will break long chains of fragile diatom species and damage or even kill individual cells of sensitive species thus altering the particle characteristics, size structure, and composition of the phytoplankton community and the resulting bulk optical properties of the water column.

Methods

We conducted our field tests in May 2009 and 2010 in East Sound, WA. Past work has shown that we can use autonomous moored profilers and small boats to repeatedly sample the populations of large chain forming diatoms that form stratified blooms in this system between intense turbulent mixing events. In each experiment we used three sampling techniques. First, we used an autonomous moored profiler deployed in upper East Sound to collect the time series of profiles need to (a) quantify the exposure of the phytoplankton community to small-scale shear and turbulence before, during and after wind events, (b) quantify the resulting temporal changes in the fine-scale physical, chemical and bio-optical structure, and (c) estimate changes during the wind event in the intensity, vertical extent, and persistence of lateral flows in the surface mixed layer and pycnocline. Second, we used real-time data from a ship-deployed high-resolution profiler to quantify the spatial extent of the impact of storms on fine-scale physical, chemical and bio-optical structure, and select locations and depths for the collection of discrete water samples. Third, we used these water samples for (a) immediate on-board analysis of individual particle characteristics using video microscopy and scanning flow cytometery and (b) post-cruise analysis of species abundance in the lab.

Results

A storm on May 11-12, 2010 provided an opportunity to test our approach to quantifying the impact of episodic enhanced turbulent events on a diverse community dominated by large non-spheroid phytoplankton. This storm generated a strong wind event that mixed the water column in upper East Sound down to 11 m in less than 2 hours. As observed in previous studies, surface layer currents were weak and consistent with the formation of an eddy that retains the recently mixed water in the upper sound. Hourly profiles collected during the storm by our autonomous moored profiler showed that

phytoplankton in near surface waters were exposed to more than 6 hours of very high levels of turbulence (turbulent energy dissipation rates of 10^{-4} to 10^{-3} $m^2s^{-3)}$ that were sufficiently high to break chains and kill sensitive species in lab studies. Flow-cytometric and microscopic analysis of samples collected from the upper water column before and after the storm showed a dramatic reduction in the length of large phytoplankton immediately after the storm and a subsequent increase in dead cells over the next few days.

In contrast to the high turbulence in the surface layer during the storm, hourly profiles collected by the autonomous moored profiler showed that phytoplankton in the highly stratified pycnocline were exposed to much lower levels of turbulence (turbulent energy dissipation rates of about 10^{-7} m^2s^{-3}). These levels of turbulence are similar to those to be optimal for growth and formation of long diatom chains in lab studies. More importantly, these hourly profiles showed that multiple persistent thin layers were formed in the pycnocline at the same time that the storm was eliminating any fine-scale structure in the surface layer. These thin layers had very different temperature, salinity and optical properties from the surrounding water. For example, a thin phytoplankton layer rapidly developed in the upper pycnocline in association with a salinity minimum. This high chlorophyll a, low salinity layer occurred just below a layer of low phytoplankton, but higher salinity and temperature. A third thin layer deeper in the pycnocline had extremely high backscattering characteristics as well as different T/S and geochemical characteristics. Our ongoing analysis of the temperature, salinity and velocity data is consistent with the hypothesis that these layers are the result of the storm creating lateral density gradients that drove multiple very thin lateral intrusions in the upper pycnocline. However, our analysis of the bio-optical and geochemical data suggests that other processes may be involved.

In summary, our field tests have allowed us to refine our approach to the point where we can design and conduct *in situ* tests of our lab-based models by using our scanning flow cytometer deployed on an ORCAS profiler to measure changes in particle characteristics *in situ* during episodic wind events. In addition, our field tests not only have provided critical new evidence for the formation of thin layers in the pycnocline, but they have also provided new insights into the potential importance of very thin lateral intrusions in creating thin particle layers that have unusual bio-optical characteristics. Sampling the sub-particle characteristics of such layers clearly will require deploying the scanning flow cytometer *in situ* on our autonomous moored profiler and then using real time data from the profiler to guide adaptive sampling of these fine-scale structures as the storm evolves.

Notes:

TRANSPORT OF GAS AND SOLUTES IN PERMEABLE ESTUARINE SEDIMENTS

Markus Huettel, Richard Wildman, Chiu Cheng, Lee Russell
Department of Earth, Ocean and Atmospheric Science, Florida State University, Tallahassee, FL, 32306
mhuettel@fsu.edu, (850) 645-1394

Background

Buried gas bubbles are a common phenomenon in shelf sediments (Willie, 2005), and through their compressibility and composition affect physical, chemical and biological properties of the seabed. By entraining fluids and due to small particles adhering to them, bubbles that are released from the sediment can increase the exchange of solutes and solids between seabed and overlying water. In shallow nearshore sands, oxygen bubbles produced by microalgae occur at abundances of >100,000 m^2, indicating that they are central for the characteristics of the surface layer and interfacial exchange of solutes and particles. Despite their potential impact on sediment and water column biogeochemical processes, very little information is available regarding the role of buried bubbles for the cycling of matter, sedimentary biology and the physical characteristics of the sea bed. Buried bubbles affect sound penetration into the sediment and thus the ability of acoustic methods to detect layers of different sound reflectivity as well as the detection of buried objects (e.g. buried mines).

Objectives

The goals of this project thus are to (1) assess temporal and spatial distribution of bubbles in sublittoral sands, (2) measure size spectrum and composition of the bubbles, (3) determine migration velocities and fluxes of bubbles, (4) quantify fluxes of solutes and particles caused by bubble volume change and migration and (5) develop a model permitting prediction of bubble release in sublittoral sands. In order to address goal (1), a technical objective of this project was to (6) develop a method that can detect buried bubbles in sand at high spatial resolution non-invasively.

Methods

The project includes field measurements (goals 1, 2, 3), laboratory experiments (goals 3, 4, 5), and instrument development (goal 6). The latter utilized a programmable square wave generator with high output (400V), a digital oscilloscope and high-frequency (1 MHz) acoustic transducers to assemble a system that can measure acoustic reflection at high temporal and spatial resolution in the surface layer of saturated sands in-situ. The fieldwork is conducted at St. Joe's Bay in the northeastern Gulf of Mexico, a sandy bay with shallow water column and strong sedimentary algal growth. Tents manufactured from clear PVC foil are placed for quantitatively trapping bubbles released from the sediment and subsequent gas analysis on a gas chromatography. Parallel sampling of sediment cores allows assessing the ratio between sedimentary gas concentration and bubble ebullition. Benthic chambers, placed over gas-release nozzles embedded at 5 cm in the sediment are used to quantify sediment-water solute exchange processes for defined ebullition rates. Laboratory work included dye tracer experiments in clear chambers addressing the release mechanisms associated with ebullition and experiments in chambers quantifying inert tracer release from sediments subjected to defined gas ebullition. Column reactor experiments are used to quantify the exchange of gases in gas bubbles in sediment and water (gas stripping). The effect of wave-induced pressure oscillation on solute exchange associated with embedded bubbles and on the ebullition rate from sandy sediments is investigated in a column that can be pressurized with controllable pressure oscillations.

Results

The oxygen bubble ebullition at our study site in St. Joe's Bay shows a seasonal cycle with low ebullition rates in winter (max: 23 ml m^{-2} d^{-1}) and high rates in summer (max: 374 ml m^{-2} d^{-1}). The free gas produced and stored in the sediment shows high volumes in spring and fall, lower volumes in summer and small amounts of gas being present during the winter. The lower sedimentary gas in summer is explained by strongest gas production and highest bioturbation during this time of the year that lead to frequent ebullition events as reflected by the maximum in measured ebullition. The gas ebullition follows a daily cycle. Photosynthetic oxygen builds up in the sediment during daytime following an exponential trend and reaches maximum values close to sunset. A novel high-frequency acoustic method we developed for this project permits non-invasive observation of

the bubble formation in the upper layer of coastal sand at a submillimeter vertical resolution (Fig. 1). Shortly after sunset, increasing wave action caused by convection-related sea breeze and enhanced activities of bottom dwellers cause peak ebullition rates. Ebullition continues through the night reaching a minimum in the morning (Fig. 2). Tidal pressure oscillations were not a dominant trigger for bubble release. Oxygen concentration in the bubbles scaled with ebullition volume and contributed up to 60% of the gas in collected bubbles. Oxygen concentrations <20% in early morning hours reflect gas stripping from the bubbles that function as small (<10 mm) oxygen reservoirs in the sediment. The laboratory experiments demonstrated that bubbles initiate pore water circulation and exchange while buried in the sand and when emerging from the sediment. With a computer-controlled pressure tank we show that oscillating pressure as caused by surface gravity waves generate oscillating pore water flows that cause dispersion of solutes and particles in the pore space. Bubbles emerging the sediment initiate pore water circulation that reaches deeper than the origin of the bubbles. Depending on size and burial depth, each bubble releases a pore water volume equivalent to 1 to 10% of its volume. With abundances that can exceed 100,000 m^{-2}, these bubbles can cause interfacial solute exchange of >100 L m^{-2} d^{-1}. Small bubbles released at a higher frequency from the sediment surface layer are more effective in exchanging pore water than larger bubbles released at lower frequency from deeper sediment layers. We conclude that small photosynthetic gas bubbles embedded at high abundances in shallow coastal sediments can significantly alter physical sediment characteristics and sediment-water exchange of matter on hourly, daily and seasonal time scales.

References:

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Widman, R.A., Jr., Huettel, M. (2012). Acoustic detection of gas bubbles in saturated sands at high spatial and temporal resolution. Limnol. Oceanogr.: Methods 10, 2012, 12-141.

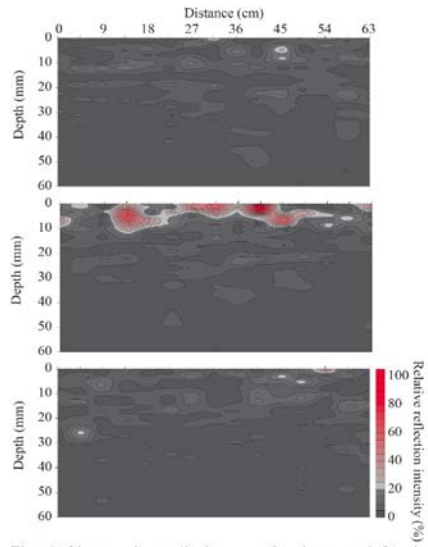


Fig. 1. Upper: Acoustic image of submerged St. Joe's Bay sand without bubbles in the morning. Middle: Mid day situation with a well-developed bubble layer. Lower: The same sediment after ebullition.

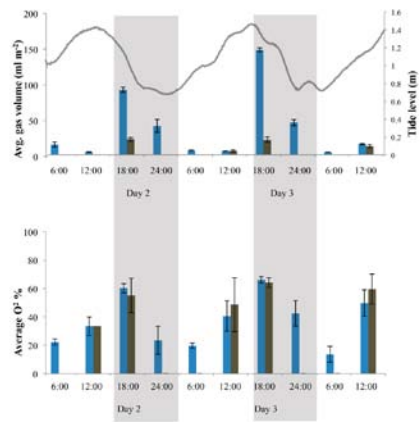


Fig. 2. Upper graph: Example of daily gas ebullition cycles measured in May 2011. Blue bars represent ebullition, brown bars sedimentary gas bubbles. Lower graph: Oxygen concentration in the gas bubbles collected from water column and sediment.

DEVELOPING A PREDICTIVE CAPABILITY FOR BIOLUMINESCENCE SIGNATURES

Michael I. Latz, Grant Deane, M. Dale Stokes, Mark Hyman
Scripps Institution of Oceanography, University of California San Diego
mlatz@ucsd.edu, 858-534-6579

Background

Bioluminescence represents an operational threat to naval nighttime operations because the flow field associated with moving objects stimulates naturally occurring plankton to produce light. In the littoral, the primary sources of bioluminescence are dinoflagellates, common unicellular plankton that are also known to form red tides. Flow stress exceeding a threshold level rapidly stimulates bioluminescence in the boundary layer and separated flow regions of moving objects, fixed objects subjected to flow, and in breaking surface waves, leading to bright displays of bioluminescence during periods of high dinoflagellate abundance. Thus the oceans can be considered a luminescent minefield where bioluminescence is triggered by sufficient flow disturbance.

The bioluminescence signature of a moving object depends on the bioluminescence potential of the organisms (related to their species abundance and measured by bathyphotometers), the spatial characteristics of stimulatory flow regions, level of flow stress, and the detectability of the light source from a surface observer based on radiative transfer of the light through the water and surface interface, as well as surface ambient light conditions. We are interested in predicting bioluminescence signatures, specifically in developing the capability to computational predict levels of flow stimulated bioluminescence. This predictive capability is based on a thorough understanding of the light-emitting characteristics of the source organisms and the measurement of bioluminescence potential by ocean sensors, and will allow us to explore mitigation strategies that reduce the bioluminescence signature of moving objects to decrease the threat of detection.

Objectives

A challenging goal is the need to predict the intensity and spatial footprint of bioluminescence signatures of naval relevance. Advances in computational fluid dynamics (CFD) led by PI Hyman make it possible to model the flow around a moving object, and now a new bioluminescence stimulation (BIOSTIM) model developed by PI's Deane and Stokes, based on laboratory studies by PI Latz, provides an initial capability to estimate bioluminescence levels as a function of flow properties, specifically fluid shear stress, which we have previously shown to be the flow property most closely correlated with flow-stimulated bioluminescence.

The primary objective of this project is to couple the BIOSTIM and CFD models to predict bioluminescence signatures associated with a moving object for a given level of bioluminescence potential. In the process we re-evaluated the BIOSTIM model based on the latest evidence; evaluated computational approaches using Reynolds-averaged Navier-Stokes (RaNS) and Direct Numerical Simulation (DNS) solvers, to determine which is more suitable for bioluminescence predictions; and validated the BIOSTIM model with laboratory tests involving independent flow fields that are characterized using CFD models, so that model predictions of bioluminescence intensity can be compared to experimental results. In addition we evaluated some of the flow agitators used in measuring bioluminescence potential, to determine the effect of chamber design and flow rate on the measurements. Finally, we investigated the cellular regulation of dinoflagellate bioluminescence as a mitigation strategy. In sum, we are working to understand the regulation of dinoflagellate bioluminescence, predict bioluminescence signatures for flow fields of naval interest based on levels of bioluminescence potential, and characterize systems used to measure bioluminescence potential, as contributions to the data products of NAVOCEANO and NRL and future strategies for bioluminescence mitigation.

Methods

The BIOSTIM model assumes that the probability of dinoflagellate cell flashing over any small time interval depends on the level of fluid shear stress, the rate of change of shear stress, and a desensitization process. Here we consider a typical situation in which the rate of change of shear stress is high and time scales are sufficiently short to minimize desensitization.

The BIOSTIM model is applied to results from a CFD-derived flow field to predict the stimulation probability of bioluminescence as a function of space and time. Predictions of bioluminescence intensity are then based on bioluminescence potential. The BIOSTIM model is formally applicable using a stress field at the scale of the organism, best obtained by Direct Navier-Stokes (DNS) simulations in which all relevant length scales in the flow are resolved. Unfortunately, this simulation is unachievable for bodies of common interest. Flow over such bodies is obtained by CFD algorithms that solve the Reynolds-averaged Navier-Stokes (RaNS) equations to compute average velocity, turbulent kinetic energy, and turbulent energy dissipation. From these, turbulent shear stress is estimated. RaNS-derived shear stress best characterizes the stress associated with **large** turbulent structures. The scale disparity forced a modification to the BIOSTIM model to allow RaNS results to predict bioluminescence stimulation. To accomplish this, DNS and RaNS results were compared for the same sized sphere as a representative object. Model predictions were validated using a sting-mounted sphere moving at speeds up to 1 m/s.

Two different bathyphotometer flow agitators were evaluated in the laboratory with cultured dinoflagellates as a function of volume flow rate and dinoflagellate concentration, to determine the critical volume flow rate, and the spatial pattern and residence time of flash trajectories. A previous data set using turbulent pipe flow was used to scale bioluminescence intensity by bathyphotometer bioluminescence potential.

Laboratory experiments with the well-studied dinoflagellate *Lingulodinium polyedrum* used a pharmacological approach to target specific areas of the signaling pathway involved in the cellular regulation of bioluminescence.

Results

Model predictions were made for a 32 mm diameter sphere moving at a speed of 1 m/s. Near-DNS results were obtained by increasing grid resolution to a fine resolution version involving 10^9 grid points. The stimulation region extended nearly 2.5 diameters downstream and exhibited a roughly cylindrical shape. The solution suggests that unsteady vortex shedding should lead to a stimulation field slightly larger than the sphere diameter, with maximum stimulation probability a small distance downstream of the body. These computational predictions were not observed in processed tow tank tests. Images in which the stimulation field is averaged over 5 runs show a stimulation peak along the sphere wake centerline. Comparison of the RaNS results to these images is considerably better. These observations suggest that, contrary to our original expectations, a RaNS-derived flow field may be the better approach to obtaining a prediction of stimulation since those flow fields are inherently averaged.

Laboratory characterization of two bathyphotometer flow agitators used by naval oceanographers revealed the presence of a critical volume flow rate, above which bioluminescence potential remained nearly constant and scaled with dinoflagellate cell concentration. One agitator had dominant secondary recirculating flows that were the origin of most of the stimulated bioluminescence. Tests using natural plankton samples indicated that scaling using bioluminescence potential allows predication of flow-stimulated bioluminescence across different flow fields.

Pharmacological treatments of the dinoflagellate *Lingulodinium polyedrum* indicated that cellular regulation of bioluminescence involves a stretch-activated component of the signaling pathway that is hypothesized to be a transient receptor potential (TRP) channel. In other organisms these channels are known for their role in the sensing of mechanical stimuli. Understanding the components of the dinoflagellate regulatory pathway for bioluminescence is important for future chemical mitigation strategies.

Notes:

FIELD DEMONSTRATION OF A HIGH-FREQUENCY, BROADBAND ACOUSTIC BACKSCATTERING SYSTEM FOR IMAGING, CLASSIFICATION, AND QUANTIFICATION OF WATER-COLUMN SCATTERERS FROM AN AUTONOMOUS VEHICLES (REMUS-100)

Andone C. Lavery, Gareth L. Lawson, Peter H. Wiebe, and Jonathan Fincke
Woods Hole Oceanographic Institution
alavery@whoi.edu; 508-289-2345

Background

For decades, significant research effort has been directed at using high-frequency acoustic scattering techniques to remotely investigate marine organisms and small-scale fluid processes. Acoustic scattering techniques provide a rapid, high-resolution, synoptic, remote-sensing tool that complements more traditional sampling strategies such as profilers, nets and optics. Emerging broadband scattering techniques result in increased range-resolution and spectral coverage, improving imaging, classification and quantification capabilities. In this study a low-power, short-range, compact, autonomous, broadband (120- 1200 kHz) backscattering system appropriate for mounting on autonomous platforms has been developed. Autonomous platforms, such as gliders or AUVs, offer advantages in persistence and/or spatial coverage, and are expected to play a critical role in ocean observing systems. The primary goal of this project is to combine these two technologies for improved ecosystem understanding. After successful tests of the autonomous, low-power, broadband backscattering system in an estuary to image stratified turbulence, this system was recently mounted on a REMUS-100 AUV for studies of zooplankton and fish ecology. Test deployments in the vicinity of Stellwagen Bank demonstrated the system is most suitable for measuring strong scattering sources at short ranges, and that the system was able to perform multi-mode operations of varying depths, spatial patterns, and transducer orientations, to complement data collected simultaneously with ship-board acoustic systems and traditional optical and net systems.

Objectives

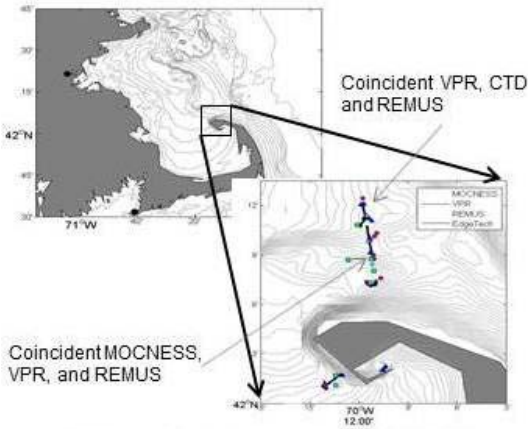
The specific objective of the work proposed here is to assess the performance of a REMUS-mounted broadband scattering system with regards to fish and zooplankton classification and quantification, in comparison to existing, cabled, high-power acoustic systems and more traditional sampling systems, namely a MOCNESS net sampling system and a Video Plankton Recorder optical sampling system.

Methods

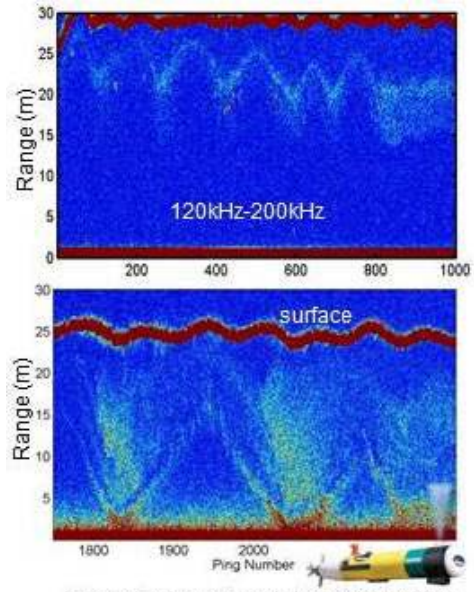
The REMUS-100 bioacoustics module was calibrated in a 3-m-deep, salt-water tank at WHOI using 8.9-mm and 21.2-mm diameter tungsten carbide (WC) standard targets. Details of the system, including power requirements, size, and beamwidths can be found in ONR progress reports. The system was further tested in the WHOI sea well and on short missions in the Woods Hole harbor.

The REMUS-100 bioacoustics module was deployed on 17 missions during a 3-day cruise in and around Stellwagen Bank from 11-13 July 2011 from RV Tioga. This location was easily accessible from WHOI, has water depths commensurate with the capabilities of the REMUS-100 (depth rated to 100 m) and typically has diverse zooplankton assemblages, as well as sandlance being typically abundant. In addition, various species of both baleen and toothed whales are known to present at different times of the year. All operations were performed during daylight hours. Three closely co-located (in time and space) MOCNESS net tows were performed. The VPR was profiled together with a CTD and 10 casts were performed, often involving multiple profiles. A high-powered, pole-mounted, broadband backscattering system (35-600 kHz) collected data simultaneously.

WHOI's REMUS-100 broadband bioacoustics system



Stellwagen Bank deployments of REMUS-100 broadband bioacoustics system



Internal waves imaged on Stellwagen Bank using the REMUS-100 broadband bioacoustics system

The REMUS-100 missions varied in length from 20-minute to 4-hour missions, and in complexity: Starting from simple surface tracking along a single line with the vessel in close proximity, to long missions involving multiple depths (with and without bottom tracking) and missions while the ship was involved in other operations (such as performing a MOCNESS net tow and VPR/CTD casts). The REMUS-100 bioacoustics module was also used to image multiple internal waves, and to track a particularly large amplitude internal wave, illustrating the feasibility of rapidly re-programing for more versatility. Initially the transducers were mounted downward facing. However, much of the observed scattering was concentrated in scattering layers in the top 10 m, so the transducers were mounted upward facing, and the REMUS-100 deployed below the shallow scattering layer, allowing it to be imaged.

Results

The primary result of this field demonstration was to successfully show that it is feasible to use broadband acoustic scattering techniques from an autonomous vehicle. The logistical aspects of this field demonstration were seamless. The useful detection and imaging range was frequency-dependent, with maximum ranges at low-frequencies to about 10-15m, but with a useful range of less than 5 m at the higher frequencies. Over these ranges, the REMUS-100 bioacoustics module compared favorably qualitatively to the performance of a high-power, cabled, broadband system. Analysis of the MOCNESS and VPR data indicates that the abundances of zooplankton throughout the study site were not particularly high, and that numerical abundance of zooplankton was dominated by small copepods that were relatively evenly distributed throughout the water-column, and not able to explain the scattering layers observed close to the surface. Due to the relatively low abundances of zooplankton during the field demonstration, it was not possible to conclusively address the success of the system for ecological studies of zooplankton. However, much higher abundances of small fish in the WHOI sea well and harbor (mostly silverside of length 5-10 cm) during the system testing made it apparent that the REMUS-100 bioacoustics system can be successfully used for fish ecology studies.

Notes:

DYNAMIC MODELING OF MARINE BIOLUMINESCENCE AND NIGHT TIME LEAVING RADIANCE

Igor Shulman[(1)], Mark Moline[(2)]
[(1)]*Naval Research Laboratory, Stennis Space Center*
igor.shulman@nrlssc.navy.mil, 228 6885646
[(2)]*California Polytechnic State University*
moline@marine.calpoly.edu, 805 7562048

Background

Prediction of the location, timing and intensity of bioluminescence potential (BL potential) and intensity of bioluminescence water leaving radiance (BLw) are critical for numerous naval operations including preventing detection of covert operations involving submarines, Swimmer Delivery Vehicles and UUVs, as well as in aiding detection of enemy incursions. Risks and opportunities from bioluminescence radiance directly depend on the Inherent Optical Properties (IOPs), as the propagation of BL radiance depends on the optical properties of the water. Therefore, joint modeling and predictions of BL potential and IOPs are very important for Navy objectives. Present Navy predictive capabilities of BL potential, however, are limited to climatology with no capability for short-term predictions of BL potential and BLw.

Objectives

Our objectives are to develop the methodology for short-term BL potential and BLw predictions, and to better understand the coupled bio-optical and physical processes in the coastal zone that governs the variability and predictability of BL potential.

Methods

Approach is based on joint studies of the BL potential and IOPs over relevant time and space scales. Dynamical, biochemical, physical and BL potential models are combined into a methodology for estimating BL potential and BLw. The physical model is based on the Navy Coastal Ocean Model (NCOM), the biochemical model simulates dynamics of two sizes of phytoplankton, zooplankton, nutrients, ammonium, and detritus pools (Chai et al., 2002). The BL potential model is based on advection-diffusion-source model, with velocities and diffusivities taken from the physical model (Shulman et al., 2011). The research is being significantly leveraged by the interdisciplinary and multi-institutional modeling and field efforts of the NRL BIOSPACE project. Bio-optical (including BL potential), physical observations from the historical and ongoing field programs are being used in this study. We design predictive experiments when the model is initialized by using a set of BL potential observations. After that we conduct forward in time simulations without assimilation of new observations, in this case the experiments simulate the forecasting of the BL potential. The forecasts are compared to the non-assimilated observations. Bio-optical, physical observations are being used also for verification and interpretation of our numerical experiments results.

Results

In the upwelling-driven system of Monterey Bay, CA, results showed that the offshore water masses with the subsurface layer of bioluminescent zooplankton were replaced by water masses advected from the northern coast of the bay with a relatively high presence of mostly non-bioluminescent phytoplankton (Shulman et al., 2011). Offshore observations show a deeper BL potential maximum below the surface layers of high chlorophyll and backscatter values during the earlier stages of upwelling development. Later, the observed deep offshore BL potential maximum disappeared and became a shallower and much weaker signal. Our analysis showed that during the upwelling, bioluminescent dinoflagellates from the northern part of the Bay were able to avoid advection by strong southward currents developed during the upwelling event. Predictive physical, biochemical and bioluminescence intensity models were used to interpret the observed dynamics during the upwelling. The results (Figure 1) show high values of BL potential and estimated BLw in areas along the coastline, where high values of BL potential were observed and model-predicted. At the same time, the model showed high values of BL potential along the entrance to the Bay (Figure 1, Shulman et al., 2011), which was not in agreement with observations. In the model, the BL potential dynamics were controlled by advective and diffusive processes only, and as it

was speculated in Shulman et al, 2011, the lack of modeling of behavioral dynamics of bioluminescent organisms (as for example, vertical migration of dinoflagellates to avoid advection losses) is responsible for the model's inability to predict the observed weakening of the BL potential along the entrance to the Bay. In Shulman et al., 2012, we tested the hypothesis that vertical swimming behavior explains observed ability of dinoflagellates' to avoid advection by strong currents. The dynamics of dinoflagellates was modeled with the tracer model where the dinoflagellate population is modeled as a concentration, and vertical swimming velocity is introduced into the tracer advective-diffusive-source model. Three swimming behaviors were considered: sinking, swimming to the target depth and diel vertical migration. Swimming velocities in all cases were considered in the range of documented velocities for the dinoflagellates species observed during the upwelling development in the Monterey Bay. Results demonstrated that through swimming behavior, dinoflagellates avoid complete advection out of the Bay during upwelling events (Shulman et al., 2012). With a modeled swimming velocity of 20m/day (a reasonable estimate at half the observed maximum) 40% of the dinoflagellates population was advected from the northern part of the Bay compared to no swimming. This is in agreement with the observed mean BL potential ratio of 0.45 at the Bay entrance compared to the northern part of the Bay. While some of the salient features of short-term changes in BL potential can be predicted and explained with the modeling of advective-diffusive processes, it was demonstrated that the modeling of BL sources and sinks is needed to reproduce the observed spatial and temporal variability of the BL even on short-time scales. It is especially valid in situations when swimming behavior of bioluminescent plankton impacts the BL potential distribution. Continued modeling efforts such as these will gauge the measure of bioluminescence as a tool for integrating ecosystem information, evaluate dynamical optical properties in the ocean, and help in short-term prediction of oceanographic conditions, including BL potential and BLw. We acknowledge contributions to this project by Matt Oliver of UDel, Steven Haddock of MBARI, Brad Penta, Stephanie Anderson, Peter Sakalaukus and Alan Weidemann of NRLSSC.

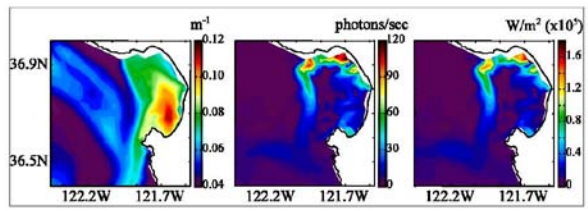


Figure 1. (right) Water-leaving radiance at the surface due to stimulation of the modeled BL potential at 5m depth.
The modeled BL potential at 5m depth (middle panel), and a sum of a (absorption) and b_b (backscattering) averaged from the depth of BL potential stimulation (5m) to the surface (left panel).

Notes:

PHOTOSYNTHESIS AS A POSSIBLE SOURCE OF GAS BUBBLES IN SHALLOW SANDY COASTAL SEDIMENTS

D.V. Holliday (deceased), J.E.B. Rines (current PI), C.F. Greenlaw and D. Thistle
Graduate School of Oceanography, University of Rhode Island
jrines@gso.uri.edu, 401-874-6691

Background

Beneath the vast expanse of ocean waters lies a complex sea floor – sands, silts and rocks of differing types, textures and topography define an intricate submarine landscape. Accurate mapping of the sea floor is critical to both naval interests and numerous areas of oceanographic research. Acoustically based approaches are currently employed in naval sensors used to detect objects on, in, or near the seabed. They are also used for mapping benthic habitats in the littoral zones of many coastal nations. Evaluation of the factors impacting acoustical data acquisition, interpretation and predictive modeling are therefore critical to both endeavors. Gas bubbles scatter and attenuate sound, thus modifying the performance of such sensors. It is well known that gas bubbles can be found embedded in marine sediments, and that their presence will increase the acoustic reflectivity of the seabed and modify the spectral shape of reverberation from the ocean bottom. However, most previous research has been focused on gas hydrates, hydrocarbon seeps and biogenic methane as potential sources of bubbles. Very little attention has been given to the production of oxygen in marine sediments by photosynthesis. Evidence from our previous laboratory studies clearly demonstrates that gas bubbles can be formed when photosynthesis by benthic microalgae causes pore water in sands collected from the surf zone to become supersaturated with oxygen. The next logical step is to determine whether this phenomenon also occurs in the coastal ocean.

Objectives

Our long-term interests focus on the possibility that biogenic activity can influence acoustic scattering at the water column-seabed interface and propagation of sound in and over a sandy substrate in shallow water coastal marine environments. Our first-order objectives are (1) to investigate the potential for microalgal photosynthesis to produce conditions leading to the formation of oxygen bubbles in the top few millimeters of shallow sandy coastal sediments and (2), if bubbles are present, evaluate how they change acoustic reflectivity of the seabed. Once successfully demonstrated, our second-order objective is (3), to investigate the interaction between photosynthetically produced interstitial oxygen bubbles and benthic zooplankton emergent behavior.

Methods

We measured incident light levels, water temperature and acoustical backscattering from the seabed at two shallow coastal zone sites on the north Florida shelf in the Gulf of Mexico. During each experiment, sand samples were collected and microscopically examined for the presence of microalgae. Integral to this work are acoustic backscattering measurements made with *SandScan* (Figure 1).

Figure 1. SandScan, ready for deployment

This prototype acoustic sensor was developed by Greenlaw and Holliday in order to obtain backscattering data from the seabed. The original instrument used frequencies around 700 kHz, which could also detect larger zooplankton. For these experiments, our first-order goal was to reproduce *in situ* the bubble effect seen in the lab. Therefore, the transducer and software were modified to move the frequency span down to 200-315 kHz, more closely matching the frequencies of peak response observed in laboratory experiments. In this configuration, the

instrument cannot be used to detect and study zooplankton. Deployments lasted about one week. Field data was examined for the temporal changes expected if production of oxygen via photosynthesis is sufficient to produce bubbles.

Results

This field project was inspired by laboratory experiments where diel fluctuations in scattering strength due to oxygen production by the algae were on the order of 20 dB – an increase in backscattered bottom echo intensity of 100 fold.

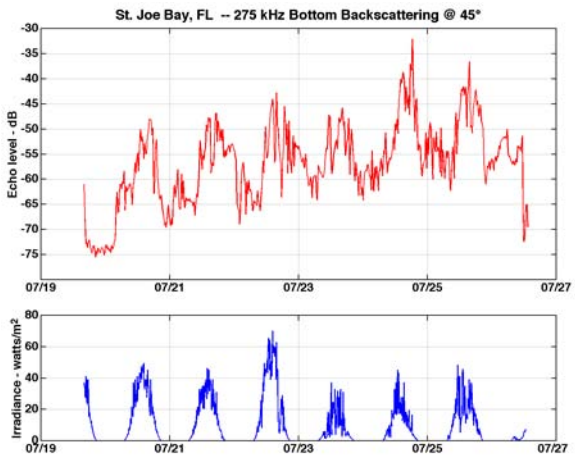


Figure 2. Data from St. Joe Bay, Florida, July 2011. Backscattered bottom echo intensity and irradiance. Note that diel increases in scattering strength are synchronized with diel fluctuations in light level, as expected from photosynthetically produced O2 bubbles.

In situ data from St. Joe Bay, FL (July, 2011) shows a very similar diel pattern (Figure 2), clearly demonstrating that the same phenomenon occurs in the coastal ocean. Moreover, the acoustic signals are just as strong as observed in the laboratory! We repeated this experiment at this site in November 2011 with similar, although weaker results. In both cases, a diverse microalgal community was present. Our St. Joe Bay site was located in 1m of water on a clean, sandy bottom. For comparison, deployments were also made at 4-5m depth in St. George Sound, where the seabed is a well-sorted medium sand. Here, the water was quite turbid, and ripple fields were observed in the sand. Sizeable fluctuations in bottom scattering strengths were recorded, but did not correlate to insolation. Very few benthic microalgae were observed, and migrating sand dollars likely caused bioturbation. We conclude that both biotic and abiotic factors contribute to variations in the dynamics of interstitial oxygen bubbles.

Our evidence clearly supports the hypothesis that supersaturating photosynthesis by benthic microalgae results in the formation of oxygen bubbles in and on the seabed. Large (up to 100X) diel variations in backscattered bottom intensity imply that this phenomenon can interfere with naval sensors. 20 dB fluctuations over a 12-hour period dictate that temporal and spatial scales of variation can be confounded during seafloor mapping exercises. We can expect that the degree of bubble formation (and resultant acoustical signal) by supersaturating photosynthesis of microalgae will vary depending on the species-specific composition of the microalgal community, variations in insolation, season, sediment type, perturbation factors, and geological/geographic variation. The logical next step in this work is to undertake a preliminary geographic and seasonal survey, to further understand the nature of this phenomenon from both a biological, and sensor-related perspective.

Notes:

DRIVERS OF PLANKTON PATCH FORMATION, PERSISTENCE AND DECLINE IN EAST SOUND, ORCAS ISLAND, WASHINGTON

Susanne Menden-Deuer
University of Rhode Island, Graduate School of Oceanography
smenden@gso.uri.edu, phone 401 874-6608

Background

Localized concentrations of plankton (i.e. patches) alter the optical and acoustical properties of the water column and can have significant ramifications for the ecological dynamics of marine communities. The goal of this research is to develop a mechanistic understanding and predictive capability of the relative importance of biological processes in the formation, persistence, and decline of plankton patches. This goal is addressed by concurrent characterization of physical water column structure, advective fluid flow, and rates of plankton population growth and mortality.

Objectives

The objective of the funded work is to quantify the relative importance of advection and ecological processes as drivers of plankton patchiness in the coastal ocean.

Methods

The methodological approach of this research is to combine high-resolution analysis of in-situ plankton distributions and the chemical, physical and biological conditions they occur in with laboratory-based measurements of plankton abundance, productivity, and grazer-induced mortality rates. Upon discovery, plankton patches are seeded with Lagrangian drifters and revisited at daily intervals to track the horizontal position of patches and quantify the rates of advection. This research utilizes methods widely used in biological oceanography, including primary production measurements using radio-labeled bi-carbonate, the dilution method to determine zooplankton grazing pressure. In addition more recent methodological approaches established and tested during my work in East Sound, including sampling of discrete water parcels and rapid assessments of water column structure using statistical discrimination analysis (Graff & Menden-Deuer, in prep).

Results

Details on the methods and results can be obtained in publications resulting from the ONR support (Menden-Deuer, 2008, Menden-Deuer et al. 2010, Menden-Deuer & Fredrickson, 2010, Menden-Deuer, in review).

In brief summary, we were able to accomplish the research proposed and exceeded the goals in some instances. We will formalize our results as peer-reviewed publications, in addition to those already published or in review during the upcoming year. Highlights from the results are as follows:

Deployment of <u>surface drifters</u> revealed a highly dynamic picture of water motion in the sampling area, including export of water masses and plankton out of the southern end of the fjord, and concurrently, quiescent conditions in the northern section of the fjord (Figure 1). Analyses of plankton population dynamics are placed within the advective regime and general physical conditions they occur in. Together these data deliver a predictive frame work for the formation, persistence and decline of plankton patchiness and the resultant effects on water column properties.

Second, measurements of <u>plankton population dynamics</u> over several years in diverse environmental conditions revealed that zooplankton grazing proceeds at much higher rates within plankton patches than outside. This differential grazing pressure has important ramifications for the development of patchiness and the magnitude of plankton biomass with layers. Most notably, these biological forces can reduce the degree of plankton patchiness within 24-48hrs (Figure 2). Concurrent measurements of primary production showed that patches only occupied ~12% of the water column but generated >50% of total water column production (1117 mg C m^{-2} d^{-1}). In the absence of advective or predatory losses, primary production within patches was sufficient to support formation and persistence of discrete patches, provided additional processes, such as vertical shear enforced continued separation of water masses. are not significantly

Lastly, we are capable of predicting the <u>likelihood of plankton patchiness</u> as a function of

passively measured water column characteristics. Thus, we can link autonomous observational capacity with a prediction of water column properties, the effects on optical and acoustical characteristics and the biologically driven rates of change in these properties.

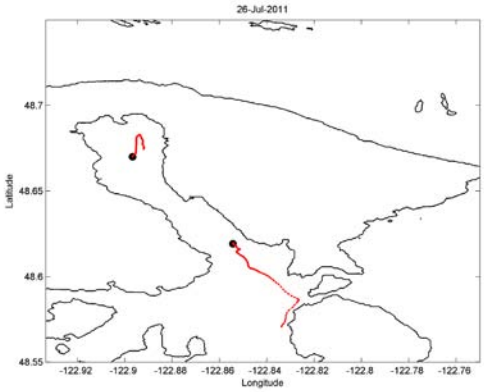


Figure 1 Progress of 2 Lagrangian Drifters (Pacifc Gyre SVP) in East Sound, Washington over a 24 hr. deployment on July 26th 2011. Deployment position is indicated by black spot. Despite a common tidal regime, the northern drifter net displacement was <0.2 km, whereas the southern drifter was displaced by >3km. Analyses of plankton population dynamics are analyzed in conjunction with the fluid dynamics of the area to establish a predictive frame work for the formation, persistence and decline of plankton patchiness.

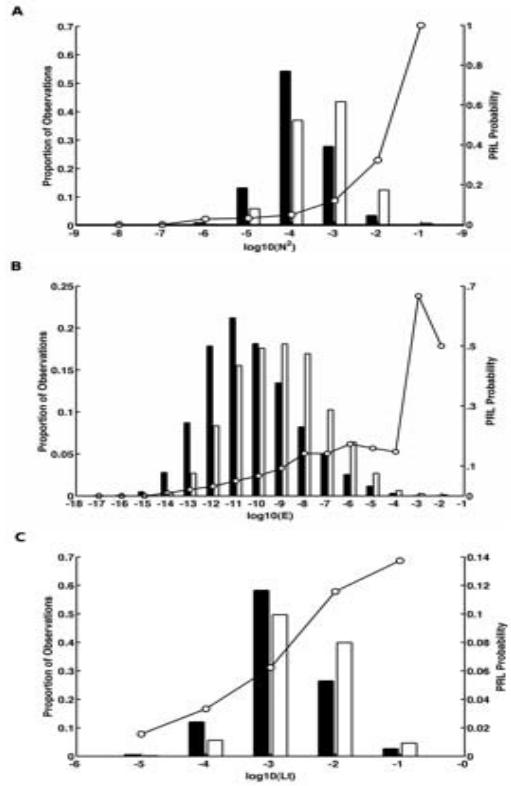


Figure 3 Normalized histograms of A) the Brunt-Väisälä frequency (N^2), B) the turbulent dissipation rate (ε), and C) the Thorpe scale (L_t) for all samples (black) and patch samples (white). Probability (circles) of samples occurring within patches increased significantly with increasing water column stability. Patch occurrence can be predicted from water column properties for the majority of samples.

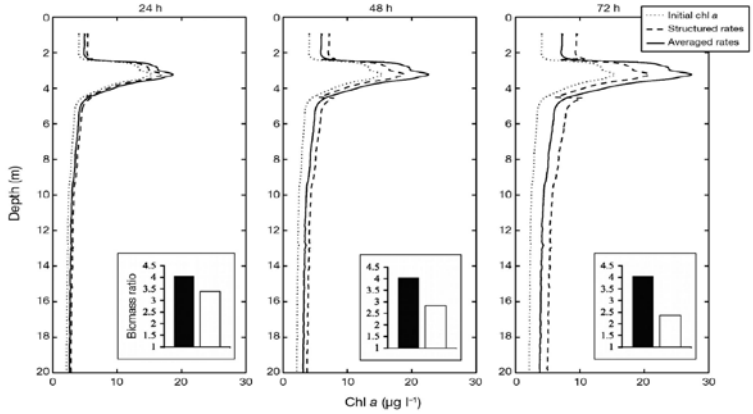


Figure 2 Model predicted development of a phytoplankton layer over 72 hrs assuming averaged vs structure dependent zooplankton grazing rates. Inset shows the ratio of biomass inside vs outside the layer, for the average (black bars) and structured rate models (open bars). Assumption of the empirically observed, structure-dependent grazing rates predicted rapid biomass accumulation outside layers and a decrease in layer intensity over time. These differential biomass accumulation rates lead to patch erosion after 48 h compared to persisting layers assuming uniform and averaged grazing rates. Note reversal of peak biomass accumulation inside and outside of layers depending on whether averaged or structured rates were assumed.

PLANKTON PRODUCTION BIOLOGY

Karl Banse
University of Washington, School of Oceanography, Box 357940, Seattle, WA 98195-7940 Phone: (206) 543-5079

Background

In the central Arabian Sea between about 150 and 1,000 m one of the three major **Oxygen Minimum Zones** (OMZ) of the world occurs. Primarily because of the tenuous balance between low O_2 and NO_3^- reduction to N_2 and the greenhouse gas N_2O, the OMZ is of global geochemical significance. Independently, during the 4-5 months of the southwest (summer) monsoon season, upsloping and actual upwelling to the surface along India's west coast affect the large fisheries for prawns and bottom fishes. For the last 15-20 years during the latter part of the season over almost ten degrees of latitude, the upsloped water has turned into sulfidic anoxia. The **significance** of our studies is that the modeling of the physics of this major upwelling continues to be in flux, and the reason(s) for the change of chemistry is not understood (temporary change in the sub-thermocline source water or coastal eutrophication?). The issues need pushing but offshore, the Somalian piracy, and on the shelf, India's inability to maintain time series and conduct oceanographic sections during the windy SW monsoon season hamper progress.

Objectives

I continue to investigate geographic and seasonal distributions of hydrography and nutrients with respect to plankton production in the central and eastern Arabian Sea including India's continental shelf. Occasionally I address general oceanographic or ecological principles.

Methods

Mostly together with colleagues at India's National Institute of Oceanography in Dona Paula (Goa; NIO), I employ the cost-efficient mining of existing old and new oceanographic data, some of which are not yet in data centers. The principal tools are vertical property plots for the upper 500 m, temperature-salinity diagrams, and regression analysis. A new essay of top-down regulation of the pelagic food web is based on the literature.

Results Since the FY2011 Report of September 2011

Decadal Trends of Mesopelagic O_2 in the Central Arabian Sea OMZ, ctd.

Our previous regressions of O_2, as observed near 200, 300, 400, and 500 m depth in selected squares, on year between 1960 and 2004 were recalculated after correcting the reported values from visual endpoint determination for the overestimate of O_2 by interference from NO_2^-. The slopes of declines between 15 and 20°N and the absence of or positive slopes to the north remained, as did the significant climatological differences between the elevated lines of the NE monsoon and those of the SW monsoon seasons. Also, our conclusion holds that an O_2 budget for the OMZ cannot be attempted until a 3-D salt budget has been accomplished.

On Chance in a Scientific Career and about the Top-Down Regulated World

Due on 1 April 2012, the 8,500-word manuscript of an invited prefatory chapter to volume 5 of the 2013 Annual Review of Marine Science is almost completed. The underlying reason for the admonition is my longstanding concern about the current (false) emphasis on the "bottom-up" approach to plankton production. It is especially prevalent among phytoplankton workers, including those using satellites to estimate chlorophyll in the sea, and the biogeochemically inclined oceanographers. The prevailing approach proceeds as if all that really matters are the resources for phytoplankton growth (nutrients, underwater light, and a little physical oceanography). The fallacy is to neglect the "top-down" processes (mortality from grazing or predation and, of late, viruses).

The draft of the **Abstract** is as follows (I was born in 1929).

Paraphrasing Pasteur, in scientific work *Fortuna* favors only the prepared mind. This is illustrated by my career after mentioning the incidental escape from the former German East Prussia just ahead of the Red Army, the switch in Kiel from zoology to oceanography, and learning of a vacancy in Seattle. Treated are the accidental discovery of upwelling during the southwest monsoon along India's west coast, studies of benthic polychaetous annelids in the Oregonian zoogeographic province, discovery of phytoplankton blooms and absence of upwelling during the northeast monsoon in the northern Arabian Sea, and ocean-wide description of seasonality of

satellite-derived chlorophyll. My admonition is that grazing rather than cell division rates regulates abundance and size composition of phytoplankton and affects the dynamics of the understudied zooplankton. I end with a pessimistic view about predicting vertical flux of particulate organic matter from the euphotic layer with an accuracy useful for deep-sea carbon budgets.

Translations of Monographs from the Russian

Scientists in the "West" are largely ignorant about Soviet and Russian-Ukrainian oceanographic publications unless they appear in the few journals translated from cover to cover. To open windows, therefore, in some of my earlier grants ONR had supported translations of monographs since the mid-1990s. During FY2011 the editing of the translation of a fourth monograph, by L.I. Sazhina (1985), was largely completed. The book provides **illustrated keys for the six stages of the nauplii (copepod larvae) of 85 species** broadly distributed in the Atlantic with its adjacent seas, the eastern tropical Pacific, and the warm parts of the Indian Ocean. It is the first and after 26 years still the only identification key of its kind and will permit the study of stage-specific population dynamics (growth rate, production, mortality). After all, biology proceeds through species rather than carbon or chlorophyll.

Last week, publication arrangements were finally completed. We will submit the manuscript for layout, etc., to the Indian Academy of Sciences in Bangalore (Karnataka), which will print 500 hard-cover copies copyrighted by India's National Institute of Oceanography (NIO) in Dona Paula (Goa). NIO and my ONR grant will pay for the printing, with the lion's share borne by NIO. The advertisement will be done through the International Association of Marine Libraries, copepod newsletters, and similar channels. NIO will also pay for the shipping of the work to be freely distributed.

Notes:

USE OF ELECTRONIC TAG DATA AND ASSOCIATED ANALYTICAL TOOLS TO IDENTIFY AND PREDICT HABITAT UTILIZATION OF MARINE PREDATORS

Daniel P. Costa, Barbara Block, and Patrick W. Robinson
University of California, Santa Cruz
100 Shaffer Rd, Santa Cruz, CA 95060 Phone: (831) 459-2786

Background

Key to assessing the risk of naval activities (such as sound exposure) on marine animals is an understanding of where animals occur and what factors motivate these movements. The rapid advancement of electronic tracking and remote sensing technologies has enabled researchers to link pelagic predator movements and oceanic processes. This information is critical for understanding distribution and residence time of vertebrates within an ocean area and for managing interactions with anthropogenic activities. Marine predators interact with a dynamic ocean that change on time scales ranging from minutes to millennia. Knowledge of these movement interactions is incomplete but critical to understanding dynamic distributions, managing anthropogenic disturbance, and predicting responses to climate change. This project utilizes the largest database of existing marine vertebrate tracking and behavior data to build upon the significant advances in tag technology, data analyses and management accomplished under the Tagging of Pacific Predators (TOPP) program. This is accomplished by establishing a behavioral baseline to assess the potential costs of displacement in terms of reduced foraging success. The project also involves a synthesis of electronic tracking and remote sensing data, focusing on a cross-taxa examination of marine predator distribution and movement patterns to identify hotspots, foraging patterns and movement corridors in the California Current

Objectives

Identify and map focal feeding, breeding, and migration routes. Model spatio-temporal oceanographic habitat utilization and predict regions of animal occupancy and use based on oceanographic features. These data will then be available for use is planning for naval operations and environmental assessments.

Methods

We will use existing TOPP tracking data to generate overall utilization distributions as well as single species distributions. These data will then be used to model the links between oceanographic parameters and animal movements. The output from these models will be used to develop predictive models of marine vertebrate distribution based on oceanographic parameters. We will also use this data set to develop guidelines on how to best carry out tracking and tagging studies.

Results

The tracking data reveal that the California Current Large Marine Ecosystem (CCLME; Figure 1) is an important habitat for tunas (Pacific bluefin, *Thunnus orientalis*; yellowfin*, T. albacares*), sharks (shortfin mako, *Isurus oxyrinchus*; white, *Charcharodon carcharias*; salmon*, Lamna ditropis*; blue, *Prionace glaucus*; common thresher, *Alopias vulpinus*), cetaceans (blue whales, *Balaenoptera musculus*), pinnipeds (Northern elephant seals, *Mirounga angustirostris*; California sea lions*, Zalophus californianus*), seabirds (Laysan albatross, *Phoebastria immutabilis*; black-footed albatross, *P. nigripes*; sooty shearwaters, *Puffinus griseus*), and turtles (leatherback turtle, *Dermochelys coriacea*; loggerhead turtle, *Caretta caretta*). Annual migratory periodicity was evident in the movements of many tagged animals that showed fidelity to the cool, nutrient rich waters of the CCLME. Extended residency within the CCLME was revealed by examining tracks that spanned multiple seasons. Numerous species exhibited a strong attraction to the CCLME and undertook long migrations (> 2,000 km) from the western, central, or south Pacific basin (leatherback sea turtles, black-footed albatrosses, sooty shearwaters, bluefin tuna, and salmon sharks). Species exhibited a seasonally recurring north-south migration (bluefin and yellowfin tunas, mako, white, and salmon sharks, blue whales, male elephant seals and leatherback sea turtles) in the North Pacific and within the CCLME. Other taxa undertook movements between nearshore and offshore waters, with a residency period within the CCLME or Gulf of Alaska, followed by an offshore migration that ranged into the North Pacific Transition Zone (female elephant seals, salmon sharks, Laysan albatrosses), the Subtropical Convergence Zone (blue and mako

sharks, leatherback turtles), or the eastern Pacific and Hawaiian Islands (white sharks, albacore tuna, and black-footed albatrosses). The mechanisms and cues underlying fidelity to seasonally-modulated migration pathways are not entirely known, but may represent a capacity to discriminate among areas of seasonal significance for foraging, or reproduction.

Notes:

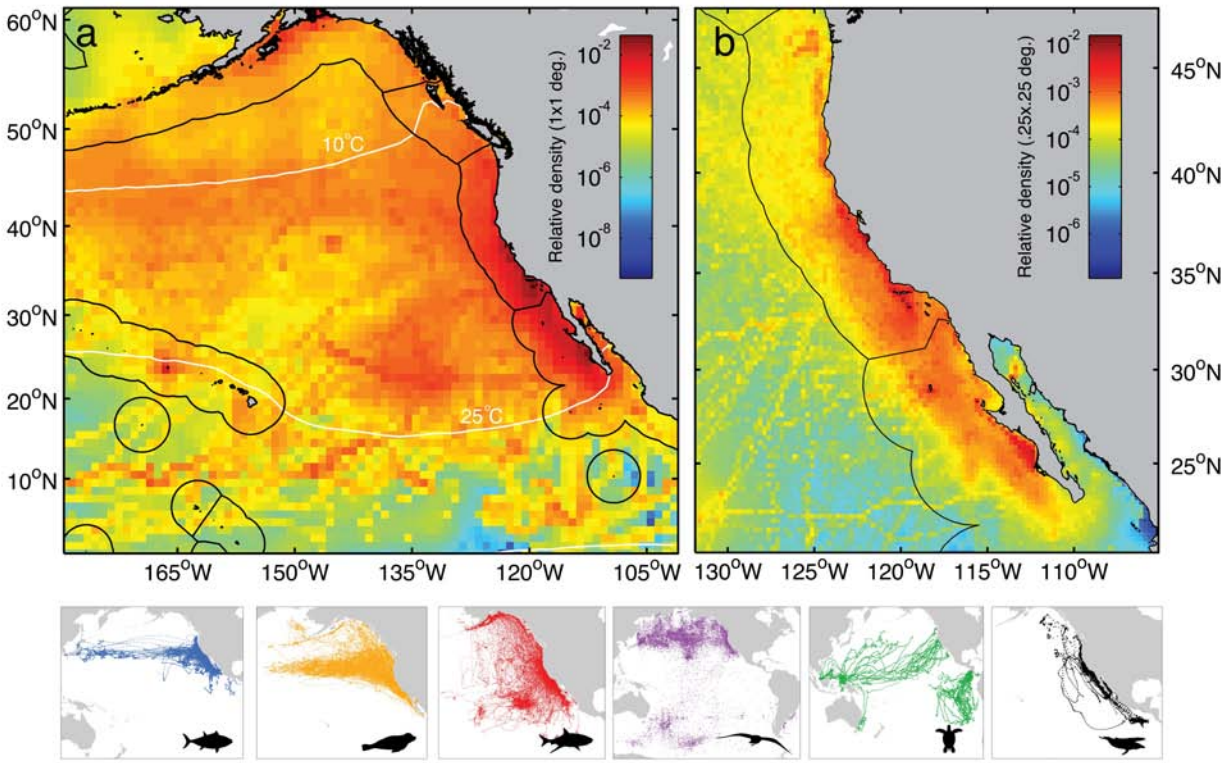


Figure 1. Predator density maps and residency patterns. a, Density of large marine predators within the eastern North Pacific. SST contours in a are denoted by solid white lines. Exclusive economic zones are delineated by solid black lines. Bottom panels show the daily mean position estimates of the major TOPP guilds (from left): tunas (yellowfin, bluefin and albacore), pinnipends (northern elephant seals, California sea lions and northern fur seals), sharks (salmon, white, blue, common thresher and mako), seabirds (Laysan and black-footed albatrosses and sooty shearwaters), sea turtles (leatherback and loggerhead) and cetaceans (blue, fin, sperm and humpback whales).

DISTIBUTION, ABUNDANCE AND POPULATION STRUCTURING OF BEAKED WHALES IN THE GREAT BAHAMA CANYON

Claridge D.E.[1], Durban J.W.[2]
[1]*Bahamas Marine Mammal Research Organisation*
[2]*NOAA Southwest Fisheries Science Center*
dclaridge@bahamaswhales.org (242) 366-4155

Background

Atypical mass strandings and behavioral responses of beaked whales have been correlated with naval sonar, highlighting a need for a fuller understanding of beaked whale population ecology. This project is filling key data gaps on the distribution, abundance, and population structuring of beaked whales in the Great Bahama Canyon. The study area (Figure 1) includes (1) the US Navy's Andros-AUTEC Operating Areas where fleet readiness training involves regular use of mid-frequency active sonars and (2) coastal waters off southwest Abaco Island where data exist from a 15-year photo-identification study, and where the March 15th, 2000 stranding occurred.

Objectives

The objectives of the study are:

1) To use visual line-transect surveys to document beaked whale distribution and estimate relative abundance and density.

2) To fit mark-recapture models to photo-identification data for Blainville's beaked whales (*Mesoplodon densirostris)* to estimate abundance, including comparisons before and after the 2000 stranding, and on / off the AUTEC range.

3) To collect skin and blubber biopsy samples to investigate beaked whale diet through fatty acid, stable isotope and contaminant analyses (see 2009 Program Review); and stock structure using molecular genetic approaches (not completed).

Methods

Using standardized line-transect methods, three ship-based visual and acoustic surveys covered 3,687 km, to estimate relative abundance and densities of beaked whales in the Great Bahama Canyon. Transect lines were randomly placed within four rectangular strata (NW Providence Channel (NWP), NE Providence Channel (NEP), Tongue of the Ocean (TOTO) and the Cul de Sac, Figure 1) using an equal-angle saw-tooth pattern to allow equal area coverage. After sightings, the ship broke transect to confirm species identification, estimate group size and to collect individual photo-identifications and biopsy samples.

Line transect data were analyzed using the program Distance and multi-covariate distance sampling was used to test effects of different variables on detection probability.

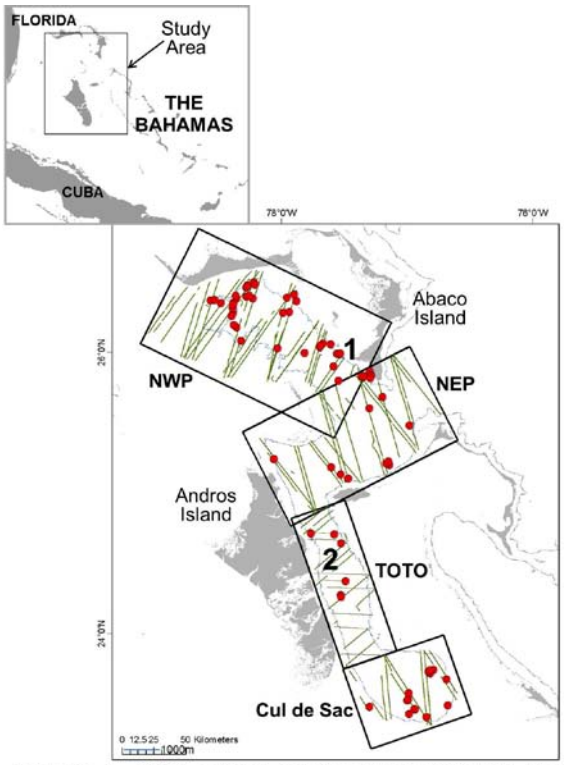


Figure 1. Map of the study area showing the four rectangular strata, line transects (green lines) and beaked whale sightings (red circles) and AUTEC range (1) and SW Abaco coast (2).

Bayesian mark-recapture models were fit to photo-identification data collected off the southwest coast of Abaco Island from 1997 to 2011 to estimate abundance of *M. densirostris*. Additionally, rates of whale movement on and off the AUTEC range were compared to movements in the Abaco study area, considered a "control" site.

Results

Ship surveys in the Great Bahama Canyon, resulted in 75 on-effort sightings of beaked whales (Figure 1) which were used to build our detection function. These comprised 3 species: Blainville's beaked whale (*M. densirostris*, *n*=42), Gervais' beaked whale (*M. europaeus*, *n*=3) and Cuvier's beaked whale (*Ziphius cavirostris*, *n*=20), plus 10 sightings where species was undetermined. Effects of ship platform and observer on detection probability were minimal but sea state had a large effect and was added as a factor variable to the detection function. The resulting detection function fit the data well (K-S test, *p*=0.93) with a truncation distance of 3,000m. Thirty-five sightings occurred while on transect lines with a mean cluster size of 2.71 (SE 0.22). Overall estimates of abundance and density of Mesoplodon beaked whales in the Great Bahama Canyon were 1,426 whales and 51.1 beaked whales/1000 km2 (CV 0.40). Abundance and density estimates for Ziphius were 1,380 whales and 49.5 beaked whales/1000 km2 (CV 0.49). Relative densities by the four different strata are given in Table 1[a].

Table 1. Relative density of beaked whales by strata (whales/1000km^2 (CV))

Strata	Mesoplodons	Ziphius
NWP	57.6 (0.50)	80.0 (0.67)
NEP	39.3 (0.55)	15.5 (1.03)
TOTO	39.5 (0.65)	n/a
Cul de Sac	73.4 (0.61)	109.0 (0.65)

Relative density of beaked whales varied by strata with the highest densities occurred in NWP, providing a context to interpret the potential impact of the 2000 stranding and also in the Cul de Sac, which despite being part of the Andros-AUTEC OpArea, is an acoustically "quiet" region and is currently not used for tactical sonar exercises.

Mark-recapture model selection supported the inclusion of parameters for emigration and re-immigration in addition to mortality in our open-population models. Preliminary results suggest there are consistent numbers of whales using the southwest Abaco study site each year (Figure 2), with an annual average of 54 whales, 75% highest probability distribution intervals (HPDI) 48-60). The highest estimated abundance was in 2000 just after the atypical stranding (64 whales, 75% (HPDI) 51-80).

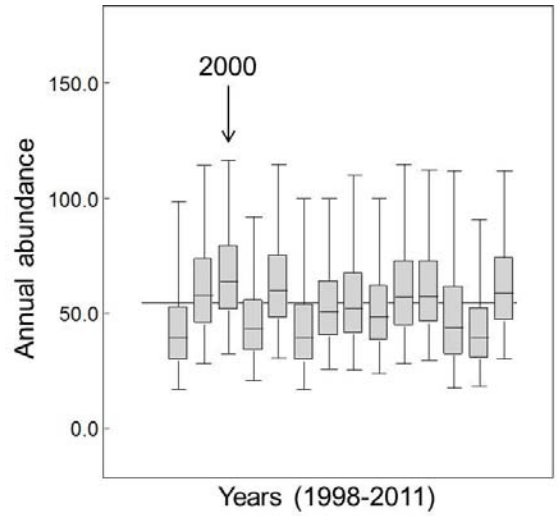


Figure 2. Preliminary results showing variation in annual abundance estimates of Blainville's beaked whales off southwest Abaco Island from 1998-2011. Boxplots represent the median and 75% highest posterior probability intervals of the posterior distribution fro each estimate, vertical arms extend to show the 95% intervals; black line displays the overall mean estimate across years.

Comparisons of the posterior probability distributions for movement parameters revealed similar annual rates of temporary emigration for the two areas (*p*[Abaco>AUTEC]= 0.55), but the probability of re-immigration was notably higher at Abaco compared to AUTEC (*p*=0.69). This suggests that although whales ranged beyond the boundaries of both study areas, there was a higher rate of return to the Abaco site than to the AUTEC Weapons Range.

This project is providing baseline data on the population ecology of beaked whales on and around the US Navy ranges in the Bahamas, information which is important to mitigation and future monitoring.

Notes:

a. The authors wish to acknowledge Dr. Len Thomas (U St Andrews) and Dr. Jay Barlow (Southwest Fisheries Science Center) for their contribution to these analyses.

FACTORS INFLUENCING THE ACOUSTIC BEHAVIOR AND NEARSHORE RESIDENCE OF THE GRAY WHALE (*ESCHRICHTIUS ROBUSTUS*) ALONG THEIR MIGRATION ROUTE

Timothy J. Cowles, Kelly J. Benoit-Bird, and David K. Mellinger
Oregon State University
tjc@coas.oregonstate.edu, kbenoit@coas.oregonstate.edu, David.Mellinger@oregonstate.edu 541-737-2063

Background

Our long-term goal is to quantify the acoustic behavior of gray whales in the coastal waters of the Northeast Pacific Ocean and to characterize the link between coastal residency patterns of these migratory mammals and nearshore conditions, particularly the distribution of hyperbenthic swarms of their primary prey (mysids).

Objectives

This pilot project concentrated on an intensive, one-month study of *E. robustus* occurrence, oceanographic conditions, and prey availability. The goal was to determine the effectiveness of coordinated passive and active acoustics in a study of nearshore ecological interactions, and to point the way toward longer term observations with passive and active acoustics that can address the role of ambient noise on whale behavior. A few of the key questions were:

What are the spatial limits, in both distance and resolution, for passive acoustics to identify and locate gray whales during their residency and foraging along the central Oregon coast?

What aspects of mysid swarm dimensions and concentration can be characterized with active acoustic moorings?

Over what time scales must we integrate variability in mysid swarm characteristics to reflect the foraging time scales of the gray whales?

Methods

For a period of 5 weeks in July and August of 2010, 3 upward-looking moored echosounders were deployed. Two of the echosounders sampled at 420 kHz while the center instrument sampled at 200, 420, and 730 kHz. All echosounders operated at a 1 Hz sampling rate with a vertical resolution of 5 cm. Periodically throughout the mooring period, sampling was also conducted from a research vessel with 5 echosounder frequencies (70, 120, 200, 333, 710 kHz) to reveal the abundance, distribution, and size of mysids. Acoustic sampling was complemented by vertically integrated net tows and video camera and CTD profiles. Surveys were also used to locate gray whales. The locations of whale sightings by the numerous whale-watching boats in the area were also recorded.

Simultaneously, four passive acoustic recorders were deployed in the same area to detect vocalizations of gray whales. Three were arranged in a short-baseline (~1 km) array to allow localization of vocalizing gray whales, while the fourth was deployed 5 km offshore to investigate gray whale occurrence farther out on the shelf.

Results

We obtained bottom temperature records at the three active acoustic moorings (8.25 inches above the bottom, approximately 10 m water depth), and have derived the surface wave elevation from the bottom pressure record recorded by the Nortek AquaDopp Profiler hourly (burst sampling, 512 samples per burst, 2 Hz). Waves were derived from the bottom pressure record using linear wave theory. The bottom temperature record revealed strong upwelling characteristics at the beginning of the deployment, with intervals of warming and subsequent cooling during the month-long deployment.

Mysids were found highly aggregated in dense bottom-associated features throughout the study period. Local fishermen reported that these aggregations appeared two weeks before our study began, at the onset of a strong upwelling event, appearing in the stomachs of bottomfish at that time. Whale-watch operators reported gray whales appeared close to the coast a few days afterwards. Mysid patches often covered more than half of the water column vertically and sometimes reached all the way to the surface. These aggregations were found between 10 m of water where sampling began and 20 m where they abruptly ended. Net tows revealed that the size of mysids in these aggregations ranged from 1 to 3 cm with some aggregations

containing a range of size classes while others were monospecific with respect to size.

Aggregations of mysids were spatially discrete with horizontal scales of tens of meters. Individual patches were consistently detected in the same locations despite strong tidal currents though their vertical extent and density changed dramatically throughout the study period. It is interesting to note that the mysid swarm locations were subject to 1-2° C temperature variations within a tidal cycle at the 10m isobath, on the order of the temperature variation signal from upwelling. However, the currents from upwelling were substantially stronger than those from tidal fluctuations. Our results indicate that mysids are actively swimming to remain in specific locations.

Passive acoustic monitoring revealed only one instance in which gray-whale-like vocalizations were recorded. Despite evidence from elsewhere that foraging gray whales produce calls frequently, it appears that summer residents are largely silent when foraging on mysids in this area. Their silence made it impossible to track them acoustically as originally planned, and thus visual observations made up the only data available on locations of gray whales.

Despite the limited sounds made by gray whales and thus our inability to track them with high resolution, gray whales were observed at frequent intervals within the study region. We combined our observations with those of whale-watch operators to document the location of each whale over time, type of foraging behavior observed, and identification if the observed whale was a local 'resident' and in the photo-ID catalog. We found that individual whales were generally resident in the area for much of the study period but moved rapidly over the region, foraging in many locations. Our energetic estimates show that mysids continuously presented an abundant food source that despite small scale variability, was highly predictable throughout this area of the Oregon coast. However, the northernmost area of our study had no mysids and whales were not observed to forage here so regional characteristics likely play an important role in residency of gray whales along their migration route.

Notes:

IMPORTANCE OF THIN PLANKTON LAYERS IN HAWAIIAN FOOD WEB INTERACTIONS: RESEARCH SPANNING FROM PHYSICAL CIRCULATION TO SPINNER DOLPHINS

Kelly J. Benoit-Bird[1] and Margaret A. McManus[2]
[1]*Oregon State University*
kbenoit@coas.oregonstate.edu, 541-737-2063
[2]*University of Hawaii at Manoa*
mamc@hawaii.edu, 808-956-8623

Background

Understanding the relative roles of the biological and physical factors that control populations and communities is a central challenge in ecology. Trophic interactions, which in many systems determine distributions and abundances of organisms, are regulated by a combination of factors including resources and predators. While some researchers have argued that environmental heterogeneity must be considered in assessing the relative roles of ecological forces, a widespread and fundamental ecosystem characteristic, patchiness, or the spatial variability in biomass at relatively small scales, has been difficult to incorporate in studies of these controls. Results of our ONR funded efforts around Hawaii indicate that biotic layers of plankton and nekton are persistent, real features that are common in nearshore Hawaiian waters - these layers are highly likely to affect the behavior and habitat use of spinner dolphins.

We examined the relationships among four trophic levels that are found in distinct, extreme spatial aggregations to examine the relative importance of biotic and abiotic forces in structuring and regulating the pelagic marine food web. This understanding is critical for producing predictive models for organism distributions and our ability to predict acoustical and optical scattering in the coastal ocean.

Objectives

Our goals were: (1) to quantify aggregations of the phytoplankton, zooplankton, and the nearshore sound-scattering layer around Hawaii, (2) to identify the physical, optical, and acoustical characteristics associated with these aggregations, (3) to assess the scales of coherence between these various levels of biological aggregations and understand their interactions, (4) to assess the impacts of biotic layers on spinner dolphin behavior and habitat use, (5) to assess the impact of these layers on optical and acoustical measurements in the nearshore environment, and (6) to use this information to develop the capability to predict the occurrence of biological aggregations of plankton, micronekton, and dolphins in coastal waters.

Methods

We used a combination of continuously sampling moored sensors complemented by shipboard sampling to measure the temporal variation, abundance, and vertical distribution of four trophic levels in Hawaii's nearshore pelagic ecosystem. Ship-based sampling with a downward looking acoustics package and a high-resolution profiler instrumented with optical, acoustical, and hydrographic sensors was conducted close to continuously sampling instruments moored at the 25 m isobath off leeward Oahu over three, 24-hour periods, as well as during four other days and nights dispersed over the study period. Moored sensors at the 25 m isobath included an autonomous profiler collected hydrographic and chlorophyll fluorescence data every half hour between the bottom and the surface with <1 cm vertical resolution, a calibrated, moored upward looking 200, 420, 740 kHz echosounder that collected acoustic backscatter once per second with a vertical resolution of 1 cm, and an ADCP that collected high resolution current data. Additional moored sensors in the area were used to describe the regional circulation and across shelf movements of micronekton and spinner dolphins.

Results

We found strong aggregations in the four trophic levels examined in Hawaii's nearshore pelagic ecosystem. At all levels, these aggregations formed in response to gradients in biotic and abiotic factors. The importance of biotic factors increased with increasing trophic level while the importance of physical factors decreased. Because of the short lived duration of physical gradients driven by thermal stratification that overturned convectively each night, biological aggregations were very short lived in comparison to those observed in temperate

systems (McManus et al, in press; Sevadjian et al., in review). However, despite the rapid time scales, the biological responses to gradients were very strong at every trophic level. Using an analysis approach from trophic dynamics, we found that the frequency and intensity of spatial aggregations, rather than total biomass, in each step of a food chain involving phytoplankton, copepods, mesopelagic micronekton, and spinner dolphins (*Stenella longirostris*) were the most significant predictors of variation in adjacent trophic levels. Patches of organisms had impacts disproportionate to the biomass of organisms within them, masking resource limitation in this ecosystem. Our results are in accordance with resource limitation - mediated by patchiness - regulating structure at each trophic step in this ecosystem, as well as the foraging behavior of the top predator. As a result of this consistent bottom up forcing, simply measured patch characteristics of phytoplankton could be used to predict 72% in the variation in local habitat use by dolphins and 83% of variation in their aggregation while foraging (Benoit-Bird and McManus, in review). Because of the high degree of heterogeneity and the low levels of resources present in tropical pelagic systems, ecosystem-level effects of patchiness like this may be particularly common. Observing the processes driving these ecosystems, however, requires high temporal and spatial resolution sampling to capture the important yet ephemeral events that ultimately drive the responses of animals like spinner dolphins.

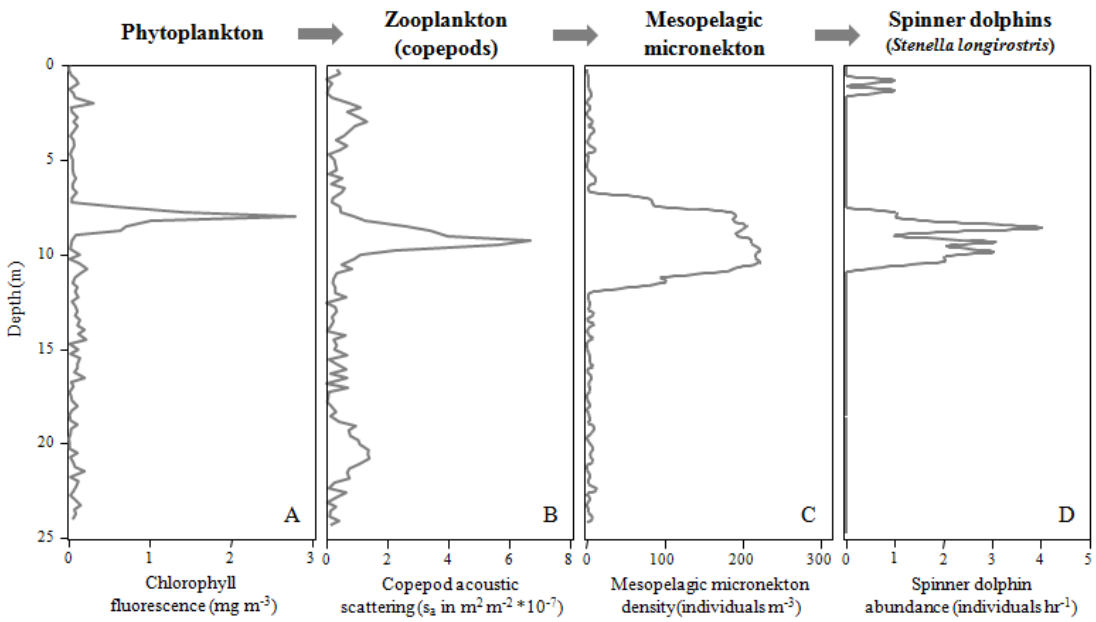


Figure 1. An example of the vertical distribution of each step in the food chain in Hawaii's nearshore pelagic ecosystem measured at 2300 on 4 May 2009 using instruments moored on the 25 m isobath.

Notes:

USING ACOUSTICS TO UNDERSTAND ECOSYSTEM DYNAMICS IN THE BERING SEA

Jennifer L. Miksis-Olds[1], Jeffrey A. Nystuen[2]
[1] *Applied Research Laboratory, Penn State, PO Box 30, Mailstop 3510D, State College, PA 16804, jlm91@arl.psu.edu, 814 865-9318*
[2] *Applied Physics Laboratory, University of Washington, 1013 NE 40th Street, Seattle, WA 98105-6698, nystuen@apl.washington.edu, 206 543-1343*

Background

Zooplankton population dynamics are a dominant component of the ecosystem that 1) provide the crucial trophic link between primary production and Federally-protected species such as marine mammals and 2) can be observed by measuring acoustic backscatter from the water column. From a bottom-up perspective, the timing, magnitude, and dominant species of plankton may shift in response to changes and reductions in ice cover; prey availability and ice cover are important factors, and potentially the most dominant factors, influencing long-term habitat use by marine mammals in Arctic and sub-Arctic regions. Understanding the relationship between ice cover and zooplankton community structure in different regions of the Bering Sea will provide information for predicting upper-level trophic dynamics, including marine mammal distribution and range, as sub-Arctic conditions continue to change.

From a top-down perspective, reductions in ice cover are predicted to be accompanied by changes in habitat use for animals and humans. Longer periods of open water may result in an increase in predators and human utilization of the region, and sound related to human activities have been shown to elicit short-term and long-term reactions from marine mammals including behavioral disruption and displacement from occupied habitat. An assessment of potential acoustic changes must also consider the interaction and cumulative effects of sound, animal behavior, and environmental factors, as some environmental conditions may result in a high level of marine mammal impact whereas others would result in relatively lower levels of impact.

Objectives

The original proposal objectives focused only on cetaceans. The scope of the project was broadened to include pinnipeds during the first year as a result of preliminary analyses of the passive acoustic dataset; thus, cetacean was changed to marine mammal in all objectives.

The long-term goal of this collaborative research effort was to enhance the understanding of how variability in physical, biological, and acoustic signals impact marine mammal habitat use.

1. To determine the temporal variability in sound level and sources in the southern and central areas of the Middle Shelf domain in the Bering Sea
2. To investigate the relationship between physical processes related to wind intensity, storms, and sea ice coverage with zooplankton/fish abundance and marine mammal presence
3. To examine the relationship between temporal prey abundance and marine mammal habitat use
4. To investigate the combined effect of physical processes, environmental sound and prey availability on marine mammal habitat use.

A one-year expansion of the original project was granted to more closely examine the details of acoustic backscatter beyond simple abundance estimates.

The overall expansion objective was to characterize acoustic backscatter connected to estimates of zooplankton/nekton abundance, spatial and temporal variability, dominant size class, and taxa, and to relate the backscatter characteristics to marine mammal detection patterns on the central and southeastern Bering Sea shelf.

Methods

Synoptic measurements of marine mammal vocal presence, habitat use, prey characteristics, physical oceanographic processes, and noise levels in the Bering Sea were made with a combination of active and passive acoustic technology. An adaptive sub-sampling Passive Aquatic Listening (PAL) recorder and three-frequency echosounder system were integrated into biophysical moorings on the southeastern (site M2) and central (site M5) Bering Sea shelf. The passive acoustic data provided a simultaneous time series of marine mammal vocalizations and changing soundscapes (sound levels and spectral shapes) related to surface conditions.

Acoustic backscatter recorded by the echosounders provided information on relative prey abundance, community composition, and water column distribution.

Interactions between marine mammal and zooplankton abundance and other environmental variables are currently being investigated using General Additive Mixed Models as appropriate for each objective. Variables included in the model include daily species specific presence, ice cover, ice thickness, volume backscatter, zooplankton/fish community structure, sound levels, and wind.

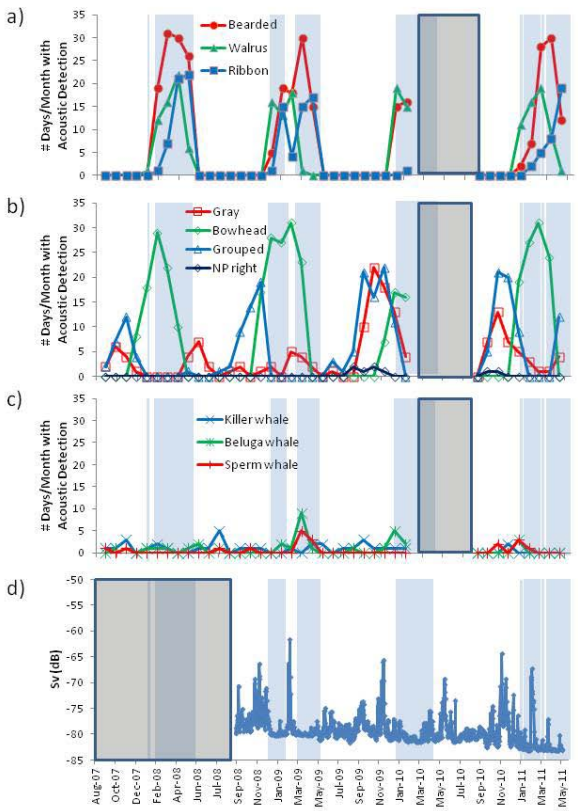


Figure 1. Monthly detections of pinnipeds (a), mysticetes (b), and odontocetes (c) time aligned wi 200 kHz volume backscatter (d). Light blue areas represent ice cover and gray regions are periods no data collection. Grouped mysticetes calls (b) are attributed to humpbacks, bowheads, and rig whales not classified to species level.

Results

In the Bering Sea, pinniped and bowhead whale acoustic detection was tightly coupled to ice presence (Figure 1). The acoustic detection of mysticete species other than bowhead whales was strongly related to the fall bloom of zooplankton and has increased over the past two years in the central shelf area (Figure 1). In the southeastern region blue whales and fin whales were detected all year with peak detections corresponding to the spring and fall zooplankton blooms. These species were not detected at any time at M5. The zooplankton community structure during open water periods differed between the two sites with the southern site having a greater proportion of large scatterers indicative of adult euphausiids (Figure 2), which may be a strong predictor of blue, fin whale, and other mysticete species presence.

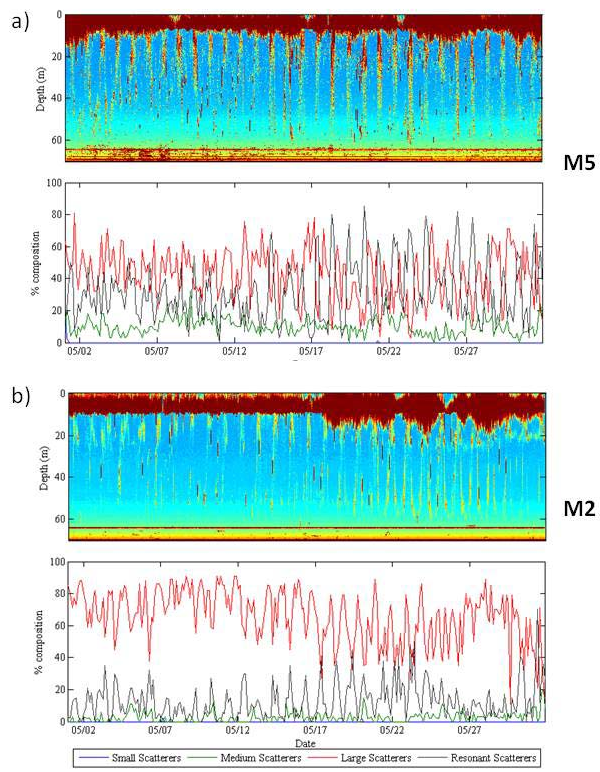


Figure 2. Month long 200 kHz echogram with time aligned percent species composition at the central shelf location M5 (a) and the southeastern shelf location M2 (b) in May 2009. Diel vertical migration patterns are evident at both sites.

Notes:

PREY FIELDS AND HABITATS OF DEEP DIVING ODONTOCETES: 3D CHARACTERIZATION AND MODELING OF BEAKED AND SPERM WHALE FORAGING AREAS IN THE TONGUE OF THE OCEAN

Douglas P. Nowacek[1], Patrick N. Halpin[1], and Louis St. Laurent[2]
[1]*Division of Marine Science and Conservation and Electrical and Computer Engineering, Duke University*
dpn3@duke.edu 1.252.504.7566
[2]*Physical Oceanography, Woods Hole Oceanographic Institution, Woods Hole, MA 02543*

Background
Relatively little research has combined the study of cetacean foraging behavior with concurrent measurements of prey fields and physical oceanography, but new research tools are providing such opportunities. We have studied the foraging ecology of short-finned pilot whales (*Globicephala macrorhynchus* - Gm) and Blainville's (*Mesoplodon densirostris* - Md) and Cuvier's (*Ziphius cavirostris* - Zc) beaked whales.

Objectives
Quantitative descriptions of the distribution of prey are critical to interpreting cetacean foraging ecology, and we endeavored to measure several aspects of the whale's environment so as to obtain a more detailed picture of their foraging ecology.

Methods
We combined behavioral data from multi-sensor tags (Gm) and a bottom-mounted array (Md and Zc) with synoptic measurements of the acoustic volume backscatter of potential prey using calibrated EK-60 echosounders and described the physical environment using ADCP, CTD, and, in one case, a turbulence profiler.

Results
We deployed 15 tags on Gm for a total recording time of over 113h. Echolocation buzzes, representing prey capture attempts, occurred 7.1 times per dive and 14.3 times per hour. Overall, whales foraged at depths where biomass and/or single targets were greatest, but not all foraging decisions were based on vertical variation in biomass. For beaked whales, we sampled the prey field with an 8 km, 4-leaf clover sampling pattern so as to examine the spatiotemporal scales and relationships among turbulence levels, biological scattering layers, and beaked whale foraging activity (Figure 1). We found a strong correlation among increased prey density and ocean vertical structure relative to increased click densities. The physical structure of the water column in the Tongue of the Ocean reveals features that could influence the prey field structure. Lastly, we are investigating whether the echosounders themselves affect the behavior of the cetacean species being studied.

Notes:

FINE-SCALE SURVEY OF RIGHT AND HUMPBACK WHALE PREY ABUNDANCE AND DISTRIBUTION

Joseph D. Warren
School of Marine and Atmospheric Sciences, Stony Brook University
joe.warren@stonybrook.edu, 631.632.5045

Background

In order to study the behavioral responses of marine mammals to external stimuli it is important to measure other factors that may also strongly affect or cause a behavioral response (Weilgart, 2007, Nowacek et al, 2004). Perhaps the most important interspecies stimuli for marine mammals is the distribution and abundance of their prey as feeding and searching for food are primary factors in determining animal behavior as well as their distribution and abundance (Baumgartner et al, 2003; Baumgartner and Mate, 2003). Without knowledge about marine mammal food resources, determining the importance and impact of other stimuli (such as external noises) may be problematic. Therefore studies of marine mammal behavior that include measurements of their food resources may provide additional insights into the interactions of various stimuli and how marine mammals respond to them.

Objectives

(1) Identified the prey type (e.g. copepod, krill, or fish) and numerical abundance of zooplankton and nekton in the vicinity of marine mammals by integrating multiple frequency acoustic survey data with net and video measurements (Foote and Stanton, 2000; Warren et al., 2003). The distribution and numerical density of prey (in both the horizontal and vertical dimensions) and the variability of the preyfield over length and time scales (1 m - 10s km, 10 sec - days) that are important for right and humpback whale feeding behavior and success were measured.

(2) Measured environmental parameters (hydrographic and meteorologic) during these surveys that may be correlated with marine mammal behavior, the presence of prey species, or sub-surface acoustic scattering processes

(3) Collect visual observations of surfacing marine mammals and their behavior during the survey which can be integrated with the preyfield data and observations from other vessels or instrumented tags.

These objectives support the following ONR research goals: Understanding the links between ocean physics and production and the location, movement and ecology of marine mammals; The use of sound to detect, identify and enumerate fish; The dynamics of intense and vertically thin plankton layers; Behavioral responses of marine mammals to man-made and natural sounds; and Acoustics- and optics-based technologies for measuring marine biota.

Methods

A separate research project (led by Susan Parks) placed DTAGs on right and humpback whales during the spring in Cape Cod Bay. Concurrently we deployed (from the tagging team's support vessel) a towfish (equipped with 38, 120, 200, and 710 kHz echosounders and a 600 kHz ADCP) to measure the abundance and distribution of whale prey species; video drop cameras and ring nets to ground-truth the acoustic data; and CTD and Video Plankton Recorder vertical profiles.

Results

This project had two field seasons, spring of 2009 and 2010. The 2010 field season will be the focus of this abstract. Over a 3 week period, we conducted 15 CTD casts, 12 Video Plankton Recorder profiles, 54 net tow stations (with tows to 1, 5, and 20 m at most stations), continuous measurement of meteorological conditions while surveying, multiple drop-camera deployments, and several hundred kilometers of acoustic trackline survey effort. We have acoustic backscatter data during every tag deployment and the majority of the data are in close proximity to the tagged animal (roughly within several hundred meters of the tagged animal and/or at the location of a surfaced animal within 60 seconds of the animal diving or moving away). We feel that these data characterize the whale's preyfield at relevant temporal and spatial scales. Whale prey were identified using a dB difference method which compared the volume backscatter strength at different acoustic frequencies.

Scattering targets were identified as small calanoid copepods when the 710 kHz backscatter was more than 10 dB than 120 kHz backscatter. Copepod aggregations were also observed on the 600 kHz ADCP. Scattering identified as copepods was converted to numerical density estimates (# of animals per m3) by calculating the predicted Target Strength of a 1.5 mm copepod (mean length from net tow samples). The numerical density of copepods were compared with that from net tows and video plankton recorder casts. Acoustic estimates of copepod abundance were usually larger than that from net or video sampling.

Our ability to use acoustics to identify copepod scattering patches is somewhat unique to this location, ecosystem, and our instrumentation as it depended on using a high frequency echosounder, a shallow depth (as high frequency echosounders are limited in range), a towfish towed near the surface, and very high abundances of copepods. This approach will be less effective in regions where these conditions are not met. Comparison of tagged right whale behavior showed that these animals spent the majority of their time within the upper few meters of the water column which correlated strongly with the highest abundances of copepod prey (Figure 1). Estimates of energy gained by skim-feeding right whales in these conditions were much greater than then other feeding behaviors (e.g. diving in the nearby Great South Channel).

Other scatterers were identified as small fish (usually herring, but occasionally sand lance) when backscatter at 120, 200, and 710 kHz were within 3 dB of each other (or in some cases when the 710 kHz backscatter was lower than the 120 or 200 kHz values). In some cases, we could confirm the scatterer identity with visual observations but not in all cases. In some areas where fish schools were abundant, humpback whales were feeding in competition with several other species (gannets, white-sided dolphins). Humpback whale dive depth was much more variable than that of right whales as was the location of their prey (Figure 2). Whale dive depth was still correlated with depth and abundance of their prey.

Our data analysis is ongoing as the processing of net tow samples was completed just before the end date of this project. Participants supported (in part) by this project include three female graduate students and more than a dozen undergraduate students. Data from this project was used in graduate and undergraduate courses at Stony Brook as well as the ONR-sponsored SeaBASS graduate course at Penn State.

Notes:

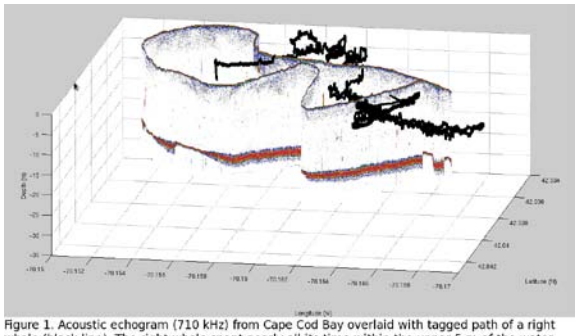


Figure 1. Acoustic echogram (710 kHz) from Cape Cod Bay overlaid with tagged path of a right whale (black line). The right whale spent nearly all its time within the upper 5 m of the water column. Blue areas in the echogram represent patches of calanoid copepods with numerical densities > 1000 animals / m3 while the red line is the seafloor. The track of the tagged right whale is psuedo-georeferenced so the horizontal uncertainty is on the order of 50 m.

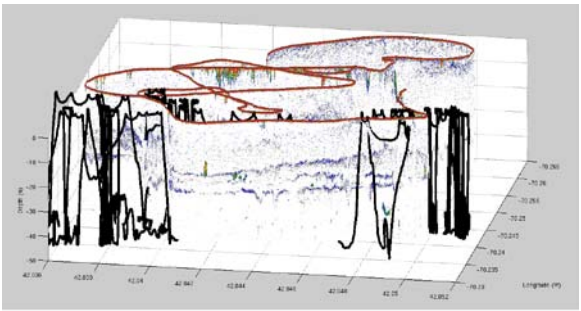


Figure 2. Acoustic echogram (120 kHz) from near Race Point overlaid with path of a humpback whale (black line). The dive depth of the humpback whale was variable shifting between dive depths of 50 m and 15-30 m. Blue areas in the echogram represent fish schools with numerical densities ~ 10 fish / m3, while red/yellow aggregations are ~ 50-100 fish / m3. Bottom depth was ~ 90 m. The track of the tagged whale is psuedo-georeferenced so the horizontal uncertainty is ~ 50-100 m.

CONTINUING INVESTIGATIONS OF THE RELATIONSHIP BETWEEN FIN WHALES, ZOOPLANKTON CONCENTRATIONS AND HYDROTHERMAL VENTING ON THE JUAN DE FUCA RIDGE

W.S.D. Wilcock, R.E. Thomson, M.J. Weirathmueller, D.C. Soule, B.J. Burd
School of Oceanography, University of Washington
wilcock@u.washington.edu

Background

Fin whales are an endangered species of baleen whale found throughout the world's oceans. Their social behavior, habitat usage and migratory patterns are incompletely understood. Studies that constrain the spatial and temporal density of fin whales, their calling and swimming behavior and their exploitation of potential food sources can contribute to our basic understanding of this species and provide important data for assessing how they might be impacted by anthropogenic activities. The tools developed for such studies are potentially useful for investigating other marine mammal species.

Objectives

Using data from the Endeavour segment of the Juan de Fuca Ridge in the Northeast Pacific Ocean, we are investigating a potential correlation between fin whales, enhanced zooplankton concentrations and hydrothermal vents. The long-term scientific goal is to understand such correlations in terms of the influences of globally distributed hydrothermal plumes on the trophic ecology of the ocean. The specific objectives of this study are to:

1. Complete the tracking and analysis of ~400,000 fin whale calls recorded over 3 years by a seafloor seismograph network.
2. Compare call counts from the Endeavour with sites away from the mid-ocean ridge to determine if the density of vocalizing fin whales is unusually high near the vent fields.
3. Complete the calibration of ADCP backscatter intensities in terms of biomass using data from combined net/ADCP tows and utilize this calibration to analyze ADCP time series in order to understand the relationship between the seasonal vertical migration patterns of zooplankton and their enhanced concentrations above the hydrothermal vents.

Methods

We use recordings of the fin whales' 1-s 20-Hz call obtained from a network of 8 ocean bottom seismometers (OBSs) deployed on the Endeavour segment from 2003-6 and from single OBSs deployed at sites in the middle of the Juan de Fuca tectonic plate and on the continental slope. On the Endeavour, we use an automatic picking and grid-search location algorithm to detect and model direct and multipath arrival times recorded by the seismic network. We analyze each resulting whale track for calling and swimming patterns and the full track data set for seasonal variations and the spatial density of calling whales. We also apply the double-difference technique (a method developed to locate earthquakes) to selected tracks. Instead of finding the location that minimizes the difference between observed and predicted times, this technique seeks to eliminate unsystematic errors by minimizing the differences between the observed difference and predicted difference in arrival times for pairs of nearby calls on a common station. The double-difference technique works well for fin whale tracks because the cross correlation of the repetitive calls provides accurate difference times. Within the network, uncertainties in the relative locations of adjacent calls are a few tens of meters.

To compare call counts on single OBSs at different sites, we implement a matched filter detector and validate its performance against a baseline set of manual detections. We apply this detector to single stations using a uniform detection threshold to account for differences in noise. Because source levels are important for converting call counts to call densities, we estimate source levels for tracked whales that swim near an OBS in the Endeavour network by converting the vertical ground velocity measured by the OBS to the amplitude of the acoustic wave at the seafloor using the Zoeppritz equations, and then apply a correction for the transmission loss through the water column.

We examine the relationship between biomass obtained from 197 mixed-species zooplankton net samples and proximate acoustic backscatter data obtained over 6 summers, and full water depths up to 200 km from the vents. A linear regression of total net biomass versus the

corresponding sum of acoustic ensembles for the specific net tow is obtained based on the highly accurate flow volume measurements through the nets. High-resolution CTD and transmissometer data from sensors included in the net-tow/ADCP package further enable us to examine the relationship between zooplankton concentrations and the vertical temperature, salinity and water clarity structure in the water column. Upward looking 75 kHz ADCPs deployed on moorings 250 m above the seafloor in the axial valley of the Endeavour segment as part of the NEPTUNE Canada cabled observatory provide a temporal record of acoustic backscatter (zooplankton biomass) variability over the ridge.

Results

Fin whale calls are strongly seasonal on the Endeavour with high rates of calling between September and March. To date we have determined over 150 call tracks lasting in duration from ~2 hours to 1 day. In early fall nearly all the tracks are relatively straight and to the north. They have a complex pattern of inter-pulse intervals (IPIs) and variable frequencies that is indicative of multiple calling whales swimming together. After October the tracks tend to meander and most have a southward component. They are mostly characterized by a regular 25-s single IPI or 24/30-s dual IPI that are interpreted as single calling whales. There are also a few 13/24-s dual IPI tracks that appear to be two whales based on differing frequencies.

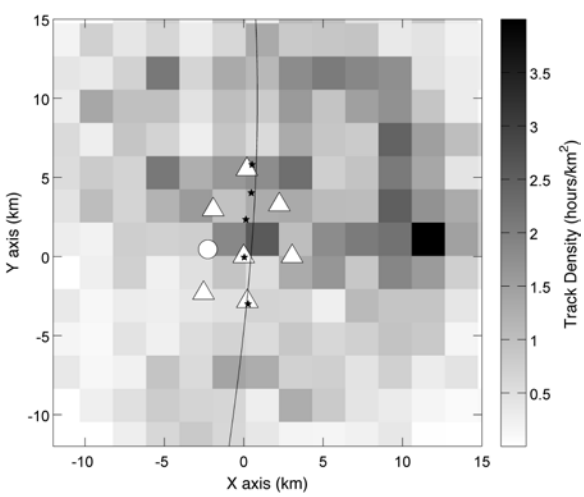


Figure 1. Density of call tracks observed around the Endeavour seismic network showing the ridge axis as a solid line, OBSs as open symbols and hydrothermal vent fields as black stars.

The call density (Figure 1) is higher within the network and to northeast and east and lowest to the southwest. Although it is not clear that calling whales are linked to feeding, this distribution is consistent with a food source near the ridge that is advected to the east and northeast by the mean ocean current in the region associated with the West Wind Drift and Subarctic Current.

Call counts measured with single OBSs at mid-plate locations and on the continental slope are generally higher than those on the Endeavour. However, it is unclear if the differences reflect changes in the density of calling whales because the range of detection may be strongly influenced by differences in water depth and seafloor lithology and roughness. Our goal is to convert the measurements of call counts to estimates of the density of calling whales. Fin whale source levels determined using a data set of 2500 calls that are located <1 km horizontally from an OBSs in the Endeavour network are 190 ± 6 dB re 1 µPa-m. We are presently adapting our detector to identify multipaths and developing a means to estimate the range to a calling whale based on the separation of multipaths and the recorded sound level.

Logistical challenges, time, and the cost of towed net surveys make it difficult to measure secondary biomass and biological production in the open ocean outside the summer sampling season. Results from our calibration study show that the acoustic backscatter data from a single-frequency (150 kHz) acoustic Doppler current profiler mounted near the opening of the towed net system accounts for 84% of the variance in total net biomass, despite the remarkable mix of faunal types, depth range, and broad spatial and temporal extent of the study. The present findings demonstrate that profiling or moored acoustic backscatter instrumentation can provide a less challenging methodology than net tows for obtaining bulk estimates of deep-sea zooplankton biomass in the open waters of the northeast Pacific.

We are now using the data and calibration curve obtained during the first part of this study to work on other ADCP profile data and to focus on the zooplankton biomass in the upper 800 m of the water column. We are also using the high-resolution (1-s sampling) time series ADCP records obtained from the NEPTUNE Canada moorings to examine possible seasonal changes in vertical zooplankton migration between the axial valley and the upper ocean.

HABITAT MODELING OF MARINE MAMMALS AS FUNCTION OF OCEANOGRAPHIC CHARACTERISTICS: DEVELOPMENT OF PREDICTIVE TOOLS FOR ASSESSING AND MANAGING THE RISKS AND THE IMPACTS DUE TO SOUND EMISSIONS

Arianna Azzellino (PI), Caterina Lanfredi (PhD candidate)
POLITECNICO DI MILANO – DIIAR, Piazza Leonardo da Vinci, 32, 20133 Milano, Italy.
phone: (+39) 02-239-964-31 fax: (+39) 02-239-964-99 email: arianna.azzellino@polimi.it

Background

The effects of anthropogenic sound on marine mammals have receive considerable attention from scientists, regulators and industry. To manage the impact that acoustic energy may have on the marine mammals a quantification of the risks is needed. Since these species are so diffuse a critical step forward the developing of risk assessment tools is the understanding of their habitat requirements and preferences.

Avoidance of sensitive species' habitats is surely a straightforward mean of reducing the potential effects of underwater noise emissions. Some areas of high diversity and abundance are known, but the geographic distribution is poorly known for most species. An improved understanding of the species basic biology will advance the potential for predictive habitat modeling and may help managers and sound-producers in predicting which areas support high densities and should deserve a higher protection level. On this perspective, systematic surveys including oceanographic data (i.e. CTD measurements) can provide additional information to identify key habitat characteristics. Once determined the key habitat characteristics it is possible to manage the estimated risk through the establishment of a decisional framework allowing to choose between mitigations alternatives.

Objectives

Specific objectives of this study are: Objective 1: development of models to predict the environmental risk for the sensitive species integrating acoustic and visual data in marine mammal distribution/density models. Objective 2: The evaluation of the transferability of the developed models to areas different from the zone of calibration, and the assessment of behavioral differences of the same species inhabiting different areas. Objective 3: the definition of a knowledge-based decision support framework for managing the impact of the noise-producing human activities**.**

Methods

Several interdisciplinary sea trials were conducted in the western Mediterranean Sea mostly operated by NURC, the Nato Underwater Research Center, with the objective of improving the knowledge about cetaceans distribution Fig.1.

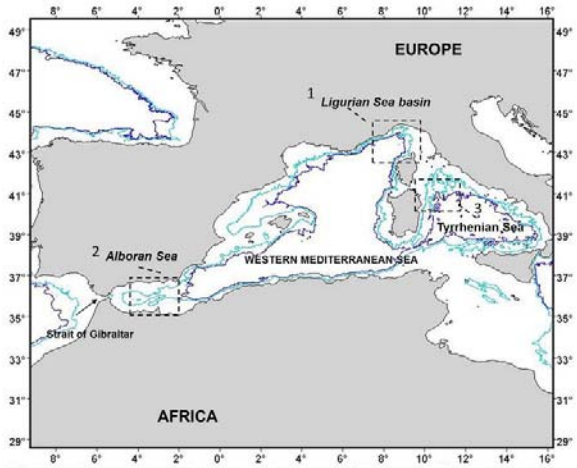


Figure 1. Mediterranean Sea study areas: 1. Northwestern Mediterranean Sea (Ligurian Sea Basin) and 2. Southwestern Mediterranean Sea (Alboran Sea) and 3. Central Mediterranean Sea (Tyrrhenian Sea). 1000 m (light blue lines) and 2000 m (blue lines) depth contours are shown.

Visual sightings, passive acoustic detections and environmental data (i.e. oceanographic measurements) were collected. Cetacean observations were made through big-eye vertical-scale binoculars while the ships were transiting at an average speed of 5–6 knots in good sea state conditions (i.e. Beaufort < 4). Passive acoustic data were collected through a broadband towed array of hydrophones. Oceanographic parameters such as temperature, salinity, sound velocity, dissolved oxygen, fluorescence and turbidity were measured as a function of depth using sensors installed on a CTD (Conductivity, Temperature, Depth) Rosette Frame, deployed from the research vessel. Regression exercises were run for the different study areas. Visual observations and passive acoustic detection were both used as cetaceans presence/absence indicators. Topographic predictors, remote sensed chlorophyll-a concentrations, and water column

statistics of oceanographic parameters, were all investigated as potential covariates.

Results

Cuvier's Beaked whale presence/absence modeling:

Static versus dynamic predictors

Being known as sensitive species, Cuvier's beaked whale was chosen as the main target species in the first modeling exercise[1]. The Ligurian sea dataset was used for the model calibration, whereas the Alboran sea dataset was used to evaluate the Ligurian sea models (Fig.1). The presence/absence classification performances of the models developed in the Ligurian Sea were evaluated using both dynamic (i.e. the remote sensed chlorophyll-a) and static predictors (i.e. sea bottom topographic features). The accuracy was found slightly lower when using the dynamic predictors with respect to the static predictors (i.e. 73% vs 87%). However, despite to the differences in accuracy, the two models showed a very good agreement in their predictions. A prediction map of presence and absence cells was produced *a priori* for the Alboran Sea area, based on the Ligurian sea models. Model accuracy was evaluated by overlaying the Cuvier's beaked whale observations collected in the field. To increase the evaluation data set, visual observations were integrated with acoustic detections. Model predictions, either based on bathymetry or on chlorophyll features, were found surprisingly comparable in both the study areas. Based on a priori predictions of this kind, risk maps could be drawn and used as knowledge-based support for minimizing the potential impacts induced by human activities at sea.

Dynamic predictors collected in the field

In this second modeling exercise the correlation between Cuvier's beaked whale presence/absence and oceanographic parametetes derived from measurements was analyzed for three key areas: the Genoa canyon area in the Ligurian Sea, the waters surrounding Alboran island in the Alboran Sea, and the Northwestern Tyrrhenian Sea (Fig.1)[2]. 39 water column statistics were computed for every measurement station. Principal Component Analysis was performed to reduce the set of variables. A stepwise logistic regression analysis was then applied. In all the study areas, the species presence was found significantly ($P < 0.05$) correlated with features of the dissolved oxygen (D.O.) profiles, although with different sign, and particularly with the depth (m) of maximum D.O. (Depth O_2 Max). All the models using Depth O_2 Max as predictor showed a good overall accuracy, (> 70%). The correlation with the predictor was inverse in the Alboran and in Tyrrhenian sea areas while it was direct in the Ligurian Sea area. This may suggests that Depth O_2 Max is a sort of tracer for water masses exchanges, the sign of the correlation being explained by the specific dynamic of the water masses involved (i.e. downwelling or upwelling phenomena). Both Alboran and sea Tyrrhenian sites are in fact characterized by upwelling phenomena, respectively topography- and wind-induced. On the other hand, the Genoa canyon area is characterized by a topography-induced downwelling phenomenon. This study suggests that such marine environments, with highly energetic hydrodynamic activity, might be areas of special ecological meaning for beaked whales.

Acoustic-based and visual-based data modeling

Visual and acoustic data collected during the research expediton MED-09 in the Tyrrhenian Sea area were employed in the third modeling exercise[3]. Depth and sea bottom slope were used as covariate of the cetacean occurrence through a stepwise logistic regression analysis. Finally the results obtained from acoustic-based and visual-based presence/absence data were compared. Significant correlations were outlined ($P < 0.05$) for all the species using both visual or acoustic data. All the models showed good fit, however visual-based models had higher accuracies, (60% to 89% vs 51% to 63%). Acoustic detections were proved effective for modeling cetacean presence/absence although further work need to be done to understand how to improve the accuracy of the acoustic-based models.

Notes: [1] Azzellino A., Lanfredi C., D'Amico A., Pavan G., Podestà M., Haun J. 2011. Risk mapping for sensitive species to underwater anthropogenic sound emissions: model development and validation in two Mediterranean areas. *Marine Pollution Bulletin,* 63: 56- 70.

[2] Lanfredi, C., Azzellino, A. , D'Amico, A., Ampolo Rella, M., Podestà, M., Pavan, G., Francia, C. Does dissolved oxygen play a role in Cuvier's beaked whale habitat selection? A comparison between three study areas in the western Mediterranean Sea. In Proceedings of 25th Annual Conference of the European Cetacean Society. Cadiz , Spain , 21-23 March 2011

[3] Podestà M., Lanfredi C., Azzellino, A. , D'Amico A. , Pavan G. , Francia, C. Comparison between visual-based and acoustic-based distribution models to predict cetaceans presence in the Northwestern Tyrrhenian Sea. Proceedings of 25th Annual Conference of the European Cetacean Society. Cadiz, Spain , 21-23 March 2011.

Day 2: Tuesday April 17, 2012

2012 ONR
Marine Mammal & Biology
Program Review

RIGHT WHALE DIVING AND FORAGING BEHAVIOR IN THE SOUTHWESTERN GULF OF MAINE

Mark F. Baumgartner
Woods Hole Oceanographic Institution
mbaumgartner@whoi.edu, 508-289-2678

Background

Mitigation of a variety of anthropogenic threats to endangered baleen whales depends on information about how the whales use the water column. For example, reducing ship strike risk requires an understanding of how much time whales spend at the surface, and mitigating fishing gear entanglements by ground lines requires an understanding of how often and why whales might dive near the bottom. Depending on the structure of the water column, exposure to acoustic sources can also depend strongly on diving behavior. For many baleen whales, data on diving behavior is not often observed concurrently with associated environmental conditions (e.g., oceanographic measurements, prey distribution), so inferring the causes of particular behaviors is typically not possible.

Research on the diving and foraging behavior of right whales can be immensely useful for understanding important biological oceanographic processes that occur high on the trophic ladder. Right whales sit atop a relatively simple food chain consisting only of phytoplankton, copepods, and whales. This system is a convenient model to study trophic interactions in the marine environment because both predator and prey can be monitored with available technologies (e.g., animal-mounted archival tags, video plankton recorder). Other top predators, such as odontocetes, billfish, tuna, or sharks, are much more difficult to study because of their varied diets and our inability to systematically assess the abundance, behavior, or even the life history of their prey. In contrast, North Atlantic right whales feed primarily on a single species of copepod, *Calanus finmarchicus*, which has been studied extensively, and whose abundance, distribution, and behavior can be rapidly assessed with instrumentation developed in the past two decades. Moreover, right whales have no known means to organize prey into manageable aggregations (unlike dolphins or humpback whales that herd fish); therefore, they are utterly dependent on the physical and biological oceanographic processes that aggregate prey into thin layers upon which they can efficiently feed. Within the context of this unusual system, it is possible to simultaneously investigate the processes that aggregate prey and the response of a predator to those processes. Thus, investigations of right whale foraging behavior can inform us about broad ecological interactions and feeding strategies that would be difficult if not impossible to study in other taxa.

Objectives

My long-term goal is to characterize baleen whale foraging behavior by studying diving behavior with respect to vertical/horizontal prey distribution, physical water column features (e.g., mixed layer, stratification, turbulence), and the acoustic environment. This approach will allow me to characterize not only where in the water column whales feed, but also where the prey are located, why the prey are organized as they are, and how the whales respond to variability in prey distribution.

The specific objectives of this project are to (1) characterize right whale diving and foraging behavior in a major springtime habitat, and (2) investigate the biological and physical oceanographic processes that promote the thin, aggregated layers of copepods upon which the whales feed. The current grant was awarded to support analysis of existing tagging data for publication in a peer-reviewed journal.

Methods

Suction-cup attached archival tags were deployed on right whales, and the tagged whales were closely tracked with the aid of a high-frequency acoustic transmitter incorporated in the tag. Upon resurfacing after each long dive, the whale's exact resurfacing position was relayed to an oceanographic vessel and the ship deployed a vertical profiling instrument package at this location. The instrument package collected vertical profiles of temperature, salinity, chlorophyll fluorescence, and zooplankton abundance and community composition using a conductivity-temperature-depth profiler, chlorophyll fluorometer, optical plankton counter, and video plankton recorder. The tag detached after 1-3 hours via a corrosive release

mechanism, and was subsequently recovered to access the dive data collected by the tag's time-depth recorder. From 2004-2010, we tagged 19 whales in the Great South Channel of the southwestern Gulf of Maine with attachment durations ranging from 45 minutes to 3 hours.

Results

As in previous studies in this and several other right whale habitats, we found that the zooplankton community near right whales was dominated by late-stage *Calanus finmarchicus*. We observed significant variability in diving behavior, including feeding at the surface (Figure 1a,b), mid-water (Figure 1c), and at the bottom (Figure 1d,e). Surface and near-surface feeding are commonly reported in the Great South Channel, so we were surprised to observe regular near-bottom feeding. We discovered highly concentrated near-bottom aggregations of *C. finmarchicus* (within 1-2 m of the bottom) that have never before been described in the Gulf of Maine. After observing bottom feeding in 2005, we modified our profiling instrument package to be capable of sampling *C. finmarchicus* within tens of centimeters of the sea floor.

During complementary studies of *C. finmarchicus* (Baumgartner et al. 2011), we observed considerable variability in the diel vertical migration (DVM) behavior of *C. finmarchicus*: sometimes DVM was quite strong such that most *C. finmarchicus* migrated to depth during the day and to the surface at night, whereas at other times, only a small portion of the population migrated while the majority of copepods remained at the surface during the day. We hypothesize that right whales faithfully track these changes in distribution, such that when DVM behavior is strong, near-bottom feeding during the day is prevalent, whereas when DVM behavior is weak, right whales can exploit daytime near surface concentrations of *C. finmarchicus*.

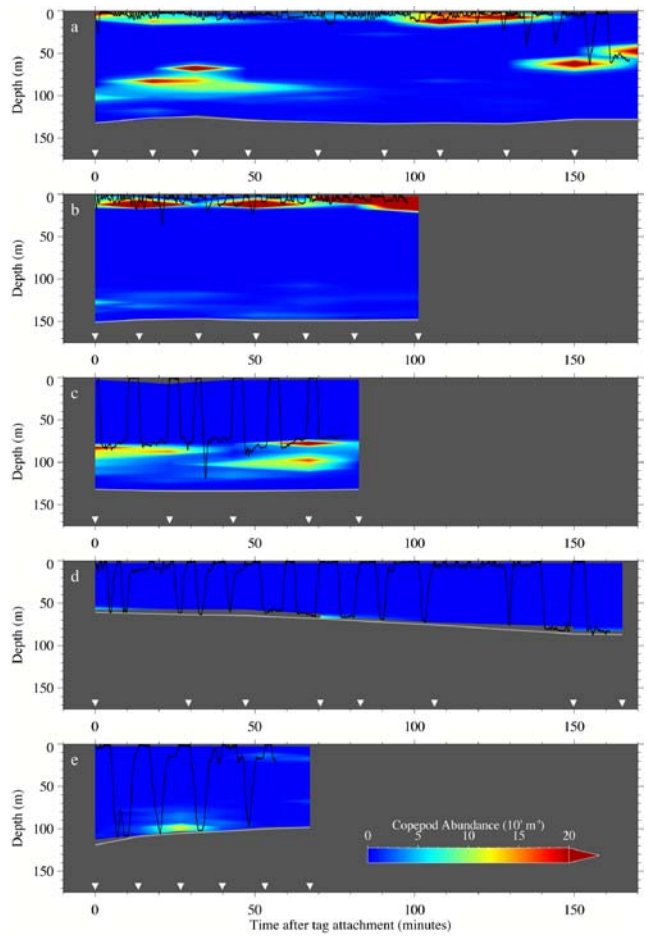


Figure 1. Examples of North Atlantic right whale diving and foraging observations in the southwestern Gulf of Maine from archival tags and collocated environmental sampling. Dive profiles of individual whales are shown as a black line, the sea floor is shown as a gray line, the abundance of copepods is shown in color, and the inverted triangles depict times when the profiles of copepod abundance, temperature, salinity, and chlorophyll fluorescence were collected.

IMPROVING ATTACHMENTS OF REMOTELY-DEPLOYED DORSAL FIN-MOUNTED TAGS: TISSUE STRUCTURE, HYDRODYNAMICS, IN SITU PERFORMANCE, AND TAGGED-ANIMAL FOLLOW-UP

Russel D. Andrews[1], Robin W. Baird[2], M. Bradley Hanson[3], Laurens E. Howle[4], Rajat Mittal[5], Gregory S. Schorr[2]

1: Alaska SeaLife Center and the University of Alaska Fairbanks; 2: Cascadia Research Collective; 3: Northwest Fisheries Science Center, NOAA; 4: BelleQuant Engineering; 5: Cartesian Flow Solutions, Inc;
email: russa@alaskasealife.edu; phone: (907) 224-6344

Background

Understanding the potential for impacts of naval activities on protected species of marine mammals, as well as estimating the number of individuals potentially impacted, requires information on movements and habitat use. We recently developed small satellite-linked telemetry tags that are anchored with small attachment darts to the dorsal fins of small- and medium-sized cetaceans. These Low Impact Minimally-Percutaneous External-electronics Transmitter (LIMPET) tags have opened up the potential to monitor the movements of numerous species not previously accessible because they were too large or difficult to capture safely, but too small for tags that implant deeply within the body. Our goal is to improve our existing tagging methodology to achieve longer, less variable attachment durations by carefully examining the factors that affect attachment success. We aim to develop a method for attaching tags to cetaceans that provides the data needed to answer critical conservation and management questions without an adverse effect on the tagged animal. Therefore, we are also conducting follow-up studies of LIMPET tagged whales to accurately quantify wound healing and the effects of tagging on whale survival, reproduction, and behavior.

Objectives

1. Design an improved tag shape for remote-deployment by assessing the hydrodynamic properties of various designs
2. Examine tissue structure and material properties of dorsal fins from multiple species for better informed implanted attachment design
3. Examine the in-situ performance of our current attachment devices and then design and test improved retention systems
4. Conduct follow-up studies of tagged whales to accurately quantify wound healing and the effects of tagging on whale survival, reproduction, and behavior

Methods and Results

Computational fluid dynamics (CFD) modeling was conducted to understand the effect of tag shape, orientation relative to flow, and location on the fin on hydrodynamics forces. Initial work focused on drag but our hypothesis is that lift forces might also play an important role in tag detachment. A sequence of 3D, unsteady direct numerical simulations were carried out for two different tag designs (old AM-240A and new AM-240C; Wildlife Computers model #'s) The simulations employed an immersed boundary solver that allowed us to simulate flow past complex boundaries on fixed Cartesian grids. The simulation, being 3D and unsteady, requires super computing resources and we employed large-scale parallel computers. Given that the typical sequence of tag migration and eventual detachment involves an increase in the gap between the tag and the epidermal surface as well as an upward tilting of the leading edge of the tag, we used CFD simulations to examine the effect of both these features on the hydrodynamic forces. Our hypothesis that lift forces are important in producing a pulling force on the tag has been confirmed by these simulations with lift forces exceeding drag forces in many configurations. Thus, reduction of lift forces needs to be an important factor in the hydrodynamic design of these tags.

Water tunnel experiments measuring lift, drag, and side force were gathered in the closed-circuit water tunnel at the US Naval Academy. Flow speed was varied from 2.2 m/s - 12.7 m/s and tag orientations were varied from 20 to 90 degrees. Lift, drag, and side-force measurements were compared for 3 tag configurations: the old AM-240A tag and the new AM-240C tag with and without drag-reducing dimples. In many orientations, lift force was comparable or greater than drag, confirming CFD results. At an orientation of 0 deg, the old-style tag produced lower forces than the new designs. The old tag generated lower lift than the new tags at all orientations at all angles. At flow angles > 30 deg, the old-style tag generated

significantly more drag and side force than the newer tag designs. Overall, the new tag designs outperformed the old tag design over the majority of the parameter space. Lessons learned are being applied to a tag redesign

Dorsal fins from 4 species, short-finned pilot, Bryde's, Cuvier's beaked, & melon-headed whale, were examined to assess geometry and collagen composition of primary structural layers. Percent composition of sub-papillary, vertical or ligamentous sheath, and central core layers was measured by image analysis of histological slides from horizontal cross sections. Ligamentous sheath always comprised a higher percentage of collagen than central core, ranging from 91% in pilot whales to 77% in melon-headed whales. Inter-species variability was greater for the central core, with pilot whale at 77% collagen but Cuvier's beaked whale at only 29%, with the other 2 species at ~ 50%. Material properties of central core and ligamentous sheath were measured with a uniaxial tester on samples excised from various orientations. Stress/strain curves showed similar post-transitional phase performance for ligamentous sheath in all species except Cuvier's, which exhibited lower strength. Additional work is underway to examine the anomalously high strength of the melon headed and Cuvier's beaked whale central core relative to their low collagen density.

Tag deployments on 4 species (short-finned pilot, killer, false killer, and fin whale) were used to assess transmission duration as a function of several factors, e.g. tag version, location on fin, flushness of attachment, age/sex class, dart type, and range deployed. Tags deployed in the mid-fin area transmitted longer on average, but no other factors stood out as significant predictors of transmission duration. A new biopsy tip, designed to collect dorsal fin tissue samples for histological assessment of tag implant sites was developed. Field testing proved that remote collection of dorsal fin tissue is possible and several samples were collected, although no samples from previously tagged whales have yet been collected. Wound healing assessment is being undertaken by examination of high resolution photographs of tag attachment sites and FLIR imaging of dorsal fins before and after tag loss. Preliminary FLIR results confirm that LIMPET tagging does not compromise the ability of the fin vasculature to radiate heat.

Follow-up studies of survival and reproduction of previously tagged whales were undertaken with 6 species of resident odontocetes in Hawaii. Field work was undertaken off the island of Hawaii in 2011 and off Kauai in 2011 and 2012, involving deployment of additional tags and photo-ID efforts of all species previously tagged. Photos (> 80,000) were compared to long-term photo-ID catalogs maintained by Cascadia Research Collective and provided re-sightings of previously tagged animals of all 6 species. Analyses of re-sighting rates for short-finned pilot and false killer whales took into account long-term social groupings. Thirty of the 38 short-finned pilot whales tagged off the island of Hawaii prior to Oct. 2011 have been re-sighted. We have not yet re-encountered the social groups of the remaining 8 whales. For false killer whales, 18 tags have been deployed on 16 individuals from 1 social cluster. Of those, all individuals have been re-sighted with re-sightings post-tagging for 17 of the 18 tag deployments. Such high re-sighting rates suggest that LIMPET tagging has little or no effect on survival for several years post-tagging. Assessing reproduction for females post-tagging is limited by small sample sizes, long inter-calf intervals, and unknown sex of some individuals, but both Cuvier's and Blainville's beaked whales have been documented with calves born after tagging.

Notes:

TOOLS TO COMPARE DIVING-ANIMAL KINEMATICS WITH ACOUSTIC BEHAVIOR AND EXOPOSURE

William C. Burgess[1] and Colin Ware[2]
[1]*Greeneridge Sciences, Inc. DBA Acoustimetrics*
burgess@greeneridge.com (831) 335-9600
[2]*Center for Coastal and Ocean Mapping, University of New Hampshire*
cware@ccom.edu (603) 862-1138

Background

Intense international concern has arisen over the potential effects of anthropogenic sound on protected marine wildlife. To study this issue presents a challenge, however, because most wild marine species spend the majority of their time submerged and out of sight of researchers. Thus instrumentation to monitor the behavior and sound exposure of wild, free-ranging marine animals is essential.

Broadband acoustic recording tags offer a promising avenue for studying the relationship between behavior and sound exposure for free-ranging animals. Since 1995, when the first combined broadband-acoustic and behavior recorders were deployed with northern elephant seals, such tags – predominantly the DTAG, the Bioacoustic Probe, and the Acousonde (Figure 1) – have seen extensive use in the study of whales and seals. These studies have generated dramatic quantities of acoustic, depth, and orientation data, and as such tags become increasingly available the amount of data will continue to grow. An increase in available raw data will not, however, support commensurate increase of understanding unless the wider research community is equipped with adequate tools to process and interpret those data. Kinematic data in particular require complex transformation and visualization by custom software such as TrackPlot (Figure 2) before they can be interpreted in terms of behavior.

Objectives

Under this effort, Greeneridge Sciences (the Acousonde) and the University of New Hampshire (TrackPlot) improved their respective tools in concert for smoother transition of these tools to the wider bioacoustic community. The primary objective was to increase the community's ability to acquire useful kinematic data from bioacoustic recording tags applied with a wide variety of species and environments. The effort centered on four tasks: (1) evaluation and improvement of Acousonde sensor hardware and calibration procedures; (2) broad improvements to TrackPlot, including the capability to import data from the Acousonde and to display acoustic as well as kinematic data; (3) "ground truth" experiments with a captive to assess Acousonde and TrackPlot performance; and (4) evaluation of the Acousonde and TrackPlot with a wild animal.

Results

Early in the effort, an Acousonde was provided for PI Ware's permanent custody. Working with this unit allowed Ware to confirm that both magnetometer and accelerometer produce high quality data, while noting offset and polarity concerns with the magnetometer. Further evaluation suggested that Acousonde kinematic axes should conform with the "North, East, Down" (NED) convention common among aircraft and underwater vehicles. These improvements were implemented in subsequent releases of the Acousonde firmware. Ware then developed and documented a calibration process to be performed by users at field sites.

Figure 1. First deployment of the Acousonde 3B, on a pantropical spotted dolphin in Hawaii. NMFS Permit 731-1774.

In May 2011, the new Acousonde 3B – redesigned for consistent kinematic self-orientation as well as for longer deployments

and reduced noise – was tested at sea in collaboration with ONR-supported investigators Robin Baird (Cascadia Research) and Erin Oleson (NMFS). The test took place with a pantropical spotted dolphin, a small odontocete species known for locational affinity with tuna and consequent fishing-boat interactions. As shown in Figure 1 the Acousonde self-oriented within 84 seconds of attachment. Visual contact over the next 3 hours 21 minutes confirmed that its position and orientation remained stable afterwards (the unit detached after 12 hours 18 minutes on the subject). The ability to self-orient and remain stable supports repeatability in kinematic studies without requiring modeling of package orientation for each deployment. Acoustic recordings documented frequent presence of fishing vessels and the onset of subject echolocation behavior in the evening.

Captive tests were planned in 2011 with beluga at the Vancouver Aquarium. During training, however, Aquarium personnel found that the Acousonde 3B's suction-cup design did not hold well on the subject. We now plan captive tests with a harbor seal at UC Santa Cruz.

Significant improvements in TrackPlot optimized its use with bioacoustic-tag data, not only from the Acousonde but from the DTAG as well. These improvements included: (1) a method to construct georeferenced pseudo-tracks from raw data, using a straightforward graphical interface; (2) integration of acoustic data handling, including the ability not only to read acoustic files and display spectrograms referenced to track locations but also to filter acoustic data, for example to provide estimates of speed from flow noise; (3) integrated dive statistics and plotting capabilities; (4) automated kinematic feature finding, used for example to identify feeding lunges; and (5) support for simultaneous analysis of two tracks, used for interpretation of mother-calf interaction. These features have been field tested in an extensive Antarctic (Ware et al., 2011) cruise using data from tagged humpbacks, as well as with data from pilot whales, blue whales, Florida manatees, elephant seals and Mediterranean beaked whales.

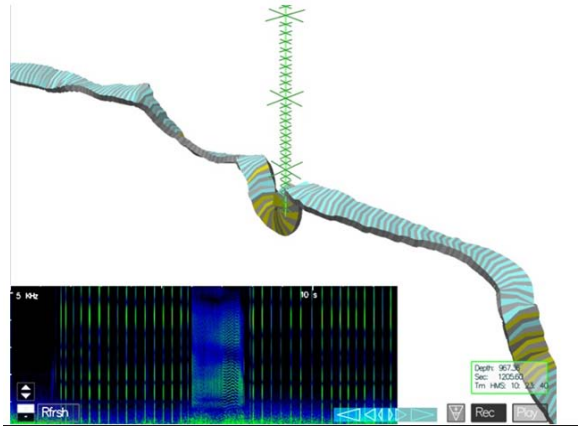


Figure 2. TrackPlot image showing foraging patterns of a beaked whale at 967-m depth. The acoustic spectrogram shows clicks and buzzes. Data courtesy of Brandon Southall.

The user base of both the Acousonde and TrackPlot continues to expand. Five groups have applied the Acousonde as a wildlife tag, including Cascadia Research, the University of Alaska Fairbanks (UAF), the French *Centre National de la Recherche Scientifique* (CNRS), and two separate PIs at Scripps. TrackPlot is being used by researchers at Duke, SBNMS, Penn State, and UAF; preliminary work has been done with several other researchers.

Ware, C., Friedlaender, A.S., Nowacek, D.P. (2011) Shallow and Deep Lunge Feeding of Humpback Whales in Fjords of the West Antarctic Peninsula. Marine Mammal Science. 227(3) 587-605.

Notes:

IMPROVED SATELLITE-MONITORED RADIO TAGS FOR LARGE WHALES: DEPENDABLE ARGOS LOCATION-ONLY TAGS AND A GPS-LINKED ARGOS TO REVEAL 3-DIMENSIONAL BODY ORIENTATION AND SURFACE MOVEMENTs

Bruce R. Mate
Oregon State University, Marine Mammal Institute
bruce.mate@oregonstate.edu 541-867-0202

Background

Long-term tag technologies are needed to document the seasonal distributions and migrations of large whales, as well as their site fidelity, underwater behavior and foraging efforts, which may be affected by anthropogenic activities.

Objectives

1) Create and test inexpensive modern location-only (L-O) tags capable of using different attachments. 2) Add 3-axis accelerometers to GPS-/TDR tags to describe the underwater foraging behavior and site fidelity of large whales for >1 month. 3) Evaluate tag wound healing.

Methods

Working with manufacturer Wildlife Computers, we developed 2- and 3-battery versions of a L-O tag that allow the use of different attachments. L-O spot-5 tags were epoxy cast in a stainless sleeve with a half inch-long stud at the distal end, to which various attachments could be used. To conserve ONR funds, tags were field tested on gray and sperm whales with funds from ExxonMobil, IUCN, IWC, JIP & SEIC, who were interested in the resulting whale data.

We tagged 18 Pacific Coast Foraging Group (PCFG) gray whales with L-O tags (9 with a 2--cell version and 9 with a 3-cell version). The tags were photographed for up to 20 months so a panel of 7 marine mammal veterinarians could evaluate potential tag effects. In 2011, we deployed 4 long version (3-battery) tags on sperm whales in the Gulf of Mexico.

Working again with Wildlife Computers, 3-axis accelerometers were added to JIP-funded semi-implantable Mark 10 GPS/TDR tags, designed to eject from the whale at the end of the experiment so recovered pitch, roll, and yaw data could evaluate lunges (foraging effort). Eleven such tags were applied to sperm whales during a 2011 NRDA-funded study following up on the DWH oil spill in the Gulf of Mexico.

Results

The application of on PCFG gray whales determined the 1.5" longer version lasted twice as long, possibly due to the attachments being deployed below the tough fascia between the blubber and muscle layers. Average attachment was 123 days using 1/4-in. wide stainless steel "petals". Eight whales departed on the winter migration to Mexico and only one stopped briefly at San Miguel Island en route to Laguna Ojo de Liebre (Scammon's Lagoon). The 6 whales arrived in three separate groups that did not overlap during their 21-22d stay, before starting their northbound migration. This duration and turn-over have not been previously un-documented and means the population cannot be estimated from counts on the reproductive grounds because the entire population is never present at the same time. Migration speeds north and south were consistent between indi-viduals.

This is the first documentation of the round-trip migration of gray whales. Three whales migrated back into the PCFG area, with one going up to Icy Bay, AK for a period of 6 weeks before coming south into British Columbia. One apparently healthy adult male was tracked for 383d and did not migrate, spending its time off northern California and southern Oregon.

L-O tags were applied to 7 western gray whales (WGW) off Sakhalin Island Russia in 2010 and 2011. Three WGWs were tracked to the eastern North Pacific. One tag on a WGW, Varvara, is still transmitting after 201d and has documented the longest migration (10,880 km) of any mammal as it also visited all the known eastern gray whale breeding areas (Fig. 1). These results suggest reconsideration of the WGW's status as the second most critically endangered large whale. At a minimum, WGW numbers are even less than previously thought.

One sperm whale L-O tag is still transmitting at 219d and they have so far averaged 148d.GPS/TDR tags with 3-axis accelerometers were applied to 11 sperm whales during a 2011

NRDA-funded sperm whale project, following up on the Gulf of Mexico DWH oil spill. We recovered 60-70% of the durations and maximum dive depths from all of the tags via satellite while the tags were still attached (for up to 45 days). The tags were designed to come off the whales after a programmed period, but none of them did. Most tags were shed from the whale while still in their attachment sleeve and sank to the sea floor. One tag later detached and was recovered. From it, we determined that a programming error at the manufacturer limited the electrical corrosion of the attachment wire to 9 hours, which was inadequate to separating the tag from its holder. The recovered tag demonstrated lunges occurring primarily during the deepest portion of the dives, which have previously been associated with acoustic "creaks" and foraging efforts during D-tag applications (Fig. 2).

With other funding, device to measure the resistance of skin, muscle, and blubber has been developed and simulated materials have been prepared to test tag attachment designs.

Notes:

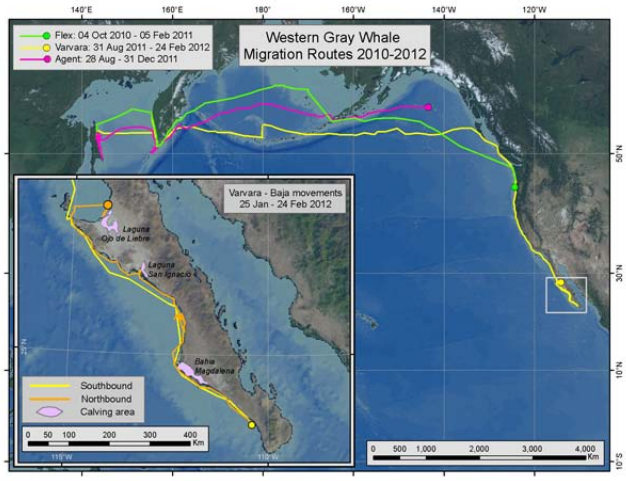


Figure 1. The winter migrations of three western North Pacific gray whales into the usual breeding range of eastern gray whales.

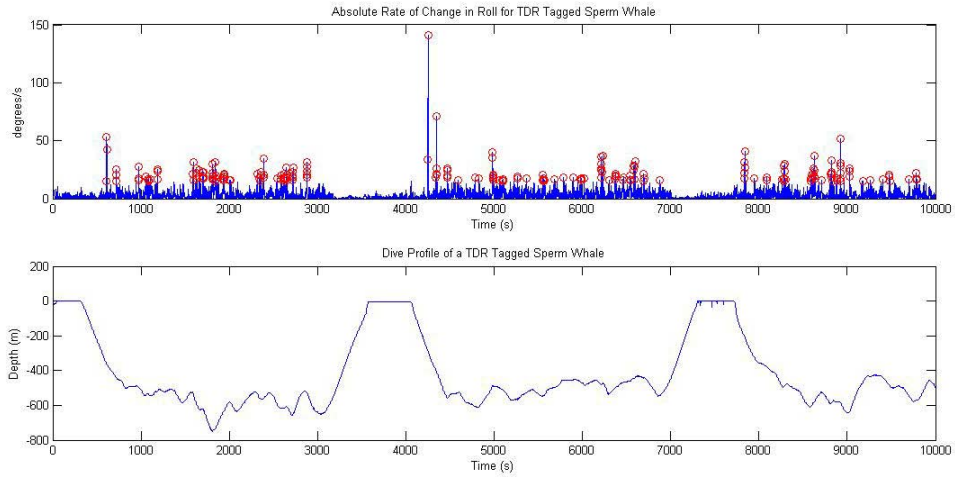


Figure 2. Satellite-monitored sperm whale dive (lower) from a GPS/TDR and 3-axis accelerometer tag showing lunges (upper).

DEVELOPMENT OF A PEDUNCLE BELT AS A MEDIUM TERM TO LONG-TERM TAG ATTACHMENT PLATFORM FOR CETACEAN STUDIES

Becky Woodward, Jeremy Winn, & Michael Moore
University of Maine
becky.woodward@maine.edu, (406)-529-3852

Background

A recoverable medium to long-term tag attachment platform would enable detailed data sets to be collected over extended time periods (multiple days to multiple months) and would aid in understanding natural whale behaviors and assessing anthropogenic impacts on vulnerable populations. Long term studies of terrestrial animals often use a collar around the neck to attach an electronic tracking package. A similar principle can be applied to cetaceans. Although whales lack a neck in the traditional sense, the aft taper of the body through the peduncle generates a “necked” region just before the fluke insertion which is suitable for a “collared” tag attachment.

Objectives

- To develop a peduncle style tag and tag deployment system as a means of attaching medium to long-term tags to free swimming whales. Two different systems are currently under development:

1) a net gun deployed towed telemetry buoy for large whales
2) a pole deployed peduncle saddle pack tag for small whales

Methods

Net gun deployed peduncle tag for large whales

A net gun mounted on the bow of a 17 ft runabout has been designed to remotely deploy a padded harness around the tail stock of a whale as it raises its flukes on a terminal dive. The regular net typically used with the net gun has been replaced with a custom designed 10 ft x 15 ft open rectangular lasso with a trailing line running back to the tagging boat. Half pound cylindrical weights are attached to each of the lasso’s four corners and loaded into the four barrels of the gun using an o-ring seal. The net gun uses a blank .308 cartridge to propel the weights out of its four barrels, and the splay of the gun barrels ensures that the corners of the lasso are widely spread to fully deploy the loop. Once the lasso clears the fluke tips, a spring powered retraction device starts the cinching process. As the loop closes, a custom designed carabiner clips onto the eye ring of the lasso, latching the 10 ft padded harness closed into a loose loop around the peduncle. Continued pressure on the trailing line to the boat triggers a lightweight breakaway on the carabiner, releasing the weighted lasso line from the whale and leaving only the padded harness encircling the peduncle. This peduncle attachment can be used with two different tag configurations: 1) a towed telemetry buoy and 2) a “charm” tag. In the towed buoy configuration, a hydrodynamic, torpedo shaped buoy houses a satellite/GPS unit and trails behind the whale. In the charm tag configuration, the tow tether is shortened such that the electronics package is integrated directly into the harness. Multiple redundant release systems (electronic timed release, galvanic timed release, and breakaway link) are incorporated in the harness to ensure that the harness releases from the whale allowing the whale to go gear-free should a problem arise.

Pole deployed peduncle tag for small whales

For small whales, two different prototype peduncle tags were developed: 1) a form-fitting, hydrodynamically fared, semi-rigid saddle pack tag that sits on the dorsal ridge of the peduncle just before the fluke insertion, and 2) a loose belt “charm” tag similar to the large whale system. The saddle pack tag incorporates a gullet space over the dorsal ridge and "bars" to distribute the weight and pressure of the saddle pack onto the sides of the peduncle rather than the dorsal ridge itself. The fore and aft portions of the gullet are also slightly rockered to give even more room for the body to flex without the dorsal ridge coming in contact with the saddle. To provide protection against chafe, the underside of the saddle and the girth are lined with ultra-soft, shear-resistant padding. A small lower saddle unit is also used to protect the ventral ridge of the peduncle. The loose belt configuration was developed as an alternative to the fitted saddle. In this case, the belt consists of a loose strap of webbing encased in a gel sleeve. A short tether connects the tag electronics to the harness. The small whale systems use a hand pole with a pneumatically powered armature for tag deployment. Once triggered, the armature’s sickle shaped arms close, latching a buckle

around the caudal terminus of the whale. As with the large whale system, an electronic timed release combined with a backup corrosive galvanic release and a break-away link form a redundant release system for reliably removing the harness and tag system at a pre-set time or in the event that the harness becomes fouled on any gear or other debris in the water.

Results

Net gun deployed large whale peduncle tag

Initial field trials of the large whale peduncle belt system were conducted on humpback whales in the Bay of Fundy, Canada. Over a 3 year period (2009-2011) the net gun deployment system was iteratively refined and tested to improve its efficacy as a tag deployment device. Effective whale approach techniques were developed, and an optimal lasso size was determined. An active retraction system was also integrated to help cinch the lasso closed once the line encircled the tail. In 2011, 4 out of 5 lasso attempts (80%) successfully looped the tail.

Figure 3. Net gun deployed lasso looping the tail of a fluking humpback.

However, problems with the retraction system (tangling; misfire) and the breakaway link prematurely engaging prevented any successful tag deployments last year. Further refinement of the retractor system and streamlining of the lasso to eliminate potential tangle points will improve tag deployment success rates. Overall, the field trials suggest the net gun shows excellent potential as a tag deployment device for free swimming large whales with a few minor modifications to the current system.

Pole deployed peduncle tag for small whales

Prototype small whale peduncle tags were tested on a beluga whale at Mystic Aquarium and a false killer whale at the Hawaii Institute of Marine Biology. The testing revealed that the peduncle belt works well in a captive setting for short durations of high activity on multiple species with extremely varying skin types. Different tag configurations (loose belt versus saddle pack) are better suited to a species depending on the whale's typical swim behaviors (fast or slow) and their skin and peduncle morphology. The beluga peduncle morphology offers a wider and taller surface area with thicker and tougher skin. With their slower swim behaviors and softer, more spongy tissue consistency, their morphology and behaviors allow them to accommodate either the more rigid saddle pack tag or the loose belt configurations.

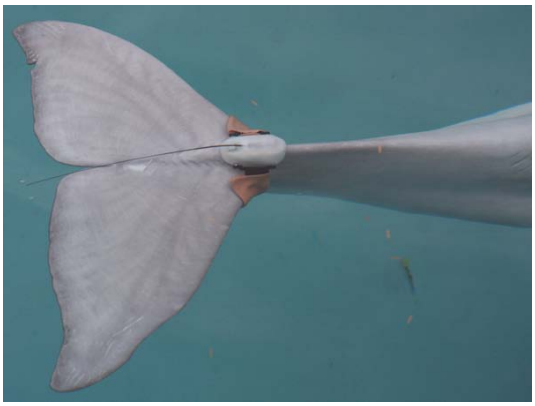


Figure 4. Prototype saddle pack peduncle tag on a beluga whale.

On the other hand, the quicker, more aggressive tail movements of the false killer whale coupled with their thinner skin and stiffer peduncle tissues tend to concentrate the forces of the snug belt at the peduncle fluke juncture leading to chafing issues. The soft and spongy beluga tissues themselves tend to act as an absorption mechanism for friction and shear whereas the harder tissues of the false killer whale do not. For this reason, the loose belt presents a better option for the faster moving, thinner skinned species such as the false killer whale and bottlenose dolphin. Additional tests are necessary to look at the effects of the tag over increasing deployment durations.

DEVELOPMENT OF A PNEUMATIC LAUNCHER DELIVERY SYSTEM FOR THE NEW DIGITAL RECORDING TAG, DTAG3

Lars Kleivane[1], Alessandro Bocconcelli [2], Peter Tyack[2], Petter H.Kvadsheim[1]
[1] Norwegian Defence Research Establishment - FFI, Horten, Norway
[2]Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA
abocconcelli@whoi.edu, 508-289-2319, Lars.Kleivane@ffi.no, 4734033886,
ptyack@whoi.edu, 508-289-2818, Petter-Helgevold.Kvadsheim@ffi.no,4795138992

Background

This proposal responds to ONR's Marine Mammals & Biology Program interests in sensing and tag development. A new version of the WHOI digital recording tag, DTAG3, is now available, and it will replace the DTAG2 currently in use, which has become harder to use due to difficulties in finding replacement parts and components. The DTAG3 is a smaller and lighter package with four small suction cups. The new body has a low profile and reduced drag. This latest version of the DTAG3 includes a larger memory (32/64GB vs. 16GB in DTAG2) which will allow longer deployment depending on the sampling rate. The DTAGs are typically deployed on large whales using a 10-12m cantilevered pole mounted on the bow of an inflatable boat. This technique works well with large whales, but mid-sized cetaceans tend to be quicker and more maneuverable than their larger cousins. The current heavy cantilevered pole system is too slow and restricted in its movements to allow tagging of these smaller and less predictable animals. Researchers often use hand poles for these species, but such hand poles have a very limited range, requiring the boat to approach within 5m of the animal to place the tag. While this works with some of the bow-riding and curious species, or slower moving species, tagging efforts on other more shy and elusive species such as beaked whales, minke whales, killer whales, etc. have met with more limited success. One option to improve tag attachments on faster moving animals is to attach the DTAG package with a pneumatic launcher. LKARTS (a private company run by Lars Kleivane) and Restech-Norway have modified a pneumatic rescue line launcher into to an Aerial Rocket Tag System (ARTS). This pneumatic launcher has been successfully used to deploy implantable satellite tags for a number of large scale whale migration studies. WHOI ,FFI, and LKARTS, have conducted preliminary tests using the ARTS to launch a dummy DTAG2. The DTAG dummy was launched on a dummy whale target using the ARTS at different ranges and different pressures. The G-force upon launching and impact were measured and compared to the G-forces on the tag during pole tagging. These tests suggest that 8 bars of air pressure allows the system to launch the DTAG package with a 20 cm accuracy up to a distance of 10m while maintaining impact forces similar to those experienced during pole deployment. The ARTS system was tested at sea during the 3S-09 cruise on pilot whales, sperm whales, and killer whales. It has proven to be a very valuable delivery system for the DTAG, especially for fast moving animals such as killer whales, which are usually approached at speeds of 6 knots or more. Further work was carried out in 2010 with funding from ONR. Modified ARTS carriers with shock absorbers were designed and built at WHOI and LKARTS and tested at the FFI facility in Horten, Norway. Also, new thicker fairings where built to provide better protection to the DTAG. Some modifications were also made to the ARTS launcher to facilitate aim and pressure regulations (Kleivane et al, 2011).

Objectives

The objective of the project is to implement a reliable attachment system to deploy non-intrusive sensors and tags on marine mammals. This system will increase the efficiency and duration of deployments of the new suction cup DTAG3, used to study baseline behavior of marine mammals and for behavioral response studies of cetaceans to naval sonar signals. We have completed a series of laboratory and field tests under current ONR funding. A reliable ARTS-DTAG3 system has been built to deliver DTAG3 without damaging the tag or the sensors and without adverse reactions from the tagged animals. A newly adapted light weight shock absorbing ARTS-DTAG3 robot arm needs to be designed, built and tested before being used in tagging projects beginning in summer 2012.

Methods

The DTAG3 was tested extensively during the Cape Hatteras project in 2011. The DTAG3 system worked very well on pilot whales but it was not successful on small delphinids. More

field testing was carried out with small modifications to the DTAG body during the SOCAL experiment and during the MED11-Alboran Sea project. At the same time indoor testing was carried out by Lars Kleivane with dummy targets and different versions of ARTS robot arms and carriers, and field testing was done during the 3S2 cruise in June 2011.

After the 2011 field season we evaluated the results and experiences in various projects with different kinds of marine mammals as target species and we decided to redesign the DTAG3 body and the robot arm. The input from the taggers and PIs of the different field tests was very valuable in this process. The DTAG3 was reinforced in the weak areas around the suction cup connection to the main body, the suction cups were completely redesigned to make them stronger and less flexible (and less prone to shear off from the tag under high stress) and a different material was used to build them. The DTAG was also modified in order to reduce the drag and the lift force that caused premature detachment on fast swimming animals. The robot arm was also redesigned in order to offer better holding force and also a “clean” release of the tag once placed on the targeted animal. It is very important to be able to equally distribute the holding force of the robot-arm on the tag in order to have the same force on the 4 suction cups in the very quick and extremely critical placement phase of the tagging operation. An improperly placed tag due to a poorly designed robot arm will release much earlier from the animal, resulting in loss of valuable data. The robot arm universal joint was kept the same but the holding saddle where the DTAG is placed was modified and rebuilt using a different material (delrin plastic vs. light aluminum plate). Two gripping flexible plates made of strong delrin plastic were placed on each side of the robot saddle to hold the DTAG in the right position and prevent early release during tagging or accidental release during boat transit due to sea motion and vibrations.

Results

Once the tag and the robot arm designs were finalized, Lars Kleivane was able to design and test a completely new ARTS robot and carrier for the latest version of DTAG3. The robot arm consists of a light plate made of aluminum and mechanical fittings on top of the plate to connect the robot arm assembly to the arrow shaft. On the bottom of this plate is the saddle, firmly holding the tag in position, and a system to absorb the extra impact energy. This system consists of three flexible stems (giraffe legs) made of soft rubber (adiprene) that can easily bend upon impact on the animal body, absorbing the extra energy delivered by the ARTS system. The tips of these stems are shaped in a way to prevent slippage on the wet skin of the animal, therefore keeping the DTAG in the desired place. The DTAG3 is held in place underneath the plate by two spring-loaded plates made of delrin plastic. The spring-loaded mechanism is mechanically connected to two shorter stems made of adiprene, also placed on the bottom part of the robot plate. Upon impact the two spring-loaded stems will open up and properly release the tag on the animal. The ARTS carrier (arrow) was also redesigned and rebuilt to accommodate the new weight and shape of the ARTS robot. The shaft is made of PVC and it is counterbalanced with adjustable weights to keep it flying on a straight trajectory once fired by the ARTS launcher. Three light plastic fletchings also help to keep flight stability during tag delivery. Typical pressure range for a target distance of 10 to 12 meters is 8 to 10 psi. The complete ARTS DTAG3 system will be field tested in early April 2012 in Vestfjorden, Norway and then during the 2012 3S2 cruise in the Svalbard islands, Norway. If these preliminary tests are successful, the DTAG3-ARTS system will be used for tagging beluga whales in Cook Inlet, Alaska and for tagging killer whales in the San Juan Islands, Washington.

Notes:

Kleivane, L., A. Bocconcelli, P.H. Kvadsheim and M. Pelletier. The Aerial Rocket Tag System (ARTS) for tagging marine mammals. The Society for Marine Mammology 19th Biennial Conference on the Biology of Marine Mammals, Tampa, Florida, 27 Nov.-2 Dec. 2011. Poster presentation.

Kleivane, L., A. Bocconcelli, P.H. Kvadsheim, M. Pelletier and P. Miller. The Aerial Rocket Tag System (ARTS) – A novel tool for tagging marine mammals. Effects of Sound in the Ocean on Marine Mammals (ESOMM) Conference, Amsterdam, The Netherlands, 5-9 Sept. 2011. Poster presentation.

BEHAVIORAL RESPONSE OF DOLPHINS AND SEA LIONS TO SIGNALS SIMULATING MID-FREQUENCY SONAR

Dorian S. Houser, Laura Yeates, Daniel. E. Crocker and James J. Finneran
U.S. Navy Marine Mammal Program, Space and Naval Warfare System Center Pacific, San Diego, CA
dorian.houser.ctr@navy.mil, 619-553-9058

Background

Major acoustic activities conducted by the Navy in the ocean must address potential impacts to marine mammals resulting from those actions in accordance with the National Environmental Policy Act (NEPA), the Marine Mammal Protection Act (MMPA), and the Endangered Species Act (ESA). A core issue with the determination of potential impacts is relating acoustic exposure levels to behavioral or physiological responses of marine mammals to the exposure.

Navy environmental impact analyses utilize a risk function to predict the probability of a significant behavioral response by a marine mammal as a function of its acoustic exposure level. The data used to create the form of current risk functions are open to contention and are potentially difficult to defend in litigation. Broader issues of whether behavioral responses are of biological significance are also debated. Because of the lack of consensus on this subject, physiological measures of stress, which can be related to energetic costs and altered behavior, are warranted.

The study described here addresses some issues related to current risk functions by assessing the behavioral response of dolphins and sea lions under controlled acoustic exposure conditions. *A priori* severity scoring of behavioral responses from a cross-section of marine mammalogists is used to provide an unbiased score of the response data. Heart rate and stress hormones are collected to address acute and prolonged stress responses to the sound exposure. Physiological and behavioral responses are investigated for correlations with increasing levels of sound exposure.

Objectives

The objectives of this effort are to:

1a) Determine the occurrence and magnitude of behavioral responses observed in bottlenose dolphins and sea lions exposed to variable levels of mid-frequency (~3 kHz) sounds similar to tactical sonar signals; 1b) apply a scoring analysis to the observed responses; and 1c) calculate delphinid and otariid risk functions.

2) Record heart rate on a subset of the subjects to determine whether an acute stress response occurs due to the sound exposure.

3) Collect blood samples from dolphins prior to, immediately following, and approximately one week following the sessions. Samples will be analyzed for cortisol, aldosterone, and epinephrine (i.e., stress hormones).

Methods

Thirty dolphins and 15 sea lions were trained to a nominal degree of performance on an “A to B” task. The subjects were cued by a trainer to leave a station (A), travel to another station (B) and touch a paddle, and then return to the original station (A) for a fixed fish reward; hereafter termed the ABA task. Subjects were trained on the task until there was a 100% completion percentage across a 10 trial block. Upon meeting the nominal performance criterion, the subjects performed a 10 trial control session followed by a 10 trial sound exposure session.

Control and exposure sessions were performed in a 30×60 ft floating pen with an underwater sound projector placed approximately 1 m behind station B. Each trial was limited to 30 s. The reward for completing each trial was a fixed number of fish equating to ~1% of the weight of the daily allotment of fish for each animal. For the control session, each subject performed 10 trials of the ABA task without acoustic exposure. A second session was then conducted during which the subject, on each trial, received an acoustic exposure at the midpoint along its trajectory to station B. Acoustic exposures consisted of a 0.5 s upward FM sweep (center frequency ~3250 Hz) followed by a 0.5 s CW (~3450 Hz). Subjects were naïve to the exposure and only one trial block was used for each subject.

Exposure sound pressure levels ranged from ~115 to 185 dB re: 1 μPa for tests involving

dolphins. This design permitted 5 individual dolphins to be tested at a set exposure level and the entire sample set to be tested across a range of exposure levels. The range of exposure levels and number of subjects per exposure level were reduced for sea lion tests to accommodate the smaller number of available animals.

Sessions were video recorded and intercom and underwater recordings were mixed down with the video recordings to obtain aligned acoustic and visual events. Audio/video files were used for post-session analysis of behavioral responses by participants that were not involved with data collection and blind to the acoustic exposure conditions.

Behavioral responses anticipated to occur were *a priori* scored for severity in order to avoid a potential bias in severity scoring after data collection. Alternative scoring methods were also attempted to account for the inadequacy of the group scoring approach to establish a graded severity scale. The multiple approaches were used to attempt the creation of an equation to predict the dose-response relationship between the received sound level and the severity and occurrence of behavioral reactions.

Blood samples were collected approximately one week prior, immediately following the exposure session, and approximately one week after testing. Samples were analyzed via radioimmunoassay to assess circulating levels of cortisol, aldosterone and epinephrine. Levels were compared between categories and related to exposure level to determine whether acute or chronic stress responses resulted from the exposure. In addition, a subset of the animals previously trained to wear a harness, wore an ECG system to record heart rate during sessions. Variations in heart rate were assessed for changes associated with the sound exposure.

Results

All dolphins and sea lions completed the test matrix. For both species, there was an increasing probability of abandonment of the ABA task with increasing level of sound exposure. At a received level of 185 dB, 100% of the dolphins abandoned the task. No physiological indicator of acute stress was observed in the animals in either the hormone panels or the heart rate measures.

A risk function analysis was attempted using all of the behavioral response categories and the composite severity scores determined from the *a priori* scoring of behaviors. Although there was similarity between scorers with respect to the ranking of severity, the absolute scores averaged out so there was relatively little distinction between most of the behavioral responses. Therefore, a canonical correlation analysis was performed to determine which independent and dependent factors best explained the observed exposure-response relationship. Using only statistically significant canonical variates and canonical loadings greater than 0.32, the factor space was reduced to five dependent variables in the dolphins and six dependent variables in the sea lions. The independent variables were reduced to two in the dolphins, but were unaffected in the sea lions. Utilizing a previously proposed scoring scheme (Southall et al. 2007), it was found that an asymmetric dose response function best fit the exposure-response relationship, not a sigmoidal function such as that currently in use by the United States Navy.

Notes:

BLUE WHALE BEHAVIORAL RESPONSE STUDY & FIELD TESTING OF THE NEW BIOACOUSTIC PROBE

Erin M. Oleson, John Calambokidis, Megan F. McKenna, Jeremy Goldbogen, John A. Hildebrand
Scripps Institution of Oceanography & NOAA Fisheries Pacific Islands Fisheries Science Center
erin.oleson@noaa.gov, 808-944-2172

Background

Our project is divided into two components: understanding the behavioral response of blue whales to ships and loud ship noise, and field-testing the new Acousonde acoustic recording tag. The behavioral response of large whales to commercial shipping and other low-frequency anthropogenic sound is not well understood. The PCAD model for assessing sound impacts on marine mammals calls for studies on sound source characteristics and the behavioral impact of specific sources on individual animals. Our goal is to understand the behavioral response of individual blue whales to high-intensity ship noise and close ship approach. Field trials of the Acousonde with several species of cetacean will help refine the operation of the tag and make it more for robust for future field operations.

Objectives

For the blue whale response study our objectives are the following:
(1) Determine if blue whales exposed to high-intensity ship noise or close ship approach change their calling or diving behavior
(2) Determine the form and duration of the response (cessation of feeding, etc)

Our primary goal in field testing the new Acousonde tag is to evaluate the functionality of the tag when used with odontocetes and to begin collection of vocal and diving behavior on a wide variety of odontocete species.

Methods

We evaluated the behavioral response of blue whales to intense ship noise and close ship approach using suction-cup attached acoustic recording tags and GPS Fastlock location tags. Field effort has been conducted for this project since 2008, with effort concentrated in the shipping lanes traversing the Santa Barbara Channel and into Long Beach Harbor, as well as near the Farallon Islands off of San Francisco.

Ship locations are monitored using a real-time AIS receiver installed aboard the tagging boat and from two shore stations. The shore stations provide the entirety of the ship approach through the broader region and spatial patterns in traffic. Once tagged, the tagged whale's position and surface behavior are monitored and the whale is photographed for individual ID. Position data from MK10 GPS tags are used to evaluate fine-scale movements of the animals within and near the shipping lanes over longer periods.

Acoustic data collected by the tag are analyzed to determine the presence and spectral characteristics of sounds produced by the whales and the ambient noise level prior to ship approach. Because of high levels of flow noise present in the acoustic tag records it is not always possible to measure the received sound level of the passing ship. During most behaviors the animal is swimming, therefore flow noise is usually high and broadband (150 dB and 0-1,000 Hz). For this reason some analyses are now based on ship proximity and speed, and with reference received levels measured for different ship types from seafloor recorders, rather than on the received level measured by the tag. Close approaches during quiet periods in the tag record do allow for direct measures of received level of the ship on occasion.

Dive depth and body orientation are measured by the sensors on the tag, and additional behavioral variables are derived from the auxiliary sensors, including acceleration, fluke rate, and feeding behavior. These behavioral measures are used to describe swimming mechanics, which may be used to derive energy expenditure.

Acousondes were placed on various cetacean species off Southern California and Hawaii in conjunction with ongoing survey and tagging efforts in those regions. Off Southern California, our efforts are coordinated with visual and acoustic surveys underway as part of the SoCal BRS and our ship strike work. Acoustic and dive data are analyzed as described above to assess the quality of the data collected by the new tag and to assess vocal and dive behavior of specific species.

Results

In four field seasons, we have completed 30 deployments of acoustic recording tags (BProbe, Acousonde, or DTag) on blue whales, as well as 38 deployments of the GPS MK10 location tag for evaluating animal movements. A type 3A Acousonde was delivered in summer of 2010 and was tested on blue whales off Southern California that year. In early 2011, the new streamlined form factor (3B) became available and two were made available for use during a number of field efforts for testing. Test deployments of the Acousonde 3A and 3B included one week of dedicated tagging effort off Kona, Hawaii in May, 2011, and opportunistic deployments on blue whales during our blue whale ship strike work in summer 2011.

We have collected acoustic and high-resolution tracks from four blue whales that were very closely (<200 m) approached by commercial ships within the shipping lanes. Analysis of these records suggests that the close approach does not elicit a strong reaction by the whales; however, the whales do appear to alter their surfacing behavior immediately following the close ship approach. We found a significant increase (>1 standard deviation from the mean of all dives) in the surface time and number of breaths. High-resolution tracks of MK10 tagged animals indicate that whales are foraging within the shipping lanes and remain in the area for at least several hours.

Four additional long term deployments, (>18 hours) with the MK10 GPS tags provided records of movements and behavior that when matched with ship AIS data allowed for evaluation whale reactions during close ship approach. For example, one deployment revealed 12 close approaches (<5km). These data suggest a threshold distance for response, where changes in whale behavior are observed only when the ship was less than 1 km.

In May, 2011, we conducted two deployments of the Acousonde on odontocetes off Kona, HI. The Acousonde 3A was deployed on an adult pilot whale, providing ~2 hours of acoustic data, including clicks and whistles produced by the whale. The Acousonde 3B was deployed on spotted dolphins, demonstrating the benefit of the smaller and more streamlined form-factor of the tag. This deployment is the longest known suction cup tag deployment on a spotted dolphin and occurred while the spotted dolphins were surrounded by 8 different fishing boats. The acoustic record of the tag includes not only the sounds of the tagged and nearby dolphins, but also the sounds of various fishing boats as they passed over the dolphin school.

Tagged blue whale during close ship-approach near the entrance of Long Beach Harbor

Notes:

CETACEANS AND NAVAL SONAR: BEHAVIOURAL RESPONSE AS A FUNCTION OF SONAR FREQUENCY

Patrick Miller
Sea Mammal Research Unit, Scottish Oceans Institute, U of St. Andrews, St Andrews, UK
Email: pm29@st-andrews.ac.uk phone: (44)-1334-463554

Background

The collaboration named "3S" was motivated to study effects of sonar by reports of possible killer whale reactions to sonar exercises in the Vestfjord basin of Norway (WWF-Norway, 2001). Such perceived responses to sonar have negatively impacted the public image of the Navies involved, and may have harmed the whale-watching industry. Unfortunately, data on the thresholds at which free-ranging cetaceans react to sonar are lacking, with only a few species having been studied in relation to a few types of sonar signals (Nowacek et al., 2007).

The scientific hypothesis that we are exploring under this award is whether hearing sensitivity at different sonar frequencies influences behavioral response threshold or severity. The term "sensation level" refers not to absolute intensity of a sound, but intensity relative to the hearing threshold for that sound for a given individual. While initial acoustic criteria proposed a rather flat correction for hearing sensitivity ('m-weighting'; Southall et al., 2008), recent data indicate that dolphin perception of loudness of sounds at different frequencies appears to follow the general shape of the hearing curve (Finneran et al., 2011). Some European navies are interested in comparing the possible effects of sonars at 2 different frequencies because many are acquiring frigates with 1-2 kHz sonar sources, lower in frequency than the 6-7 kHz sonars that have been common to date. The hearing curve of the killer whale indicates 20-30 dB lower sensitivity at 1-2 kHz than 6-7 kHz (Szymanski et al., 1999). Less is known about the hearing thresholds of long-finned pilot and sperm whales, but the typical U-shaped audiograms of odontocetes indicate greater sensitivity at 6-7 kHz than 1-2 kHz.

Objectives

- Collect detailed behavioral records of research subjects before, during, and after sonar exposures at 2 different frequencies (LFAS:1-2 kHz and MFAS:6-7 kHz), and relevant control sounds (silent vessel approach and orca sound playbacks). Monitoring and mitigation protocols reduce risk of harm to research subjects;
- Describe behavior during sonar exposures versus baseline and controls, and interpret the biological significance or severity of observed behavioral changes;
- Explore how response thresholds vary by sonar frequency.

Methods

We presented sonar signals in blocks at 2 frequencies (1-2 kHz and 6-7 kHz), and control sounds, to cetaceans while observing their behavior using Dtags, towed hydrophones, and visual observations. Each tagged animal was observed visually and acoustically from an observation vessel. Sonar exposure sessions started with a ramp-up to maximum source levels of 196-199dB for 6-7 kHz trials, and 209-214 dB for 1-2 kHz trials. The source vessel approached the position of the tagged whale at 8 knots while transmitting at a 20s duty cycle. The source level ramp-up and vessel approach achieved an *escalation* of the sonar dose throughout each exposure session. Each subject was exposed to multiple approaches, with the order of 1-2 kHz sonar, 6-7 kHz sonar, and silent approach blocks changed for each subject.

Behavior records were synchronized, and inspected and analyzed quantitatively to identify behavioral changes that could have been responses to the sonar exposure. The descriptive approach used expert interpretation of the data records by two independent teams and an adjudicator to interpret the vast range of different behavioral changes apparent in our data-set. The experts identified behavioral changes that were unusual compared to baseline observations, and therefore putative responses to the exposure, and judged their severity following the 0-9 point scale of Southall et al. (2008). Descriptive analysis of the full data set indicated that movement away from the vessel or path of the moving vessel was commonly observed. Quantitative break-point analysis of horizontal movement was conducted to identify unusual changes in movement during exposure conditions.

Behavioral change events identified by expert scoring or quantitative analysis were tallied, and the sonar received sound pressure level (SPL) at the onset of each behavioral change was determined. When avoidance was not detected in an exposure session, the threshold was considered to be uniformly likely between the maximum received level and 200 dB re 1μPa. Horizontal avoidance thresholds were fit to a Bayesian dose-response model, following established methods for Phase-I clinical trials in medicine (Simon et al., 1997), with the expected response threshold of each whale as:

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

where μ_i is the expected threshold for subject *i* in exposure session *j*. The β terms quantify the shift in threshold due to sonar frequency (MFAS vs LFAS) and exposure order. Mean thresholds and within- and between-animal variation computed by the model allow derivation of a population-level dose-response function.

Results

Three 4-week CEE trials were conducted in winter 2006 and summers of 2008 and 2009, during which a balanced data set was collected with 4 killer, 4 sperm, and 6 long-finned pilot whales during which 39 separate sonar or silent approaches were conducted (Miller et al., 2011).

Expert scoring indicated a large number of putative responses during exposures, with a suite of behavioral changes (e.g. diving, horizontal movement, and sound production) often being associated with single complex events. We found that the most severe behavioral change within a session was more likely to be 4 or greater (scale in Southall et al., 2008) during 1-2 kHz exposure sessions (15/18: 83%) than 6-7 kHz (8/14: 57%) or silent control (2/7: 29%) sessions (G-test: $p<0.05$). Post-hoc contrasts indicate that the 1-2 kHz vs 6-7 kHz contrast was not significant ($P=0.101$). More responses during 1-2 kHz exposures could have been a consequence of higher maximum received levels than during 6-7 kHz sessions.

Avoidance thresholds were lower and more variable for killer whales than long-finned pilot whales. Previous exposure (β_1) appeared to reduce avoidance thresholds in pilot whales, but not for killer whales. Sonar frequency (β_2) was estimated (mean ± s.d.) at -5.0 ± 9.2 dB and -5.7 ± 21.6 dB for killer and long-finned pilot whales, respectively. This indicates that thresholds were ~5-6 dB lower for 6-7 kHz than 1-2 kHz sessions, but the high variance of the estimate gives little confidence that sonar frequency had a consistent influence on avoidance thresholds.

Overall, these results indicate little consistent influence of sonar frequency on either the severity of behavioral changes or avoidance response thresholds in our experiments.

Notes:

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BEHAVIORAL RESPONSES OF ODONTOCETES TO PLAYBACK OF ANTHROPOGENIC AND NATURAL SOUNDS; 3S2 - BEHAVIORAL RESPONSE STUDIES OF CETACEANS TO NAVAL SONAR SIGNALS IN NORWEGIAN WATERS

Peter L. Tyack
Scottish Oceans Institute, University of St Andrews, East Sands, St Andrews, Fife, KY16 8LB, United Kingdom
email address: plt@st-andrews.ac.uk; phone number: +44 (0)1334 462630

Background

This project studies the effects of sound on marine life, part of the Behavioral Response Studies (BRS) thrust, which "strives to safely study responses of marine mammals to naval sources and other anthropogenic sounds to understand and characterize the causal chain of events leading from sound exposure to "biologically significant" behavioral reactions that might increase risks of stranding" (1) or have the potential to negatively affect vital rates. Recent interdisciplinary research efforts have focused on defining / characterizing behavioral effects of sound exposure on tagged whales and to measure the exposure required to elicit responses that are safe" (1) within the experiment but indicate potential for risk of real-world sonar use. The 3S2 project has also aimed to study whether "ramp up" (or "soft start"), which involves a gradual increase in source level, actually mitigates the risk of detrimental effects of underwater sound on marine mammals. Ramp up is currently in use by several navies to reduce environmental impacts of sonar, but, to date, its efficacy is untested. The playbacks of killer whale sounds are based upon the argument of Frid & Dill (2), that behavioral responses of animals to predation risk represent a good model of disturbance. The question of relevance to the Navy is whether disturbance stimuli such as sonar sounds create trade-offs similar to predation risk between avoiding perceived risk or continuing fitness-enhancing activities (e.g. feeding, parental care, mating displays). Thus, killer whale playbacks provide a model of behavioral disturbance which is particularly important to interpret the reactions of animals to sonar exposures that are usually highly variable.

Objectives

The 3S2 objectives that I will discuss include a study on the effectiveness of ramp-up to reduce acoustic exposure to humpback whales, tagging and playback results with minke whales, and responses of sperm and long-finned pilot whales to sounds of killer whales.

Methods

Ramp up: In order to conduct the ramp-up study, humpback whales are equipped with sound recording tags and GPS loggers, their movements are tracked visually, and group behavior variables are recorded from an observation boat. Experiments consist of 1-3 vessel approaches: either no-sonar silent approaches, or ramp-up runs with source levels of 1.3-2 kHz sonar increasing over 5 min. In all approaches, transmissions start at 1.0-1.5 km distance from the whale and the source ship sails with a fixed speed and heading towards an estimated intercept point with the focal whale.

Tagging and Playback with minke whales: whales are tagged and then tracked visually from an observation boat. Experiments consist of a silent source vessel approach and 1-2 kHz sonar approaches starting from 6-8km distance. Source levels are increased from 152 to 214 dB re 1μPa. The ramp-up of source level and vessel approach achieve an effective escalation of the sonar received level.

Playbacks of killer whale sounds to pilot and sperm whales: Behavioral data were collected using D-TAGs (3) that were attached to the whales prior to the start of the playbacks. Behavioral data comprised: heading relative to the sound source, direction of horizontal movements, dive profile, group size and acoustic recordings. To assess whether killer whale playbacks induced behavioral changes in the targeted animals, we compared behavioral data collected before sound exposure to those collected during sound exposure. To control for the potential that the animals would react to any sounds, we also played back to several subjects a broadband noise.

Results

Ramp up: In 2011, five experiments were conducted in the Arctic waters west of Svalbard and Bear Island. In the six ramp-up approaches, the whales received maximum sound pressure levels of 163-177 dB re 1 μPa and cumulative sound exposure levels of 170-181 dB re 1 μPa^2

s. Full-power sonar runs, such that full-power transmissions were initiated close to the whale, without ramp up, were not conducted to avoid the risk of harming the whale. For comparison with the ramp-up approaches, sound levels received in that situation were modelled from silent approach geometries and sound propagation models.

Minke tagging and playback: Suction-cup Dtags did not remain attached properly to minke whales, so an experiment was carried out using a C-tag with an invasive anchor attachment to the one minke whale. The Ctag, developed by our Norwegian research partners, includes a TDR, a radio transmitter and a compass, but not hydrophones, thus excluding the possibility for measuring the received sound level of the sonar. However, a hydrophone array was towed close to the animal, enabling us to model the RL quite accurately. The minke whale did not show any apparent reaction to silent approach of the source vessel. Prior to exposure of LFAS sonar, the whale was skim-feeding with shallow dives close to the surface. A sudden change in dive behavior from shallow to deep diving at sonar onset indicated cessation of feeding. This deep and unusually long-duration dive coincided with the depth of source sound channel, and may represent an orientation dive to localize the source. Halfway into the exposure, diving behavior abruptly changed to shallow diving, coinciding with a further increase in speed. During the entire exposure period, the whale showed a clear horizontal avoidance, moving directly away from the source vessel. The change in behavior occurred at a low received level, indicating that the minke whale may be a species with high sensitivity to such sonar signals. Therefore, carrying out additional experiments with minke whales under this award will be a high priority.

Playbacks of killer whale sounds to pilot and sperm whales: Killer whale playbacks were conducted in the Norwegian Sea with 5 sperm whales and 5 long-finned pilot whales, and in the Alboran Sea with 4 long-finned pilot whales (as part of N000140910528. Our most striking results showed that in sperm whales, killer whale sounds elicited an interruption in the descent phase of diving and a return to the surface (4/5 experiments). For pilot whales tested in the Norwegian Sea, killer whale vocalizations specifically attracted animals which diverted their course towards the sound source (4/5 experiments) and induced a decrease in inter-group spacing. For pilot whales tested in the Alboran Sea, killer whale playbacks induced a tightening of the group and an increase in vocal production. These clear and consistent reactions to killer whale playbacks provide a model of how animals react to a natural disturbance stimulus, and should help in the interpretation of reactions to sonar.

Notes:

Literature Cited:

1. http://www.onr.navy.mil/Science-Technology/Departments/Code-32/All-Programs/Atmosphere-Research-322/Marine-Mammals-Biology/Marine-Mammal-Biology-Thrusts.aspx
2. Frid, A., and Dill, L. M. (2002). "Human-caused disturbance stimuli as a form of predation risk," Conservation Ecology 6, 11.
3. Johnson, M. P., and Tyack, P. L. (2003). "A digital acoustic recording tag for measuring the response of wild marine mammals to sound," IEEE Journal of Oceanic Engineering 28, 3-12.

SOCAL-BEHAVIORAL RESPONSE STUDY

J. Calambokidis, B. Southall P. Tyack, D. Moretti, A. Friedlaender, S. DeRuiter, J. Goldbogen, E. Falcone, G. Schorr, A. Douglas, A. Stimpert, J. Hildebrand, C. Kyburg, R. Carlson, T. Yack, J. Barlow

Cascadia Research

calambokidis@cascadiaresearch.org, Tel 360-943-7325

Background

Understanding the impact of mid-frequency on sonar on cetaceans has been a high priority for the Navy. The SOCAL-BRS (Behavioral Response Study) is a multi-year effort (2010-2015) designed to better understand marine mammal behavior and reactions to sound. It is an interdisciplinary research collaboration, building on previous efforts in the Bahamas and Mediterranean Sea.

The SOCAL-BRS involved collaborations among scientists from private sector and academic scientists, the U.S. National Oceanic and Atmospheric Administration (NOAA), and U.S. Navy researchers and operational personnel. It is jointly funded by the U. S. Navy, Chief of Naval Operations, Environmental Readiness Division (OPNAV N45) and the Office of Naval Research (ONR). The SOCAL Behavioral Response Study was a 5-year This represents the 2nd year of an anticipated 5-year study and follows the very successful effort in SOCAL-10. The overall BRS study seeks to address a number of priority issues for the Navy including examining the behavioral responses of cetaceans to Navy sound sources.

The specific grant from ONR covered in this program review (N00014-11-1-0565) was to Cascadia Research and focused on funding for the primary vessel platform to be used in the 2011 field season as a base of operations as well as for deployment of the sound source, and another vessel for operation of the towed acoustic array. Since this was just one essential part of the collaborative SOCAL-BRS this abstract will cover some of the overall program accomplishments.

Objectives

The overall objective of the SOCAL-BRS is to provide a better scientific basis for estimating risk and minimizing effects of active sonar for the U.S. Navy and regulatory agencies. SOCAL-BRS is also part of a larger international collaboration to measure the impacts of noise marine mammals using opportunistic and experimental approaches (including controlled exposure experiments, or “CEEs”).

Methods

The 2011 field effort was the second year of the SOCAL-BRS and involved continuation of the multi-species flexible approach started in 2010. Focal species included blue whales, Risso's dolphins, and beaked whales. Similar to past years the study involved finding suitable species, deploying suction-cup attached Dtags, conducing behavioral monitoring prior to sound exposure, conducting a 30 min playback of mid-frequency sonar sounds with a custom developed portable sound source, and then continuing post exposure monitoring. The specific funding to Cascadia from ONR provided the charter of the vessel Truth to serve as an observational platform, base of operations, and platform for deployment of the sound source for two 14-day legs in July to October 2011. Additionally, it also funded for the platforms for the passive acoustic monitoring for two legs of 7 and 14 days to be used in collaboration with Southwest Fisheries Science Center.

One important addition to the 2011 effort was inclusion of prey monitoring for baleen whales under a separate grant from ONR. Prey information will be useful in interpreting the behavioral response of animals especially since preliminary results from 2010 indicate that response by blue whales may depend on behavioral context.

Results

Like the 2010 effort, the 2011 field season was extremely successful and provided new insights into the response of three species: blue whales, Risso's dolphins, and Cuvier's beaked whales. in total, 18 CEEs on 18 individuals of these three species were completed. All of these involved successful deployment of suction cup acoustic tags and the animals were tracked both visually and acoustically. Simulated military sonar signals (several orders of magnitude less intense than real sonar) and noise bands of comparable frequency (identical to SOCAL-10) were presented as experimental stimuli under very specific protocol. Changes in behavior from baseline conditions were measured as a function of sound exposure. Preliminary results based primarily on clearly observable behavior in the field and from initial data assessment were similar to those made in SOCAL-10, but extended sample size considerably in blue whales and Risso's dolphins. These preliminary results indicate variable responses (ranging from no observable response to apparent temporary avoidance behavior), depending on species, type of sound, and behavioral state during the experiments. A strong response was seen in the Cuvier's beaked whale tagged during the field effort in 2010. The second deployment on a Cuvier's beaked whale in 2011, a species that appears to be sensitive to mid-frequency sonar, was one of the more significant accomplishments of this effort.

LEG I Tag Summary:	20 individuals of 2 marine mammal species (with 22 tags of 2 types)	
14 days	Blue Whales:	19 individuals (21 Dtags)
	Rissos dolphins:	1 individual (1 Dtag)
LEG II Tag Summary:	13 individuals of 4 marine mammal species (with 14 tags of 4 types)	
14 days	Blue Whales:	6 individuals (2 Dtags, 5 MK-10s)
	Rissos dolphins:	6 individuals (5 Dtags, 1 sat tag)
	Cuvier's Beaked Whales	1 individual (1 Dtag)
	Bottlenose Dolphins	2 individuals (2 Dtags)

While additional analysis is underway of the nearly 200 hours of tag data from 2011 and this is still early in the overall study, results obtained to date have already provided adequate material for a number of scientific publications. A methodological paper is in review that describes the experimental approach and the development of the smaller sound source that was a critical enabler. A manuscript will be submitted later this year on the results of the Cuvier's beaked whale CEE responses relative to baseline diving behavior. A manuscript will also be submitted later this year on blue whale responses to the initial CEEs including a full characterization and a multi-variate analysis assessing exposure, diving and/or vocal behavior, and a host of environmental and contextual covaiates. Finally, a host of additional baseline behavioral analyses are underway (e.g., vocal and diving behavior using high resolution acoustic and movement tags in Risso's dolphins, baseline vocal behavior in fin whales) and will yield additional new information in publications to be submitted later this year.

The SOCAL-BRS has proved successful in a broader context including the efficient and cost-effective mode of operations this grant supported.

Notes:

OBSERVATION LOGGING AND DECISION SUPPORT USING SSC PACIFIC DEVELOPED SOFTWARE, WHALE IDENTIFICATION, LOGGING AND DISPLAY (WILD)

Christopher Kyburg, PI and Rowena Carlson, Co-PI
SSC Pacific
christopher.kyburg@navy.mil, (619) 553-5752
rowena.carlson@navy.mil, (619) 553-2505

Background

The Navy has been conducting Behavioral Response Studies on marine mammals since 2007 in an attempt to better understand how anthropogenic sound affects various species of marine mammals. Some species of marine mammals are particularly difficult to track and tag.

The WILD system was developed to assist in gathering data to support both tagging animals of interest in preparation for BRS Controlled Exposure Experiments as well as for collection of marine mammal survey data to support better species density estimates.

Objectives

There are four main objectives of the WILD software system:

- To provide a logging tool for conducting systematic marine mammal surveys to support animal density calculations.
- To provide a logging system to support focal follow operations for animal tagging and recording behavioral events.
- To provide a graphical tactical decision aid for tagging and BRS operations which can be seen and manipulated in multiple locations on the research platform.
- Create a display system that can integrate visual and acoustic observations and display them in the context of vessels, shorelines and bathymetry and other relevant geospatial information in real time.

Methods

The WILD software was created using Microsoft Visual Studio C# programming language and ESRI ArcGIS COM objects.

The software was developed as three main components: a logger application, a communications application, and a display application. The three components are loosely coupled which permits custom configurations which can integrate a variety of sensors into a single, real time data stream. Once all information streams are integrated, the stream is sent to the mapping component.

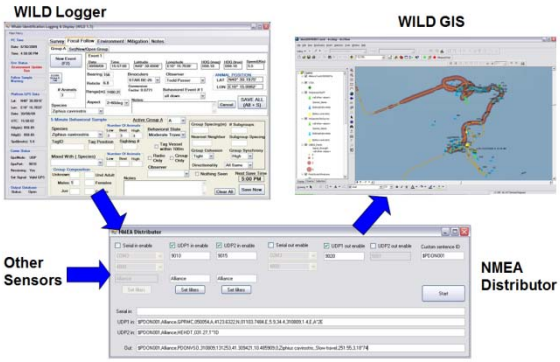

Figure 1. The three main components of the WILD software.

Results

WILD software has been successfully used on a number of sea trials including MED 09, SOCAL-10, SOCAL-11, and several years of San Diego Bay pinniped surveys.

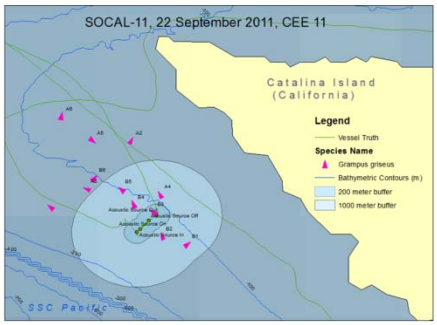

Figure 2. WILD Software display during a Controlled Exposure Experiment

The system has been instrumental as the primary decision aid to set up successful CEEs throughout the SOCAL BRS. WILD has also proven helpful in maintaining compliance with permit requirements. At a glance the chief scientist can see if any animals have crossed into the 200 meter 'shutdown' zone and see the number and types of animals counting as 'takes' within the 1000 meter zone.

TAGGING AND PLAYBACK STUDIES TO TOOTHED WHALES / BEAKED WHALES AND PILOT WHALES IN THE ALBORAN SEA (SW MEDITERRANEAN)

Peter L. Tyack[1] and Ana Cañadas[2]
Scottish Oceans Institute, University of St Andrews
[1]East Sands, St Andrews, Fife, KY16 8LB, United Kingdom
Email: plt@st-andrews.ac.uk; phone number: +44 (0)1334 462630
[2]ALNILAM Research and Conservation Ltd.
Cándamo 116, 28240 Hoyo de Manzanares, Madrid, Spain.
email address: anacanadas@alnilam.com.es; phone number: +34 676481284

Background

This project is part of the Behavioral Response Studies (BRS) thrust, and has also provided data useful for acoustic monitoring and detection and integrated ecosystem research. Recent interdisciplinary research efforts have defined behavioral effects of sound exposure on tagged beaked whales and have measured the exposure required to elicit responses that are safe within the experiment but indicate potential for risk of real-world sonar use (Tyack et al. 2011). However, no such data are available outside of naval training ranges where animals are regularly exposed to sonar for Cuvier's beaked whale, *Ziphius cavirostris*, the species that predominates in the record of sonar-related atypical mass strandings. Previous work suggests that beaked whales, which have a flight reaction to threats such as sonar, may be at higher risk than delphinids with social defenses against threats, but testing this suggestion requires further work with delphinids such as pilot whales.

Objectives

1. The main objectives of cruise in 2009 involved:

- Design, plan, permit, and conduct a study involving sound playback experiments with beaked and other whales carrying sound and orientation recording tags.
- Develop, test, and validate shipboard Passive Acoustic Monitoring (PAM) of marine mammal vocalizations for Detection, Classification, and Localization (DCL) during survey, focal follow and playback.
- Merge a survey mode with a focal follow mode that involves tagging and controlled exposure
- Identify habitats that host sensitive species
- Map the range of doses of noise to which animals are exposed
- Collect environmental data to support habitat modeling

2. The main objectives of the cruises in 2010 and 2011 were to tag, observe baseline behavior, and conduct playback experiments with pilot whales (and beaked whales if possible). This included achieving the following sub-objectives:

a. To understand their acoustic behavior, feeding behavior, social structure and dynamics, both under "normal" circumstances (e.g. when resting, feeding, travelling) and how they behave and react to playbacks.

b. To estimate the proportion of time the animals spend underwater, and therefore estimate $g(0)$ to be able to obtain an absolute estimate of abundance for the population.

Methods

The Med09 cruise utilized the NATO RV Alliance, a silent ship, with scientific teams for visual and acoustic monitoring, tagging, and conducting playback experiments. Passive acoustic monitoring used two towed arrays of hydrophones that were capable of monitoring *Ziphius* echolocation clicks in real-time. This was critical for the playback protocol, which called for cessation of playback once echolocation-based foraging stopped. Sonobuoys were also regularly deployed to measure ambient noise.

The Med10 and Med11 cruises utilized smaller vessels to observe, tag, and conduct playbacks to pilot and beaked whales. Simultaneous tagging of pilot whales within a group was developed as a method to study social behavior, especially contact calls used to maintain cohesion.

Results

The Med09 cruise left from La Spezia Italy on 29 July 2009, worked in the basin North of the Balearics, then in the Alboran Sea for most of the cruise duration, then in the Tyrrhenian Sea before returning to La Spezia on 6 September 2009 (Fig 1). The Med09 cruise involved a combination of visual and acoustic surveys

(172.5 hours) and focal follows (85.2 hours). Oceanographic data were collected at the same time for habitat modeling. Over 550 hours of passive acoustic monitoring were also collected from two towed hydrophone arrays capable of recording frequencies up to 90 kHz, with 53 contacts identified as *Ziphius cavirostris*. A significant new capability developed and validated during Med09 involved using the towed hydrophone arrays to record nearly continuous series of echolocation clicks from a group of beaked whales that had been sighted when it started a deep foraging dive. The visual teams and passive acoustic monitoring teams were able to routinely pass focal *Ziphius* from visual to acoustic monitoring. This was critical for the playback protocol. The tagging boat was deployed 17 times for tagging Cuvier's beaked whales, yielding a total of 400 pictures collected, 47 used in the catalog, and 17 individuals photo-identified, but the tagging team was unable to tag a beaked whale, therefore making it impossible to achieve the goal of playbacks to beaked whales. Two pilot whales, *Globicephala melas* were tagged in the Alboran Sea on 7 August 2009, but the permit did not allow playback to this group, which contained calves. Detections of different species were related to oceanography to model habitat usage (Fig 2).

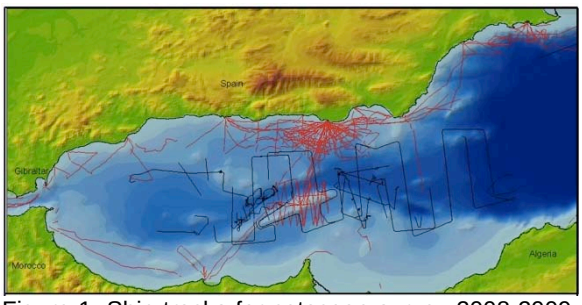

Figure 1. Ship tracks for cetacean survey 2008-2009. Black=Alliance; Red=Toftevaag.

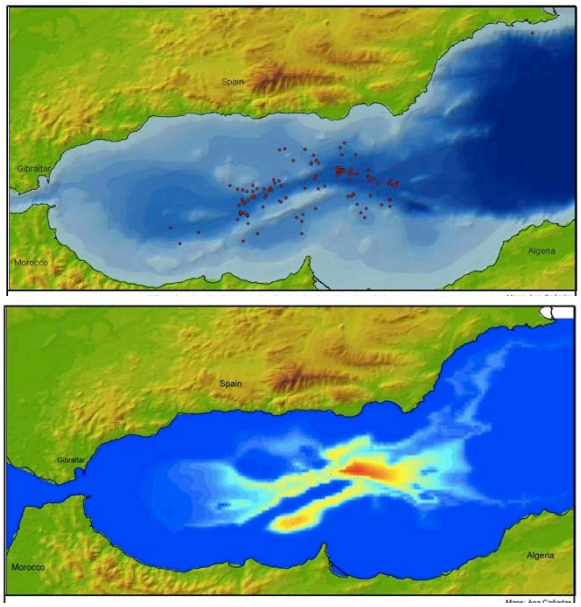

Fig 2. *Ziphius* sightings (top) and estimated abundance (bottom). Max density (red)=0.6 anim/km^2.

A total of 35 tags were deployed in 2010 and 2011 on Mediterranean pilot whales. Three cohesive groups had several animals simultaneously tagged, demonstrating a high degree of synchrony in both shallow dives and deep foraging dives. One pair of tagged animals completed 7 simultaneous foraging dives but increased their vertical separation while foraging at different depths. The whales spread out during foraging and rejoined on ascent by exchanging short click series called rasps. There was one case where a tagged whale remained at the surface while the other completed a deep foraging dive. During the ascent from this dive, exchanges of stereotyped calls occurred over distances of more than 350m. Stereotyped calls also predominate in situations such as stress or excitement (Sayigh et al. 2011) and might serve as valuable proxies for disturbance to animals relying on a social defense against threats rather than acoustic crypsis. Playback experiments were conducted to four pilot whales, described in Charlotte Cure's abstract. Tag and follow data were also used to improve estimates of *g*(0) for pilot and beaked whales.

Notes:

Sayigh L, Jensen F, Cañadas Ana, Hickmott L, Bocconcelli A, Lang W, Macfarlane N, Tyack P (2011) Contexts of stereotyped call production in long-finned pilot whales (*Globicephala melas*). 19th Biennial Conference on the Biology of Marine Mammals, Tampa, Florida, December 2, 2011

Tyack PL, Zimmer WMX, Moretti D, Southall BL, Claridge DE, Durban JW, Clark CW, D'Amico A, DiMarzio N, Jarvis S, McCarthy E, Morrissey R, Ward J, Boyd I. 2011. Beaked whales respond to simulated and actual navy sonar. PLOS One 6(3):e17009

LATTE – LINKING ACOUSTIC TESTS AND TAGGING USING STATISTICAL ESTIMATION: MODELING THE BEHAVIOR OF BEAKED WHALES IN RESPONSE TO MEDIUM FREQUENCY ACTIVE SONAR

T. A. Marques[1], L. Thomas[1,*], J. Harwood[1], I. Boyd[1], D. Moretti[2], E. McCarthy[2], A. Dilley[2], J. Ward[2], N. DiMarzio[2]

[1] University of St Andrews

[2] Naval Undersea Warfare Center

** len@mcs.st-anc-ac.uk, 00441334461801*

Background

The US navy routinely uses active sonar during naval exercises. The effects of active sonar on marine mammals is a matter of rising concern, with increasing evidence linking the use of sonar to detrimental effects in some marine mammals, namely stranding of cetaceans. Therefore, understanding the impact of sonar on marine mammals is a matter of the utmost importance, due to an intrinsic awareness of the Navy's responsibility to legal requirements, and public, and consequentially political, pressure.

Objectives

LATTE focuses on studying the effect of active sonar on beaked whales at the AUTEC navy range. Beaked whales at AUTEC are viewed as a case study which will help to develop models useful for a wider range of scenarios and species.

LATTE aims to link information on beaked whales contained in data collected at different spatial and temporal scales, ranging from a very fine, highly detailed, but extremely expensive, scale (DTag animal level) to a very coarse, more noisy yet less expensive, scale (AUTEC range hydrophone level).

This will be done using state-of-the-art statistical methods, fitting models to the available data to link information collected at the different levels.

The endgame of LATTE is to use those models to predict the effect of active sonar on the behavior of beaked whales, by comparing relevant model parameter estimates in the presence and absence of sonar emission.

Methods

We are currently pursuing two independent and complementary approaches: (1) a more traditional modeling approach, likely to yield some results but less interesting and innovative, and (2) a more state-of-the-art approach, in which a state space approach is used to model the movement and behavior of whales over space and time, relating changes in that behavior to the use of active sonar; however, the outcome is more uncertain due to the higher complexity of the approach.

For the first, more conventional, approach, the effect of sonar on beaked whale activity is inferred by modeling measures of beaked whale activity, like the number of clicks, probability of diving, or inter dive interval, in some temporal and spatial unit, as a function of sonar use. This involves the mapping of sound fields and modeling of activity as a function of these and other relevant covariates.

For the second, essentially blue sky research, approach, we are fitting state-space models to DTag data, in order to model the animal movement and sound production at the individual level. This will then have to be linked to the data collected at the range level, which implies building from individual animal movement and sound production to group level, and then to population level movement and sound production.

Results

We have processed AUTEC hydrophone data on vocal activity of beaked whales from 2009-2011, before, during and after heavy range activity due to Submarine Commander Courses. We also have been leveraging DTag data analyzed in a previous project, DECAF.

Currently, we have solid results from the more traditional approach. We have been able to link the presence of sonar on the range with a clear decrease in animal activity, measured by the number of group foraging dives detected on the range. This is illustrated in Figure 1, which shows a clear reduction in the activity of beaked whales on the range during runs of exercises (ON) from a Submarine Commander Course, with activity resuming between exercises (OFF), although to levels below pre-exercise.

For the state-space model approach, we have defined a conceptual animal movement model in which an animal can be in one of several behavioral modes, namely: (1) at the surface or (2) deep diving. These categories could be sub-divided into (1a) resting at the surface and (1b)

shallow diving and (2a) descending, (2b) foraging and (2c) ascending. We have reasonable information about movement within each of these states from DTag data. We are working on improving methods for geo-referencing of tracks based on jointly using DTag data and dead-reckoning based tracks with positional information from independent localization of the tagged whale. This will be a component of a larger model, in which we combine individual animal movement models to obtain group movement models. The key issue there lies in the lack of information on group movement and group acoustic behavior. Additionally, information on larger scale movement of animals is still lacking. Information about sound production is available from DTag data, and information on the detection process, required to link any produced sounds to range detections, is available through leveraging results from DECAF. The next stage is to continue preliminary simulations from these models, to verify and fine-tune model specification. This is the natural precursor of the final stage, which is to integrate the different model components, and to fit such integrated models to the available data.

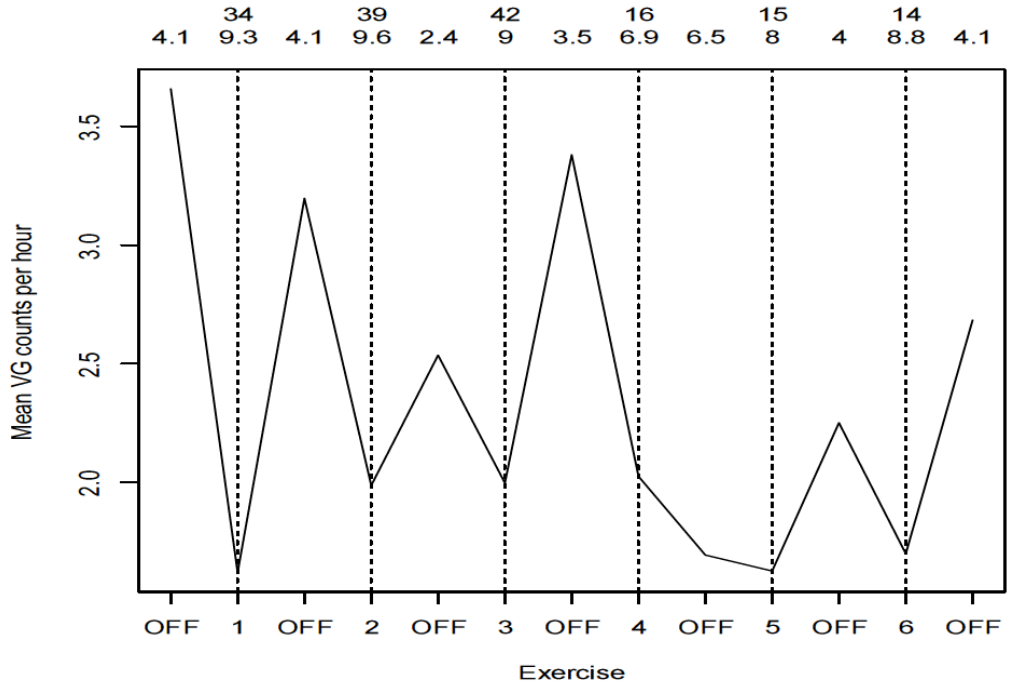

Figure 1 : The mean number of vocal groups starting per hour, during the mini wars period, as a function of whether or not an actual exercise is going on.

Notes: In Figure 1, above, the top row of numbers represents the number of level 3 sonar events in each period, and the bottom row represents the duration of the corresponding time period, in hours.

THE ESME WORKBENCH VERSION 3.0

D.C. Mountain, D. Anderson, A. Brughera, G. Voysey, M. Cross, D.S. Houser, M. B. Porter, and M. Siderius

Boston University Hearing Research Center and Department of Biomedical Engineering
dcm@bu.edu; 617-353-4343

Background

The ESME Workbench is the result of an ONR collaborative research initiative (Effects of Sound in the Marine Environment) aimed at simulating the propagation of sound in the ocean and its effect on the physiological function and behavior of marine organisms. The goal of the ESME program is to create novel modeling and simulation tools to aid in understanding the potential environmental impacts of underwater sound.

Objectives

The objective of this project is to create a full-featured acoustic simulator that can be used by scientists, educators, and environmental planners who do not have a strong background in computer programming or physical acoustics. The current version of the ESEM Workbench is designed to produce predictions about the impact of a variety of sound sources on marine animals. The methodology is designed to closely emulate the approach used by the US Navy for environmental compliance purposes. Future versions will include the ability to simulate other sound sources such as marine mammal vocalizations and echolocation signals.

Methods

The ESME Workbench allows the user to import site-specific environmental data such as bathymetry and sound-speed profiles and to use these data to predict sound propagation in a wide range of scenarios. The system features a ribbon-style graphical user interface similar to that used in Microsoft Office. For geo-referenced data, the Workbench uses a GIS-like approach to display various data layers and to display simulation parameters (figure 1).

The simulator incorporates three major components: sound source models, acoustic propagation models (BELLHOP, RAMGEO), and animal behavior models (Houser, 2006). The sound source models are specified through parameters such as platform type (e.g. surface ship, submarine, helicopter), source type (e.g. mid-frequency sonar, air gun, explosive), and source acoustic parameters (e.g. frequency, intensity, beam pattern). A relational database is used to maintain a library of commonly used source parameters).

Species specific density data are used to seed the simulation with virtual animals (animats). Animal behavior is simulated via a Markov chain where each state represents a different behavior (e.g. diving, ascending, or traveling on the surface). State transition probabilities as well as other parameters such as maximum diving depth are specified separately for each species of interest. The system can also simulate pod behavior and animals reacting to loud sound sources.

The acoustic propagation models use range-dependent depth profiles and depth dependent sound speed profiles to compute the received sound level for simulated animal from each simulated source. The propagation models use bottom and sea surface characteristics to account for losses that occur during reflection at these boundaries. For fixed sound sources, the user can compute and plot the three-dimensional sound field by scrolling through a series of vertical or horizontal slices.

Results

To create and run a simulation, the user runs through a sequence of modules. The Scenario Builder module allows the user to choose the region for the simulation, the time of year, and the types of platforms to be used in a specific simulation, their behavior, and their associated sound sources.

The next step is the Environment Builder module which allows the user to browse the ESME Environmental Databases and choose the data sources for environmental parameters (eg. Bathymetry, sound speed profiles, bottom type. Once the environment is specified, then the user works with the Acoustic Simulator module to specify locations for sound field calculations and then to calculate the sound fields.

The Scenario Simulator steps through the simulation updating source and animat locations. Animal behavior is simulated using a Markov model for each individual. The animal's position and state are typically updated every second.

The pre-computed sound fields are used by the Scenario Simulator to calculate the sound fields for each source by choosing the appropriate pre-computed sound field that is nearest to the current source location and shifting that sound field to the current source location.

Animat location as well as instantaneous and cumulative sound exposure is logged for each time step and stored for subsequent analysis. For a given animat, the exposures due to each source are logged separately so it is possible to analyze how each source contributed to the total exposure experienced by an animat.

A Report Generator module is also included that allows the user to create tables of summary statistics such as the number of each species that are exposed to peak sound pressures or cumulative received energy levels that exceed preset thresholds.

A demonstration version of the software will be available after the meeting for download from: http://esme.bu.edu

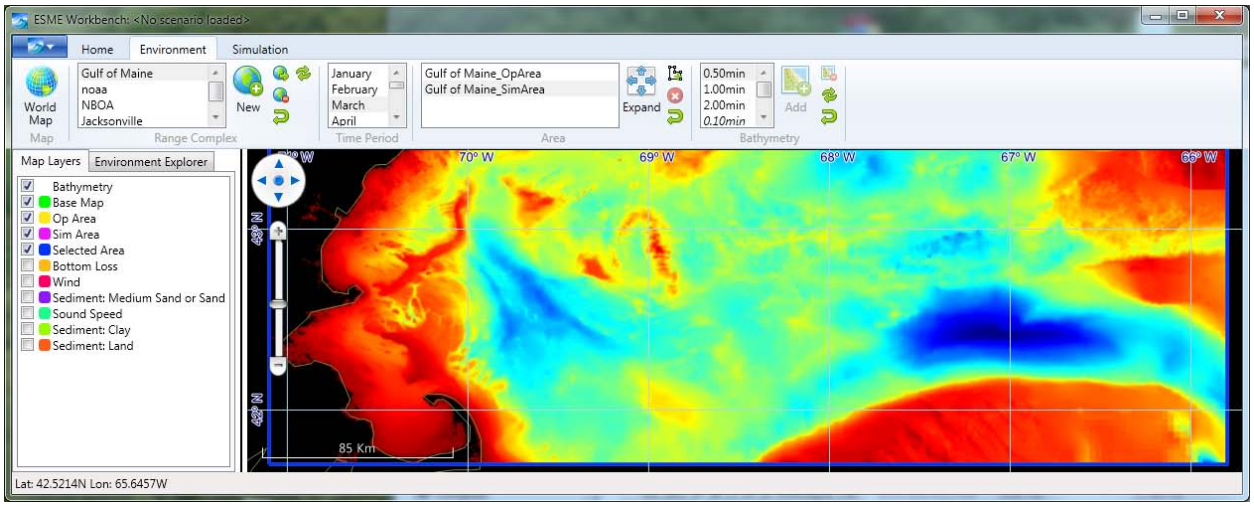

Figure1. The ESME Workbench user interface for the Environment Builder.

DATABASE DEVELOPMENT FOR OCEAN IMPACTS: IMAGING, OUTREACH, AND RESPONSE

D.R. Ketten
Biology Department, Woods Hole Oceanographic Institution, Woods Hole, MA 02543
email: dketten@whoi.edu phone: (508) 289-2731 website: http://csi.whoi.edu

Background

The overall goal for this project is to provide a resource for the research community to improve accuracy of models and representations of marine mammal anatomy as well as standardization of diagnostic procedures on strandings, which will improve our understanding and response efficacy for stranding events. To achieve this, a web-accessible database was proposed illustrating the anatomy and physiology of marine mammals, their prey species, and other endangered marine species for which there are concerns for underwater acoustic impacts. Creating this database for the scientific community is critical for several research fronts attempting to solve acoustic impact issues; e.g., finite element and finite difference models (FEM/FDM) of acoustic propagation characteristics in different species, modeling tissue responses to determine dynamic tolerance thresholds, understanding response differences for specific sound sources, and the education of stranding responders and pathologists in the recognition and interpretation of normal variants vs. pathologies in multiple peri and post mortem states.

Objectives

This multi-year effort provided the scientific community, stranding network, and public research data and educational materials at the lay and professional level on anatomy as well as clinical case histories and interpretative and technical manuals on imaging procedures and determination of normal vs abnormal findings for *in vivo* and post mortem exams of marine mammals and sea turtles. It also demonstrated the potential for imaging to assist a wide-range of Navy related research areas.

Methods

The web database (http://csi.whoi.edu) is an on-going project that was launched publicly May 2011. It is hosted on a WHOI Apache web server (cetus.whoi.edu) configured to host the Drupal based Content Management System (CMS)/Image and has security and backup configurations updated daily by the WHOI Computer Information Services. Site traffic is monitored by Google Analytics. XML site maps have been configured to automatically update major search engines including Google, Yahoo, and Bing to improve internet visibility.

The open database at present provides examples of 2D CT images, 3D reconstructions, videos, and interactive anatomy as well as tutorials and manuals on scanning and necropsy procedures and photos of the scanning process, field, and laboratory dissections. More comprehensive data on diagnostic findings for stranding cases are available under the sections on pathologies. Whole animal data sets and multi-segmented images related to FEM model development are found in the video, 3D, and model sections of the website.

Results

Unlike most research projects, the principal output of this project is not a set of discoveries and conclusions but rather the compilation, categorization, and annotation of data sets acquired from multiple projects and diagnostic procedures on stranded animals. The first year of this project was devoted largely to completion of the design and to testing accuracy and efficiency of each component in an operational website. The following 2 years were devoted to transitioning existing data to a web-accessible database and increasing the sophistication of the website as well as testing security of proprietary data for individual researchers. To increase the value of the data, manuals on the scanning procedures used and interpretations of the data sets were completed and published as well. This final year focused on transitioning major filesets for the full range of archived species data and exploration of new protocols for challenging imaging subjects; e.g., high density, multi-meter coral cores, mega specimens, live invertebrates, deep sea cabling, and deep sea cores.

A total of 866 specimens were scanned directly under the funding of this project, with 274 scanned in the last year alone. Of these, 102 cases were live or post mortem strandings. These data are in addition to pre-existing scan

datasets obtained over 20 years at WHOI and Harvard Medical School imaging facilities. The website currently holds over 3500 sample images, 43 videos, and 116 publications for viewing and download. Full CT data sets and reconstructions are available on request for any of the 170 species in the data archive, including approximately 400 data sets for cetaceans alone. Data available for most cases include 3-5 mm sectional images of the entire body plus 0.1 to 0.5 mm images of selected regions and tissues with specialized multi-segmented imaging of some tissues (Fig. 1). Images are linked also to audio galleries of sound recordings at WHOI and Cornell Sound Library sites. Complete case files of necropsy and CT images and all Level A**,** gross necropsy, and histologic findings are available to registered users.

From May, 2011 to March, 2012 the site produced 11,841 visits with 28% returning visitors, 79,920 page views, and an average of 6.75 pages per visit. New imaging studies and repeat users of the CT to obtain research data have increased from 12 at the onset of this project to over 80 at the end of the last year. The potential for scan data is illustrated by the following examples of recent CT studies supported by this grant, which range from in-depth stranding evaluations to micro to macro FEM data to international climate change and environmental impact studies and resulted in 32 refereed papers and meeting presentations.

- Corals and climate change (A. Cohen, WHOI, The Australian Nuclear Science & Technology Organization, Univ. of Puerto Rico, Univ. of California, Santa Cruz).
- Stretch hoses to evaluate optical cable breaks for the Right Whale Monitoring Program (Applied Ocean Physics & Engineering department, WHOI,)
- Stromatolite climate change research (J. Bernard, A. McIntyre-Wressnig, WHOI)
- Humboldt squid brain (*Dosidicus gigas*)(Iliana Ruiz-Cooley, NOAA)
- Midshipman and toadfish hearing (R. Fay and R. Sisneros; Marine Biology Laboratory).
- Oil samples from Deepwater Horizon (C Reddy, WHOI)
- Ray and Shark hydrodynamics (F.Fish, Robert Russo, Univ.Virginia Dept. of Mechanical & Aerospace Engineering)

Notes:

- Marine mammal lung in hyperbaric conditions (A. Fahlman, WHOI)
- Odontocete and seal stranding diagnostics (IFAW/NOAA NMFS)
- Turtle hearing (C. Carr, U. MD)
- Blue whale ears for stranding evaluation (J. Jacobsen, Humboldt State)
- Shipworm infestation experiments (S. Gallagher, WHOI)
- Minke whale head FEM (M. Yamato, D.Ketten, WHOI)
- *Ziphius cavirostris* ears, stranding evaluations (N. Hauser, Cook Islands)
- Tiger Low Frequency hearing studies (E. Walsh, Boystown)
- Chinese river dolphin (*Neophocoena phocaenoides*) strandings (W. Ding and D. Ketten)
- Cetacean prey species (S. Strobel, WHOI)
- Dolphin-Bat inner ear micro CT (J Simmons, Brown Univ.)
- Circuit board crystal defects (E. Gallimore, WHOI)
- FEM of whole beaked whales (K. Foote, WHOI)

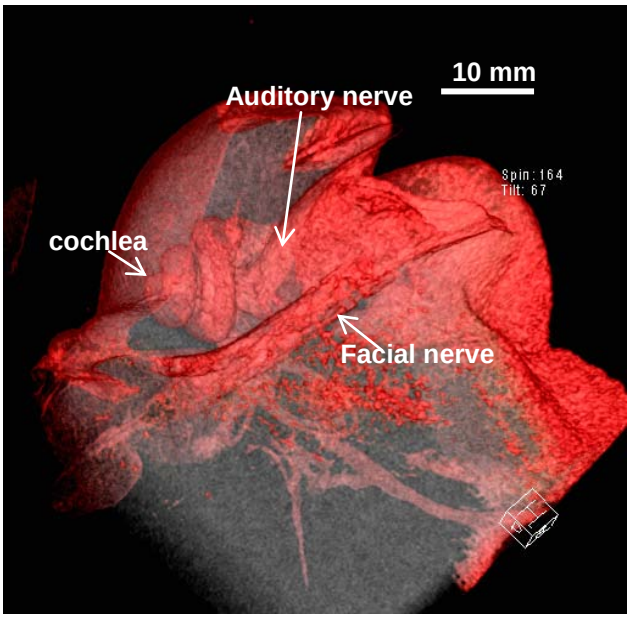

Figure 1. The inner ear of a Right Whale (*Eubalaena glacialis*) in 3D view reveals the relationship and dimensions of the inner ear, facial nerve, and auditory nerve within the periotic bone. The reconstruction was imaged from 800, 100 micron CT images obtained from an intact head. The cochlea in this specimen is 56 mm. in length .

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Day 2: Tuesday April 17, 2012
POSTER SESSION

2012 ONR
Marine Mammal & Biology
Program Review

COMPARISON OF BEAKED WHALE ECHOLOCATION SIGNALS

Simone Baumann-Pickering, Anne E. Simonis, Erin M. Oleson, Sean M. Wiggins, John A. Hildebrand
Scripps Institution of Oceanography, UCSD
sbaumann@ucsd.edu, (858) 534-7280

Beaked whale echolocation signals are mostly frequency-modulated (FM) upsweep pulses, which appear to be species specific. We review and compare beaked whale FM pulses of known and unknown origin from the Pacific (Aleutian Islands, southern California, Gulf of California, and Pacific Islands) and Gulf of Mexico. Currently, we are able to identify FM pulses made by Baird's, Blainville's, Cuvier's, Gervais', Longman's and Stejneger's beaked whales as well as seven distinct signals of unknown origin. All of these signals are distinguishable by their spectral and temporal features. Four of these signals from unknown species occur in the Gulf of California and offshore of southern California. They potentially represent Hubb's, Perrin's, Ginkgo-toothed and Pygmy beaked whales. Two signals from unidentified species have been recorded and described for the Pacific Island region. One unknown signal occurs in the Gulf of Mexico and is highly similar to those described from Cross Seamount, Pacific Island region.

Evolutionary processes of niche separation may have driven differentiation of beaked whale echolocation signals used for spatial orientation and foraging similar to what is described for bats. While very little is known about the differences in habitat preference and foraging behavior for all of these species, there are a few indications for trends of variation within the signals themselves. There is a linear inverse correlation between the average adult body length and peak frequency in which larger whales produce lower frequency signals. This relationship could be a result of anatomy and physiology or it could be an evolutionary adaption in which smaller whales use higher resolution, higher frequency pulses to detect smaller prey.

Comparison of known species at various locations suggests that despite inter-regional differences, their signal characteristics allow discrimination to species level. Evaluating the geospatial distribution, habitat preference and temporal occurrence patterns for unidentified species, and comparing those to sighting information may be useful for additional species acoustic identification. Furthermore, diel and seasonal analysis of these signals may help with planning field work for concurrent acoustic and visual species identification. Additional detailed analysis of echolocation behavior may give insight into reasons for this strong acoustic differentiation, potentially due to niche separation.

Better understanding of these signals and the behavior of the various beaked whale species will lead to effective mitigation techniques for various anthropogenic acoustic operations such as military, seismic exploration, and commercial shipping.

AN ULTRA-LOW POWER SYSTEM-ON-CHIP (SoC) PLATFORM FOR MARINE MAMMAL TAGS AND PASSIVE ACOUSTIC SIGNAL PROCESSING

Ben Calhoun[1], Brian Otis[2], David Mann[3], Alicia Klinefelter[1], Jason Silver[2], Yousef Shakhsheer[1]
University of Virginia[1], University of Washington[2], Loggerhead Instruments[3]
bcalhoun@virginia.edu, botis@uw.edu, dmann@loggerheadinstruments.com

Background

There has been much investigation into the connection between naval sonar and the occurrence of whale stranding/beaching events, particularly for beaked whales. Beaked whales produce clicks and buzzes that are used to echolocate on prey during deep foraging dives as well as for communication, and there is a belief that mid-frequency (3-8kHz) sonar signals can interfere with the whale's echolocation causing abnormal behavior or death.

Recently, acoustic and orientation recording tags have been developed to study marine mammal acoustic and diving behavior. Current tag designs use general-purpose commercial-off-the-shelf (COTS) parts and can collect large amounts of detailed data from multiple sensors over short periods of time. These tags have provided information about whale foraging behavior, diving depths and frequency, as well as vocalizations. Increasing the duration of deployments typically presents two limiting factors: power and memory capacity. Tags using COTS parts consume too much power (~10-100 mW), prohibiting long lifetimes unless the form factor constraint isn't met from the use of a very large battery.

Objectives

The long term goal of this project is to develop and build an ultra-low power (ULP) system-on-chip (SoC) that will increase the useful lifetime of animal tags for monitoring marine mammals to weeks or months and to integrate the chip into a new monitoring tag. Although the tag is application specific, the chip will be designed to do general purpose low-power acoustic processing with an ability to interface to a variety of sensors. We hope to provide fundamental research into the optimal tag partitioning between custom and COTS components, novel analog/digital co-design for acoustic event detection, and ULP on-chip power and event management control. A ULP SoC has been designed that consumes 19µW to process EKG signals, and we expect this chip to operate in the same range and consume < 50 µW.

Methods

To complete the chip, there will be five possible datapaths that need to be determined, one for each sensor. The optimal partition of the analog and digital processing for each will be determined with the goal of reducing the power consumption and maintaining data fidelity. Through a system model of a low-power system similar to this, the best access method to the non-volatile memory (NVM) will be determined (e.g. burst data as fast as possible or slow).

Results

Our group has been looking into designing the datapath for the hydrophone sensor. We are also working with a sensor test board that will be used to classify data for the sensors to aid in datapath design. We have begun to classify the signals based on their frequency content to determine detection thresholds and filtering methods. Also, determining the method to interface to the non-volatile memories is a big research question. A variety of NVM chips are also being tested for their power consumption and how it scales with frequency.

Notes:

VARIATION IN THE SONGS OF HUMPBACK WHALES (*Megaptera novaeangliae*) WINTERING IN THE NORTHWESTERN AND MAIN HAWAIIAN ISLANDS

Jessica Chen[1,2], Marc O. Lammers[2], Whitlow W.L. Au[2]
[1] Department of Zoology, University of Hawaii at Manoa
[2] Hawaii Institute of Marine Biology, University of Hawaii at Manoa

A study of the humpback whale song in the Northwestern Hawaiian Islands (NWHI) and the Main Hawaiian Islands (MHI) during the 2009 season suggests that humpback whale song may be more variable than previously suggested. Data from five autonomous acoustic recorders deployed at locations in the NWHI and MHI were analyzed to compare the frequency of occurrence of song units by whales in the island chain. Recordings from each site were randomly selected. Song units were classified as one of 23 units. Units were counted from the chosen recordings to compare between sites. Differences in the frequency of occurrence in a few of the most abundant units suggest a gradual change throughout the island chain. Therefore there appears to be a gradient of change in song units throughout the Hawaiian Island chain. However, a cluster analysis shows that humpback whale song in the two MHI locations group together, and the three NWHI locations group together. This suggests the whales at the NWHI may be a different breeding population than whales in the MHI. However, this may be confounded by changes that occur throughout the season and throughout the ocean basin. Further work examining the amount of variation both between and within humpback whale breeding populations in a year should be conducted. This would be a way, alternatively to photo ID and genetic studies, to determine more conclusively whether the whales should be considered separate breeding populations. Once the population status of humpback whales around the Hawaiian Islands is determined, it can be used to better manage the conservation policies of management agencies.

KILLER WHALE PLAYBACKS IN BRS STUDIES: A CONTROL TO DEFINE AVERSIVE REACTIONS

Charlotte Curé (1), Antunes Ricardo (1), Alves Ana Catarina (1), Visser Fleur (2), Kvadsheim Petter-Helgevold (3), Tyack Peter (1), Jensen Frants (4), Sayigh Laela (4) and Miller Patrick (1)

(1) Sea Mammal Research Unit, University of St Andrews, Fife KY16 8YG, UK (2) TNO Defense Security and Safety, Observations Systems, the Netherlands (3) FFI Norwegian Defense Research Establishment, Maritime systems, Norway (4) Woods Hole Oceanographic Institution, USA

C. Curé: cc201@st-andrews.ac.uk;Phone: +44 1 334 463 554

Background

These studies are part of BRS studies investigating how naval sonar affects cetaceans' behavior. To do so, it's necessary to1) collect baseline behavior defining normal behavioral patterns, 2) conduct sonar exposures and assess the behavioral responses of the tested animals, and 3) compare such responses to a control, a model defining what is disturbed behavior in cetaceans (see Tyack *et al.* 2011). The behavioral responses of animals to predation risk represent a good model of disturbance (Frid & Dill 2002). Disturbance stimuli (such as sonar sounds) should be analogous to predation risk as they create similar trade-offs between avoiding perceived risk and continuing fitness-enhancing activities (e.g. feeding, parental care, etc.). The aim of the present work is to provide a model of disturbance for BRS studies in cetaceans.

Objectives

Killer whales (*Orcinus orca)* predate upon a number of cetacean species. We conducted playback experiments to test the hypothesis that *cetaceans' behavior is altered by the detection of killer whales' vocalizations that simulate predator presence.*

Methods

Killer whale playbacks were conducted in the Norwegian Sea with 5 sperm whales (*Physeter macrocephalus*) encountered off Andenes and 5 long-finned pilot whales (*Globicephala melas*) encountered inside the Vestfjord basin, and in the Alboran Sea with 4 long-finned pilot whales. Behavioural data were collected using D-TAGs (Johnson & Tyack 2003) that were attached to the tested animals prior to the start of the playbacks. Behavioral data comprised: heading relative to the sound source, direction of horizontal movements, dive profile, group size and acoustic recordings. To assess whether killer whale playbacks induced behavioral changes in the targeted animals, we compared behavioral data collected before sound exposure to those collected during sound exposure. To ensure that the animals do not react to any unspecific sounds, we also played back to several subjects a broadband noise.

Results

Sperm whales reacted to playback of killer whale sounds by interrupting the descent phase of their dive and returning to the surface (4/5 experiments). For pilot whales tested in the Norwegian Sea, killer whale vocalizations specifically attracted animals, which diverted their course towards the killer whale sound source (4/5 experiments) and induced a decrease in inter-group spacing. For pilot whales tested in the Alboran Sea, killer whale playbacks induced a tightening of the group and an increase in vocal production. These clear and consistent reactions to killer whale playbacks provide a template, a model of how animals react to a natural disturbance stimulus. This model of behavioral disturbance is an important support to interpret the reactions of animals to sonar exposures that are usually highly variable.

References:

- Frid A, Dill L. 2002. Human-caused disturbance stimuli as a form of predation risk. Cons. Ecol. 6:11.
- Tyack PL, Zimmer WMX, Moretti D, Southall BL, Claridge DE, Durban JW, Clark CW, D'Amico A, DiMarzio N, Jarvis S, McCarthy E, Morrissey R, Ward J, Boyd I. 2011. Beaked whales respond to simulated and actual navy sonar. PLOS One 6(3):e17009
- Johnson, M. P and Tyack, P. L. 2003. A digital acoustic recording tag for measuring the response of wild marine mammals to sound. IEEE. J. Oceanic Engineering 28: 3-12

DETECTION OF MARINE MAMMAL VOCALIZATIONS FROM SPARSE SPECTRAL TIME HISTORIES

Samuel L. Denes[1], Jennifer L. Miksis-Olds[1], Jeffrey Nystuen, David K. Mellinger
[1] *Applied Research Laboratory, Pennsylvania State University, sld980@psu.edu 814-863-5313*

Background

Autonomous passive acoustic monitoring of marine mammals greatly increases the capacity for collecting data about vocalizing animals in remote, inaccessible, or hazardous areas. Many different recording systems are currently used for studies with widely varying objectives. The results of these efforts provide information on animal distribution, behavior, and reactions to environmental change, all of which have the potential to inform resource management. Memory and power are often the limiting factors for long term deployments. Strategies including sub-sampling and on-board spectral analysis are utilized to extend deployment durations without increasing the device size. Understanding the relative strengths, weakness, and impacts of different sampling strategies on data interpretation and results is crucial for synthesizing data from different data collection methods.

Objectives

1. To assess the feasibility of accurately detecting marine mammal presence from PAL (Passive Aquatic Listener) data.
2. To determine the accuracy of species classification from PAL detections.

Methods

Two passive acoustic recorders, a PAL and an AURAL, were deployed on an oceanographic mooring in the eastern Bering Sea. The AURAL operated on a 30% duty cycle with a sample rate of 8192 Hz. The PAL is an adaptive sub-sampling recorder that collected 4.5 second soundbites with a sample rate of 100 kHz at varying intervals based on feedback from an on-board event detector. All detections result in saved spectral data, and, if memory allocations permit, saved soundbites. Saved spectral data from the PAL consist of 8 spectra equally spaced throughout the soundbite and decimated into 64 frequency bins resulting in low spectral and temporal resolutions. Identifications of marine mammal species from PAL spectral time history data were made by comparing spectral time history samples to vocalization templates from the PAL soundbites. Classifications from this dataset were compared with classifications from the AURAL to determine reliability and accuracy of the detections.

Results

Comparison of detections from PAL soundbites and AURAL data showed the AURAL outperformed the PAL when one species dominated the soundscape; the PAL detected echolocation signals, whereas the low sampling rate of the AURAL precluded echolocation detection. Spectral time histories saved by the PAL provided additional data from which marine mammal classifications are possible, increasing the amount of time from which vocalizations could be classified in PAL data. New techniques to classify non-echolocation signals from the spectra time series reduced the disparity between the two recoding systems for ribbon and bearded seals. Recognition of patterns associated with stereotyped vocalizations within the spectra was limited by the reduced resolution of the saved spectra. Increasing the resolution of saved spectra may improve our ability to classify more signal types from an adaptively sub-sampled dataset.

Notes:

CHEAP DECAF: DENSITY ESTIMATION FOR CETACEANS FROM ACOUSTIC FIXED SENSORS USING SEPARATE, NON-LINKED DEVICES

Danielle Harris[(1)]*, Luis Matias[(2)], David K. Mellinger[(3)], Len Thomas[(1)]
(1) Centre for Research into Ecological and Environmental Modelling (CREEM), University of St Andrews, St Andrews, UK.
**(+44 1334) 461826, dh17@st-andrews.ac.uk*
(2) Centro de Geof́ sica, Universidade de Lisboa, Lisbon, Portugal.
(3) Cooperative Institute for Marine Resources Studies, Oregon State University, Newport, OR 97365.

Background

Monitoring cetacean density or abundance in areas where naval activity takes place forms part of the Navy's environmental stewardship responsibilities. Historically, visual surveys have been used to monitor cetacean populations but, in recent years, acoustic monitoring has been the focus of research effort. Static (or fixed) hydrophone arrays have been used to estimate cetacean density in several case studies. However, in many of these examples, there was a need for many instruments, making this form of monitoring costly. The focus of this project is cetacean density estimation using isolated instruments. The use of isolated instruments will improve the cost-effectiveness of fixed acoustic monitoring, as either fewer instruments will be required to monitor a given survey area, or a larger survey area can be monitored with the same number of instruments.

Objectives

There are three main strands to this project:

(1) Demonstrate that distance sampling, a standard animal density estimation method, can be applied to isolated instruments that are capable of estimating a bearing to an acoustic source.

(2) Develop new density estimation methods that account for the movement of animals within a monitored area.

(3) Develop a new density estimation method that uses the total acoustic energy produced by calling animals in a specified frequency band. This negates the need to detect individual calls, greatly reducing data analysis requirements.

Methods

An array of 24 Ocean Bottom Seismometers (OBS) was deployed off the south coast of Portugal between August 2007 and July 2008. At least 30 km separated adjacent instruments, so the array is considered to be a collection of isolated instruments. Numerous fin whale (*Balaenoptera physalus*) calls have been recorded by this array. This dataset will be used to demonstrate the application of existing density estimation methods and also to develop new methods, as outlined in the Objectives.

Results

This 2-year project began in September 2011. Preliminary results for Objective 1 include the processing of one day of data from January 2008. Ranges to calling fin whales were estimated, and distance sampling conducted. Only call density could be estimated due to a lack of a call rate, required to convert call density to animal density. For Objective 3, methods have been developed, which will now be refined by using more accurate parameters.

Notes:

BASELINE BEHAVIOR AND ACOUSTIC COORDINATION MECHANISMS IN LONG-FINNED PILOT WHALES (GLOBICEPHALA MELAS)

Frants H. Jensen, Alessandro Bocconcelli, Ana Canadas, Leigh S. Hickmott, Nicholas MacFarlane, Laela Sayigh, Peter Tyack
Biology Department, Woods Hole Oceanographic Institution, Woods Hole, MA 02543 USA
Email: fjensen@whoi.edu; phone: +1-508-524-8436

Background

An important research topic for the Marine Mammals and Biology program at ONR is to study the responses of whales to sonar and other anthropogenic sounds. Recent studies have reported on how beaked whales respond to mid-frequency sonar and other anthropogenic sounds at levels about 140 dB (Tyack et al. 2011). However, the responses of other species, including the deep-diving pilot whales, are less well understood. Both long-finned and short-finned pilot whales are large enough to be studied with sound and movement recording suction cup tags (DTAGs) and playback experiments have been conducted with tagged pilot whales both in the Bahamas and in Norway. However, the behaviour of pilot whales is more varied and much less understood than that of beaked whales. Long-finned pilot whales (*Globicephala melas*) are believed to have a complex social structure with high degrees of philopatry, but little is known of how the group structure affects the behavior and responses of the individual. A greater understanding of baseline behaviour and the social signalling that is essential for keeping pilot whale groups together over long time periods will greatly facilitate the interpretation of existing playback data and help improve playback protocols for future controlled exposure studies.

Objectives

1) Improve understanding of baseline behavior of long-finned pilot whales in a social context
2) Identify acoustic signals that are important for mediating group cohesion over varying spatial scales

Methods

Long-finned pilot whales in the Alboran Sea, Spain, were instrumented with suction-cup mounted DTAGs. Pre-tagging focal follows were conducted to select closely associated animals for tagging. Tagged animals were followed throughout the day while behavioral observations were collected.

Results

Through 2010 and 2011, a total of 35 tags were deployed on Mediterranean pilot whales. In three cases, highly cohesive groups of animals were tagged. These animals demonstrated a high degree of synchrony in both shallow dives and deep foraging dives. One pair of tagged animals was highly cohesive and surfaced near-simultaneously. These two whales completed 7 simultaneous foraging dives but increased their vertical separation and foraged at different depths (mean difference of 83m). This indicates that whales spread out during foraging but rejoin during ascent. Exchanges of short and rapid click series (rasps) occurred during the ascent, suggesting an important role for close-distance coordination. One asynchronous dive was observed where one tagged whale remained at the surface while the other completed a deep foraging dive. During this ascent, rasps were exchanged by highly stereotyped calls repeated frequently, and call exchanges occurred over distances of more than 350m. Our results suggest that separate acoustic cohesion mechanisms are important for mediating group cohesion across different spatial scales, with simpler click-based signals sufficient for keeping contact over short distances, and stereotyped calls essential for establishing contact during separations or periods of stress. Stereotyped calls also predominate in situations such as stress or excitement (Sayigh et al. in press) and might serve as valuable proxies for disturbance to animals relying on a social defense against threats rather than acoustic crypsis.

References

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QUEPHONE: AN ACOUSTIC FLOAT FOR MARINE MAMMAL MONITORING

Haru Matsumoto, Chris Jones, Holger Klinck, David K. Mellinger
Cooperative Institute for Marine Resources Studies, Oregon State University haru.matsumoto@oregonstate.edu, 541-867-0272

Background

Acoustic methods are frequently used for mitigation of potentially harmful anthropogenic effects on marine mammals, because of some distinct advantages including the ability to detect animals underwater, and to work at night and in poor weather conditions. To be able to monitor marine mammal species in areas outside of instrumented Navy ranges, recent work focused on the development of autonomous instruments such as acoustic gliders and floats. Within the scope of this project we developed a profiler float equipped with a passive-acoustic system and a cetacean-click detection algorithm running on a high-power DSP (digital signal processor). One advantage of this approach is the fact that floats are relatively inexpensive and can be easily deployed in any number to cover a large area. This passive-acoustic float called QUEphone (quasi-Eulerian phone) was tested at the U.S Navy ranges AUTEC and SCORE and the performance evaluated using data from the Marine Mammal Monitoring on Navy Range (M3R) systems.

Objectives

The goal of the project is to develop an inexpensive and easy-to-use passive-acoustic profiler float to autonomously scan the ocean for cetaceans of interest.

Methods

A 2000 m rated APEX profiler float (Teledyne Webb Research) was equipped with a passive-acoustic recording and detection system. The detection system is based on the click detection algorithm known as ERMA (Klinck *et al.*, 2011) running in real-time on a high-power DSP (BF537® Analog Device) with 128 GB of data storage. During surfacing events, detection logs are send to shore via Iridium satellite link. The maximum deployment duration of the instrument ranges between 2 weeks (alkaline batteries) and 4 weeks (Lithium batteries). Field tests were conducted at AUTEC and SCORE in June 2010 and Jan 2011, respectively. Figure 1 shows the comparison of beaked whale clicks reported by a QUEPhone (Q1, yellow) and the M3R system (H28, blue) during the 6-day AUTEC field trial. QUEPhone 1 was deployed approximately 7 km northwest of hydrophone H28 and drifted at 2 cm/s (at 1000 m) towards this hydrophone. As it got closer to H28, number of detections at both instruments were very similar (see FIG. 1). Sea state during this experiment was ~0.

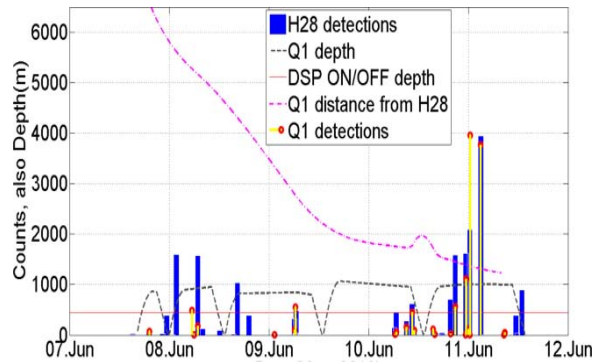


FIG. 1. QUEphone 1 vs. M3R detections at AUTEC (6/7-12/2012).

Results

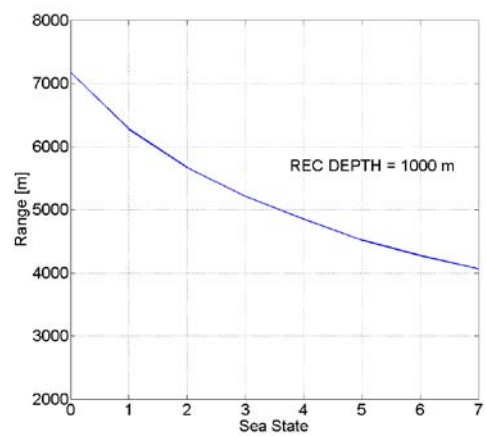


FIG. 2. Detection range estimated utilizing a generic wind noise model and QUEphone depth of 1000 m.

FIG. 2 indicates the theoretical detection range of beaked whale echolocation clicks (SL 210 dB) by the QUEphone or similar platform at a depth of 1000 m as a function of sea-state. At sea state 0 maximum detection range is approximately 7 km. Whereas at sea state 7 and near the noisy shipping lanes, the range could be as low as 4 km.

SEASONAL SOUNDSCAPES FROM THREE OCEAN BASINS: WHAT IS DRIVING THE DIFFERENCES?

Jennifer L. Miksis-Olds
Applied Research Laboratory, Pennsylvania State University, jlm91@psu.edu 814-865-9318

Background

Sound is capable of propagating over great distances in the ocean, and loud, low frequency sources can propagate half-way around the globe. For this reason, sound can be used to observe a variety of signals in marine ecosystems ranging from natural phenomena to anthropogenic activities indicative of global ocean use and climate change. The acoustic characteristics of marine habitats have direct implications on marine animal communication, navigation, and sensing of their environment. Ocean sound is also important to humans for tasks related to signal detection associated with military surveillance and environmental monitoring of animals for mitigation and regulatory purposes. Effective sound transmission in the marine environment is impacted by many factors including physical and chemical properties of the seawater, as well as human generated noise linked to ocean transportation, energy exploration, and military operations.

Objectives

3. Determine the major sources (or drivers) of variation in low frequency ambient sound levels on a regional and ocean basin scale.
4. Investigate the impacts of variation in low frequency ambient sound levels on signal detection range, marine mammal communication, and distribution.

Methods

Over a decade of historical acoustic data from the Comprehensive Nuclear Test-Ban Treaty Organization (CTBTO), oceanographic, and shipping information is being used to investigate the relationship between ambient ocean sound, its variability, and signal detection. Regional and ocean basin noise variability statistics will be quantified and applied to calculations of the range over which signals can be detected given the inherent environmental variability. Implications of the variability in signal detection range, or active acoustic space, will then be related to the detectability and acoustic behavior of low-frequency sound producing marine mammals. Recent work has focused on the use of visual soundscapes to illustrate the seasonal sound levels and variability from opposite sides of an island in three oceans by comparing 2 bandwidths: 10-30 Hz and 85-105 Hz.

Results

The soundscapes, as characterized by the ratio of 2 low frequency bandwidths, showed distinct differences in recordings made from the north and south sides of Diego Garcia and Ascension Island in the Indian and Atlantic Oceans, respectively. In contrast, very little to no differences were observed in the recording made from opposite sides of Wake Island in the Pacific Ocean. The Pacific Ocean recordings showed the most variability between seasons with the most spatial soundscape separation between seasons compared to the Indian and Atlantic locations. Examination of the spatial soundscape shifts indicates how the potential drivers of the ambient sound change over the course of the seasons at each location. At the Indian and Atlantic locations, seasonal differences were observed between recordings made from the northern and southern island sites. No analogous pattern was observed from the Wake Island recordings.

Notes:
This project is funded by ONR Young Investigator Program.

BIOACOUSTIC BEHAVIOR OF HAWAIIAN INSULAR FALSE KILLER WHALES AND MELON-HEADED WHALES: A PRELIMINARY FIELD REPORT

T. Aran Mooney, Robin W. Baird, Peter Tyack, Paul Nachtigall, Aliza Millete, Daniel L. Webster and Gregory S. Schorr

Biology Department, Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA
amooney@whoi.edu, (508) 289-3714

Background

The waters surrounding the State of Hawaii are regions that form the habitat for more than 20 species of federally protected marine mammals including melon-headed whales (*Peponocephala electra*) and false killer whales (*Pseudorca crassidens*). These species are of particular interest as species of concern because (a) the Hawaii insular stock of false killer whales (FKWs) is currently a candidate for listing as Endangered under the Endangered Species Act due to evidence of a population decline, small population size, and a number of threats, thus are potentially vulnerable to stochastic events, and (b) a melon-headed whale (MHW) mass near-stranding event was associated with a Rim of the Pacific exercise. Surprisingly little baseline information has been established for these animals, making it difficult to evaluate baseline behavior and mitigate potential anthropogenic impacts. Here we describe the first stage and preliminary efforts of an ongoing project which employs non-invasive, acoustic behavior and orientation tags (DTAGs) to establish critical baseline information on the ecology and sound use of these protected species.

Objectives

Through detailed, non-invasive, bioacoustic behavior measurements:

1) Quantitatively examine the acoustic signals of Hawaiian insular false killer whales (FKWs) and melon-headed whales (MHWs).

2) Determine baseline acoustic behavior, diel activities, detailed dive patterns and fine-scale habitat use for both species.

3) Pair data on the acoustic characteristics of calls with behavioral ecology information to evaluate the potential for species classification, passive acoustic detection, and density estimates.

Methods

Data will be collected with non-invasive, suction cup tags (DTAG3) attached to individual Hawaiian insular false killer and melon-headed whales. This project will be conducted over four, 2-week tagging periods spread between three years. The DTAG is a miniature sound, orientation, acceleration and depth recording tag. Dive, movement analyses and bioacoustic signals of the tagged animal and conspecifics will be examined.

Results

In this first field season, six acoustic and two satellite tags were deployed on MHWs. One DTAG and one satellite tag were deployed on FKWs. A substantial amount of acoustic information was recorded for both species. MHWs were extremely vocal with sounds recorded almost constantly during the set of recordings. Burst pulse, standard clicks and whistles were all recorded from the tagged animal and conspecifics. Whistle contours were often variable with multiple inflection points. FKWs were more limited in call rates. Vocal activity was greatest during the first half (100 min) of the tagging period when the overall group was observed to be foraging. During this time, 20 m dives (mean) were almost continuous. Clicks and whistles, potentially from the tagged animal, were often overlapping. Whistles were rich in harmonics but near constant-frequency. FKW call rates decreased during apparent travel periods with 75% fewer dives. Records from both species are currently being evaluated for on-axis signals to address relative spectra, comparisons between species and to evaluate potential differences between D-tagged animals from the Bahamas. Overall patterns of vocal activity and apparent behavior will also be addressed for the Hawaiian-D-tagged groups.

ASSESSMENT OF ACOUSTIC ADAPTATIONS FOR NOISE COMPENSATION IN MARINE MAMMALS

Susan E. Parks
Syracuse University
sparks@syr.edu, (315) 443-1795

Background

This project focuses on fundamental theoretical issues related to noise compensation mechanisms in marine mammal vocal communication. Noise compensation mechanisms are important for improving signal transmission with an energy limited source. A better understanding of marine mammal noise compensation mechanisms can potentially provide effective means of improving signal transmission in a noisy marine environment and for assessing the impact of man-made sounds on the use of sound by marine mammals.

Objectives

The primary objectives of this project are to: 1) generate testable hypotheses of vocal responses of marine mammals to particular noise types; and 2) test these hypotheses with data from baleen whale species in coastal shallow water environments.

Methods

Hypotheses about vocal behavior modifications for noise compensation in marine mammals were developed by reviewing general trends for noise compensation documented from other animal species in response to noise sources in the environment and propagation modeling of baleen whale signals through their acoustic habitats. These hypotheses were then tested using an existing database of acoustic tag data collected from the North Atlantic right whales (*Eubalaena glacialis*) in the Bay of Fundy and collection of bottom-mounted passive acoustic recordings of Southern right whales (*Eubalaena australis)* made in Brazil in collaboration with Projeto Baleia Franca and Universidade Federal do Rio Grande do Norte. These data will be used to further test the general noise compensation hypotheses developed in the first part of the study and to compare the vocal behavior between the two right whale species.

Results

A review of research on mammalian vocal modifications in noise was conducted, focusing on the common mechanisms in vocal recognition in mammalian acoustic communication systems. Hypotheses for vocal modifications that marine mammals may employ in increased noise were developed from this review. A preliminary modeling study assessing the propagation range of vocalizations from four baleen whale species in shallow and deep water habitats identified a match between call structure and maximum communication range in the habitats commonly associated with each species. Results from the analysis of the 2001-2005 Dtag data from right whales in the Bay of Fundy indicate that individual call production is modified in increased ambient noise conditions with changes to call intensity. Individual whales producing multiple calls showed increases in received call amplitude in increasing ambient noise conditions. Preliminary analysis of data from two sites in Brazil will be discussed.

Notes:
This project is funded by ONR Young Investigator Program

ACOUSTIC METADATA MANAGEMENT AND TRANSPARENT ACCESS TO NETWORKED OCEANOGRPAPHIC DATA SETS

M.A. Roch, S. Baumann-Pickering, C. Berchok, D. Cholewiak, J.A. Hildebrand, D. Hwang, L. Munger, E.M. Oleson, D. Risch, A. Sirovic, M.S. Soldevilla and S. Van Parijs
San Diego State University
marie.roch@sdsu.edu 619 594-5830 / 858 534-7280

Background

As the output of detection, classification, and localization systems for marine mammals grows, it becomes critical to develop data management systems capable of assessing long-term impacts, census, and enabling the use of physical and biological variables in the subsequent analysis.

Acoustic metadata are semi-structured and portions of the metadata representation do not fit well into the traditional view of data records as having a fixed structure. Examples of this for acoustic analysis effort include recording when, where, and how the data were analyzed along with what species, calls, and other phenomena were being detected. Parameter sets will vary greatly from algorithm to algorithm and cannot reasonably be expected to have standardized fields.

Objectives

This project is building a flexible data standard for representing acoustic metadata and providing a single interface access to remote datasets such as NASA's Ocean Color or ephemeris data from NASA JPL.

Methods

Data is stored using a freely available database that decomposes extensible markup language (XML) into relational data for efficient storage and access. We leverage existing data access toolkits such as Duke's Marine Geospatial Ecology Tools and NOAA's Environmental Research Division's Data Access Program (ERDDAP).

The participation of acousticians from each of the NOAA Fisheries Science Centers is key to providing a broad range of community input to ensure representations and interfaces that are useful to the marine mammal community. Efforts are being made to provide interfaces to major languages such as Matlab, Java, and R.

Results

Currently, we have implemented representations to track species detections, network interfaces, and access to a wide variety of environmental data sets. As a result of our first annual workshop of participants, we have revised data layouts to ensure that community needs are met. The project's first biological result has been an analysis of biological ambient noise that may be attributable to vertical migration of the deep scattering layer. This noise was analyzed across twelve different sites and covered a ten year span. At a number of sites, there was a crepuscular noise pattern with significant circular correlation between moon phase and noise levels as illustrated by a plot tracking noise at dusk and lunar rhythm (Figure 1).

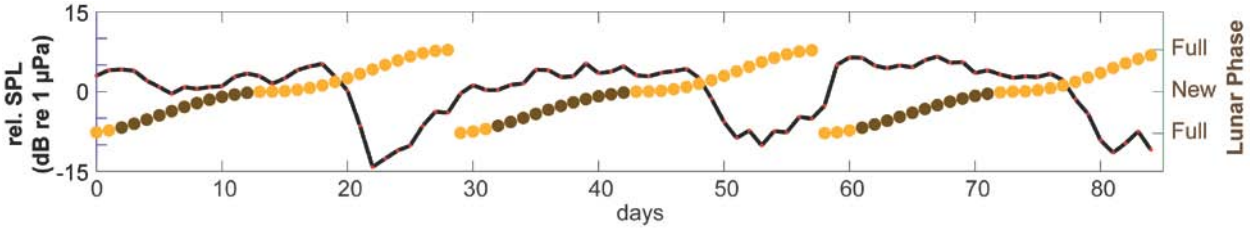


Figure 1 - Band limited ambient noise at dusk around Wake Island drops during full moon. Lighter circles indicate moon visibility during this period (Baumann-Pickering et al., unpublished data).

This project is funded by the NOPP.

MODELING STATISTICS OF FISH PATCHINESS AND PREDICTING ASSOCIATED INFLUENCE ON STATISTICS OF ACOUSTIC ECHOES

Tim Stanton, Daniel Grünbaum (UW), Tom Weber (UNH)
Woods Hole Oceanographic Institution
tstanton@whoi.edu. 508.289.2757

Background

Long-term goals include improving fundamental understanding of fish behavior, especially in aggregations, and quantifying characteristics of 1-10 kHz clutter associated with random distributions of fish. These studies will yield new scientific understanding of fish behavior as well as improve predictions of performance of Navy active ASW sonars.

Objectives

To develop new models of fish behavior associated with aggregations, including the fission/fusion process, and to describe the echo statistics associated with the stochastic fish behavior using existing formulations of echo statistics.

Methods

Develop new advanced models of fish behavior inspired by, and grounded by, existing 3-D images of fish aggregations. Key parameters to be observed/modeled: fission/fusion rates, group cohesion/polarity, and group heading distributions. Behavioral models are used as input into existing models of echo statistics for direct path and waveguide geometries for 1-10 kHz active sonars.

Results

*****A new fish behavior model has been developed that integrates cognition by fish in assessing nearest neighbor movements as well as favorable scalability properties and time-stepping in an Equation-Free Modeling context.

*3-D images of aggregations show a power law distribution for large aggregation dimensions.

*Predictions of clutter due to a finite number of aggregations in a waveguide show a non-Rayleigh behavior.

Notes:

These developments are inspired, in part, by Stanton's work under the ONR HIFAST FNC program in which fish behavior is accounted for in predictions of sonar clutter and transitioned to the U.S. Navy's Surface ASW Synthetic Trainer (SAST).

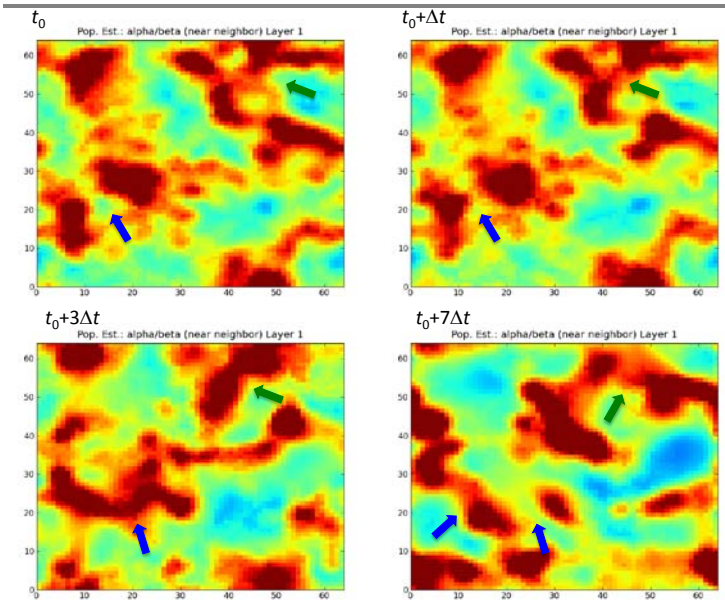


Figure 1. Fission-fusion dynamics in the cognitive schooling model, reflected in population-level density distributions at four sequential time steps (note varying time increments between images). Blue arrows indicate approach and then fusion of two groups, followed by a subsequent fission event and incipient fusion with another group. Green arrows indicate a simultaneous approach/fusion/fission sequence in a different part of the

BROADBAND (1-9 kHz) ACOUSTIC STUDIES OF FISH AT MULTIPLE SCALES

Tim Stanton, Roger Gauss (NRL), and Mike Jech (NOAA Fisheries)
Woods Hole Oceanographic Institution
tstanton@whoi.edu, 508.289.2757

Background

Long-term scientific goals include accurately describing the spatiotemporal distributions of fish, and quantifying the 1-9 kHz clutter characteristics of fish. To this end, this project has collected a unique set of field data that is not only revealing important information on fish behavior but providing valuable information on fish clutter characteristics that is serving as a basis for improving the Navy's active ASW sonars.

Objectives

To conduct a new class of quantitative acoustic studies of swimbladder-bearing fish utilizing new broadband, high-resolution acoustic technology that is optimized for use in the resonance scattering region of the fish.

Methods

Two cruises (2010 and 2011) collected data in three distinct geographical regions of the Gulf of Maine using a unique combination of long-range horizontal-looking and short-range downward-looking broadband acoustic systems. The broadband acoustic studies were coordinated with trawl sampling and conventional narrowband acoustics as part of annual surveys conducted by the NOAA Fisheries.

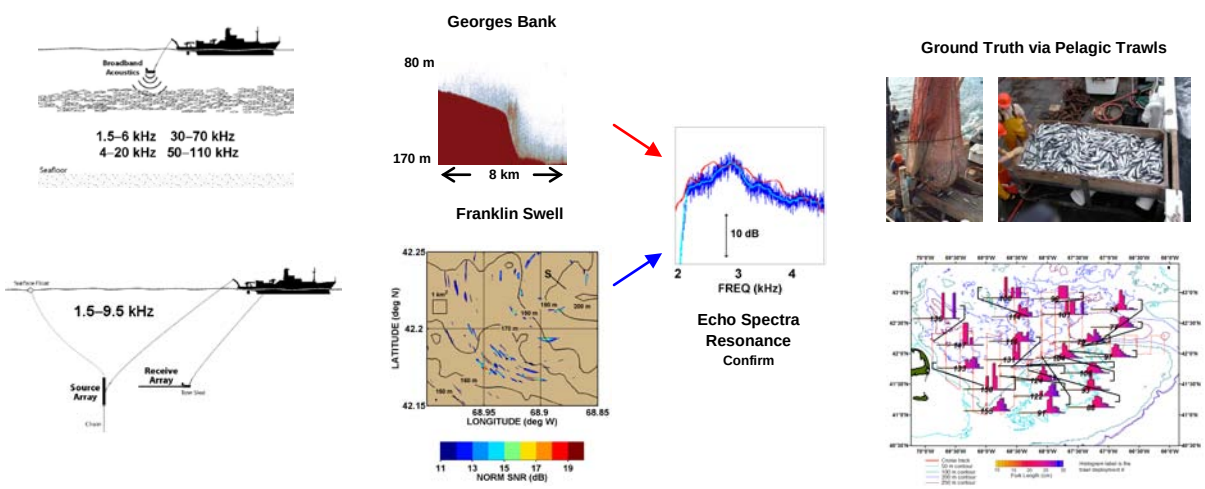
Results

- Spatial characteristics of fish and echo statistics were observed to be specific to geographic region
- Spectral peaks showed the presence of mixed assemblages of fish
- Long-range sonar detected fish out to 20-km range. Echo statistical distributions were consistent with fish spatial characteristics.

Notes:

Under the ONR HIFAST FNC program, this project has transitioned acoustic fish clutter models to the U.S. Navy's Surface ASW Synthetic Trainer (SAST).

This project is funded by the NOPP



A unique combination of broadband downward- and horizontal-looking sonar systems used to identify large fish aggregations on Georges Bank and in compact, sparse fish schools on Franklin Swell. NOAA pelagic trawls revealed the fish in each region were predominantly Atlantic herring

DISCOVERY OF SOUND IN THE SEA

Kathleen J. Vigness-Raposa* and Gail Scowcroft
**Marine Acoustics, Inc., 809 Aquidneck Ave., Middletown, RI 02842*
kathleen.vigness@marineacoustics.com, 401.847.7508

Background

The scientific community and the general public have become increasingly aware of and concerned about underwater sound. In addition, abstract physical science concepts can be challenging for students to understand and military personnel need engaging, technical refreshers. As interest in underwater sound and its potential effects on the marine environment increases, there is a continuing need for resources on the fundamental concepts of underwater sound.

Objectives

The Discovery of Sound in Sea (DOSITS) website (http://www.dosits.org) and associated publications have been designed to provide comprehensive scientific information on underwater sound at a level appropriate for the general public and for educational, media, and public affairs professionals.

Methods

The DOSITS website introduces the physical science of underwater sound and how people and animals use sound to accomplish various tasks in three science sections (science, people, animals), three resources sections (teachers, students, media), and three galleries (audio, technology, scientist). Two public affairs publications, a tri-fold pamphlet and an educational booklet, introduce the public to the issues and science content of DOSITS and provide an in depth look at Sound in the Sea and targeted issues for interested stakeholders, policymakers, and the public, respectively.

On the website, scientific information is presented in three major sections including the Science of Sound in the Sea, People and Sound in the Sea, and Animals and Sound in the Sea. The Science of Sound in the Sea section provides a thorough introduction to fundamental concepts of underwater sound, including topics such as sound movement and measurement, as well as advanced concepts such as an introduction to decibels, cylindrical versus spherical spreading, and ocean noise variability and noise budgets. The People and Sound in the Sea section describes the many everyday activities that depend on underwater sound. The Animals and Sound in the Sea section includes information on the use, production, and reception of sound by marine life. In addition, the best available, peer-reviewed, published literature on the effects of underwater sound on the marine environment is summarized in comprehensible, efficient pages.

Results

The DOSITS website and printed publications are resources for educating and exposing the public to the basic science of sound in the sea and how it is used to communicate, navigate, and explore the oceans. By providing information in multiple formats, teachers can bring this content into their classrooms; public affairs personnel can inform themselves of controversial issues and provide materials to Congress; and the public can begin to include science in their decisions. Since its launch in November 2002, the DOSITS website has had almost 50 million hits. An extensive 10th anniversary celebration is planned for this fall.

Notes:

THE AUDITORY ANATOMY OF THE MINKE WHALE (*Balaenoptera acutorostrata*): A POTENTIAL FATTY SOUND RECEPTION PATHWAY IN A BALEEN WHALE

Yamato, Maya[1]; Ketten, Darlene[1,2]; Arruda, Julie[1,3]; Cramer, Scott[1]; Moore, Kathleen[4]
(1)Woods Hole Oceanographic Institution, 266 Woods Hole Road, MS#50, Woods Hole, MA, 02543, USA
(2)Harvard Medical School, 243 Charles Street, Boston, MA, 02114, USA
(3)Massachusetts Eye and Ear Infirmary, 243 Charles Street, Boston, MA, 02114, USA
(4) IFAW Marine Mammal Rescue and Research, 290 Summer Street, Yarmouth Port, MA 02675, USA
myamato@whoi.edu

Cetaceans possess highly derived auditory systems adapted for underwater hearing. Odontoceti (toothed whales) are thought to receive sound through specialized fat bodies which contact the tympano-periotic complex, the bones housing the middle and inner ears. However, sound reception pathways remain unknown in Mysticeti (baleen whales), which have very different cranial anatomies compared to odontocetes. Here, we report a potential fatty sound reception pathway in the minke whale (*Balaenoptera acutorostrata*), a mysticete of the balaenopterid family. The cephalic anatomy of seven minke whales was investigated using computerized tomography (CT) and magnetic resonance imaging (MRI), verified through dissections. Findings include a large, well-formed fat body lateral, dorsal, and posterior to the mandibular ramus and lateral to the tympano-periotic complex. This fat body inserts into the tympano-periotic complex at the lateral aperture between the tympanic and periotic bones and is in contact with the ossicles. There is also a second, smaller body of fat found within the tympanic bone, which contacts the ossicles as well. This is the first analysis of these fatty tissues' association with the auditory structures in a mysticete, providing anatomical evidence that fatty sound reception pathways may not be a unique feature of odontocete cetaceans.

Day 3: Wednesday April 18, 2012

2012 ONR
Marine Mammal & Biology
Program Review

MARINE MAMMALS: HEARING AND ECHOLOCATION AT COCONUT ISLAND

Paul E. Nachtigall
University of Hawaii, Marine Mammal Research Program
nachtiga@hawaii.edu, 808 247-5297

Background

The effects of sound on marine mammals is best determined by first measuring what animals hear. Audiograms can be obtained from stranded animals before naval exercises to determine baseline levels and, if animals strand during or after exercises like RIMPAC, the effects of naval sounds can be determined. Echolocation is essential for animal foraging and therefore required for healthy populations of toothed whales and dolphins. Knowledge of the effects of sound on echolocation and an understanding of echolocation processes is therefore vital. Echolocating whales produce loud sounds themselves (up to 238 dB) and recent work demonstrates that, partially for protection of their own hearing, whales and dolphins reduce their hearing sensitivity. Recent work has shown that whales will reduce their own hearing sensitivity by 15 dB if they are warned that a loud sound is about to arrive. Further knowledge about this self-mitigation phenomenon is required.

Objectives

-Different species of whales and dolphins hear differently. We have basic measures on only 17 of the 85 species of whales and dolphins. Therefore it is critictal to measure the hearing of new species.
- Examine the directionality of hearing tones and clicks to determine hearing pathways.
- Determine focusing capabilities of the outgoing echolocation beam patterns
- Measure whether most odontocetes control their hearing sensitivity during echolocation
- Measure whether animals will reduce their hearing sensitivity when presented with a warning signal predicting impending loud sound and determine the best parameters for self-mitigation.
- Respond to all stranded cetaceans before, during and immediately after Navy exercises to establish hearing baselines and measure the effects of Naval sonar on cetaceans in the Pacific.

Methods

Audiograms from stranded animals are obtained using evoked auditory potential measurements taken from skin surface electrodes embedded in suction cups. Amplitude modulated sounds are played at various frequencies above and below threshold. Peak evoked potential levels are determined via Fourier transforms that are then examined with linear equations to determine zero crossing points to estimate thresholds for audiograms. New audiograms of the long-finned pilot whale and beaked whale were published.

The directionality of hearing tones and clicks is determined by training the dolphin to swim into a hoop and then bite a bite bar to precisely position its head. Sounds are then played from a large variety of positions in the free field and evoked potential thresholds are determined in a manner similar to those obtained for stranded animal audiograms.

Examination of focusing capabilities is conducted by placing a 15 element acoustic array in front of the hoop-stationed animal as it does echolocation detection and discrimination tasks. The distance from the animal to the array is varied and the angles of the outgoing click are measured as a function of frequency and distance to the array. Recently published efforts demonstrate that the false killer whale differentially focuses its outgoing echolocation beam depending on target distance and task difficulty.

Measures of whether animals control their hearing while echolocating are collected by placing suction cup surface electrodes on the whale, dolphin or porpoise while it echolocates. Measures of evoked potential responses of the animal to its own outgoing echolocation signals as well as its echo returns are measured in a variety of echolocation tasks including varying size of targets, distance to targets and whether the targets are real or phantom targets produced by the computer and played back appropriately to the animal when it produces an outgoing click. Many recent publications demonstrate fine control of hearing sensitivity during echolocation. Measures of whether a whale will reduce its hearing sensitivity when presented with a warning signal just before a loud sound were also measured with evoked potentials. The whale was stationed within a hoop station while listening to the test sound stimuli. The sounds

were played through a piezoceramic transducer positioned at 1 m in front of the hoop station. The test sounds were trains of tone pips, 16 pips a train with a rate of 875/s, each pip containing 8 cycles of 20-kHz carrier frequency. These trains were presented at a rate of 20/s during the test period that varied randomly from trial to trial, either from 1 to 9 s (in one series) or from 20 to 140 s (in another series). Levels of test sounds varied up and down from 80 to 120 dB re 1 microPa by 5-dB steps. In a series of 1 to 9 s-long signals, one level was presented during a trial; in a series of 20 to 140 s-long signals, one to five levels were presented during a trial. These test sounds evoked rhythmic brain potentials (auditory evoked potentials, AEPs) following the rate of tone pips, i.e., 875/s. The AEPs were picked up through suction-cup electrodes, amplified, analog-to-digitally converted, and averaged on-line within every trial and additionally off-line among the trials. The averaging procedure allowed extraction of AEPs from the background noise and detection of AEPs as low as tens of nV. The extracted rhythmic AEPs were Fourier transformed to obtain their frequency spectra. The spectrum peak magnitude at the stimulation rate (875 Hz) was taken as the response magnitude that was plotted as a function of test-signal level. The level resulting in zero response magnitude was taken as a threshold. The baseline trials contained only these test sounds. After obtaining the baseline data, the conditioning trials were presented. In the conditioning trials, a loud sound immediately followed the test sound. The loud sound was a 20-kHz tone of a level of 170 dB re 1 microPa lasting 5 s

Results

The results of the reduction of hearing sensitivity measures showed that the whale reduced her hearing by 15 dB if the warning occurred between 0 and 9 sec but no reduction in hearing occurred if the tone occurred between 20 and 140 sec before the presentation of the loud sound as shown in Figure 1.

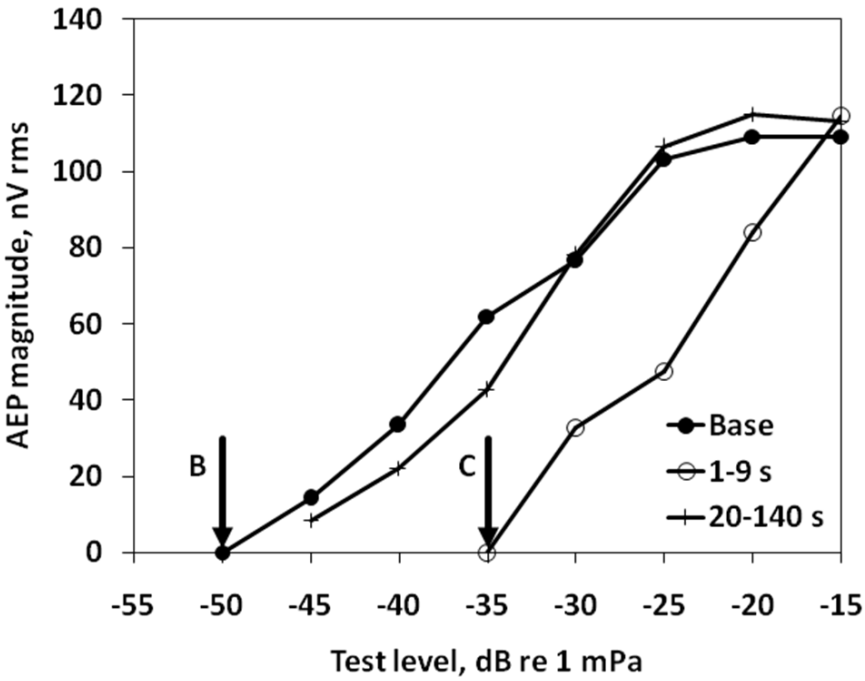


Figure 1. Auditory evoked potential (AEP) root-mean-square (rms) magnitude (ordinate) as a function of test sound level (abscissa). *Base* – baseline (no loud tone), *1-9 s* and *20-140 s* – loud tone delayed 1 to 9 and 20 to 140 s, respectively. Arrows mark baseline threshold (B) and conditioned threshold (*C*), respectively.

PINNIPED HEARING IN COMPLEX ACOUSTIC ENVIRONMENTS

Colleen Reichmuth
Institute of Marine Sciences, Long Marine Laboratory, University of California Santa Cruz
coll@ucsc.edu, 831.459.3345

Background

Following more than a decade of intensive research into the basic hearing capabilities of marine mammals, there remains a pressing need to extrapolate laboratory data to real world scenarios involving potentially deleterious anthropogenic noise exposures. Pinnipeds are marine mammals that may be uniquely vulnerable to noise in nearshore environments due to their amphibious lifestyle, their reliance on sound for communication, and their broad range of aerial and underwater hearing sensitivity. Direct studies of auditory capabilities in carefully controlled but realistic testing environments are required in order to strengthen predictive models of hearing and the effects of noise for pinniped species.

The knowledge gained from this research contributes to noise exposure criteria developed for free-ranging marine mammals, which in turn are used by the operational Navy, industry, and US and international regulators to establish appropriate guidelines and mitigation for noise emissions in sensitive marine environments.

Objectives

The long-term goals of this effort are to improve present understanding of (1) the sound detection capabilities of pinnipeds and (2) the auditory effects of noise exposure on pinnipeds.

Specifically, we aim to improve understanding of hearing in seals and sea lions by extending psychoacoustic profiles of sound detection obtained from simplified auditory processing tasks to those obtained under increasingly complex acoustic conditions. We will test and develop metrics for acoustic weighting functions to inform risk assessments for representative species, and examine how signal structure and noise environments interact to constrain auditory performance in motivated, trained animals. We will relate our measurements of auditory performance obtained in the laboratory to findings from concurrent field studies of acoustic communication in fluctuating natural noise backgrounds.

Methods

Hearing thresholds for synthetic and biologically significant signals are obtained from trained individuals from representative pinniped species including California sea lions and harbor seals. The auditory scene in which the subjects are tested varies by physical medium (air or water) and with respect to the level, type, and composition of background noise that is present. Careful application of operant conditioning techniques and signal detection theory allows specific experimental questions to be addressed while reducing confounding variability. This behavioral approach enables detailed studies that comprise whole animal measures of hearing including auditory reception and perception.

Psychoacoustic methods are used to examine the hearing of trained seals and sea lions in controlled aerial and underwater testing environments.

Comprehensive field studies of vocalizations, typical ambient noise conditions, and functional communicative behavior are also conducted to improve understanding of hearing by pinnipeds in naturally complex acoustic environments.

Results

The original timeline of 36 months was extended to 48 months to support completion of the project and to accommodate funding delays. About 60% of the revised timeline has been used to date.

Underwater hearing in sea lions. A young California sea lion was added to the program and trained for hearing testing. A detailed underwater audiogram was obtained in the absence of interfering noise. The results from this animal are consistent with a revised interpretation of earlier data obtained for this species (see Reichmuth and Southall, 2010) and can be considered the most appropriate hearing data currently available for otariid pinnipeds (15 species of sea lions and fur seals).

Hearing and aging in sea lions. Data on presbycusis, or age-related hearing loss, are rare for long-lived mammals other than primates. Such data provides insight into likely hearing demographics within a species or functional hearing group. Data obtained through periodic testing of a California sea lion over a >10 year period shows substantial loss of auditory sensitivity. Hearing loss appeared earliest and was greatest in the high frequency portion of the audiogram (>10 kHz) but eventually extended across the frequency range of hearing. Measurements made both in air and under water reveal similar trends.

Low frequency temporal processing in seals. To address conflicting studies concerning the temporal processing of acoustic signals by seals, we tested the hypothesis that seals may have unusually long integration times for low-frequency auditory signals. Auditory thresholds and precise reaction times were obtained for low frequency signals of different durations in air and under water. Results confirmed that integration times for 100 and 200 Hz tones were less than 500 ms. These data will improve predictive range estimates for the detection of low-frequency signals by seals.

Assessment of weighting functions derived from equal response latency measures. The most extensive study completed thus far is an evaluation of the metric of reaction time as a proxy for perceptual loudness measurements. Equal loudness profiles are the basis of useful auditory weighting functions for humans but comparable data are difficult to acquire from animals. Studies with primates indicate that sound level contours drawn from equal reaction times across the frequency range of hearing approximate those of equal perceptual loudness. To investigate the utility of this approach in seals and sea lions, we measured response latencies for signals of constant frequency but varying sound pressure level. The resultant latency-intensity functions for each test frequency were used to develop equal latency contour plots. The data obtained show that auditory reaction times (72 to 980 ms) can be reliably measured and that they behave predictably as signal amplitude changes over the frequency range of hearing. The pinniped *M-weightings* currently used for regulatory purposes are conservative and can be improved by applying these data.

Auditory masking in progressively complex testing scenarios. This research is underway and will be completed within the next 18 months.

Acoustic communication in wild pinnipeds. To better understand hearing and acoustic communication in natural noise environments, comprehensive observations of ambient noise, vocal signaling, behavioral interactions, physical characteristics, and spatial movement patterns are conducted at pinniped breeding rookeries. These studies enable accurate characterization of relevant biological signals and representative background noise that inform ongoing laboratory experiments. In additional, these studies also provide specific and unique perspective into functional communication systems that is presently lacking for other marine mammals.

Notes:

DOLPHINS USE MULTIPLE AUDITORY MECHANISMS FOR DETECTING TONAL SIGNALS IN NATURAL AND ANTHROPOGENIC NOISE

Brian K. Branstetter
National Marine Mammal Foundation
brian.branstetter@nmmpfoundation.org, (808) 779-3077

Background

Over the past two decades, a concerted effort has been made to understand the potential negative effects of anthropogenic noise on marine mammals. Research has been tailored to address specific aspects of the so-called "zones of noise influence" that include: 1) zones of audibility, 2) zones of responsiveness 3), zones of masking, and 4) zones of hearing loss, discomfort or injury. Significant advances in scientific understanding have been made primarily in the areas of the "zones of audibility," and "zones of hearing loss, discomfort or injury." Comparably, our current understanding of auditory masking is rudimentary and restricted to a handful of studies which employ noise types (i.e., Gaussian noise) that likely overestimate masking thresholds that would occur in realistic environments. Although measures of temporary threshold shifts (TTS) have been used extensively in Navy compliance documents to determine safety zones for marine mammals, the negative impact of auditory masking from anthropogenic noise is an issue the Navy needs to understand in the immediate future. Depending on the temporal nature of the received sound, auditory masking will affect a much larger percentage of an animal population near a noise source compared to noise induced hearing loss (TTS), which requires animals to be in close proximity to a high amplitude source. Masking predictions based on models developed from white noise maskers (i.e., the power spectrum model) are not realistic and overestimate the level of masking that actually occurs with environmental maskers. This study is designed to directly address this issue by measuring masking patterns using noise sources marine mammals encounter in the wild.

Objectives

The objectives of this effort are to: 1) record and characterize environmental noise sources (e.g., anthropogenic, weather related, biological), 2) conduct psychophysical experiments to measure auditory detection, discrimination, and recognition thresholds, 3) develop and test hypotheses to describe the auditory processing governing the resulting masking patterns, and (4) develop predictive quantitative models to describe masking with environmental noise.

Methods

For detection thresholds, the dolphin's ability to detect a 10 kHz tone masked by a variety of noise types was measured using a standard band-widening paradigm and a psychophysical procedure. Maskers included natural noise (rain, snapping shrimp, ice squeaks), anthropogenic noise (pile saw, boat propeller cavitation) and synthetic noise (Gaussian and comodulated noise). For discrimination thresholds, a same-different paradigm was used where the dolphin was trained to discriminate between frequency modulated "whistle-like" sounds in the presence of the noise types used in the detection paradigm.

Results

Only the results for detection thresholds are reported here. For most noise types, detection thresholds increased as noise bandwidth increased up to 1 kHz (the dolphin's critical bandwidth at 10 kHz). Masking patterns for narrow-band maskers were similar regardless of the masker type. However, for noise bandwidths greater than 1 kHz, masking patterns diverged by as much as 23 dB depending on the noise type. The pressure spectral density of the noise (dB re 1 μPa^2 / Hz) provided reasonable predictions for Gaussian, rain, pile saw, and boat noise masking patterns. Additional experiments suggested that mechanisms related to temporal envelope processing (across-channel envelope comparison and within-valley listening) determined masking patterns for snapping shrimp and comodulated noise. A linear model with two parameters related to across-channel envelope coherence and the pressure spectral density provided good fits to masked threshold data (FIG2). Detection thresholds in ice squeak noise, which proved to be the most effective masker, were related to the dolphin's inability to discriminate the signal from the background noise rather than its inability to detect the signal. These results demonstrate that the dolphin auditory system uses multiple mechanisms for signal detection in complex noise and threshold predictions cannot

be reliably predicted by spectral density estimates alone. With the exception of ice squeak noise, a simple linear model with two parameters: 1) the pressure spectral density and 2) across-channel envelope coherence provided good masked threshold predictions.

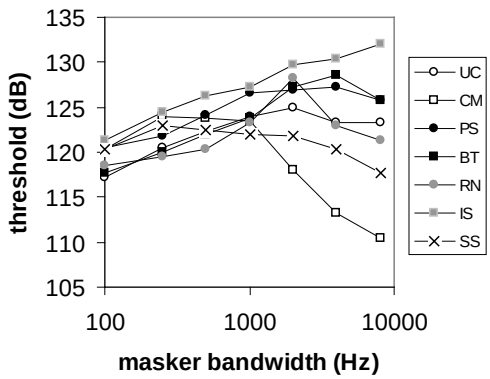


FIG1. Detection thresholds as a function of masker bandwidth for each noise type. (UC=Gaussian, CM=comodulated, PS=pile saw, BT = boat noise, RN = rain, IS = ice squeaks, SS = snapping shrimp). All noise types had a flat pressure spectral density of 95 dB re 1 μPa^2 / Hz. Masking patterns were similar up to 1 kHz masking bandwidth. Masking patterns diverge for bandwidths greater than 1 kHz. Each data point represents the average of four thresholds. Error bars were removed for clarity but the standard deviation was less than 3 dB for each data point.

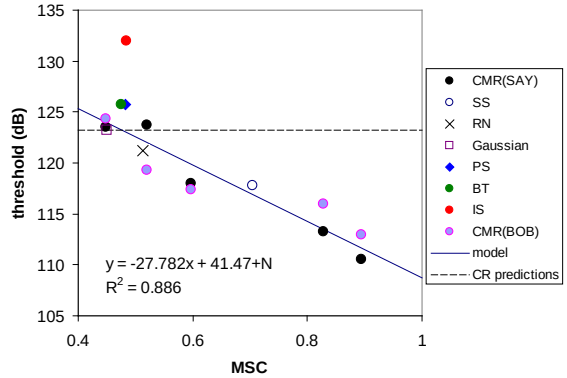


FIG2. Detection thresholds as a function of the magnitude squared coherence (MSC) between the Hilbert envelopes of a noise band centered on the 10 kHz signal (9.5 – 10.5 kHz), and flanking bands (6 – 9 kHz and 11 – 14 kHz). The parameter N in the linear model is the noise pressure spectral density (PSD). The noise types are the 8 kHz bandwidth noise from FIG1, with the addition of masked thresholds in comodulated noise from two separate experiments (CMR(SAY) and CRM(BOB)). The dashed line represents prediction using the dolphin's critical ratio (CR) of 28 dB. These predictions overestimate threshold with noise types that have a high degree of across-channel coherence, indicated by a large MSC. Thresholds can be predicted with a much higher degree of accuracy when using a model (solid line) that incorporates both PSD and MSC of each noise type.

Notes:

VIRTUAL EXPERIMENTS IN MARINE BIOACOUSTICS: WHALES, FISH, AND ANTHROPOGENIC SOUND

•Ted W. Cranford[1] and Petr Krysl[2]
1. *Quantitative Morphology Consulting, Inc., San Diego, CA*
2. *Structural Engineering, University of California, San Diego, CA*
Ted.W.Cranford@gmail.com
619-226-7944

Background

Ocean noise levels, particularly in the low frequency range, have risen steadily over the past 50 years with largely unknown environmental consequences. The ecological and commercial importance of this issue, with respect to fishes and marine mammals, emerges from the likelihood that these animals use low frequency sound and may experience significant impacts as a result of the increasing din of anthropogenic noise. As a consequence, it is prudent to increase our understanding of the impacts of anthropogenic sounds upon federally-protected marine mammals as well as ecologically and commercially valuable fishes.

Objectives

This project has three primary objectives: #1 – Finite Element Modeling (FEM) Validation. #2 – Build a device to measure elastic properties of tissues. #3 – Test the efficacy of simulating the effects of sound on fish using our FEM techniques.

Methods

Our team has pioneered a suite of techniques that combine anatomic geometry obtained from CT scanners, measurements of tissue elasticity, and custom FEM software (the Vibroacoustic Toolkit), which produces a versatile computational environment for acoustic simulations. These techniques can be used to assess acoustic exposure across a broad spectrum of taxa.

Results

Objective #1: We performed *three* separate tests of validation for our vibroacoustic simulation methodology. The first test compared the biosonar transmission beam formed by live animals to those generated in our simulations. This test showed that the beam axis and dimensions are similar in the two cases (Fig. 1), validating our methodology.

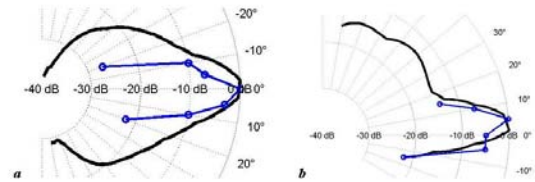


Fig. 1: Polar plot of the beam pattern in the horizontal plane (a) and in the vertical plane (b) for the simulations (black lines). The blue curve represents the results of Au et al. (1986).

These results also provided unique insights as to how the biosonar beam is formed, suggesting the independent contributions and synergistic effects given by various aspects of anatomic geometry and the details of sound source configuration.

The second validation case takes advantage of the measurements by Norris and Harvey of received sound pressure at various locations of a fresh cadaver of a bottlenose dolphin due to sound signals generated by transducer moved around the head of the animal. (Our simulations are at this point preliminary as we are working with an inadequate CT scan of the animal.).

The third test is currently underway and the process dictates that we remain blind to the results until all of the work is completed. In this test, the head-related-transfer-function (HRTF) will be described for a bottlenose dolphin using our Vibroacoustic Toolkit (Fig. 2). Comparative measurements of dolphin sensitivity to sound source location are being carried out at the University of Hawaii by Paul Nachtigall and his colleagues.

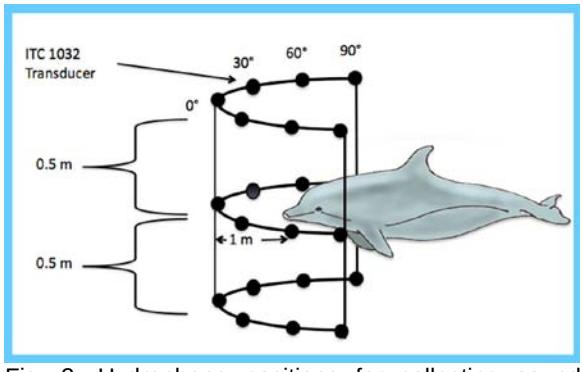


Fig. 2: Hydrophone positions for collecting sound source position sensitivity.

Objective #2: Our effort to build a device to measure tissue elasticity has been delayed by a false start. At this point we have formulated a measurement strategy that relies on simultaneous measurement of the bulk modulus from time-of-flight experiments and the force-displacement (plus phase shift) response of a linear rheometer. Computational techniques will be used to separate out the shear modulus from the known bulk modulus and the force-displacement measurement.

Objective #3: This objective attests to the robustness of our methodology by addressing vibroacoustic questions in disparate taxa. The results are remarkable, suggesting that we have uncovered a principle that could contribute to understanding how fish discriminate the frequency and direction of sounds whose wavelengths are much longer than their body. The key appears to be that the set of six otoliths are set into *rocking* motions in the presence of a progressive acoustic field. Since the otoliths sit atop beds of sensory hair cells, the collective rocking motions appear to change with frequency and direction of the acoustic stimulus and, consequently, the input to the sensory system. This work is complementary to our general methodology applicable to the study of bioacoustics in mammals and fish, and, perhaps, to aquatic organisms more broadly.

Notes:

IN VIVO DETERMINATION OF THE COMPLEX ELASTIC MODULI OF CETACEAN HEAD TISSUES

Peter H. Rogers, Michael D. Gray and James S. Martin
G. W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332
phone: (404) 894-3235 fax: (404) 894-7790 email: peter.rogers@me.gatech.edu

Background

This project is motivated by the lack of information regarding *in-vivo* viscoelastic properties of cetacean head tissues. These properties are critical for development of structural acoustic models of the cetacean head, which are being developed in order to better understand biomechanics of sound reception and production, and to understand and mitigate any harmful effects of anthropogenic sound on their health and behavior. The development and validity of these models is limited by an almost complete lack of knowledge of the mechanical properties of the constituent living tissues.

Objectives

The primary technical objective is to remotely generate and detect mid-frequency shear waves within a living cetacean and to use the measured propagation parameters waves to obtain the complex shear moduli. A further technical objective is to extract moduli for intra-mandibular and intra-cranial tissues. The final objective is to develop a prototype portable version of the technology and use it to perform examinations of stranded animals.

Methods

The foundation of the work is the capability to remotely generate shear waves in soft tissues and observe their propagation with an ultrasound-based non-invasive system. The general approach for generation, reception and interpretation of the tissue wave fields is based on a new medical imaging technology called radiation force elastography[1]. This class of techniques, which has been demonstrated in human soft tissues, cannot be directly translated to use on cetacean head tissues due to the need to propagate through much thicker tissues and through skull bone, all the while keeping within safety limitations for ultrasound exposure[2]. The current focus of the *in-vivo* program is to overcome these challenges through novel redesign of the concepts for both elastic wave generation and observation.

An embodiment of the shear wave generation system is being implemented wherein a ring-like forcing volume is formed by the ultrasonic source. As the ring radius is changed through a change in the ultrasonic carrier frequency, a fixed receiver measures the change in phase of the waves converging at the center of the ring. This receiver is a modified version of an ultrasonic Doppler vibration measurement system called NVMS, developed at Georgia Tech[3]. Algorithms have been developed to enable the magnitude and phase of vibration to be determined, as well as the range (tissue depth) along the ultrasonic beam at which the vibration is being measured. By measuring the phase of the shear wave converging from sources with two different ring radii as a function of frequency, the propagation speed and loss can be determined.

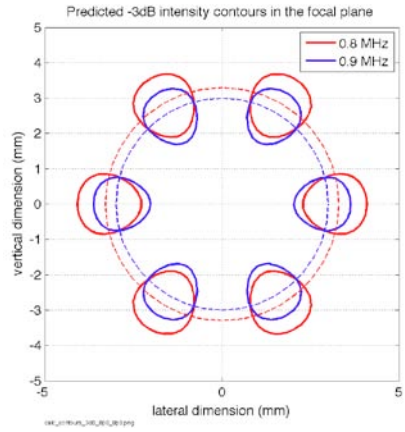
Results

Transducer calibration

3-D field calibration scans of the new system transducers were conducted in fresh water. Both transducers behaved as well as or better than expected from predictions made during the design phase. Examples are shown in Figure 1 of the normalized focal plane (z=12 cm) intensity contours produced by the force generation transducer. Each lobe of the contour pattern can be thought of as a local force acting normally to the page. The ability to shift the pattern radius with carrier frequency was as expected, and confirmed the mechanism by which shear speed is derived.

Vibrometer development

A method for artifact-free pulse compression was developed in order to reduce the minimum



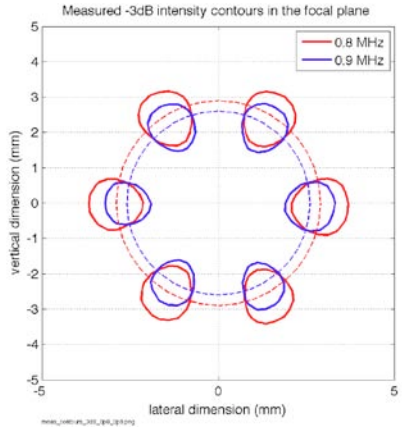


Figure 1: Examples of predicted and measured ultrasonic fields

detectable signal of the system shear wave measurement capability. The scheme was verified using a numerical model for system performance and, in the absence of noise, it was found to introduce no numerical distortion to the measurements above the level of machine precision for the requisite computations. Experiments performed with a tissue phantom indicated a reduction of 10-20 dB in the minimum detectible displacement, depending on the type of drive signal used. A paper describing prior vibrometer development under this program was published in JASA[4].

System testing

Laboratory testing of the assembled prototype system is underway. Subsequent testing is being planned for this year in coordination with Dr. Darlene Ketten (WHOI) for deceased animals and Dr. Dorian Houser (NMMF) for live bottlenose dolphins.

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Notes:

THE METABOLIC COSTS OF SOUND PRODUCTION IN ODONTOCETE CETACEANS

Dawn P. Noren, Marla M. Holt, Robin C. Dunkin, Terrie M. Williams
NOAA NMFS Northwest Fisheries Science Center
dawn.noren@noaa.gov, 206-302-2439

Background

Recent studies have demonstrated that marine mammals respond to increases in anthropogenic noise by increasing the amplitude, duration, and/or repetition rate of their vocalizations as an anti-masking strategy. Although results from recent studies suggest that several marine mammal species readily modify the parameters of their acoustic signals to compensate for masking noise, potential energetic costs of such compensation behavior are unknown because no empirical data on the energetic costs of sound production in marine mammals exist. The Population Consequences of Acoustic Disturbance (PCAD) model has been proposed as a framework to address the challenging task of linking anthropogenic sound exposure to population level effects in marine mammals. Data on the energetic cost of dolphin vocalization from this study can be used to assess the biological significance of vocal compensation in response to sound exposure and populate transfer function 2 (transfer function between behavior change to life functions immediately affected) in the PCAD model.

Objectives

The objective of this study was to measure the metabolic costs of whistles and other communicative sounds produced by two captive bottlenose dolphins to assess impacts of noise-induced vocal compensation. Because a study such as this had never been attempted in cetaceans, the focus of the first year (Phase 1, 2010) was to determine whether the metabolic cost of sound production could be measured in dolphins, and the second year (Phase 2, 2011) focused on determining the metabolic cost of vocal compensation in bottlenose dolphins.

Methods

For both phases of the study, the metabolic cost of sound production was measured in two captive male Atlantic bottlenose dolphins (Tursiops truncatus) maintained at the University of California, Santa Cruz, Long Marine Laboratory. For Phase 1 of the study, the dolphins were trained to produce social signals on command while stationed under a metabolic dome. For Phase 2 of the study, the dolphins were trained to produce relatively higher and lower amplitude sounds of the same type on command using two different discriminative cues (one for “loud” and one for “quiet”). The sounds produced by the captive dolphins of the current study are representative of those found in wild, free-ranging populations. During both phases of the study, each dolphin produced the same sound type during his vocal bouts, but the sounds produced were qualitatively different between the two dolphins. Specifically, Primo produced a whistle while Puka produced a pulsed squawk or squeak-like sound. Experimental trials were conducted in the morning, and only one trial per animal was conducted each day. To ensure that the dolphins were post-absorptive during trials, the dolphins were fasted overnight. Oxygen consumption was measured using open-flow respirometry. Experimental trials consisted of one dolphin remaining at the water surface under the metabolic dome for one 10-minute period of rest (to determine baseline resting metabolic rate, RMR), followed by two consecutive one-min bouts of sound production (the two bouts were separated by 15-20 sec of silence), and concluded with a recovery period (minimum of 10 minutes). For Phase 2 of the study, both trial types (“loud” and “quiet”) were run within one week’s worth of data collection. All experimental trials were acoustically monitored in real-time and recorded for further analysis using a calibrated hydrophone at a sampling rate of 96 kHz. In all Phase 2 trials, a contact hydrophone was placed on the dolphin’s melon for more precise measurements. During Phase 2, separate RMR trials were also conducted during weeks without experimental trials for comparison. During RMR trials, dolphins rested quietly for 10 min under the dome while oxygen consumption was measured. For both Phase 1 and 2, respirations were also recorded during all trials.

Results

In phase 1, a total of 28 trials (14 per dolphin) were completed and 13 trials per dolphin were included in the analysis. Primo produced an average of 63.3 (± 7.2 SD) whistles during the

trial vocal period. Mean whistle duration was 1.08 sec (± 0.26 SD) with a mean interval between the start of each whistle of 1.91 sec (± 0.20 SD). The geometric mean received level of Primo's whistles was 126 dBrms re: 1µPa (± 3.4 SD). During Phase 1, Puka produced an average of 242 squawks (± 42.7 SD) per trial. Mean duration was 0.167 sec (± 0.037 SD) with a mean interval of 0.488 sec (± 0.108 SD). The geometric mean received level of Puka's sounds was 114.6 dBrms re: 1µPa (± 2.0 SD). Little variation in the frequency domain was observed among vocalizations within a dolphin. It should be emphasized that the received levels reported here were measured from a hydrophone in the test pool (at 0.5 m water depth) to compare vocalization performance between trials and not to estimate source levels since sounds were produced under a reverberant metabolic dome at the air-water interface. Thus, the received levels are likely underestimates of water propagated signals since a significant amount of sound energy was propagated in air under the dome. Metabolic rates (MRs, ml O2 min^{-1} kg^{-1}) measured during vocal bouts were significantly greater than RMRs (estimated from a portion of the baseline periods). The percent increase over RMR values varied by trial and by individual. For both dolphins MRs usually remained elevated for a minimum of 2 minutes following the vocal bouts. A sophisticated analysis is currently being refined to determine the exact duration of time required for oxygen consumption values to return to baseline levels as well as the total metabolic cost of the vocal bouts (metabolic cost of vocal bouts plus metabolic cost of recovery duration) for each trial. Although metabolic rates during and immediately after sound production were higher than baseline resting levels, respiration rates recorded for two minutes immediately prior to the vocal bouts, during the vocal bouts, and for two minutes immediately following the vocal bouts did not differ significantly for either dolphin. These results indicate that increased oxygen consumption was due to increased metabolic demand related to sound production rather than to changes in breathing patterns. The data from Phase 1 of the study demonstrate that this method is successful in assessing the metabolic cost of sound production in odontocete cetaceans. Furthermore, the data show that there is a measurable energetic cost of sound production in bottlenose dolphins, and cost extends beyond the time that the animal is actually producing sounds. In Phase 2 of the study, a total of 60 trials (30 per dolphin) were completed. A few trials from each dolphin will be excluded from the final analysis due to unsatisfactory behavior. This component of the study aimed to determine if there is a metabolic cost associated with noise-induced vocal compensation (i.e. an increase in sound amplitude or duration is correlated with an increase in oxygen consumption during trials). The goal of Phase 2 was to conduct two trial types ("quiet" and "loud" of equal sample size for each dolphin) that differed by 10-15 dB. Both dolphins were able to increase their sound levels in "loud" trials, but only Puka was capable of increasing levels by 10-15 dB. Preliminary analyses suggest that differences in vocal performance between "quiet" and "loud" trials determines whether oxygen consumption values measured during vocal bouts significantly differ by trial type. Interestingly, both dolphins had a tendency to produce longer vocalizations during "loud" trials as well. Thus, an analysis of sound energy (quantified as sound exposure level or energy flux density) is warranted in addition to exploring increased vocal amplitude or duration as separate effects on metabolic rates. Empirical data collected from this study will provide valuable information about sound production costs in odontocetes including costs of modifying acoustic signals in response to anthropogenic sound exposure. Specifically, this study will provide important input data to populate transfer function 2 in the PCAD model which can then be used to assess the biological significance of such responses to anthropogenic sound exposure.

Notes:

IMAGING THE LUNG UNDER PRESSURE

[1,2]A Fahlman, [2]M J Moore, [2]D R Ketten
[1]*Texas A&M-Corpus Christi,* [2]*Woods Hole Oceanographic Institution*
andreas.fahlman@tamucc.edu

Background

Recent theoretical work suggests that beaked whales commonly experience end-dive N_2 levels that would cause a significant proportion of DCS cases in terrestrial mammals (Hooker et al., 2009). A sensitivity analysis showed that the physical properties (compliance) of the respiratory system and its effect on gas exchange (alveolar collapse depth) are important variables that determine the N_2 levels in blood and tissues. Only a few studies have investigated the anatomy and mechanical properties of any marine mammal respiratory system (Denison and Kooyman, 1973; Leith, 1976) and no study has attempted to measure the properties of the various parts of the lung (upper vs. lower airways) across species. Because precise knowledge of how marine mammal lungs compress and collapse under pressure affects gas exchange, we sought to define the physical properties of the respiratory system in several phocids and odontocetes.

Objectives

1. What are the compliances of the lower (alveoli) and upper (trachea and bronchi) respiratory system in marine mammals (seal and whale)?
2. Do species differences in compliance values result in large differences in collapse depth?
3. Estimate the total lung capacity in a range of marine mammals.

Methods

1. Fresh excised lungs from bycaught and stranded phocids and odontocetes were used to measure the relationship between pressure and volume (compliance) of the intact respiratory system (lung + conducting airways) and conducting airways (trachea).
2. A hyperbaric chamber with CT imaging capabilities was used to image intact specimens. Imaging software (AMIRA) was used to estimate air volumes of the upper and lower respiratory systems at multiple pressures and the results used to predict the alveolar collapse depth.

Results

The relationship between pressure and volume from excised lungs were similar during inflation between phocids and odontocetes. During deflation, the curves diverged between phocids and odontocetes, with lower recoil pressures in the phocids (Fig. 1). These data suggest that the collapse depth may be greater for odontocetes (dolphin and harbor porpoise) as compared with phocids. The results agree with observations on the hyperbaric chamber CT images (see Fig. 4 in Moore et al., 2011).

The anatomical characteristics of the conducting airways (Fig. 2) vary among species in ways that affect lung compliance (Fig. 3). The grey seal (*Halichoerus grypus*) had complete cartilaginous tracheal rings, while the harp seal (*Phoca groenlandica*) had open ended, horseshoe-shaped rings with connective tissue between the prongs. Odontocetes had overlapping rings and accessory bronchi that branched near the pharynx.

Gross tracheal morphology varies greatly and appears to affect compliance and may correlate to dive performance or ventilation rates. The tracheal compliance was greater in odontocetes and otariids compared to phocids. An exception was young grey and elephant seals (Hg1 and Ma). In the grey seal, the compliance decreased with age (Fig. 3).

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Figure 1: Pressure-volume loops from excised lungs of odontocetes and phocids (Fahlman et al., 2011).

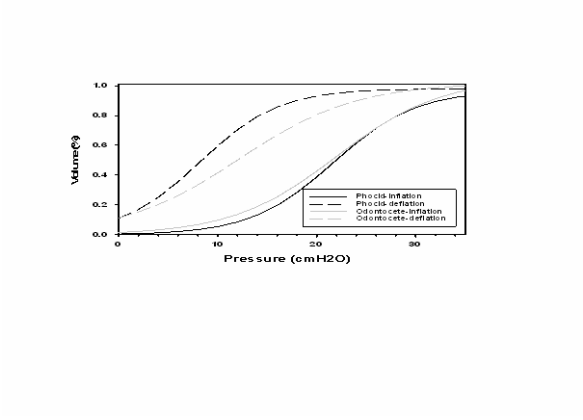
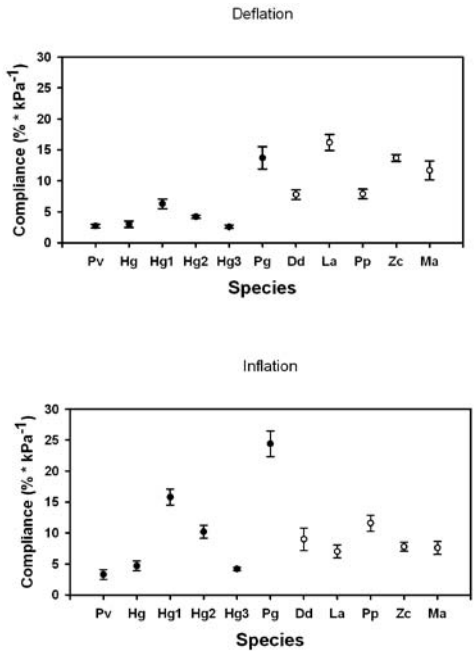


Figure 2: Excised tracheas (from left): Harp seal (*Phoca groenlandica*), white-sided dolphin (*Lagenorynchus acutus*), grey seal (*Halichoerus grypus*).

Figure 3: Compliance estimate of excised tracheas during inflation or deflation. The compliance was determined as the slope of the relationship between pressure and volume by fitting the data with a GLM using individual animal as a random factor. Pressure was expressed as the absolute trans-mural pressure and volume as a percent change from the internal volume when the trans-mural pressure was 0 kPa. Species Pg = *Pagophilus groenlandicus*, Pv = *Phoca vitulina*, Hg= *Halichoerus grypus,* La = *Lagenorhynchus acutus*, Dd = *Delphinus delphis*, Pp = *Phocoena phocoena,* Zc=*Zalophus californianus*, Ma= *Mirounga angustirostris.* Hg1-3 represents grey seals of decreasing size/age.



Notes:

PHYSIOLOGICAL MONITORING IN DIVING MAMMALS

[1,2]A Fahlman, [2]M J Moore, [2]P Tyack, [3]F Walfre, [3]W Zapol, [3]R Anderson, [4]T Austin
[1]Texas A&M-Corpus Christi, [2]Woods Hole Oceanographic Institution, [3]Massachusetts General Hospital, [4]PAXARMS
andreas.fahlman@tamucc.edu

Background

Recent theoretical work suggests that beaked whales commonly experience end-dive N_2 levels that would cause a significant proportion of decompression sickness (DCS) cases in terrestrial mammals (*1*). Model sensitivity analyses suggested that the level of the dive response (cardiac output and the blood flow distribution) strongly influences the N_2 levels in blood and tissue, and thereby DCS risk (*1-4*). It is assumed that all breath-hold diving marine mammals experience a dive response while submerged, with a reduction in cardiac output and a re-distribution of blood to the core. But the precise knowledge of how deep diving whales distribute blood flow has never been measured. Improving such knowledge would significantly enhance our ability to predict end-dive blood and tissue N_2 levels, and determine if deep diving whales are at risk of DCS. The objective with this study is to create an invasive data logger for deep diving whales. We hope to attach the logger to freely diving sperm whales at the end of the project.

Objectives

This project is separated into two aims:

Aim 1) Develop a new generation of tags/data logger for marine mammals that will contain a sensor to be implanted into the muscle. The logger will collect physiological data from muscle tissue in freely diving marine mammals. The sensor will be tested and calibrated in terrestrial mammals at Massachusetts General Hospital, Boston.

Aim 2) The data logger will be tested in freely diving marine mammals in the field, and muscle O_2 saturation data will be collected.

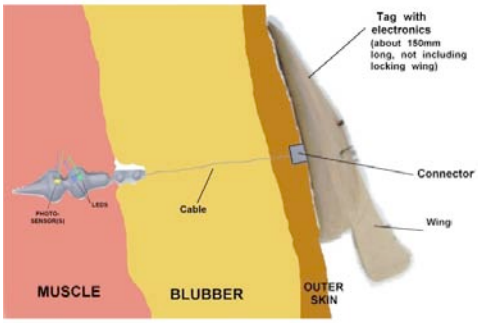
Methods

Aim 1) A near infrared spectrophotometer connected to a data logging device is being developed and used to measure myoglobin/hemoglobin O_2 saturation in freely deep diving whales (e.g. beaked whales, sperm whales). The unit is being developed based upon the successful construction of an oximeter used in Weddell seals (*5*). A delivery device will be fabricated that will allow the optical probe to be implanted into the muscle. The sensor and photodetector will be inserted through the skin and blubber into the muscle. The flexible cable will allow the muscle to move freely, resulting in minimal discomfort. Experiments on terrestrial mammals and stranded or by-caught (post-mortem) marine mammals are being conducted to assess the impact of the implantation to minimize the potential for inflammation and hematoma (*6*).

Aim 2) The data logger will be tested on a variety of diving marine mammals over 2 field seasons. We aim to perform trans-location experiments in Northern elephant seals (*Mirounga angustirostris*) with collaborators at University of California Santa Cruz (UCSC). This allows us to perform controlled field experiments and to determine if the data logger is able to collect the physiological data and to assure minimal tissue trauma. In the second field season we aim to test the oximeter when implanted into the muscle of freely, deep diving whales (sperm whales).

Results

Initial measurements indicated that there is a lot of lateral movement between the blubber and muscle layers in whales. We therefore aim to attach the LED and photosensor via a ballistic device, which will be connected to the external data logger (Fig. 1).

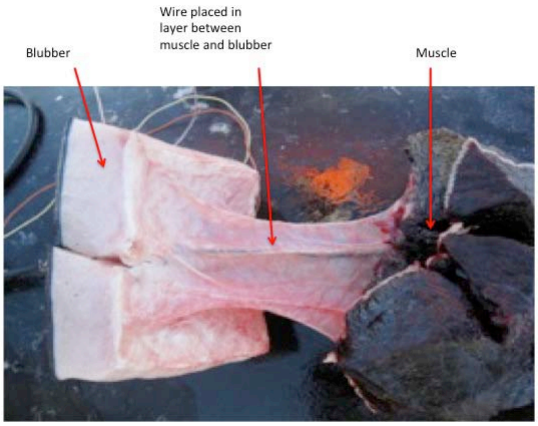


The data logger/oximeter sensor package is being delivered using a modified rifle (Fig. 2). The system was tested on stranded post-

mortem pilot whales. These tests verified that the forces during impact did not damage the sensor. In addition, the wire was placed in the blubber/muscle interface (Fig. 3) allowing lateral movement of the two interfaces without damaging the tissues or moving the sensor.

Figure 2 Prototype of rifle, Paxarms Remote Delivery System (PRDS) that will be used to implant the oximeter probe into the muscle. The PRDS consist of a rifle with a laser scope and a guideline.

Figure 3 Dissection of deceased pilot whale following implantation of ballistic sensor end and wire.



We initially tested and calibrated the LED and photo sensor at different O_2 concentrations (0% and 100% O_2). The LED and photo sensor were attached to the ballistic end and this was inserted into the muscle. The muscle was flushed with O_2 or N_2 to either remove or add O_2. These tests verified that the light source was strong enough to illuminate a considerable volume of muscle, thus allowing a the O_2 saturation to be measured accurately. Calibration will be performed in muscle tissue of live sheep.

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Notes:

BLOOD OXYGEN DEPLETION IN DIVING CALIFORNIA SEA LIONS: HOW CLOSE TO THE LIMIT?

P.J. Ponganis and B.I. McDonald
Scripps Institution of Oceanography, University of California San Diego
pponganis@ucsd.edu, 858 822 0792

Background

The management and depletion of O_2 stores underlie the aerobic dive capacities of marine mammals. The concept of an aerobic dive limit (ADL, dive duration associated with the onset of post-dive blood accumulation) has become an essential concept in the interpretation of diving behavior and foraging ecology. Yet, the actual rate and magnitude of O_2 store depletion during dives has been determined in few species and not in any otariids.

The 500m diving capacity of the California sea lion (*Zalophus californianus*) represents a model in which a generally considered shallow-diving species is potentially approaching its physiological limit during dives greater than 300m in depth. The physiology of these extreme dives is especially relevant to the performance and training of California sea lions used as part of the U.S. Navy's Marine Mammal Program.

Objectives

The specific objectives of this project are: 1) Document venous and arterial P_{O2} profiles in lactating California sea lions while diving during foraging trips to sea, 2) Characterize the O_2-hemoglobin (Hb) dissociation curve of sea lion Hb, 3) Convert the P_{O2} profiles into % Hb saturation (S_{O2}) profiles with the dissociation curve, and then calculate the rate and magnitude of blood oxygen depletion, and 4) Refine vascular access techniques to allow future investigations of blood N_2 kinetics, changes in blood pH, P_{CO2}, P_{O2} and lactate during dives, and stress responses to captivity, training, and/or sound exposure.

Methods

Objectives 1,4: Backpack recorders measured blood P_{O2} during dives of foraging trips of lactating California sea lions on San Nicolas Island, CA. Females were anesthetized and instrumented with a P_{O2} logger, time depth recorder and radio tag, released, and recaptured after 1-4 foraging trips. With ultrasound guidance over the caudal back, a P_{O2} electrode and thermistor were inserted percutaneously into the vena cava (n = 11) or aorta (n = 2).

Objective 2: The O_2-Hb dissociation curve was determined at four pH values (7.5, 7.4, 7.3 & 7.2) from blood samples obtained from sea lions at Sea World's Rehabilitation Program (n = 7) and the National Marine Mammal Foundation (n=4) using the mixing technique.

Objective 3: The S_{O2} values during dives were obtained with application of the dissociation curve analysis to the P_{O2} data. These data allowed calculation of maximum and minimum blood O_2 content of a dive, net and rate of blood O_2 depletion and rate of O_2 content depletion, and net contribution of blood O_2 to metabolic rate during diving (ml O_2 kg^{-1} min^{-1}).

Results

<u>P_{O2} profiles</u>

We obtained 2619 venous P_{O2} profiles from 8 sea lions and 1273 arterial P_{O2} profiles from one sea lion (dives > 1 min in duration). Minimum venous P_{O2} was 5 mmHg in dives greater than 7 min and minimum arterial P_{O2} was 10 mmHg in a 4 min dive, consistent with extreme hypoxemic tolerance.

<u>Hb-O_2 dissociation curve</u>

The shape of the curve was typical of mammals; the P_{50} was 28 ± 2 mmHg (n=11). The Bohr effect was unremarkable (-0.54).

<u>S_{O2} profiles and O_2 depletion</u>

Arterial and venous minimum S_{O2} were routinely greater than 50% and variable during routine shallow dives (Fig 1, 2). In deep dives greater than 4 min in duration, minimum venous S_{O2} reached values below 10%, and in dives over 6 min, were as low as 1% (Fig 1, 3). The latter are consistent with near complete venous blood O_2 depletion (Fig 3). In a 6-min dive, such depletion of venous blood O_2 would contribute 2.7 ml O_2 kg^{-1} min^{-1} to dive metabolic rate.

During deep dive bouts, both arterial and venous S_{O2} increased during ascent (Fig 1, 3, 4). The increase in arterial and venous S_{O2} during ascent from deep dives suggests that re-expansion of collapsed lungs and resumption of

gas exchange during the "ascent tachycardia" allows for lung-to-blood O_2 transfer.

Arterial P_{O2} and S_{O2} depletion patterns of serial deep dives differed from shallow dives and isolated deep dives with abrupt declines and increases at about 200m depth during descent and ascent, respectively (Fig 4). We suggest this is due to cessation of gas exchange at depth and that an O_2 reservoir in the collapsed lungs serves to supplement blood O_2 levels during ascent.

Conclusions

Although California sea lions have extreme hypoxemic tolerance and the blood O_2 store contributes significantly to metabolic rate during a dive, the lung O_2 store may play a greater role than previously suspected in serial deep dives (arterial S_{O2} is maintained). In addition, given these findings, we hypothesize that the most significant limit to dive performance and aerobic dive capacity may be depletion of the muscle O_2 store.

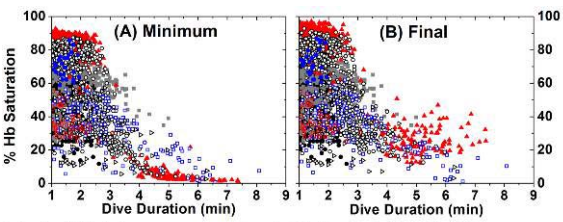

Fig 1. (A) Minimum venous S_{O2} & (B) End-of-dive (final) venous S_{O2} vs. dive duration in 8 sea lions. As duration increases, minimum and final S_{O2} decrease, but are quite variable in short duration dives. In dives > 4 min, minimum S_{O2} is often < 10%. At the end of long deep dives, final S_{O2} is > minimum S_{O2}, suggesting resumption of gas exchange and/or increased arterio-venous shunting.

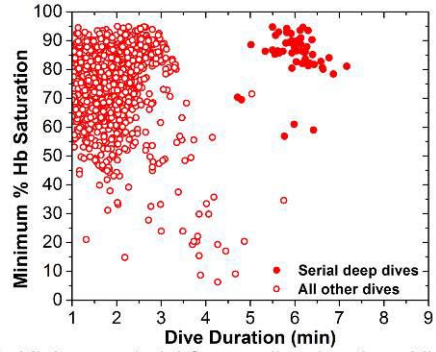

Fig 2. Minimum arterial S_{O2} vs. dive duration. Minimum S_{O2} is highly variable in short dives, but decreases with duration in most dives > 3 min. In serial deep dives minimum S_{O2} is consistently high suggesting different O_2 management strategies.

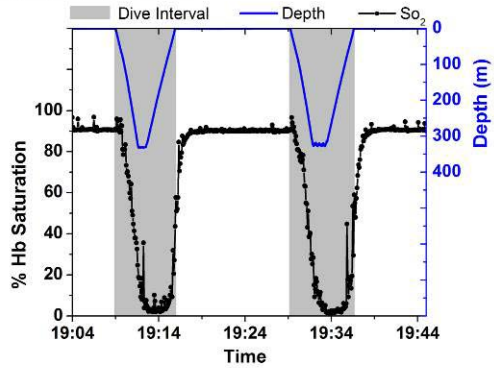

Fig 3. Venous S_{O2} profiles during 7 min dives. During the last minute of the dive, S_{O2} increased suggesting resumption of gas exchange or arterio-venous shunting.

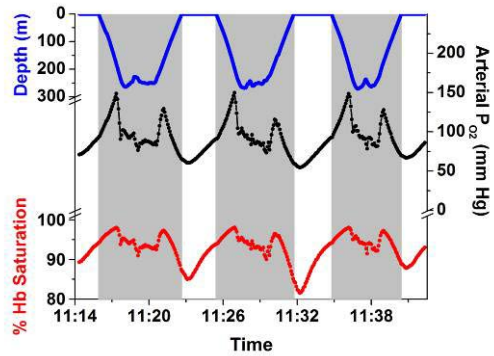

Fig 4. Arterial P_{O2} and S_{O2} profiles from serial deep dives. Abrupt declines and increases in P_{O2} and S_{O2} occur at about 200-m depth during descent and ascent, respectively, consistent with cessation of gas exchange below that depth.

Notes:

PREDICTING NATURAL NEUROPROTECTION IN MARINE MAMMALS: ENVIRONMENTAL AND BIOLOGICAL FACTORS AFFECTING VULNERABILITY TO ACOUSTICALLY MEDIATED TISSUE TRAUMA IN MARINE SPECIES

Terrie M. Williams
University of California- Santa Cruz
williams@biology.ucsc.edu, (831)459-5123

Background

With the development of novel technology to survey the oceans through high intensity (> 200 dB re: 1 uPa), low-frequency (< 5 kHz) signals, there has been increased concern regarding the effects of man-made sounds on marine organisms. The occurrence of mass strandings of marine mammals concurrent with naval and industrial acoustic activities (Frantzis, 1998; Jepson *et al.*, 2003) has led to wide spread speculation and public responses. Poor understanding of the behavioral, physiological, and physical effects of such sounds on marine mammals in particular have resulted in the cessation of naval exercises, delays in experimental research programs evaluating global warming and assessing the effects of sound on cetaceans, as well as stalled the testing of new sonar technologies.

Our study helps to mitigate this problem by identifying marine mammal species most susceptible to acoustically mediated tissue damage based on the physiological (age, species characteristics, activity level) and environmental (temperature) mechanisms that may alter this susceptibility. We begin at the tissue level with a comparative assessment of the presence and function of oxygen binding globin proteins. This includes measuring circulating (hemoglobin) and resident (cytoglobin and neuroglobin) globin proteins in the brain, and myoglobin in the swimming muscles. Moving to the whole animal/physiological level, this project also examines the susceptibility of marine mammals to decompression illness by monitoring behaviorally induced variability in the dive response. The effects of two physiological mechanisms known to alter cardiovascular function are being investigated, exercise and heat.

Ultimately, these species-specific characters enable us to elucidate the underlying mechanisms for tissue injury associated with oceanic sounds, and to develop environmentally sensitive schedules for commercial and naval acoustic activities.

Objectives

This project uses a comparative approach to determine the relative vulnerability of marine mammals to acoustically mediated trauma. It focuses on three key factors:

1. Environmental: By measuring metabolic and cardiovascular responses of trained bottlenose dolphins and pinnipeds during sedentary and active periods in warm and cold water, we are assessing the effects of ambient temperature on diving physiology.

2. Behavioral: Here we investigate the physiological significance of elevated globin levels in the cerebral cortex and skeletal muscles of marine mammals. This is being tested by comparing behaviorally induced variability in the dive response (as manifested by changes in the level of bradycardia and peripheral circulation) in deep and shallow diving mammal species including bottlenose dolphins, Weddell seals and beluga whales.

3. Physiological: By evaluating globin deposition profiles of carcasses ranging in age from neonates to adults, we are investigating how age influences neuroprotective mechanisms in a wide variety of marine mammal species.

Together these studies enable us to identify intrinsic and extrinsic factors that make some species of marine mammals, such as the family of beaked whales, more susceptible than others to non-auditory tissue damage as may occur in conjunction with man-made and natural oceanic sounds.

Methods

Methods for globin analysis in marine mammal tissues have been described previously (Williams *et al.*, 2008). For the whole animal studies we developed and tested a new submersible ECG/stroke accelerometer monitor by UFI (Morro Bay, CA). The instrument was

Fig. 1. Diving dolphin with ECG/stroke activity monitor placed in instrumentation vest.

was deployed on eight bottlenose dolphins (Fig. 1) trained to dive to depths ranging from 3 m to 16 m. Comparative measurements have been made on two beluga whales, two sea otters, and four wild Weddell seals diving to 500 m. Heart rate during surface and submerged periods were collected for all four species, including an analysis of the effects of exercise and water temperature on bradycardia for dolphins and seals. Variability in ECG signals were related to stroke mechanics during each dive and included free-ranging behaviors (dolphins and seals) and prescribed swimming courses in pools (dolphins).

Results

In contrast to the common description of diving "reflexes" in marine mammals, we find that cardiovascular responses during diving were highly variable in the species examined. Both dolphins and seals demonstrated a release from bradycardia with increased locomotory effort that was modified by age, exercise intensity, and behavior. Dolphins showed a 2.2-fold increase in heart rate from submerged rest to 72 strokes.min^{-1} at preferred swimming speeds; seals showed a 3.8-fold change in heart rate across speeds. Changes in peripheral vasoconstriction as evident from surface heat flow increased with water temperature.

Based on these results we have developed a new model for variable gas transport during diving in marine mammals (Davis and Williams, in review) that has implications for susceptibility to decompression illness. Using this model to evaluate predicted and preferred diving depths for 46 marine mammal species (Fig. 2) we find three distinct depth zones for divers defined by physiological and morphological constraints rather than optimal foraging or oxygen utilization *per se*.

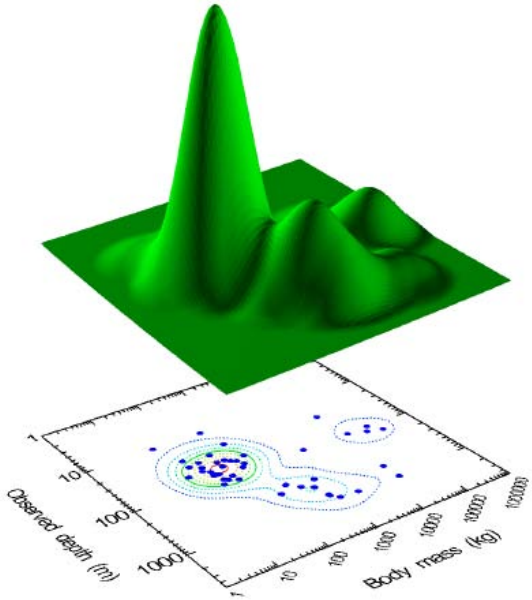

Fig. 2. Preferred diving depths in relation to body mass for 46 species of marine mammals. Peak height indicates relative number of species.

Davis, R.W. and Williams, T.M. (2012, in review) Journal of Comparative Physiology.

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Notes:

POPULATION-LEVEL EFFECTS OF DISTURBANCE ON MARINE MAMMALS

Erica Fleishman
University of California, Davis
efleishman@ucdavis.edu, (530) 754-9167

Background

The physiological and behavioral effects of sound on animals, particularly the effects of anthropogenic underwater sound on marine mammals, have attracted attention for more than two decades (National Research Council 1994, 2005; Kight and Swaddle 2011). Like any disturbance, sound can lead to alterations in physiological or behavioral state, which in turn may lead to changes in demographic rates and population or species persistence. Population-level effects of sound also may cascade among species. However, it has proven difficult to identify and model the mechanisms by which individual-level responses might propagate to the population level. A clear understanding of such mechanisms is necessary to assess trade-offs between potential responses of protected species to sound and the need to train Navy personnel in exercises that use active sonar and create other sounds (Moretti 2012).

Objectives

Our multidisciplinary working group had five foci. First, we explored how the conceptual model of population consequences of acoustic disturbance developed by the National Research Council (NRC; 2005) might be translated into a formal mathematical structure. Second, we investigated how that model might be parameterized with data on the responses of large vertebrates to disturbances. Third, we defined approaches for investigating transfer functions (e.g., time-energy budgets). Fourth, we began to conduct sensitivity analyses on different transfer functions. Fifth, we outlined methods that might be used to model transfer functions, synthesize existing knowledge, examine potential mechanisms, or inform research and management.

Methods

Our working group collaborated to model the population-level effects of disturbances on five species of marine mammals: southern elephant seals (*Mirounga leonina*), northern elephant seals (*Mirounga angustirostris*), coastal populations of bottlenose dolphins (*Tursiops spp.*), northern right whales (*Eubalaena glacialis*), and Blainville's beaked whales (*Mesoplodon densirostris*). A core group of about 12 people participated in all stages of the work. An equal number of people advised or participated in modeling of a subset of species.

Results

To more easily relate models for individual species to a transferable concept, we simplified and increased the generality of NRC's conceptual model (Figure 1). Any disturbance may affect an individual's behavior or physiology. A change in behavior or physiology may have direct or indirect effects on vital rates. We defined vital rates as all elements of individual fitness (e.g., probability of survival, producing offspring, or survival of offspring). If vital rates are affected indirectly, then a change in behavior affects an individual's health. We defined health as those aspects of the internal state of an individual (e.g., body condition, immune status) that could affect its vital rates, which in turn could affect population dynamics.

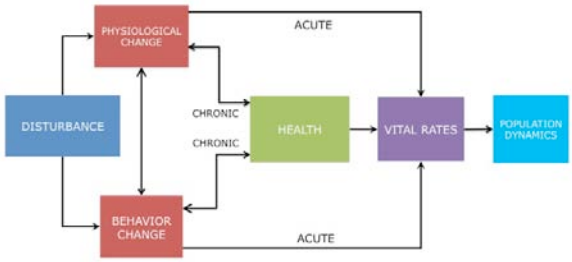

Figure 1. A simplified and more general adaptation of the conceptual model generated by NRC (2005) to illustrate the population-level effects of acoustic disturbance.

Numerous manuscripts on the five species of marine mammals are submitted or in preparation. Exclusion of northern and southern elephant seals from foraging areas, e.g. in response to changes in the extent of sea ice, may affect their condition (typically measured as lipid reserves), which in turn affects survival of offspring. A manuscript on this topic (Schick et al.) is in review. A comparison of different statistical methods of fitting models of the

process by which lipid reserves change is near completion (New et al.). An analysis of the relation among maternal condition, reproduction, and pup survival of southern elephant seals is complete (Schwarz et al. a). A manuscript on estimation of survival rate of southern elephant seals when tag loss is not independent also is in preparation (Schwarz et al. b).

We developed a model in which energetic status and the mean motivational states (hunger, fear, and need to socialize) of individual coastal bottlenose dolphins affect the activity of the school (traveling, feeding, resting, or socializing) at a given time step. The activity of the school affects the values of the states of all its individuals in the next time step. Models of responses of coastal bottlenose dolphins to disturbance from boats in Doubtful Sound, New Zealand and Moray Firth, Scotland are being refined (New et al., Pirotta et al.).

Disturbance directly affects the physiology of right whales, and by extension population dynamics. We developed a model that estimates location, health, and survival at monthly time steps for individual right whales (Schick et al.). The model is being fit to approximately 30 years of capture-recapture data from photographic identification of animals. Two detailed models of effects of disturbance on right whales have been initiated. The first will examine effects of entanglement and collisions with propellers on reproduction, health (e.g., presence of cyamids, skin condition, fatness, scarring), and survival (Knowlton et al.). The second will focus on visual measures of health and associated reproduction of whales in different locations (Rolland et al.).

In some cases, disturbance from sonar leads to changes in behavior of individuals that directly affect survival. More commonly, beaked whales at temporarily are excluded from some foraging habitat during training exercises that use sonar. We are using theoretical estimates of the energetic costs of pregnancy and lactation to explore the potential response of vital rates of individual beaked whales to reduction in foraging time. Quantification of the effects of disturbance on the population will inform development of a demographic model for Bahamian beaked whales.

We are launching a second phase of collaborative work that will focus on development of transferable models of the effects of disturbance on marine mammals. This work will be based on four major activities, which are not mutually exclusive.

First, subsets of the group will either complete models initiated relatively recently or expand on previous models to increase their generality. For example, we aim to develop a transferable model of the ability of a capital breeder to respond to disturbances that affect foraging. Second, we will provide guidance on prioritization and practicality of data collection to estimate population-level effects of different classes of disturbance on animals with different life-history attributes. Third, drawing on methods of structured decision making, we will work with regulators or regulated parties to understand what uncertainties are most likely to affect their decisions. Fourth, we will compare inferences about population-level effects of disturbance that are based on extensive empirical data to those based on expert elicitation (Martin et al. 2012).

Notes:

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ENVIRONMENTAL PERTURBATIONS, BEHAVIORAL CHANGE, AND POPULATION RESPONSE IN A LONG-TERM NORTHERN ELEPHANT SEAL STUDY

Daniel P. Costa and Lisa K. Schwarz
University of California, Santa Cruz
costa@biology.ucsc.edu; (831) 459-2786

Background

A major challenge in marine mammal conservation and management is to understand how behavioral responses affect populations. To address this challenge, the National Research Council established the Committee on Characterizing Biologically Significant Marine Mammal Behavior. This committee developed a framework for analyzing the population consequences of acoustic disturbance, or PCAD (NRC 2005). The PCAD framework defines a series of transfer functions which describe how behavioral responses to sound affect life functions, how life functions are linked to vital population rates, and how changes in vital rates cause population change (Fig. 1). The U.S. Navy included the PCAD framework in the U.S. Navy Living Marine Resource Sound Research Requirements, specifically within the "Response to Naval Sounds" requirement #5: Determine biologically significant behavioral responses from Navy sound sources on individuals representing marine mammal species of concern with respect to ... determining long-term effects of behavioral responses and how individual vital rates may affect the population. This requirement was given the highest priority under the Navy's requirements.

Implementing the concepts of transfer functions which link behavior to population change, however, requires substantial long-term data on individual animals and population size, and there are few marine mammal populations where quantifying the functions is plausible. Funding from this grant has allowed us to extend and improve a four-decade study of northern elephant seal populations in California, aiming specifically to quantify key linkages within the PCAD model. Since 1968, several thousand individual seals have been tagged and tracked for their lifetimes, and several hundred of those have been weighed or outfitted with telemetry devices in order to document pelagic foraging behavior and body condition. The study has spanned the Pacific Decadal Oscillation and several El Niño events and documented how such environmental fluctuations affect individuals and populations. Recent advances in telemetry and our understanding of foraging behavior and body condition allow us to extend this study into the future with improved methods, and with our current funding we have maintained and advanced a classic long-term study of a vertebrate population.

Objectives

Specifically we have collected data to answer two general questions: 1) How closely coupled are short term changes in foraging behavior to adult fecundity and survival? and 2) Does this link vary with environmental perturbations such as the El Niño Southern Oscillation (ENSO) that are known to impact prey availability? Such data are essential for the population modeling effort currently underway by the PCAD Working Group organized by the Office of Naval Research. These two questions translate into three hypotheses we are testing:

1) Adult survival fluctuates with ocean climate, with low survival in the year following ENSO events, and higher survival after non-ENSO years.
2) Oceanic climate cycles will impact foraging of pregnant females and weaning weight and survival of pups. Specifically, warming trends (ENSO and "sardine" regimes) will be associated with lowered weaning weights. Survival during the first year at sea will be positively correlated with weaning weight.

Population growth potential is limited by these ENSO and Decadal (PDO) impacts on foraging and thus animal condition.

Methods

These hypotheses will be tested with data gathered through five research activities, all conducted through an ENSO cycle at the Año Nuevo, California, northern elephant seal colony: 1) continue annual censuses of the breeding population; 2) measure adult female body condition; 3) weigh weaned pups to link female condition to reproductive output; 4) continue and expand tag re-sighting to refine survival estimates; 5) continue satellite tracking of adult females to map foraging. Lastly, we

have expanded and coordinated resighting efforts at two additional elephant seal colonies in central California in order to examine migration between colonies and assess population trends at larger spatial scales.

We will use data collected from these activities, as well as the legacy data of the past 40 years, to parameterize a Bayesian hierarchical population model, then use elasticity analyses to evaluate the links from ocean conditions to adult survival, nursing resources, weaner size, juvenile survival, and population growth. The results will allow us to explore potential population responses to climatic and other perturbations by building demographic models.

Results

El Niño conditions were present across the equatorial Pacific Ocean in mid-2009 which created increases in sea surface temperatures during the pupping/breeding winter season of 2009/2010. The opposite La Niña conditions persisted through the 2010/2011 winter. La Niña conditions increased and persisted during winter 2011/2012.

Our objective is to provide long-term data and analyses that will allow us to quantify all the links from disturbance to population-level effects. One of the important steps is to determine the influence of environmental factors on adult female foraging behavior and condition. Female condition in turn effects pup wean mass and pup survival. In addition, female survival and reproductive rate will also be affected.

Females from the PM 2010 foraging trip were relatively successful at sea and appeared to have more successful foraging trips than the previous three years. Females gained an average of 274.8 ± 52.2 kg (SD), approximately 94.9 ± 18.0 % mass gain, over the course of the foraging trip and gained energy at a rate of 16.3 ± 2.1 MJ/day. Energy gain over this foraging trip was the fastest rate of energy gain during the post-molting trip since 2005 (19.2 ± 3.3 MJ/day) and the percent of mass gain was also the greatest observed since 2005 (98.0 ± 21.7). The mean trip length for the PM 2010 foraging trip was 222 ± 27 days, which was the fifth longest mean trip duration over the past 7 years. Natality for the 2010 instrumented females was 86.7 %, the highest observed since 2004 (95.7 %). Adult females weighed 511.4 ± 50.1 kg five days post-partum during the 2011 breeding/pupping season (n = 22). That value was slightly higher than measurements taken the previous season. We are still processing morphometrics and tracking data from the 2011 post-molt foraging trips. Future analyses will look at changes in foraging behavior as a function of environmental conditions.

Preliminary analyses show female condition, measured as mass gain during the post-molt trip, is actually higher during years when warmer than average conditions in the North Pacific were present. However, these results have not been adjusted for animal age, and lipid mass may be a better indicator of female condition. The relationship between wean mass and ENSO was investigated directly with a large 2004-2012 sample size, and results are similar to what has been seen in previous studies: lower wean mass during warmer conditions.

Survival rate and reproductive rate analyses are still pending. We will also analyze wean mass as a function of female condition.

Notes:

FITTING MODELS OF THE POPULATION CONSEQUENCES OF ACOUSTIC DISTURBANCE TO DATA FROM MARINE MAMMAL POPULATIONS

Dr. James S. Clark, Dr. Robert S Schick
Nicholas School of the Environment, Duke University
jimclark@duke.edu, 919-613-8036, rss10@duke.edu, 919-257-9127

Background

Understanding how individuals respond to disturbance through changes in behavior or body condition is a key conservation question. Of potentially greater concern and impact, is how the response of individuals translates to the health of populations. Understanding how individuals respond and how population trajectories are influenced by these responses should allow managers to make informed decisions about the cumulative impact of disturbance. This is significant to the Navy because they want to understand how acoustic exposure impacts the long term health of cryptic marine mammal populations. It is of significance in the ecological realm, because body condition has been linked to numerous ecological processes at multiple hierarchical levels. Therefore an understanding of how hidden latent states, e.g. body condition, change through time will provide insight into how marine predators successfully acquire resources and maintain health.

Objectives

Our objectives are to build a statistical framework for understanding the at-sea health of three species of marine mammals: southern and northern elephant seals, and northern right whales.

For elephant seals our goal is to build a hierarchical Bayesian model that provides daily estimates of lipid status, as lipid status of the mother is directly linked to pup survival. This model will use the drift dive behavior of elephant seals as the link to the underlying true, yet immeasurable, lipid state.

For right whales, our scientific objective is to build a model that provides spatially and temporally explicit estimates of individual health, movement, and survival.

Methods

Elephant Seals: The state-space model for at-sea lipid gain/loss in elephant seals contains two primary components: an observation model for the drift dives, and a process model for the lipid gain/loss process experienced at sea. The observation model is:

$$D_{i,t} \sim N\left(\alpha_1 + \alpha_2 \frac{L_{i,t}}{R_{i,t}}, \frac{\tau^2}{h_{i,t}}\right),$$

where $D_{i,t}$ is the observed mean daily drift rate (in m/s) of individual *i*, α are the parameters governing the link between lipid status and drift rate, $L_{i,t}$ is the estimated daily lipid status of individual *i* (in kg), $R_{i,t}$ is the fixed daily lean mass value of individual *i* (in kg), and $h_{i,t}$ represents the number of drift dives.

The process model for lipid gain over time depends on the environment, individual differences, and model error,

$$\prod_{i=1}^{n}\prod_{t=1}^{T} N_+\left(L_{i,t} \middle| L_{i,t-1} + x_{i,t-1}\beta + w_{i,t-1}\gamma_i, \sigma^2\right)$$

$$\gamma_i \sim N(0, G)$$

The model provides estimates of the lipids time series (L), the regression parameters that govern lipid gain/loss (β), missing covariate data (X), the parameters governing the link between the lipid/lean ratio and the observed drift rate ($D_{i,t}$), the observation error $\left(\frac{\tau^2}{h_{i,t}}\right)$, and the process error (σ^2).

Using this approach, we tested three hypotheses: 1) lipid gain is a function of environmental covariates; 2) lipid gain is a function of foraging strategy; and 3) lipid gain is a function of physiological status of the mother.

We fit the model to two separate datasets for northern and southern elephant seals. There were 29 northern elephant seal tracks and 30 southern elephant seal tracks. Example tracks from each species are shown in Figure 1 and Figure 2.

Right Whales: Consider a whale *i* at month *t* occupying a geographic zone $z_{i,t} = k \in \{1,\ldots,K\}$ characterized by age $a_{i,t}$ and health status $h_{i,t} > 0$. A live individual thus is defined by state vector $[z,a,h]_{i,t}$. Depending

on its health status and differential mortality risk posed by, say, boat traffic that could differ between zones k, the individual survives $s_{ik,t} = 1$ to month t+1 with probability $q_{ik,t}$. During this month (t, t+1) it may remain in k with probability m_{kk} or move to zone l with probability m_{lk}. Using the sighting and health status evidence we wish to infer the impact of age and previous health status on current health and the effect of health and the differential risk associated with zones on survival.

Individual health is a latent state

$$N\left(h_{i,t} \middle| w_{i,t-1}\alpha, \sigma^2\right)$$

where α is the vector of fitted coefficients, and the design vector $w_{i,t-1}$ includes an intercept, an AR(1) term for temporal coherence in health, and age terms to allow for that fact that survival probabilities initially increase $(\alpha_3 > 0)$ but can eventually decline with age $(\alpha_4 < 0)$.

The probability of survival from t to t +1 is

$$\Pr\left(s_{ik,t} = 1\right) = Bernoulli\left(\theta_{ik,t}\right)$$

$$\text{logit}\left(\theta_{ik,t}\right) = x_{ik,t}\beta$$

$$x_{ik,t} = \left[h_{i,t}\ z_{i,t}\right]$$

where the design vector contains health status and a fixed effect for the geographic zone.

Results

Elephant Seals: We have shown that environmental covariates impact the lipid gain process (Table 1, Hypothesis #1); this process differs significantly between northern and southern elephant seals (Figure 3). The process for northern elephant seals differs in two ways: 1) on average they put on lipids later than their southern counterparts, and 2) they tend to put on lipids in more discrete intervals (Figure 4, Figure 5). In contrast, southern elephant seals tend to put on lipids in a more continuous and gradual fashion. We found that the effect of foraging strategy was significant; patterns in lipid gain as a function of foraging strategy were especially notable in southern elephant seals (Hypothesis #2). Finally, we found that measures of physiological status at different time scales are both significant. At longer time scales, the parameter estimates are weaker; while at shorter time scales, parameter estimates are stronger (Table 1, Hypothesis #3).

Results from modeling elephant seals have demonstrated how these top predators acquire resources and regulate body condition at fine time scales. This provides a necessary first template for understanding how spatially and temporally explicit disturbance will impact this regulation process. For impacted animals, the results also tell us which animals may be most vulnerable to disturbance.

Right Whales: While we are still working with collaborators from the New England Aquarium to finalize specific formulations of the model as it relates to changes in health, and the impacts of ship strikes and entanglements, initial results provide an intriguing glimpse into the approach. Though this dataset is incredibly rich (Figure 6, Figure 7), one of the main difficulties in analyzing health, movement, and survival is the differential use and sightability of individual right whales in their habitats zones. One of the primary advantages of this modeling approach is that we can use health observation data from individuals to make inference on true health, movement and survival at both the individual (Figure 8) and population level (Figure 9, Figure 10).

Results from this modeling effort should provide us with a quantitative understanding of both where and how health in right whales changes. This should inform conservation and management efforts to minimize disturbance effects on this population.

Notes:

DEFINING THE TRANSFER FUNCTIONS OF THE PCAD MODEL IN NORTH ATLANTIC RIGHT WHALES (*Eubalaena glacialis*): RETROSPECTIVE ANALYSES OF EXISTING DATA

Scott D. Kraus (Ph.D.), Rosalind M. Rolland (D.V.M.), Kathleen Hunt (Ph.D.) and Peter Corkeron (Ph.D.)

New England Aquarium, Boston, MA 02110
phone: (617) 973-5457 email: skraus@neaq.org
phone: (617) 973-6587 email: rrolland@neaq.org
phone: (617) 226-2175 email: huntk@neaq.org
NOAA Northeast Fisheries Science Center, Woods Hole MA 02543
phone: 508-495-2191 email: peter.corkeron@noaa.gov

Background

Anthropogenic noise has been shown to cause both behavioral and physiological changes in marine mammals, but the potential for long-term population level effects is not known. Naval operations worldwide are evaluating the environmental consequences of seagoing military operations, inclduing noise from several sources (sonar, ship operations, explosions). Short-term responses (startle behavior, avoidance) may not identify the biological costs of underwater noise. The NRC Population Consequences of Acoustic Disurbance (PCAD) model provides a framework to trace the consequences of acoustic disturbance through the life history of a marine mammal to its population status. In North Atlantic right whales, extensive data on hormone levels, health and body condition, and individual life history allows analysis of the links between stress and thyroid hormones, health, and vital rates of right whales. This research supports the modeling of PCAD transfer functions and a theoretical framework for field studies on acoustic disturbance.

Objectives

The first objective was to test a new approach to the PCAD model by substituting “behavior change” with direct measurements of physiological changes using fecal hormone levels, replacing “life function” with skin and body condition indices and investigating the links between these parameters and right whale survival, reproduction and maturation.

A second objective of this project was to analyze acoustic recordings and fecal stress hormone levels from the Bay of Fundy for the period before and following 9/11 to determine if the observed reduction in vessel activity post-9/11 resulted in a decline in ambient noise, and if there was an accompanying decrease in stress hormones in the right whales inhabiting the Bay.

Methods

We collected right whale fecal samples from known individuals, and applied radio-immunoassays to determine reproductive and stress hormone metabolite levels. From a comprehensive photo-identification dataset, we analyzed body and skin condition. We combined direct measurements of individual’s hormonal status with skin and body condition indices and then evaluated the whale condition data as a correlate of vital rates, including survival, reproduction, and maturation. In addition, we validated new fecal assays for thyroid hormone metabolites (T3), which are the primary regulators of metabolic rate in mammals and reflect nutritional state as well as prolonged chronic stress. Finally, we retrospectively analyzed underwater acoustic noise levels collected before and after 9/11 simultaneously with stress hormone levels to assess potential effects.

Results

Hormone Analyses

This work constituted a total of 52 separate hormone assays. The total hormone dataset for the project now consists of 370 samples for the reproductive hormones and glucocorticoids. This includes an additional 99 archived samples assayed for the reproductive hormones (estrogen, progesterone, testosterone) and glucocorticoids. An assay for thyroid hormones (T3) was validated, and T3 levels in RW fecal samples were analyzed. All available archived and newly collected right whale samples were assayed for thyroid hormones (n = 324).

Analysis is underway, using conditional inference trees, which take a statistical approach to partitioning, and account for the distributional properties of the data.

Health Assessment

Two additional years of right whale sightings (2008-2009) were analyzed and scored for visual health assessment. For this time period, a

total of 13,916 additional sightings of right whales were scored for health assessment. The updated health assessment database now consists of a total of 11,145 batches (sightings grouped by individual whale and scored by habitat/year) and 40,794 sightings. To analyze the relationship between fecal GC levels and Body Condition Scores, we are applying a nested linear model with GC level as the dependent variable, and the other hormone levels nested in reproductive state as the explanatory variables.

Reproduction and Mortality

We constructed individual projection matrices, to assess the the probability of each adult female right whale transitioning between Pregnancy, Lactation and Resting. Our initial analysis demonstrated that poor body condition was associated with reduced reproduction. From the health database, a Chi-squared analysis showed that those whales in poor condition at last sighting were significantly more likely to die than those in better health. Analyses with the expanded dataset are underway.

The 9/11 analysis

We compared the sound pressure level (SPL) and frequency spectrum from recordings on two days before 9/11 with two days immediately following 9/11. Acoustic data showed a 6dB decrease in underwater noise below 150 Hz related to reduced ship traffic following 9/11(Figure 1).

In a concurrent study, we compared levels of glucocorticoid metabolites (GCs; "stress hormones") measured by radioimmunoassay in right whale fecal samples before (n =114) and after 11 September (n = 30) for the years 2001-2005. The only year in which there was a significant decrease in fecal GCs after 11 September was 2001 with a significant effect of year and period (Kruskall-Wallis X^2 = 29.6889, df = 4, P < 0.0001) (Figure 2).

Figure 1. Sound pressure levels by frequency in the Bay of Fundy on two days before and two days after 9/11.

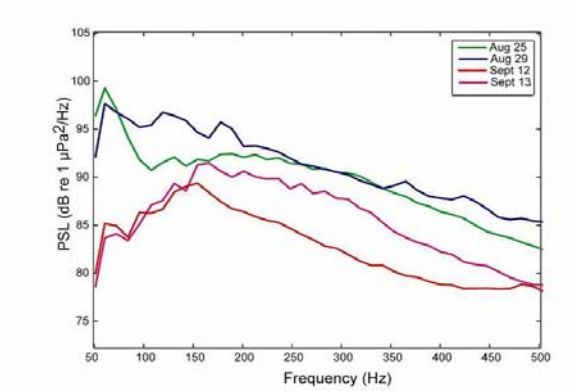
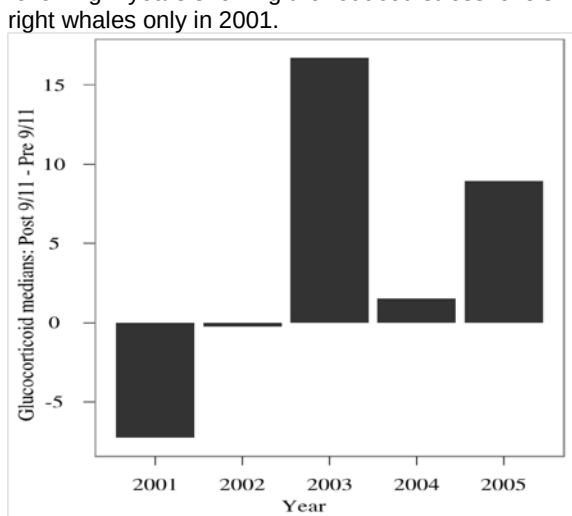


Figure 1. Change in stress hormones collected from right whales after September 11th in 2001 and the following 4 years showing the reduced stress levels in right whales only in 2001.



This is the first evidence that exposure to underwater noise from large ships is associated with a measure of chronic stress in free-ranging whales, which has implications for baleen whale populations in heavy ship traffic areas.

Notes: Evidence that Ship Noise Increases Stress in Right Whales. 2012. R. M. Rolland, S. E. Parks, K. E. Hunt, M. Castellote, P. J. Corkeron, D.P. Nowacek, S. K. Wasser and S. D. Kraus. Proc. Roy. Soc. B doi: 10.1098/rspb.2011.2429

PASSIVE AUTONOMOUS ACOUSTIC MONITORING USING SEAGLIDER™

Neil M. Bogue, James C. Luby, Geoffrey B. Shilling, William A. Jump, Trina Litchendorf, David K. Mellinger*, Holger Klinck*
Applied Physics Laboratory, University of Washington
bogue@apl.washington.edu (206) 221-7687
**Cooperative Institute for Marine Resources Studies, Oregon State University*

Background

This review describes our efforts as part of the ONR Passive Autonomous Acoustic Monitoring (PAAM) program. The long-term goal of our work is to develop a glider-based system capable of autonomous passive acoustic detection, classification, and localization of marine mammals for periods of several months, with timely communication of detections. The 2m-long, 1000m-depth rated underwater glider Seaglider™ (Eriksen 2001), has been adapted for several Navy missions, and in these configurations is called the Applied Seaglider™ (ASG).

Within the PAAM program, we have chosen to focus on automated detection, classification, and recording of beaked whale vocalizations. Beaked whales vocalize at depths greater then 200m and use frequencies above 25kHz, characteristics that are a good fit with the ASG's depth range and physical dimensions.

To support the above-described mission, we designed and built a passive acoustic detection and recording system for ASG. We have installed and deployed the PAAM recording/processing system on four different Seagliders and have deployed these systems on a variety of missions.

Objective

Our objective is to autonomously detect and classify beaked whales using passive acoustics on the Seaglider™, send the detections ashore in a timely manner, and do so at a power level that allows persistence of several months.

Methods

The PAAM system consists of a single omnidirectional HTI-99-HF hydrophone and a custom designed and built electronics board. The hydrophone is mounted external to the Seaglider™ aft fairing as shown in Figure 1 below.

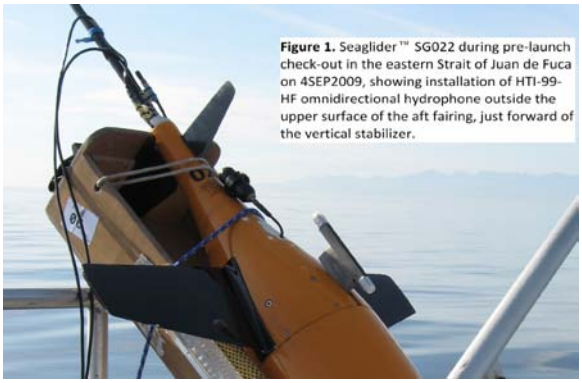


Figure 1. Seaglider™ SG022 during pre-launch check-out in the eastern Strait of Juan de Fuca on 4SEP2009, showing installation of HTI-99-HF omnidirectional hydrophone outside the upper surface of the aft fairing, just forward of the vertical stabilizer.

The PAAM electronics board fits in the Seaglider™ electronics bay just under the Seaglider™ main board. Its main features are given below.

- *4 channels, 16-bit sampling*
- *250ksps aggregate sample rate*
- *Reconfigurable active/passive filtering*
- *Up to 1 Terabyte solid state storage*
- *ARM-9 processor running Linux (13-208 MHz)*
- *Power consumption (1 channel) < 1 W*

Software was written to buffer the digitized data stream, record data to SD cards and USB sticks, implement on-the-fly time-domain click detectors and an odontocete classifier (Roch 2011), and control the PAAM system through the Seaglider Iridium telemetry. Recorder and detector log and statistics files are transmitted from the Seaglider to the basestation following each dive along with power spectral density results and selected time series snippets.

Results

Since the previous ONR Marine Mammal Program Review (DEC2009), we have focused our efforts on increasing on-board storage, implementation of new algorithms, and at-sea testing.

Table 1. summarizes all missions to date, including the initial Haro Strait mission that we reported on in the 2009 ONR Review. Operations on the Navy's AUTEC and SCORE ranges were especially valuable as they

provided opportunities to compare the detection processing results of our system with those of Navy-operated range monitoring systems (Moretti 2006).

Figure 2 provides an example of a detection of the click train of a Cuvier's beaked whale. This example was obtained on the Kona I mission using Seaglider SG022. Throughout each mission, statistics associated with the onboard signal processing were transmitted via the Seaglider Iridium telemetry link, thus demonstrating the feasibility of using PAAM-equipped Seagliders for near real-time reporting of the presence/absence of vocalizing marine mammals.

We are planning a long duration (~2 months) survey off of the coast of Washington in the vicinity of the Navy's Northwest Training Range to demonstrate the persistent monitoring capability of the PAAM system. This deployment is scheduled for May through July, 2012.

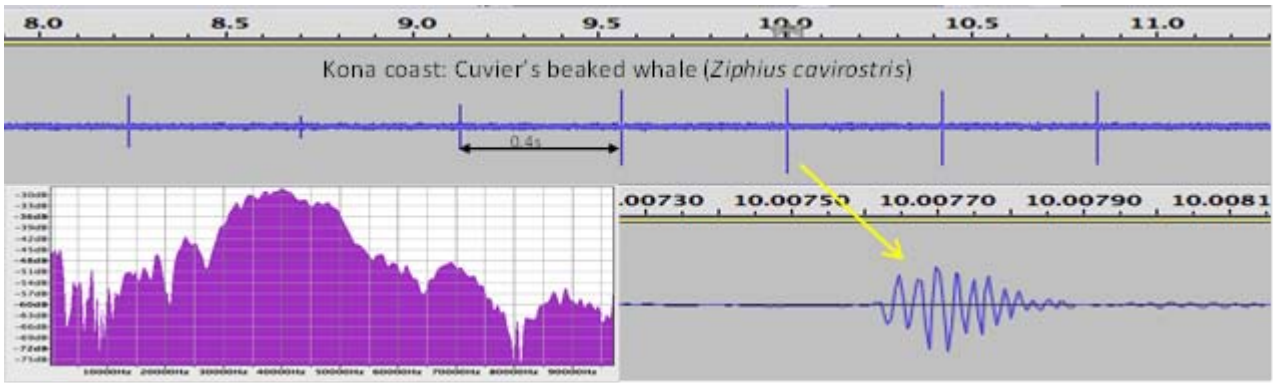


Figure 2. Beaked whale click-train, wavelet and associated power spectrum

Deployment	Seaglider	Dates	Number of Dives (1km)	Hours of Recording[1]	GB of Recording[2]
Haro Strait	SG022	4SEP2009	5 (0)	2.8	3.7
Kona I	SG022	27OCT-17NOV2009	116 (102)	170.2	141.5
Kona II	SG022	16MAR-26MAR2010	61 (42)	101.8	84.6
	SG023		94 (36)	107.1	89.0
AUTEC	SG178	7JUN-11JUN2010	35 (12)	58.5	48.6
	SG179		27 (12)	71.7	59.6
SCORE	SG178	4JAN-7JAN2011	30 (19)	56.2	46.7
	SG179		30 (19)	53.5	44.5
Total		56 days	398 (223)	621.8	518.2

[1]Duty-cycle governed by detect_below parameter
[2]Sample rate = 194162 samples per second, 16-bit A/D conversion, FLAC encoding (ratio ≈ 0.6)

Table 1. Mission summary data

References:

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Roch, M.A., Klinck, H., Baumann-Pickering, S., Mellinger, D.K., Qui, S., Soldevilla, M.S., Hildebrand, J.A., Classification of echolocation clicks from odontocetes in the Southern California Bight, J. Acoust. Soc. Am. 129 (1), January 2011.

Moretti, D., R. Morissey, N. Dimarzio, and J. Ward. 2006. Verified passive acoustic detection of beaked whales (Mesoplodon densirostris) using bottom-mounted hydrophones in the tongue of the ocean, Bahamas. Applied Acoustics 67:1091-1105.

REAL-TIME ACOUSTIC CETACEAN DETECTION WITH THE SEAGLIDER™

David K. Mellinger, Holger Klinck, Neil M. Bogue, Jim Luby
Cooperative Institute for Marine Resources Studies, Oregon State University
David.Mellinger@oregonstate.edu, 541-867-0372

Background

The U.S. Navy's use of tactical sonar has been linked to marine mammal strandings and fatalities, particularly of beaked whales, which appear to be particularly sensitive to mid-frequency sonars. These events have generated legal challenges to the Navy's peacetime use of mid-frequency sonar, and have limited the Navy's at sea anti-submarine warfare training time. A mobile, persistent surveillance system that could detect, classify and localize marine mammal species of interest will help resolve the conflict between the Navy's need for realistic training of sonar operators and the Navy's desire to protect the marine environment, especially marine mammal populations, worldwide.

Ocean gliders can be applied in several ways for monitoring marine mammals and mitigation of possible harm to them. They could form a component of a near-real-time detection and reporting system that could warn naval sonar operators of the presence of whale species of interest so they could take appropriate steps to mitigate potential harm. Gliders could also be used for a long-duration, large-area survey before naval activities commence to determine when and where sensitive species are present. They could also be used in before/during/after deployments to evaluate any potential impacts of Navy activities on marine mammals. The acoustically-equipped Seaglider™ of this project will be particularly relevant because it will also be equipped with operating procedures to handle sequences of marine mammal detections for both real-time response to detections, so that the glider could ascend to the surface upon detection of the target species.

Objectives

Objectives include

- advancements in algorithms and software to create an optimum processor for detection;
- implementation of a refined classifier in the processing environment of the Seaglider;
- development of procedures to make the Seaglider respond appropriately upon real-time detection of the sounds of interest;
- making all of these components use as little processing power as possible, as an ocean glider's mission duration is largely constrained by battery energy; and
- at-sea testing and performance evaluation of the Seaglider acoustic system.

Methods

This project is a collaboration with Neil Bogue, Jim Luby, and others at the Applied Physics Laboratory, University of Washington. They have built the acoustic data collection system for the Seaglider, including hardware and software, and we have built the detection and classification system for use in marine mammal research.

Our system for real-time acoustic detection and classification on the Seaglider comprises two stages. The first stage is a detector[1,2] that operates at all times when the acoustic system is enabled; for beaked whales, this is when the glider is diving at depths below several hundred meters. (The depth limit is used because beaked whales vocalize at depth and have a highly directional beam pattern, so that relatively little sound reaches shallow depths.) The detector identifies *candidate clicks*, ones that have a high probability of being from a given beaked whale species or other target species. Because the detector runs a large fraction of the Seaglider's total operating time, it is designed to be as computationally efficient as possible and so use as little battery energy as possible.

The second stage is a call classification system[3]. This system runs when the first stage has identified a candidate click, determining with high probability what species produced the click. Although this stage is much more computationally complex, and more computationally intensive, than the first stage, it runs such a small fraction of the time that its total battery usage is typically much lower than the first stage.

When the Seaglider equipped with this system detects sounds of the target species, it sends information about the detection to shore by Iridium™ link so that it can be manually verified. If necessary, the Seaglider's operating

parameters can be modified in light of the new information about the detection.

The acoustically-equipped Seaglider was tested for detection of odontocetes on missions in Washington state, the Bahamas, Hawaii, and California.

Results

The stage-one detector was implemented in the Seaglider's processing environment. The glider has now been tested in five sea trials, successfully detecting clicks of target odontocetes each time[4].

Two tests were off the Kona coast of the island of Hawaii in 2009-10. The target species, Cuvier's beaked whale (*Ziphius cavirostris*) was successfully detected in these tests. At one point, a tagged *Ziphius* was close to the location of the glider when the glider detected clicks from that species, and the timing of the detection and the whale's dives is such that the detected whale was probably the tagged one. The glider detected one dive of the whale but missed another because the glider was at the surface, where its acoustic system was disabled.

A field test at AUTEC in the Bahamas in 2010 resulted in detections of clicks of Blainville's beaked whales (*Mesoplodon densirostris*). These recordings were manually scanned for this species' clicks, and all 11 manual detections were indeed found by the automated detection system. There were also 3 false detections. The detection range was estimated to be 3-4 km at this site, and the detection rate (detections per unit time of operation) was relatively high below 300 m and nearly zero at depths shallower than 200 m. See Figure 1.

A field test at SCORE in southern California resulted again in detections of beaked whale clicks at several points during the test. We have been unable to compare glider detections to SCORE hydrophone detections as the acoustic recordings from SCORE remain classified.

A future test in late spring 2012 is planned off the coast of Washington and Oregon. This test is designed to test glider endurance and will last up to two months.

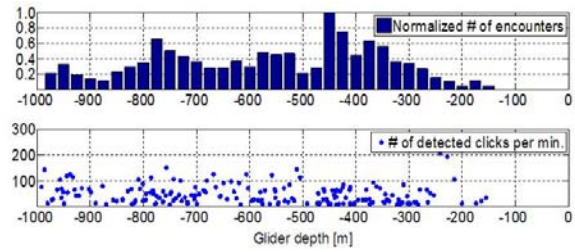

Fig. 1. (Top) Number of Blainville's beaked whale encounters as a function of glider depth at AUTEC. The number of encounters is normalized by the number of minutes that the recording system was turned on (this included some operation at depths up to the surface). This is strong evidence that these beaked whales are significantly easier to detect at depths below ~250 m. (Bottom) The number of detected clicks per minute of acoustic system operation was relatively constant below 250 m.

Notes:

[1] Klinck, H., and D.K. Mellinger. 2011. The energy ratio mapping algorithm (ERMA): a tool to improve the energy-based detection of odontocete clicks. J. Acoust. Soc. Am. 129(4):1807-1812.

[2] Yack, T.M., J. Barlow, M.A. Roch, H. Klinck, S. Martin, D.K. Mellinger, and D. Gillespie. 2010. Comparison of beaked whale detection algorithms. Applied Acoust. 71(11):1043-1049.

[3] Roch, M.A., H. Klinck, S. Baumann-Pickering, D.K. Mellinger, S. Qui, M.S. Soldevilla, and J.A. Hildebrand. 2011. Classification of echolocation clicks from odontocetes in the Southern California Bight. J. Acoust. Soc. Am. 129(1):467-475.

[4] Klinck, H., D.K. Mellinger, K. Klinck, N.M. Bogue, J.C. Luby, W.A. Jump, G.B. Shilling, T. Litchendorf, A.S. Wood, G.S. Schorr, and R.W. Baird. To appear. Autonomous underwater vehicles: a new tool for long-term monitoring of beaked whales and other cetaceans in near-real time. In press, PLoS ONE.

PASSIVE AUTONOMOUS ACOUSTIC MONITORING OF MARINE MAMMALS (PAAM): PROOF-OF-CONCEPT DEMONSTRATION

Philip Abbot
Ocean Acoustical Services and Instrumentation Systems (OASIS), Inc.
abbot@oasislex.com, 781-862-8339

Background

The overall goal is to demonstrate the feasibility of using ocean gliders integrated with acoustic sensors for autonomous detection, classification and localization of low (LF) and high (HF) frequency marine mammal vocalizations. The signal processing is done autonomously onboard using a DSP system with joint detection-classification messages transmitted to a nearby research vessel or the shore. The LF effort is focused on humpback whales, using a glider and towed hydrophone array (Fig. 1), and spectrogram correlation classification methods to determine the presence or absence of the whales with low false alarm rate. The HF effort is focused on capturing beaked whale vocalizations from a Slocum G2 glider hull-mounted mill cross array (Fig 2a).

The Slocum G2 glider is the same glider under development by NAVOCEANO for the LBSF&I (Littoral Battlespace Sensor, Fusion and Integration) program. Thus this effort, if successful, provides a potential transition to the US Navy. The development of a PAAM system will provide the Navy with tools for autonomous surveillance and classification of marine mammals in naval training and operating areas, thus mitigating the possible harm to the animals from active sonar during these types of tests. Most scientific tools presently used for passive acoustic monitoring utilize single hydrophones and the present effort of using arrays deployed from gliders provides significantly greater detection ranges and larger areas-of-coverage than can be achieved with single sensors.

Objectives

The primary objective is to build and test components and algorithms for two passive systems; one that autonomously detects, classifies and tracks LF and one for HF marine mammal vocalizations using advanced acoustic sensors incorporated into an ocean glider. Specific technical objectives are to: develop low frequency autonomous detection-classification algorithms; define the limits and capabilities of the Slocum glider LF towed array and HF hull-mounted array systems, based on open ocean experiments in the presence of humpback and beaked whales; develop an effective system performance prediction to quantify joint detection-classification ranges and coverage areas for LF and HF marine mammal vocalizations.

Methods

The project is based on an extensive build-test-build approach, in which system components, algorithms and methodologies have been designed, built, tested and evaluated, then re-designed and rebuilt in response to the test results. Optimal (LF) detectors based on existing mammal vocalizations and optimal detection thresholds have been designed and tested. Figures-of-Merit (FOMs) have been determined to quantify system performance (detection ranges, coverage areas).

Using the LF system (see Fig. 1), extensive system component integration and shakedown tests have been conducted off the Hawaiian islands of Oahu and Kauai, as well as Stellwagen Bank and the proof-of-concept has been demonstrated. The capability of the system to autonomously detect and classify humpback whales has been quantified through these tests.

The HF system has been built and integrated with a glider payload and tested in the NUWC Acoustic Test Facility (measured beampatterns at 800 psi depth pressure are shown Fig 2b). We expect to conduct the final proof-of-concept demo for this system during the summer 2012, likely at AUTEC.

Results

Real-time, 2nd generation classifier results using sonobuoys off the island of Kauai for humpbacks demonstrated the capability of the classifier [1,2] system as we measured high correct classification (92%) and low false alarm rate (< 1%) see Fig. 3. The classifier is now ready for integration with the glider-array for real-time use. Fig. 4 shows impact of algorithm improvements from 2008 to 2010.

Key findings: We have demonstrated that a glider can tow a line array to successfully detect and track autonomously humpback whales. We have built and improved the humpback whale classifier with high correct classification and low false alarms.

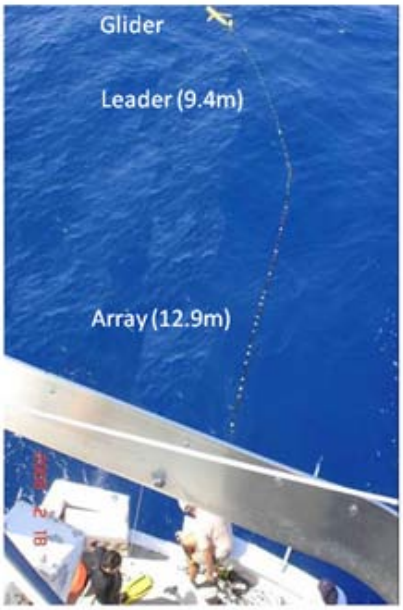

Figure 1: Glider/Towed Array System post-launch and prior to initial dive.

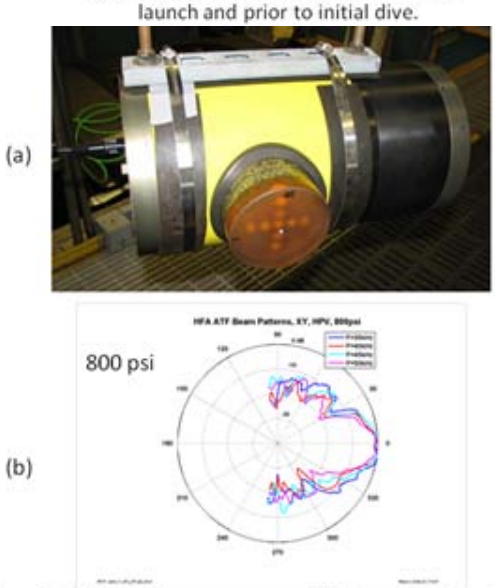

Figure 2: OASIS High frequency array: (a) G2 payload showing Mills Cross array; (b) Beampattern measurements performed at NUWC Acoustic Test Facility at 800 psi shows good agreement with theory.

The HF array has been integrated with the glider payload, statically tested to 800 psi and array beam patterns have been measured. This system will be tested in the open ocean in late summer of 2012.

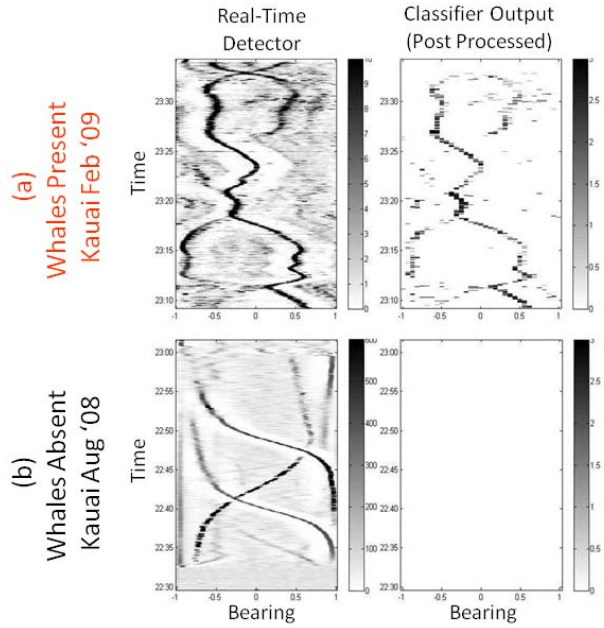

Figure 3: Real-Time detector and Post-processed Classifier output for (a) whales present (Feb '09), and (b) whales absent (Aug '08) from same location off leeward Kauai. Note lack of false alarms in whales absent case.

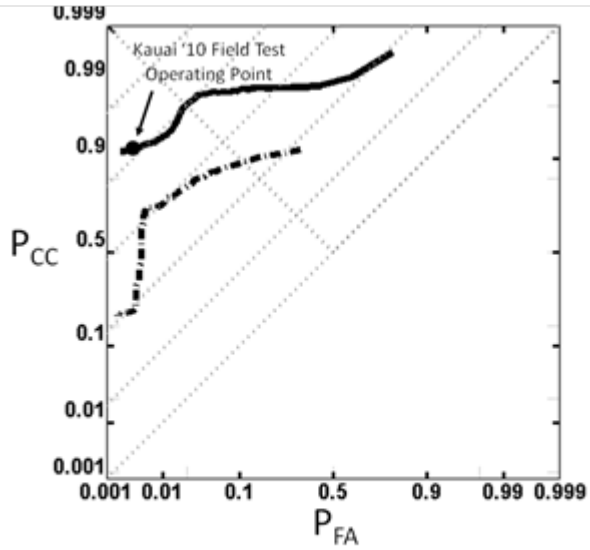

Figure 4: ROC curves quantifying evolution in system performance for the 66 hr Kauai '09 whales-absent and Kauai '10 whales-present test data set. Dashed-dot curve denotes performance of original kernel library from 2008, solid curve denotes performance of new kernel library used in 2010.

(1) Abbot, T, Premus, V., and Abbot, P., A real-time method for autonomous passive acoustic detection-classification of humpback whales, Jour. Acous. Soc. Am., Vol. 127, No.5, May 2010.

(2) Abbot, T., Premus, V, Abbot, P. and Mayer, O., Receiver operating characteristics for a spectrogram correlator-based humpback whale detector-classifier, Submitted to JASA, 12/2011.

GLIDER-BASED PASSIVE ACOUSTIC MONITORING TECHNIQUES

John A Hildebrand and Gerald L D'Spain
Scripps Institution of Oceanography, University of California San Diego
jhildebrand@ucsd.edu 858 534-4069; gld@mpl.ucsd.edu 858 534-5517

Background

Passive acoustic monitoring of marine mammal presence is needed both for Naval environmental compliance, as well as for basic scientific studies of marine mammals. Autonomous gliders have the potential to provide persistent monitoring of marine mammal presence by providing a platform for passive acoustic monitoring. Gliders may prove to be a both a less costly and more effective solution for passive acoustic monitoring than shipboard towed array monitoring. Likewise, gliders may provide more spatial cover than possible from arrays of bottom mounted acoustic sensors.

Objectives

We aim to create operational glider-based marine mammal detection, classification, and localization systems to provide timely information on marine mammal presence to support Naval monitoring efforts. Our objective is to develop and test glider-based capabilities for marine mammal call detection, classification, and localization (DCL). Because of their long-duration on-station time and acoustically silent operation, gliders provide attractive platforms for acoustic monitoring over extended periods of time, with significant processing capabilities for detection, classification and localization of marine mammal calls. For gliders to be effective in this role, efficient algorithms for automated detection and classification of marine mammal calls are needed. In addition, we are testing both submerged and near-surface platforms for marine mammal call detection, and comparing these platforms against fixed bottom-mounted acoustic sensors.

Methods

We are exploring two autonomous platforms with capabilities for real-time, persistent, passive acoustic monitoring: the flying wing ZRay glider and the near-surface Wave Glider. The ZRay is the world's largest underwater glider, employing a high lift-to-drag ratio wing design allowing efficient long distance travel at higher speeds and with greater payloads than traditional profiling gliders. The Wave Glider has a surface float connected by cable to a submerged glider, using wave action for propulsion. The presence of the Wave Glider surface float, that includes real-time data communications, allows for instantaneous notification of marine mammal presence.

We have a collaborative team to investigate the ZRay and Wave Glider capabilities for marine mammal monitoring. John Hildebrand and Sean Wiggins are responsible for Wave Glider-based development of marine mammal recording and detection/classification hardware and software. Gerald D'Spain is responsible for ZRay glider development and integration with marine mammal DCL capabilities.

A Range Validation Test was conducted to compare multiple autonomous platforms (gliders, autonomous surface vehicles, and freely drifting floats) at the Navy's SOAR Range (the instrumented part of the SCORE Range) against range-installed hydrophones. Glider operations were conducted simultaneously with the monitoring of range hydrophones by the M3R system (Dave Moretti, NUWC) and data collection by a High-frequency Acoustic Recording Package (HARP) near the range.

In addition to the ZRay (Figure 1) and Wave Glider from SIO, other autonomous platforms participating in the Range Validation Test included: two Seagliders from APL/UW, a Slocum glider and two freely drifting vertically profiling floats from WHOI, a freely drifting float from NOAA/Oregon State, and a Wave Glider from SPAWAR Systems Center Pacific. All autonomous platforms were deployed over the field of bottom-mounted hydrophones comprising the Navy's SOAR Range.

Figure 1. ZRay on the fantail of the R/V Sproul during the Range Validation Test.

Results

A comparison was conducted of the sound pressure levels recorded by a hydrophone towed behind the Wave Glider submerged wing at about 8 m depth below the sea surface, and a nearby HARP hydrophone located at about 500 m depth, 10 m above the seafloor. Both the Wave Glider and HARP passive acoustic systems are based on the same sensor and electronics, so the test reveals differences in the ambient noise environment owing to the different depths of the hydrophones and noise induced by the moving Wave Glider platform. Figure 2 shows calibrated noise spectra taken at the same time from the Wave Glider and HARP hydrophones. The Wave Glider and HARP noise levels are remarkably similar over the frequency band above 100 Hz. Below 100 Hz, the Wave Glider hydrophone spectrum increasingly diverges from the HARP spectrum, with about 35 dB higher noise levels at 10 Hz. These differences may be a product both of higher ambient noise levels being present at the sea surface, and greater flow noise for the Wave Glider hydrophone. We are continuing to test different configurations of Wave Glider hydrophone to diminish the self noise below 100 Hz. The results of this test, however, suggest that for most marine mammal species, whose calls occur above 100 Hz, the Wave Glider hydrophone can produce results comparable to those obtained from a fixed bottom sensor (HARP).

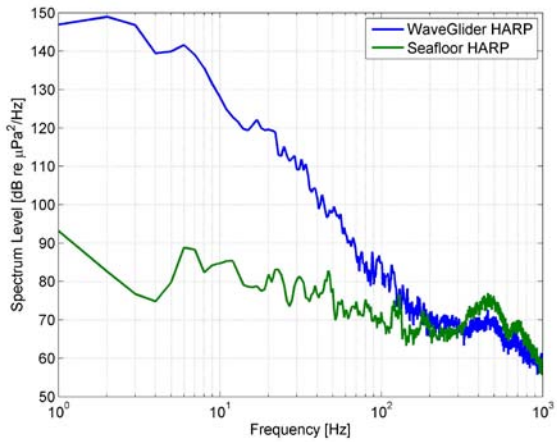

Figure 2. Sound pressure levels for a hydrophone connected to a Wave Glider (8 m depth) compared to an adjacent HARP (500 m depth).

Notes:

Day 4: Thursday April 19, 2012

2012 ONR
Marine Mammal & Biology
Program Review

BETA TESTING OF PERSISTENT PASSIVE ACOUSTIC MONITORS

Thomas P. Hurst, Dr. Mark P. Johnson, Dr. Mark F. Baumgartner, Dr. David M. Fratantoni
Woods Hole Oceanographic Institution
thurst@whoi.edu, (508) 289-2906

Background

Passive acoustic monitoring (PAM) is used increasingly for detecting the presence and abundance of marine mammals with both scientific and mitigation applications (Mellinger & Barlow 2003; Barlow & Gisner 2006; Zimmer et al, 2008; Marques et al, 2009). The usual PAM system comprises a mooring which records sound continuously to a hard-drive over several months. The mooring is retrieved periodically at which time the acoustic recording is examined for vocalizations. The 2007-2009 ONR-funded AMT program focused on utilizing the DMON to expand this technique in two ways. (The DMON is a digital acoustic monitor developed at WHOI for the purpose of passive monitoring of marine mammals.) The first goal was to combine acoustic monitoring with mobile oceanographic platforms such as gliders and profiling floats to monitor marine mammal vocalizations and oceanographic conditions over spatial scales of tens to thousands of kilometers (Baumgartner and Fratantoni, 2008; Moore et al., 2007). The second focus area was on automatic detection and classification within the PAM device. The capability to process acoustic data on-board autonomous platforms and report detections to ship or shore will greatly increase the efficiency of PAM operations and enable adaptive surveys and real-time monitoring. The 2010-2012 ONR-funded Beta Testing program continued to develop and test the DMON and foster its use as a reference design for the rapidly expanding filed of passive acoustic monitoring. The Beta test program brings together a selected group of collaborators to field and assess the DMON on a number of existing oceanographic platforms.

Objectives

Long-endurance oceanographic sampling platforms such as gliders and profiling floats provide a new opportunity for acquiring acoustic signals from marine animals with immediate applications in conservation and mitigation. Our objective was to produce a reliable system standard for persistent passive acoustic monitoring of marine animals and to get this system out to a select group of researchers to assess its worth. The system, comprising both low-power hardware and acoustic processing software, was to be extensible and able to be incorporated in a variety of autonomous platforms.

Specific objectives:

1.) Produce 20 DMON digital acoustic monitors for distribution to a group of beta test collaborators. These will be researchers developing systems for acoustic monitoring of marine mammals able to evaluate the device and its software in a range of applications. The DMON's will be in either bottle or card set form. Bottles are ready to deploy housings with a 2000m depth rating; card sets are suitable for vehicle integrations (dry space) and software development.

2.) Support the beta testers with software, hardware and user information.

3.) Continue to develop the DMON and its interface with persistent survey platforms.

4.) Accumulate information on the flexibility, function and performance of the DMON, and use this information to improve the device going forward.

Methods

Under the AMT program, we have developed a system for real-time detection and classification of marine mammals from autonomous platforms. The system is based on the DMON, a platform-independent instrument capable of collecting and processing broadband acoustic data. We have installed the DMON into two widely-used platforms: a profiling float and a glider. In tandem, we have developed detection and classification algorithms for baleen whale calls and beaked whale clicks. Under the Beta Testing program we continued this development and built a number of DMONs to distribute to selected beta test partners. To foster its use and evaluation we provided the support necessary for users to field test their units on varying platforms and different deployment methods. This included instrument training, hardware integration, deployment advice and software support.

In addition to a number of local in-water tests, the DMON was field tested in the Canary Islands (buoys, 2008-2011) where the beaked whale

detector was developed and refined. The DMON running the resulting code was implemented on both the Apex profiler and Slocum glider and tested at the SCORE trials (Jan, 2011). (See figure 1.)

Figure 1: DMON on APEX Profiler and Slocum Glider

Results

The most prominent DMON deployment to date was fielding two APEX Profilers and one Slocum glider at the SCORE trials in January of 2011. Both platforms were running beaked whale detector code where the DMON stored continuous data and real-time detections simultaneously. The continuous recordings were stored to onboard flash memory for later analysis, the real-time detections were sent to the profiler and/or glider controllers and transmitted (via iridium link) to shore when vehicles surfaced.

The beaked whale detector implemented is a pre-whitened CFAR matched filter with parametric classification. Class 1 is a probable detection, Class 2 is possible and Class 3 is unclassified. The SCORE results need a more exhaustive analysis but a post-hoc analysis focusing on Class 1 detections from one of the profilers is very promising. Profiler 6111 (see complete results below) reported 4964 Class 1 detections in just shy of 58 hours of operation. Of these: 4249 were determined to be beaked whales, 544 were determined to be dolphins and the remaining 171 false detects.

SCORE Results: Detector performance

Platform	**Hrs**	**Cl-1**	**Cl-2**	**Cl-3**
Profiler 6111	57.6	4964	8165	53928
Profiler 6114	53.9	4641	11830	88022
Glider WE04	61.9	5620	6971	25050

We currently have 13 DMON “ready to deploy” bottles out in the field with beta test partners. In addition there are 6 card sets currently being used for both vehicle test and integration and programming / detection work. Thus far, DMON’s have been deployed in New England waters, off the coast of Cape Hatteras, Oregon, SCORE, Hawaii, Canary Islands, in the Mediterranean Sea, Azores and Australia. Most deployments have been continuous short-term recordings, some in conjunction with DTAG operations.

Notable collaborator results include integrating a DMON onto the following platforms: iRobot Seaglider (Nowacek, Duke University); Liquid Robotics Wave Glider (Bingham / Howe, Univ of Hawaii); ZRay Glider (D’Spain, SIO). Duke University has adapted the beaked whale detector code to run on the iRobot Seaglider. The Univ of Hawaii Wave Glider was deployed with a DMON primarily to characterize vehicle self-noise however opportunistically recorded humpback whale vocalizations. We have also started working with IFAW in response to the Winter 2011 dolphin stranding’s in Wellfleet Harbor. The goal was to obtain records which will lead to an early warning detection system.

Notes:

REMOTE MONITORING OF DOLPHINS AND WHALES IN THE HIGH NAVAL ACTIVITY AREAS IN HAWAIIAN WATERS

Whitlow W. L. Au and Marc O. Lammers
Hawaii Institute of Marine Biology, University of Hawaii
wau@hawaii.edu, 808-247-5026

Background

The use of remote autonomous acoustic recorders can provide information about how different marine mammals utilize areas of high Naval activities. The potential future benefit for Science and/or Systems Applications is gaining knowledge about how dolphins and whales utilize the waters surrounding Kauai and Oahu, two areas of high Naval activities. From this knowledge, operations can be planned that minimize the potential for encountering marine mammals. The results and methods used in this project can also be applied to other areas with high Naval operations.

Objectives

The objective of this study is to establish the spatial and temporal distribution and relative abundance of whales and dolphins in selected regions of Hawaiian waters. The waters surrounding the islands of Kauai and Oahu, where most Naval activities occur, are the focus of this study. These include the Pacific Missile Range off Kauai and the Pearl Harbor Naval Base, which is home to the U.S. Pacific Fleet.

Methods

Ecological acoustic recorders (EARs) were deployed in deep waters (190 m – 900 m) at eleven locations around Kauai, Oahu and off Ni'ihau in the main Hawaiian island chain (see Fig. 1 for Oahu and Kauai). The EARs off Kauai sampled at a rate of 80 kHz and those off Oahu at 64 kHz. Recordings were duty cycled at 30 seconds every 5 minutes. The data were analyzed using a suite of software including the M3R (Marine Mammal Monitoring on Navy Ranges) algorithm, an energy-ratio-mapping algorithm developed at Oregon State University, Triton software developed at Scripps Institute of Oceanography and custom Matlab programs. The Real-time Odontocete Call Classification Algorithm (ROCCA) was used to establish the species identity of a subset of low-frequency whistles recorded at SW and NW Oahu

Results

A variety of deep diving odontocetes, including pilot whales, Risso's dolphins, sperm whales, spinner and pan-tropical spotted dolphins, and beaked whales were detected at all sites off Kauai and off Niihau. Foraging activity typically began to increase after dusk, peaked in the middle of the night and began to decrease towards dawn. Shown in Table 1 is the percentage of files for the dawn-dusk-night period that contain clicks of different species off Kauai and Niihau. Between 75% and 87 % of all biosonar clicks were detected at night. At present, it is not clear why some of the known deep diving species, such as sperm whales and beaked whales, concentrate their foraging efforts at night.

The seasonal occurrence and distribution of odontocete cetaceans around Oahu was examined by classifying signals as echolocation clicks, low-frequency whistles (<10 kHz) or high-frequency whistles (>10 kHz) to distinguish taxonomic groupings. High frequency (HF) whistles were more common than low frequency (LF) whistles at all sites. LF whistles were most common at SW Oahu (Kruskal-Wallis: $H = 19.58$, $DF = 4$, $p = 0.001$). LF whistles did not have a diel pattern, whereas HF whistles and echolocation clicks had strong diel trends at all five sites (Fig. 2). Both LF and HF whistles occurred less in winter than in spring, summer and fall (Kruskal-Wallis: $H = 44.95$, $DF = 3$, $p < 0.001$ and $H = 24.35$, $DF = 3$, $p < 0.001$, respectively) (Fig.3). There was also less echolocation in winter (One-way ANOVA: $F = 4.35$, $DF = 3$, $p = 0.005$) driven by reduced rates at SW, SE and East Oahu. The results reveal that HF whistling species are most common along the northern shores of Oahu. LF species are variably distributed, but most frequent around SE Oahu. Results from ROCCA suggest that short-finned pilot and false killer whales are the predominant species producing LF whistles around Oahu.

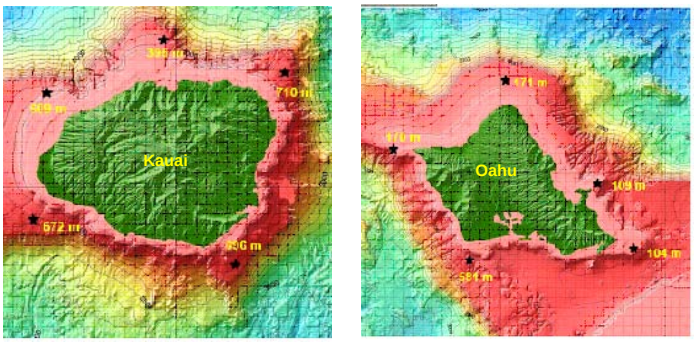

Figure 1. Locations and depth of EARs around the islands of Kauai and Oahu.

Table 1. Dawn-dusk-night foraging percentage

	Pilot whale	Risso's dolphin	Sperm whale	Sm dolphin	Beaked whale
Jun 13, 2010– Sep 19, 2011					
NE	80%	92%	86%	83%	78%
NW	68%	72%	65%	71%	68%
SE	72%	86%	68%	80%	71%
SW	68%	81%	57%	71%	84%
Oct 20, 2010 – Jan 26, 2011					
NE	80%	89%	80%	85%	91%
SE	62%	80%	62%	74%	82%
SW	68%	78%	62%	76%	75%
Jul 17, 2010 – Dec 17,2010					
NIIHAU	78%	83%	77%	85%	89%

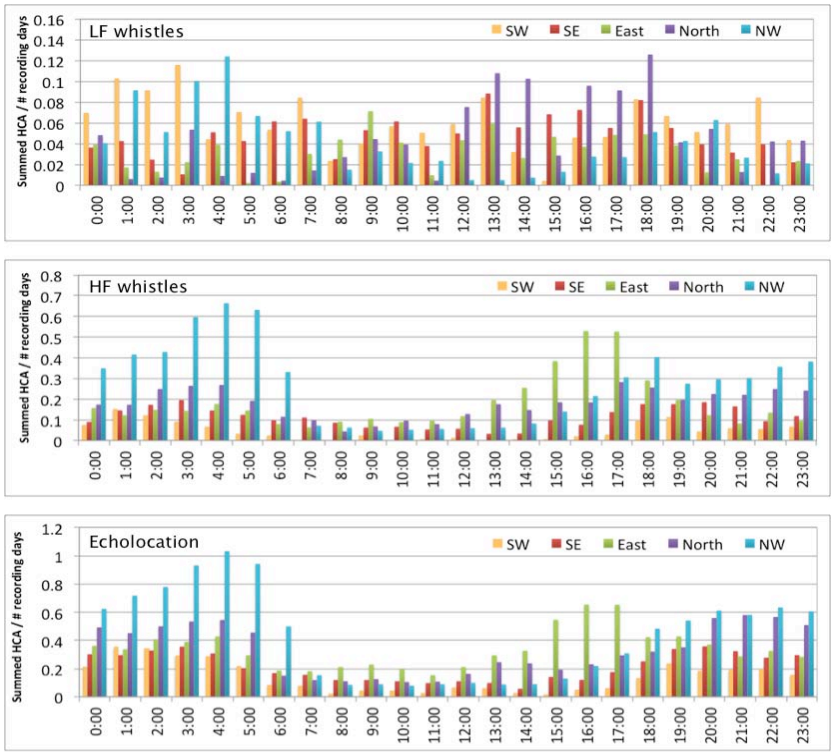

Figure 2. Diel occurrence of whistles and echolocation around Oahu

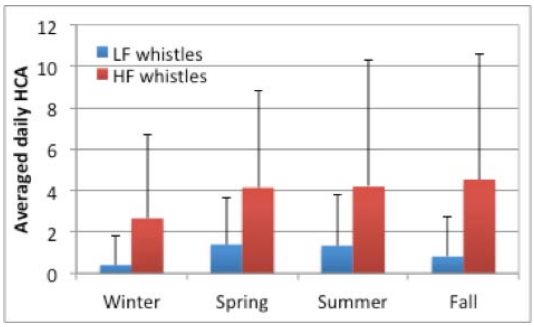

Figure 3. Seasonal occurrence of LF & HF whistles around Oahu

UTILIZING PRO-BONO COMMERCIAL ASSETS FOR MARINE MAMMAL SURVEYS IN HIGH NAVAL ACTIVITY AREA IN HAWAIIAN WATERS

Whitlow Au, Alexis Rudd
Hawaii Institute of Marine Biology, University of Hawaii
wau@hawaii.edu, (808) 247-5026

Background

Lack of information on the behavior and distribution of species can lead to inadequate ecosystem and wildlife management policies. Increased knowledge about the movement and temporal distribution of highly mobile pelagic predators has lead to many improvements in management, including the protection of important breeding, resting, and foraging areas and the establishment of international management strategies.

The probability of detecting an animal depends on many factors, including animal behavior, sea state, or observer competence. While visual surveys are generally limited to 3-7 km, animals can be detected acoustically from tens of kilometers away. Acoustic surveys for marine mammals may provide an alternative to visual methods, especially when visual methods are impossible or almost useless (at night or in rough seas). For some species of marine mammals, especially that are cryptic or with long dive times, acoustic detection rates are higher than or comparable to visual detection rates.

The navy currently uses three main strategies for avoiding impact on marine mammals: 1) spatial or temporal avoidance; 2) changes in procedure such as “ramp up” of sonar source level over time; and 3) monitoring for marine mammals at the surface. Although a combination of these methods is ideal, the simplest and most cost-effective way to mitigate the effects of sonar on marine mammals is to avoid them in space or time.

In Hawaii, survey effort to establish the distribution and abundance of cetaceans has been constrained both by weather and available funds. These surveys are generally located in concentrated areas near the main Hawaiian Islands, and effort is made to conduct surveys in sea states of less than Beaufort 4. In addition, distribution and seasonal information for multiple species has yet to be published.

Objectives

To provide seasonal data on the distribution and relative abundance of cetaceans in the deep water channels of the Hawaiian Islands

Methods

The first phase of this project consisted of adapting existing an acoustic recording technology, the Ecological Acoustic Recorder (EAR) to the purpose of this project. The electronics, batteries, and recording gear were housed in a waterproof pelican case, with an extended cable leading to the hydrophone. In addition to recording equipment, a system of maintaining the hydrophone at depth was designed, built as a prototype, tested, and manufactured.

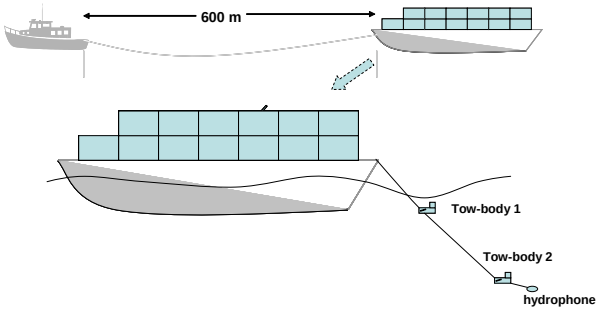

Figure 1. Experimental geometry showing towfish behind barge. The hydrophone is attached to the tow line.

Young Brothers, the largest inter-island shipping company in Hawaii, has agreed to let us locate hydrophones on either their tugs or their barges. The barges leave Honolulu approximately twice per week to Kawaihae on the Big Island, and Nawilliwilli on Kauai.

The recording equipment for this project includes a modified EAR (described in Lammers *et al* 2008). The electronics for the EAR are housed inside a pelican case, which is strapped through a metal eye in the deck of the barge, which has a length of approximately 35 ft. Two down-planed tow-fish are attached to this towline, at 25 ft and 35 ft. These towfish have been constructed out of aluminum pipe and lead weight to stabilize the hydrophone cable and

keep it as far underwater as possible. An electric cable is be secured to the towline and connects from the hydrophone to the electronics on the barge. The hydrophone has an approximate total (built in and system) gain of 30 dB, The EAR has a sensitivity of 193.5 and a frequency range of 28 kHz. Sample rate is be set at 50000-80000. These ranges are appropriate for most delphinid vocalizations, higher frequency mysticytes, such as humpback whales and minke whales, and possibly beaked whales. Acoustic data collection began in January 2011, with trial runs in July 2010.

The towline for the hydrophone cannot currently be longer than 30 feet, to avoid damage to the acoutstic equipment. Harbor depth is 20 feet and all towed equipment currently must be lowered into the water within the harbor, because no crew is allowed on the barge during the channel crossings for safety reasons. The two-towfish system maximizes the depth of the hydrophone while keeping the equipment light enough to be deployed by a single person and significantly reduces surface noise compared to a single towfish system or a weighted hydrophone. One quarter of the first year of data was randomly selected and aurally and visually inspected for acoustic detections of odontocetes and mysticytes.

In Progress

Once the whitening program is complete, we plan to whiten the entire dataset. After analysis, we will compare the detections in the visually inspected data with detections made with Osprey's contour detection function (by David Mellinger) to compare the accuracy of this program at locating whistle contours within this Once cetacean calls and whistles have been identified from the original data, ROCCA (by Julie Oswald) will be used to classify and predict species from call contours. These predictions are up to 80% accurate on known calls and NOAA and Southwest Fisheries currently use this method for real-time classification of odontocetes.

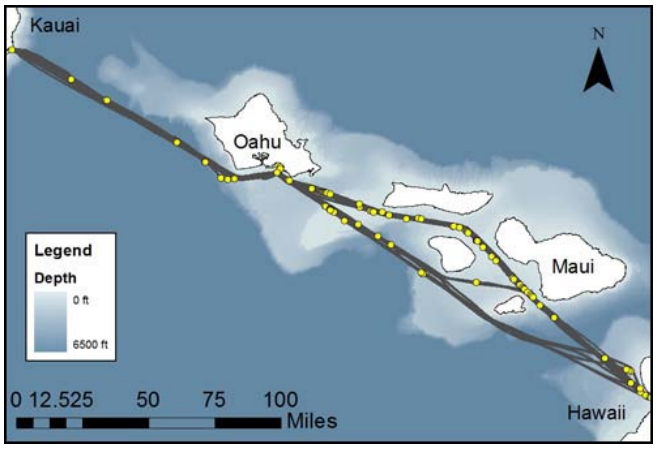

Figure 2. Map showing barge tracks, as well as detections and depths for two trips. The gray dotted line indicates the ship track, while the yellow dots indicate locations of detections

Results

Acoustic data has been successfully collected for 11 consecutive months. The following table summarizes this data:

Number of Deployments	**29**
Total Miles Surveyed	**8078**
Hours of Acoustic Data Collected	**490**
Hours Visually and Aurally Inspected	**148**
Number of Cetacean Calls	**963**

This project has been shown to be a low-cost and innovative system for collecting data on marine mammal distribution and relative abundance in waters that can be inaccessible to traditional methods, including bottom-mounted stationary passive acoustic recorders, such as the EAR and HARP.

Figure 3. Acoustic recordings of dolphin clicks and a whistle from the deployment on July 30, 2010. The animal making these sounds was visually identified as a bottlenosed dolphin (Tursiops truncatus).

BEAKED WHALE PRESENCE, HABITAT, AND SOUND PRODUCTION IN THE NORTH PACIFIC

John A Hildebrand[1], Simone Baumann-Pickering[1], and Mark A McDonald[2]
[1]Scripps Institution of Oceanography, University of California San Diego
jhildebrand@ucsd.edu, 858 534-4069; sbaumann@ucsd.edu, 858 534-7280
[2]WhaleAcoustics, 11430 Rist Canyon Rd, Bellvue, CO 80512
mark@whaleacoustics.com, 970 498-0448

Background

By studying beaked whale presence, habitat and sound production in the North Pacific, the Navy will be better prepared to conduct environmental impact assessments in this region of significant training activity. In addition, fundamental information will be gained on beaked whale foraging ecology.

Objectives

The objectives of this project are to understand beaked whale distribution and density, and improve capabilities for classification of these species from passive acoustic data. Our primary effort focuses on Cuvier's beaked whales, whose acoustics are well known, but whose density and distribution are not. Another focus is on the other beaked whale species in the North Pacific, whose acoustic signatures have not been well characterized. We aim to improve understanding of the acoustic characteristics of these species, to allow for study of their populations using passive acoustic monitoring.

Methods

Acoustic signatures from beaked whales are characterized by a frequency swept echolocation pulse. At least nine species of beaked whale are known to occur in southern California waters, mostly based on stranded animals. The most abundant beaked whale species off southern California is Cuvier's as evidenced by fishery bycatch, visual sighting surveys, and acoustic monitoring data. Other beaked whales expected to be present include: Baird's, Blainville's, Ginkgo-toothed, Perrin's, Hubb's, Pygmy, Stejneger's and Longman's.

Cuvier's beaked whales produce frequency modulated echolocation pulses with mean inter-pulse intervals of 0.4 s and durations of about 200 µs. These upswept pulses have center frequencies at 42 kHz and -10 dB bandwidths of 22 kHz. The echolocation pulses of Cuvier's beaked whale are distinct from those of other beaked whale species, allowing them to be used for quantitative assessment of population distribution and density.

Our approach for Cuvier's beaked whale population estimation is a modification of the point transect distance sampling method. The basic unit for analysis is the detection of a foraging dive for either a group of beaked whales or a single beaked whale. Due to the highly directional nature of beaked whale echolocation, we expect to detect the echolocation sounds intermittently, depending on animal orientation. We estimate the number of echolocating animals in the group using the acoustic data, looking for amplitude changes and corresponding inter-pulse intervals, and thereby derive an estimate for group size. At each site, we determine the percentage of time that beaked whales are detected each day. We further examine the setting of each site to better understand how to extend beaked whale habitat to the larger southern California region.

Results

Nine distinctive beaked whale acoustic signatures have been encountered in the Pacific ocean basin (Figure 1). Each signature has a characteristic set of parameters including center frequency, duration, sweep rate, and inter-pulse interval. We have been using these characteristics to classify beaked whale signals from a variety of sites, with the goal of estimating their density and distribution.

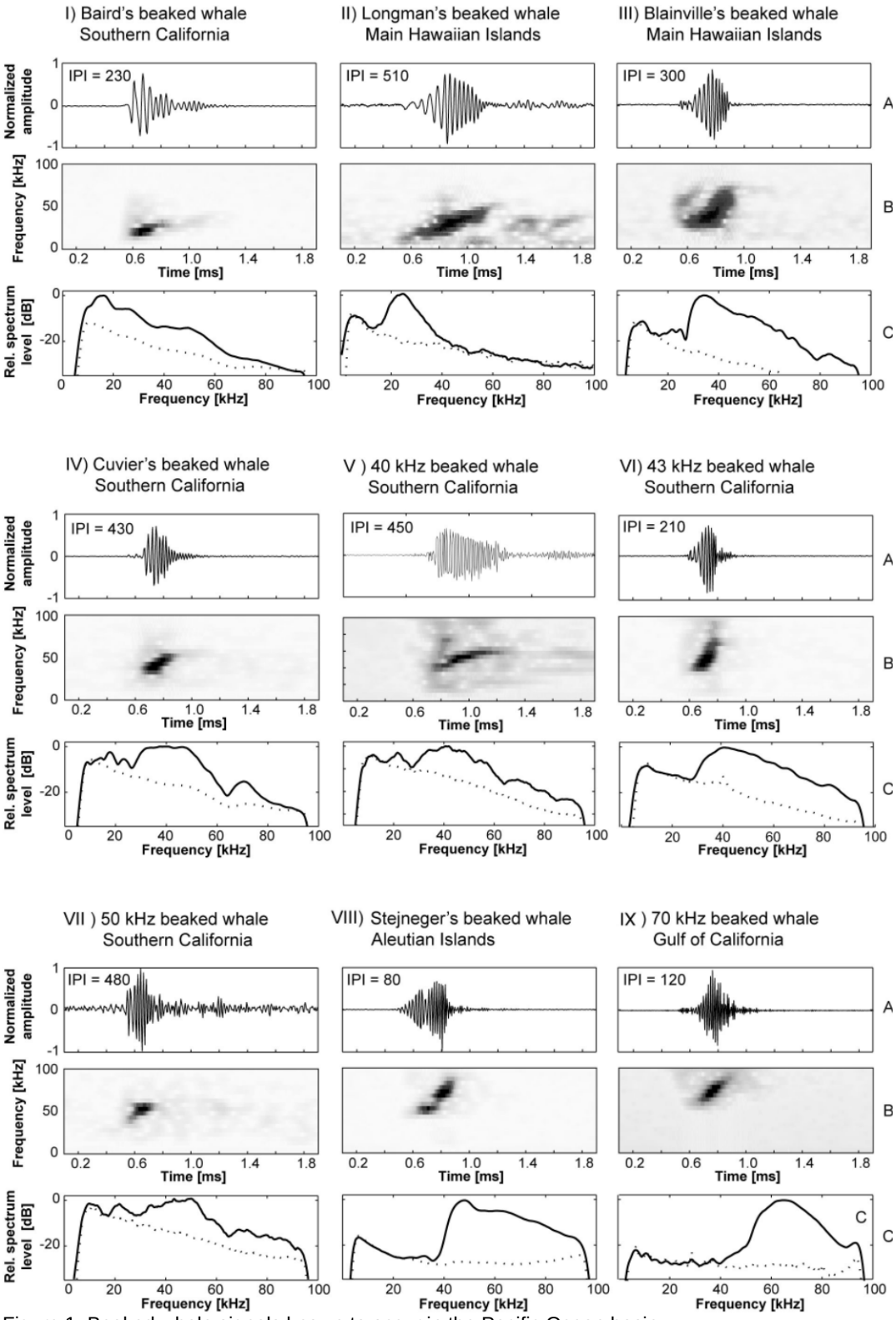

Figure 1. Beaked whale signals known to occur in the Pacific Ocean basin.

Notes:

THE ACOUSTIC ECOLOGY AND BEHAVIOR OF MINKE WHALES IN THE SUB-TROPICAL NORTH PACIFIC: LOCALIZATION, ABUNDANCE AND CHARACTERIZATION OF MINKE WHALE "BOINGS"

Thomas Norris, Steve Martin, Len Thomas, Julie Oswald, Tina Yack and Vincent Janik
Bio-Waves Inc.
Thomas.f.norris@bio-waves.net; Tel: 858-361-565

Background

The minke whale (*Balaenoptera acutorostrata*) is a small and elusive baleen whale that is rarely sighted in tropical waters of the North Pacific Ocean. During winter and spring, they produce complex sounds, known as 'boings', which likely are an acoustic display related to courtship. Although sightings are rare, boings are frequently detected around the Hawaiian Islands from deep seafloor hydrophones, and from hydrophone arrays towed from research vessels.

Objectives

The long-term goal of this research project is to improve our understanding of the acoustic ecology and behavior of minke whales in the Hawaiian and Pacific Islands. A primary goal of this study is to use and assess the effectiveness of passive towed-hydrophone arrays to localize animals so that minke whale abundance in the study area could be estimated. The abundance estimate can be used to infer call rates, an important variable required for estimating animal abundance from fixed hydrophones. A secondary goal is to compare characteristics of boings in the central North Pacific (e.g. the Hawaiian Islands) to other regions in the central and western and North Pacific (e.g. the Northern Mariana Islands). These results will be used to elucidate population structure for North Pacific minke whales.

Methods

To accomplish our objectives, we used existing passive acoustic data collection methods and analytical methods. When needed, we developed new methods that allowed us localize, track movements, and estimate densities of calling minke whales, as well as examine acoustic characteristics of their calls. The primary study area (~2000 km^2) was a deep-water region located to the northwest of the island of Kauai and encompassed a fixed seafloor hydrophone range (BSURE) that is part of the Navy's Pacific Missile Range Facility (PMRF). A secondary study area encompassed a large (580,000 km^2) study area centered on the island of Guam in the Western North Pacific and included the Marianas Trench. In March and April of 2009 and 2010, we conducted visual-acoustic surveys of the Kauai study area using a relatively quiet motor-sailing vessel towing a multi-element (2-6) hydrophone array. All geo-spatial and acoustic data were digitally recorded for post-processing. Fifteen BSURE hydrophones, part of a sparse hydrophone array, were monitored and recorded concurrent with the line-transect survey effort. Using both systems, calling animals were localized in near real-time. Visual surveys were conducted concurrently from the vessel when sea and weather conditions allowed.

Towed hydrophone arrays deployed from the survey vessel were used to obtain localizations in real-time using and a digital data acquisition system running Ishmael, Whaltrak II and PAMGUARD software. We developed a custom Matlab program (called "Boinger') to post-process the acoustic (wav files) and GPS data in order to get more precise estimates of the location of calling animals. The resulting field and Boinger localizations were reviewed by an experienced bio-acoustician and compiled for importing into the distance sampling analysis software package 'Distance'.

Due to the linear hydrophone configuration of towed arrays, a left/right ambiguity (with respect to the track line) exists for most localizations. Because there are two possibilities for locations (and distances) to choose from, a Monte-Carlo approach (using 1000 simulations and a probability for each side of 0.5) was used to determine which side to use. For encounter rates, we used only observations that were located inside the study area. For localizations with a L/R ambiguity, and where one side was outside the study area, we used the Monte-Carlo approach to choose a side. Model fitting was accomplished using the R library 'mrds' in Distance.

BSURE seafloor hydrophone data were post-processed for both animal localization and boing

call density. Data from 2009 were analyzed to compare Time-Of-Arrival (TOA) hyperbolic localization accuracy with model-based methods (developed by E.M. Nosal) and with target motion analysis methods (from towed hydrophone data). In 2010, Eleven hours of data sampled were sampled concurrently with the 2010 towed hydrophone array survey effort, and manually analyzed using 2-D TOA hyperbolic localization methods. Call density was estimated using spatially explicit capture-recapture (SECR) methods developed in the R environment. Dividing the SECR boing density by the towed array survey density estimate will result in a long-term average cue rate which can be used to estimate animal density from fixed seafloor hydrophones.

Boings recorded from towed arrays surveys in the Kauai and Guam study sites were characterized by semi-automatically measuring a suite of over 15 acoustic variables using the program Osprey. Random forest classification methods were used to determine if randomly sampled boings could be correctly classified to their respective recording locations.

Results

The 2009 field effort consisted of 11 days of effort resulting in 848 km of directed (i.e. non-systematic) survey effort inside the Kauai study site. This effort resulted in the only sighting of an acoustically localized animal near the end of the survey period. In 2010, when line transect surveys were conducted, 13 days of effort was conducted, resulting in over 1550 km of effort and culminating in 58 acoustic localizations. Both efforts were conducted concurrently with the PMRF hydrophone array recording effort.

The abundance estimation analysis using the 58 localizations from 2010 Kauai effort resulted in a density = 2.75×10^{-3} animals / km^2, or ~ 6 animals (CV = 22.7%) in the study area. Combining this result with the SECR estimated boing call density of 71.65 boings/hour/10,000km^2 (CI 63.8 to 80.4) results in a long-term average minke boing cue rate of ~ 2.6 calls/ hour/ whale.

Random Forest analysis of boings recorded in the Marianas Islands and Hawaii resulted in correct classification scores of over 80% for both Kauai and Guam from a sample about 70 randomly selected boings from each area. Pulse repetition rates, duration and dominant signal component (closely related to peak Hz) are the three most important variables for classification.

These results will be discussed in relation to our current knowledge of the acoustic ecology and behavior of minke whales. The new methods and information from our studies will allow for more effective management and conservation of this protected living marine resource.

Notes:

PASSIVE ACOUSTIC METHODS FOR TRACKING MARINE MAMMALS

Eva-Marie Nosal
Department of Ocean and Resources Engineering, University of Hawaii
nosal@hawaii.edu; 808-956-7686

Background

The focus of this effort is to improve passive acoustic localization and tracking methods. These methods are useful for monitoring and studying marine mammal bioacoustics and behavior in the wild. Methods developed to track marine mammals are useful for sources other than marine mammals (e.g. tracking of surface vessels can help to monitor fishing efforts in marine protected areas).

Objectives

This project aims to meet two specific challenges associated with tracking marine mammals using widely-spaced bottom-mounted hydrophone arrays: (1) Multiple animals whose calls cannot be easily separated or associated, and (2) Insufficient receiver coverage, in which case standard time-of-arrival (TOA) tracking methods fail. Species of direct interest are sperm whales, beaked whales, minke whales, and humpback whales.

Methods

Existing datasets are used to develop and apply the tracking methods. The main effort is directed toward data collected at Navy Ranges (esp. AUTEC and PMRF), but other datasets that use bottom-mounted sensors are also be considered if they are available and appropriate.
Although the two main tracking challenges addressed by this project (insufficient receiver coverage and multiple animals) are not exclusive of one another, initial efforts focus on isolating the problems (by identifying periods in a datasets with only one problem, for example) and solving them separately. As the separate challenges are met, efforts progress to the joint problem.

Model-based tracking methods [Thode 2005; Tiemann *et al.* 2004; Nosal 2007] are used since they can account for depth-dependent sound speed profiles (particularly important as refraction becomes significant at long distances, such as on Navy ranges [Chapman 2004]) and since they can accurately model and make use of multi-path arrivals. Methods are implemented using a Bayesian framework to incorporate available *a priori* information (e.g. maximum possible swim speed), get error estimates on position, and improve performance in uncertain and fluctuating environments. In this framework, a three dimensional grid is created and the likelihood of an animal present is calculated for each grid point and time. Calculations are based on measured TOAs, modeled TOAs, estimated uncertainties, and any available *a priori* information. All methods are fully automated through MATLAB code.

Results

A detector that traces contours in spectrograms was developed and implemented [Nosal 2008]. It is useful for automatic detection of unknown and unexpected transients in large and unexplored datasets. Although it is not optimal for expected or known sounds (where matched filters or other tuned detectors perform much better), it can be useful as a “first sweep” for large volumes of data in which unknown or unpredictable sounds might be present.

Methods developed for widely-spaced hydrophones were modified to process data from compact arrays to obtain bearing and elevation estimates for vocalizing animals [Nosal 2009b]. Range can be obtained by using two compact arrays and/or reflections. Tetrahedral configurations can be more useful than line arrays in high signal-to-noise situations since they give both bearing and elevation.

Model-based tracking capabilities were extended to multiple animal datasets by using a method that combines likelihood surfaces corresponding to multiple time-of-arrival differences [Nosal 2009a]. These methods can be automatically applied in cases in which calls can be associated between hydrophone pairs but in which individual animals cannot be indentified or separated. Figure 1 shows an example in which 2 whales were localized using this method.

An automated association method was developed for the case of stereotypical calls (including those from sperm whales, beaked whales, and minke whales) [Nosal 2009a]. The method relies on scatterplots of TDOAs vs.

TOA, in which tracks corresponding to a single animal vary slowly with animal position. These scatterplots are also useful in efforts to "fill in" lossy data in which an animal is heard intermittently on a given hydrophone (in the case of a highly directional vocalization, for example). This method of associating calls may be useful in efforts aimed at counting animals (without necessarily tracking them).

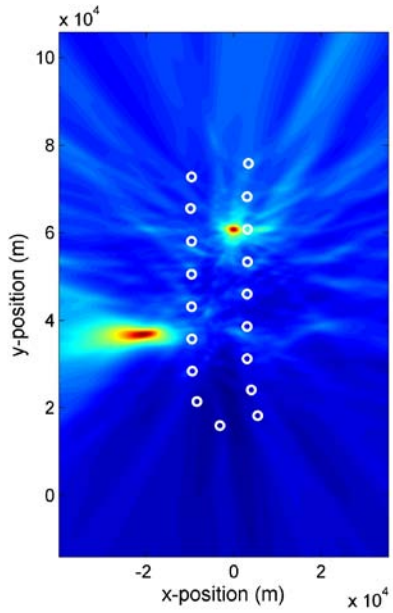

Figure 1. Multiple-animal likelihood surface (red/blue shows high/low probability of animal presence) for two minke whales at PMRF. Hydrophones are shown as white circles. Even when only 7 hydrophones at the top of the range were used for localization, both animals could be found.

It was demonstrated [Nosal 2011] that minke whales can be tracked up to 30 km away from the nearest hydrophone in a subset of hydrophones in the PMRF range to within a few hundred meters [Fig 1]. To accomplish this, multipath arrivals are extracted and identified, and the model-based methods that account for sound-speed variation with depth are employed. Tracking is possible even in cases where direct arrivals are absent but multipath arrivals are present (e.g. surface reflections, bottom reflections, bottom-surface-bottom reflections).

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Notes:

PASSIVE ACOUSTIC MONITORING FOR THE DETECTION AND CLASSIFICATION OF MARINE MAMMALS

Marie A. Roch
San Diego State University
marie.roch@sdsu.edu; 619 594 5830

Background

Passive acoustic monitoring provides the opportunity to detect and classify vocalizing marine mammals at times where other methods are not practicable such as during poor observation conditions (night, high sea state, etc.). This is relevant to fleet restrictions on the use of active sonar in the presence of marine mammals during exercises. In addition, information about how animals use their habitat can be used to inform planning and reduce the likelihood of exposure.

Objectives

The goals of this research were to develop automated methods for detecting whistles in complex auditory scenes and to provide improved methods for classifying echolocation clicks.

Methods

Two new algorithms were designed for whistle contour extraction. The first constructed graph representations of connected whistle networks from spectrogram peaks and then selected optimal connections from crossing points. The second method used a particle filter to predict whistle paths. Both methods were compared against analyst selected whistles.

Using echolocation signals to determine which species produced a vocalization is desirable as the signal generation is governed by a highly specialized anatomy. There are several factors that make this a challenging task: the received signal varies dramatically depending upon the orientation between the animal's longitudinal axis and the hydrophone, high frequencies attenuate faster than lower ones, and the animals are known to be able to control factors related to signal generation. We proposed two methods to improve classification: one geared towards rejecting detections of unknown species in a species recognition task, and the other to develop submanifold representations of feature spaces. In addition, we examined adaptive boosting, an ensemble technique based on discriminative learning and the fusion of weak classifiers.

Results

For the whistle contour extraction, we developed several methods that were ancillary to the work at hand. We developed a new set of metrics for determining whistle detection performance based on recall and precision as well as quality metrics that described items such as how much of the whistle had been detected, whether or not the detection had been fragmented into multiple segments, and statistics of the deviation from the expected contour path. Being able to measure these statistics required an extensive set of human annotated ground truth whistles, and an annotation tool was developed to fit whistles interactively with cubic splines. These metrics, annotations, and the associated data were used both for this work and as the conference data set for the 2011 Detection, Classification, and Localization of Marine Mammals Using Passive Acoustics conference.

Both contour extraction methods exhibited good performance (Roch, Brandes et al. 2011) on complex auditory scenes (Figure 1), with the particle filter being able to retrieve 71.5% of the human annotated whistles and the graph based algorithm 80.0%. Within the detections, 60.8% (particle filter) and 76.9% (graph) were correct. The vast majority of false positives were for very short detections less than a quarter second.

Our classification work deviated from the original proposal but nonetheless produced significant advances in the state of the field. Our study showed that the universal background model, submanifold learners, and adaptive boosting provided similar results to our baseline methods. This led us to conjecture that the opportunity for gains lie not in the classification method or submanifold of the baseline features, but rather in the selection of features themselves.

As a consequence, we refocused our research on refining the features themselves. Effort was devoted to determining how fine a characterization of the spectra was necessary to effectively represent echolocation clicks while reducing the dimensionality of the problem as well as determining ways to eliminate outlier spectra via elimination based on peak

frequency. These techniques resulted in a 15% reduction in error rate on a species identification task compared to previous results. The new techniques were applied to a six species identification task (Roch, Klinck et al. 2011). The work has also been successfully applied in other contexts (unpublished data, Baumann-Pickering, Roch et. al.), such as discriminating between species of beaked whales and detecting *Kogia spp.*

a

b

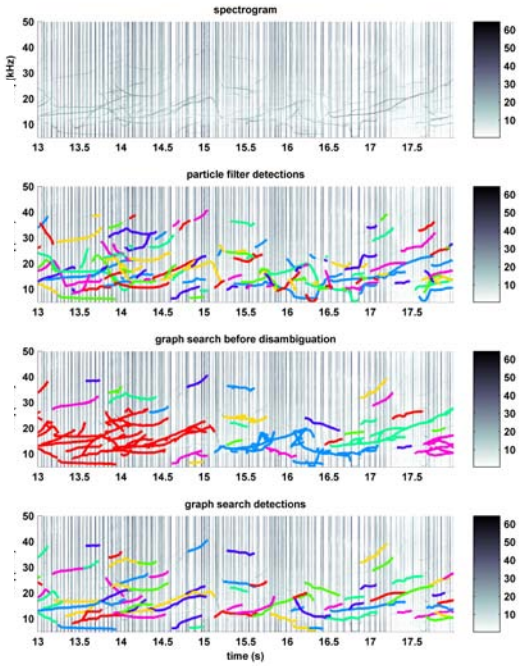

Figure 1 –Example of whistle contour extraction. Panels show a spectrogram of common dolphin calls (a) followed by the particle filter detections (b) and the graph detections before (c) and after (d) graph analysis. [color online]

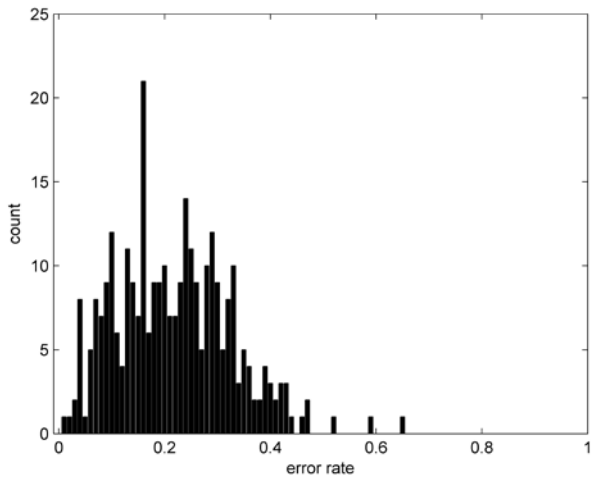

Figure 2 – Overall error rate on the classification of six species of odontocetes. The histogram shows error rates for 300 randomized trials where training and testing data came from separate sightings. The mean error rate was 0.22±0.11σ with a median of 0.21.

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Notes:

NEXT-GENERATION BIOACOUSTIC SOFTWARE

David K. Mellinger and Jonathan Dodge
Cooperative Institute for Marine Resources Studies, Oregon State University
David.Mellinger@oregonstate.edu, 541-867-0372

Background

Over the last several decades, awareness has grown that acoustic methods are often the best means for studying and monitoring marine mammals. Acoustic methods, for instance, have long been used for detection and study of sperm whales, in part because of the difficulty of visual detection. Acoustic methods, in contrast to visual ones, function well in darkness, fog, high sea states, and other inclement viewing conditions. Via the use of autonomous recorders, acoustic methods can also be used in remote or inhospitable areas where visual monitoring would be impracticable or impossible.

Software tools are needed for analyzing such data sets, even for such simple tasks as manually scanning spectrograms to find calls of interest. Analysis software for acoustic localization of calling animals is necessary. Marine mammal acoustic data is often collected in very large data sets, necessitating automated methods for data analysis. For instance, acoustic data collected at a sample rate of 200 kHz results in a one-year data set 12.6 TB in size. Automation tools are clearly needed for data sets of this scale.

Starting in 2000, ONR funded the development of one such tool, the software package *Ishmael*[1]. It is a user-friendly bioacoustic analysis package for Windows. It includes displays of sound waveforms and spectrograms, recording capability for real-time input, several methods for acoustic localization, beamforming, several methods for automatic call recognition, and a sound annotation facility. Ishmael is aimed at users wishing to analyze large volumes of data quickly and easily. Ishmael quickly became popular, with thousands of downloads by users; a large proportion those downloads were in active use, and a survey in 2005 showed that 46% of respondents use it regularly. It has also been used in much ONR-funded research.

Objectives

The objective of this effort is to make a number of improvements to Ishmael. This will improve its capability for bioacoustic processing and analysis, particularly for automated detection, classification, and localization.

Methods

The following approach is being used:

1) Recruit a software engineer to work on the project.
2) Train the software engineer on Ishmael's architecture and implementation.
3) The software engineer then makes the necessary improvements to Ishmael. These include improved localization, improved detection and classification, advanced acoustical measurement methods, filtering and re-sampling capability, multiple concurrent views of an audio stream, multi-processor capability, Mac and Unix support, and audio data input and output.

Results

Software engineer Jonathan Dodge was hired into the project to begin implementing the above changes to Ishmael. Dodge has been learning Ishmael's architecture and implementation while making changes to the code. The new version, Ishmael 2.0, has a number of improvements over version 1:

- A new interface for real-time audio data input from National Instruments. The former interface worked only for a few older types of data acquisition hardware, while the new one works for most modern hardware. The data acquisition system for the ASIO interface was also improved.
- A subsystem for making acoustic measurements of many types. These include simple measurements, such as times and frequencies, found in many acoustic analysis systems. It also includes more sophisticated measurements designed to estimate call parameters reliably in the presence of background noise[2,3]. Ishmael users can select a call and make a measurement with one click. Figure 1 shows an example of a data log with some of these acoustic measurements.
- A subsystem for audio filtering. Filters can be low-pass, high-pass, or band-pass, and can be finite or infinite impulse response. Filters are commonly used to remove noise, such as low-frequency flow noise or ship noise.

- Ishmael can show two simultaneous views of one incoming sound signal. This is helpful, for instance, when there are species widely separated in frequency such as odontocetes and mysticetes, or when different time/frequency resolutions are needed for displaying calls, as in Fig. 2.

Datalog

File

start time	end time	low freq	high freq	max intensity	center freq	center time
66.91312	73.9372	27.4692	61.33077	89.79711	41.98973	70.2398
143.9926	151.83	25.5615	48.93077	91.97063	35.46095	148.13175
186.7653	193.05	15.0692	21.26923	94.21643	17.26817	190.39037
215.2311	216.932	26.0385	67.05385	92.12994	40.247	216.11149

Figure 1. An example of a datalog from Ishmael.

The start/end time and low/high frequency measures are found in most bioacoustic analysis systems, but centroid frequency and centroid time are special measures designed to be robust in the presence of noise.

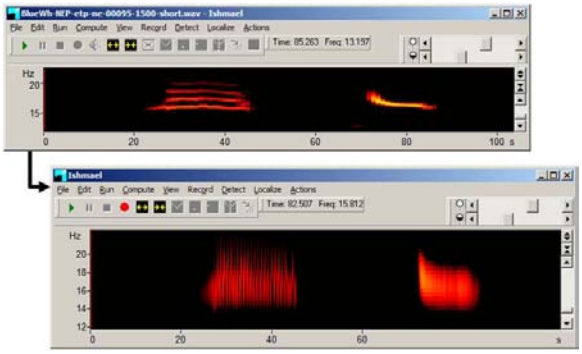

Figure 2. Dual Ishmael views.

Notes:

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