2010

Project report of virtual experiments in Marine bioacoustics: model validation

Cranford, Ted W.

Monterey, California. Naval Postgraduate School

http://hdl.handle.net/10945/713

NPS-OC-10-002CR

NAVAL
POSTGRADUATE
SCHOOL

MONTEREY, CALIFORNIA

Project Report of Virtual Experiments in Marine Bioacoustics: Model Validation

by

Ted W. Cranford and Petr Krysl

August 2010

Approved for public release; distribution is unlimited.

Prepared for: CNO(N45), Washington, D.C.

NAVAL POSTGRADUATE SCHOOL
Monterey, California 93943-5000

Daniel T. Oliver President	Leonard A. Ferrari Executive Vice President and Provost

This report was prepared for and funded by CNO (N45), Washington, D.C. The report was prepared by San Diego State University and University of California, San Diego supported under NPS grant N00244-09-1-0072.

This report was prepared by:

Ted W. Cranford
Adjunct Assistant Professor
Department of Biology
San Diego State University

Reviewed by:	Released by:
Jeffrey Paduan Chairman of Oceanography Department of Oceanography	Karl A. van Bibber Vice President and Dean of Research

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* August 2010	**2. REPORT TYPE** Contractor Report	**3. DATES COVERED** *(From - To)* 31 July 2009 – 31 May 2010

4. TITLE AND SUBTITLE Project Report of Virtual Experiments in Marine Bioacoustics: Model Validation	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER N00244-09-1-0072
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Ted W. Cranford and Petr Krysl	**5d. PROJECT NUMBER**
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) San Diego State University, San Diego, CA 92182 University of California – San Diego, La Jolla, CA 92903	**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Sponsoring Agency: CNO (N45) Washington D.C. Monitoring Agency: Naval Postgraduate School Department Oceanography, Monterey, CA	**10. SPONSOR/MONITOR'S ACRONYM(S)** NPS-OC-10-002CR
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited

13. SUPPLEMENTARY NOTES
The views expressed in this report are those of the authors and do not reflect the official policy or position of the Department of Defense of the U.S. Government.

14. ABSTRACT

A series of finite element model simulations are compared against results from various real world marine bioacoustics experiments with the bottlenose dolphin. Three significant results are revealed.

1) *Changes in relative position of fat bodies can adjust echolocation beam direction.* This is the first evidence of this.

2) *Beam direction is consistent* despite several elements being present within the sound transmission system within the dolphin's forehead. This suggests that the skull is the primary structural element in the formation of the sound transmission beam, with other elements playing a major role in concentrating or "focusing" the outgoing beam.

3) *There is evidence for focusing of the beam in stages.* The model simulations illustrate the narrowing of the sound transmission beam with various level of refinement in structural complexity. It appears as if structures like the melon and air space individually affect the narrowing of the beam, with their combined contributions being significant.

All of these results are aligned with, or similar to, results obtained from live animals performing in psychoacoustic experiments over the past fifty years.

15. SUBJECT TERMS
Marine bioacoustics, finite element model, echolocation generation, echolocation beam direction, bottlenose dolphin, Tursiops truncates.

16. SECURITY CLASSIFICATION OF: Unclassified			**17. LIMITATION OF ABSTRACT**	**18. NUMBER**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT Unclassified	**b. ABSTRACT** Unclassified	**c. THIS PAGE** Unclassified	UU	26	**19b. TELEPHONE NUMBER** *(include area code)*

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

Contents

LIST OF FIGURES ii

TITLE PAGE 1

EXECUTIVE SUMMARY 2

INTRODUCTION 3

METHODOLOGY 3

SUMMARY OF RESULTS 5

DISCUSSION 8

FUTURE PLANS 9

PEER REVIEWED PUBLICATIONS DURING THIS PROJECT 9

CONFERENCE PRESENTATIONS DURING THIS PROJECT 10

AWARDS AND HONORS 10

REFERENCES 10

INITIAL DISTRIBUTION LIST 13

List of Figures

Figure 1: Spherical bursae (a), block bursae (b) 5

Figure 2: Simulation with bursae as spheres: 7
  A. Simulation moving the bursae with skull only.
  B. Simulation moving the bursae with all CT scan data.
  C. Simulation moving the bursae with smooth melon.
  D. Simulation moving the bursae with smooth melon and air spaces.
  E. Simulation moving the bursae with smooth melon and a living dolphin.

Figure 3: Simulation with bursae as blocks: 8
  A. Simulation moving the bursae with smooth melon.
  B. Simulation moving bursae with smooth melon and air spaces.
  C. Simulation moving bursae with smooth melon and a living dolphin.

PROGRESS REPORT

9 April 2010

Project Title: Virtual Experiments in Marine Bioacoustics: Model validation.

Submitted to:
Professor Curtis A. Collins
Department of Oceanography
Graduate School of Engineering and Applied Sciences
Naval Postgraduate School
Monterey, CA 93943

Technical contact:
Ted W. Cranford

Principal Investigators: Ted W. Cranford[1] and Petr Krysl[2]
(1) *Biology Department, San Diego State University, San Diego, CA 92182,*
(2) *Jacobs School of Engineering, University of California at San Diego, La Jolla, CA 92093*

EXECUTIVE SUMMARY

Any finite element model requires validation, a distinct effort to test the results of a model simulation against the results obtained in a real world situation. We have just completed a series of simulations that we can compare against results obtained from various real world experiments with the bottlenose dolphin (*Tursiops truncatus*).

The simulations reveal three significant results.

(1) Changes in Relative Position of Fat Bodies Can Adjust Beam Direction
This is the first evidence that small changes in relative position of the fatty elements within the sound generation apparatus can produce small changes in beam direction.

(2) Consistent Beam Direction
The sound transmission system within the delphinid's forehead contains several elements. Our virtual model allows us to tease apart the contributions that these structures make to the formation of an echolocation beam. The primary finding is that the beam direction that emanates from the simulations is consistent across them. This suggests that the skull is the primary structural element in the formation of the sound transmission beam. The other elements play a major role in concentrating or "focusing" the outgoing beam.

(3) Evidence for Focusing in Stages
The simulations illustrate the narrowing of the sound transmission beam with various levels of refinement in structural complexity. It appears as if structures like the melon and the air spaces have some effect on narrowing the beam, and their combined contribution is significant.

All of these results are aligned with, or similar to, results obtained from live animals performing psychoacoustic experiments over the past 50 years.

INTRODUCTION

The research addresses two distinct and fundamental topics: model validation and understanding potential acoustic impacts on odontocetes. This research proposal has been subdivided into those two projects, plus two Options that could be implemented if additional funding becomes available. Project #1 (Model Validation) and Project #2 (Virtual Experiments) are the primary thrusts of our effort.

Scope:

The breakthroughs and discoveries from our prior work are significant because they were gathered from a little-known beaked whale species, Cuvier's beaked whale (*Ziphius cavirostris*), that is at the forefront of concerns about the potential impacts from Navy sonar. An obvious problem in working with a species for which we know so little is that we do not have any research by which to calibrate or assess the validity of the simulation results. The work reported here will remedy that problem by constructing two models. One will be based on CT scans of a postmortem specimen of an Atlantic bottlenose dolphin that was provided to us by SeaWorld, San Diego. The other will be based on CT scans of a live bottlenose dolphin that was provided by the Navy Marine Mammal Program at SPAWAR Pacific in San Diego.

The physical properties of the tissues were measured directly from the postmortem specimen. We will also use those measurements to estimate the values for the specimen from the Navy Marine Mammal Program, for which we only have scan information.

The emphasis is placed on comparison. The simulated results of our inquiry with the Atlantic bottlenose dolphin will be compared with results from the psychoacoustic literature and with our previous results on Cuvier's beaked whale.

METHODOLOGY

Technical approach:

The approach is based on physics, computing resources, and engineering principals combined with the anatomic details of the organism. To date the Vibroacoustic Simulator is the *only* tool that is currently capable of finding answers to a broad spectrum of questions that are critical to understanding the issue of marine mammal exposure to high intensity sound.

Our approach to the finite element modeling of vibroacoustic phenomena in biological tissues was described in detail in Krysl *et al.* (2008). The starting point when modeling the geometry of biological specimens is volumetric imaging: CT scans. From these images we derive directly an image-based discrete finite element model. The intensity of the 3-D images data (in Hounsfield units) is mapped to material properties. Here we used the mapping proposed by Soldevilla *et al.* (2005), and also the experimentally determined melon properties from Norris and Harvey (1974). Since all the elements are rectangular and of the same shape, the Wilson incompatible formulation is a natural choice, because both the bending response and the dilatational locking insensitivity are significantly enhanced (Krysl *et al.*, 2008). The equations of motion in the discrete form (system of ordinary coupled differential equations) is integrated from initial conditions (to be described next) in time using the centered difference algorithm.

The so-called “phonic lips” are hypothesized to be the biosonar sound source in the bottlenose dolphin (Cranford, 2000; Cranford *et al.*, 1996). The phonic lips consist of constrictions in the spiracular nasal passage. The walls of the lips contain pairs of fat bodies ensheathed in connective tissue (bursae). During sound generation, air is pushed through the phonic lips, setting them into vibration. As the opposing walls or lips vibrate, they impact one another and generate short pulses of sound. In this work we produce sound in a simplified but related manner: tissue at the two locations of the bursae is given initial velocity which starts the tissue "blobs" in opposing directions so that they collide and thereby produce an acoustic pressure wave. The location of the phonic lips could play a role in the forming of the echolocation beam. The musculature associated with the dolphin's melon suggests that the beam may be actively distorted or shaped by the animal. Evidence for “beam steering” in odontocetes does exist (Amundin; Amundin, 1991a; Amundin, 1991b; Møhl *et al.*, 2000; Moore *et al.*, 2008). Thus we also consider the location of the phonic lips among the sources of modeling error.

Placing a simulated click source at the location of the left and right phonic lips (Cranford and Amundin, 2003), we can compute a wave train (simulated echolocation beam) whose characteristics in terms of spreading in the vertical and horizontal direction can be extracted at the location of the hydrophones used in the experimental studies (Au *et al.*, 1978; Au *et al.*, 1986; Moore *et al.*, 2008).

In order to avoid the complications involved in modeling such an intricate mechanism (along the lines of, for instance, Dubrovsky, 2009) we produce sound in a simplified but related manner: tissue at the two locations of the bursae is given initial velocity, which starts the tissue "bodies" in opposing directions so that they collide and thereby produce a pressure wave or sound. In effect we are producing the sound by specifying the initial conditions of suitably distributed nonzero velocity.

We use two variants of this initial condition, which we called the *spherical bursae* and the *block bursae*. Figure 1 shows the relevant parameters. The spherical bursae model specifies initial velocity of equal magnitude and opposite direction at the centers of two touching spheres. The initial velocity is tapered off in the form of a cosine function to zero at the surface of each sphere. The line connecting the centers of the two spheres defines the direction of the generated sound pulse, which in a homogeneous medium would travel in either direction, $C_1 \to C_2$ or $C_2 \to C_1$.

The block bursae model specifies initial velocity at the center of two rectangular blocks that share a face. The initial velocity is tapered off to zero at the surface of each block. The triple of orthonormal vectors d, n, g defines the orientation of this device: d points in the direction of the connective tissue in the pair of the bursae as identified in the CT scan, n is normal to the plane that contains the bursae, and g completes the triple, defining the direction of the generated pressure pulse. The motivation for the introduction of the block bursae model is the spatially extended contact the bursae present during sound generation. It is well known that man-made transducers in the form of an array of sources can produce more focused beams than point-like sources. Apparently the dolphin's bursae use the same principle.

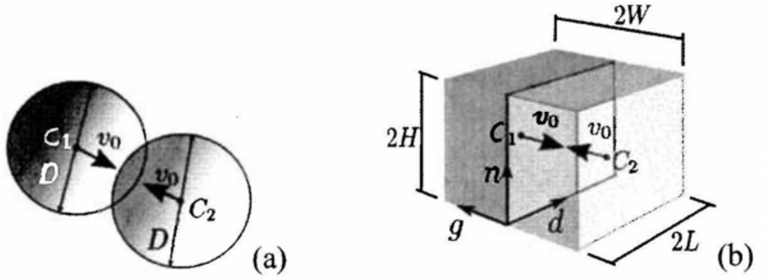


Figure 1. Spherical bursae (a), block bursae (b).

In our simulations we take $D = 8\text{mm}$, and we set $v_0 = \frac{p_{\max}}{\rho_w c_w}$, where $p_{\max} = 1\text{kPa}$ (corresponding to overpressure of 180 dB re: $1\mu\text{Pa}$), and $\rho_w c_w$ is the impedance of seawater. For the block bursae we take $2L = 11.75\text{mm}$, $2H = 7.5\text{mm}$, and $2W = 7.5\text{mm}$, and the same initial velocity magnitude as for the spherical bursae.

SUMMARY OF RESULTS

Model Validation Project

We have accomplished the following tasks.

- Conducted CT scans on a postmortem bottlenose dolphin head when provided by the stranding network or from an unfortunate death at a local captive colony.
- Collected tissue samples from this new specimen and measured tissue properties.
- Borrowed a set of CT scans from an existing library at the Navy Marine Mammal Program, San Diego. (They already had CT scans from a live bottlenose dolphin.)
- Prepared data for a sequence of successively finer grids.
- Developed simulation scripts for validation tasks.
- Completed segmentation of structures from CT scan images of bottlenose dolphins.
- Computed transmission sound beam characteristics from within the dolphin heads.

The simulations reveal three significant results.

(1) Small Changes in Relative Position of Fat Bodies Can Adjust Beam Direction
We ran simulations for eight different relative positions or configurations for the bursae, but we will only report on three of those cases: the original case (**OC**), case 1 (**C1**), and case 2 (**C2**). The original case (**OC**) represents the position that the bursae were in for each animal (D1 and D2). In Figures 2 and 3, the icons composed of closed (black) circles and open (white) circles represent the change in position from the OC. In each case, the new position is 5 mm from the OC.

In the OC and C1 the axis through the center of the circles points forward or anteriorly. The beam patterns produced by these two configurations (OC and C1) are shown in the two left-hand columns in Figure 2 (rows A-E) for spherical bursae and Figure 3 (rows A-C) for block bursae. In all of those cases, the beam generated is more focused than for C2. The axis through bursae axis for C2 points upward or anterodorsally. Clearly, these results support the conclusion that small adjustments in the relative position of the bursae can cause changes in acoustic beam focus and direction.

(2) Consistent Beam Direction

The sound generation and transmission system within the forehead of all odontocetes is composed of a similar set of basic elements. The skull is the primary structural element, supporting the remaining soft tissue structures.

One key finding from the simulations is that the beam emanates in a consistent direction, directly forward in all cases, even when only the skull is present. This suggests that the skull is the primary beam forming element for the sound transmission beam. The other elements apparently play incremental roles in concentrating or "focusing" the outgoing beam.

(3) Evidence for Focusing in Stages

These simulations (Figures 2 and 3) illustrate that the narrowing of the sound transmission beam increases with various levels of refinement in structural complexity. It appears as if each additional structure (like the melon, the air spaces, source location and configuration) adds to the effect of narrowing the beam, and their combined contribution is significant.

This notion is demonstrated by the fact that the beam gets progressively narrower as additional refinements are added to the model. The progression begins with the skull only (Figure 2A), and continues by adding the soft tissue (Figure 2B), smoothing the melon (Figure 2C), adding the acoustically reflective air spaces (Figure 2D), using a scan from a live animal (Figure 2E), and, finally, representing the shape of the bursae as blocks, which closely approximates the actual anatomic condition (Figures 3A-C).

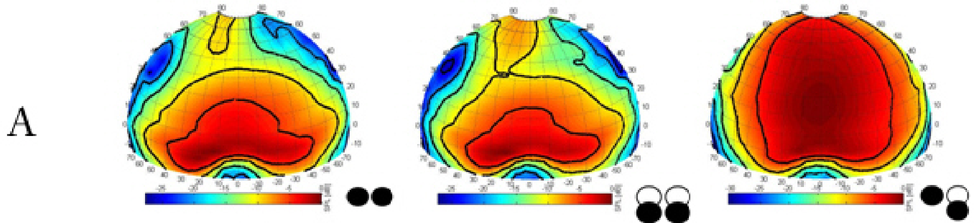
<u>The Stages could be listed as:</u>

- Skull only
- All soft tissue from scans
- Refine melon to add smoothing
- Addition of air spaces drawn in by hand
- Change conformation of source from spherical to elongate block
- Adjustments of relative position of bursae elements within each pair

All three of these primary results are aligned with, or are similar to, results obtained from live animals performing psychoacoustic experiments over the past 50 years.

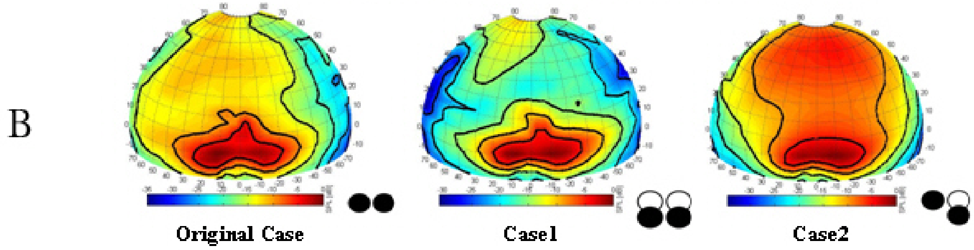
SIMULATION WITH BURSAE AS SPHERES

Simulation moving the bursae with skull only



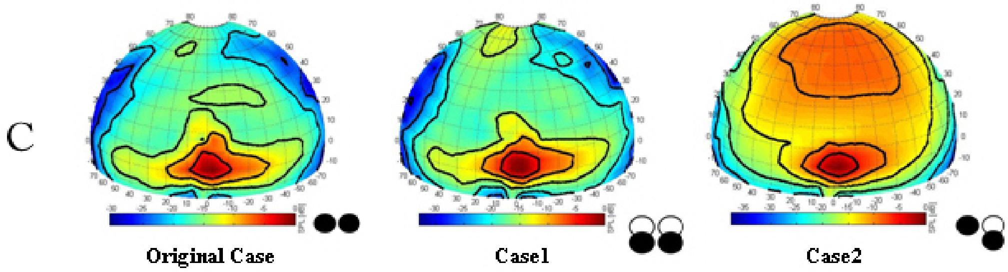
Original Case **Case1** **Case2**

Simulation moving the bursae with all CT scan data



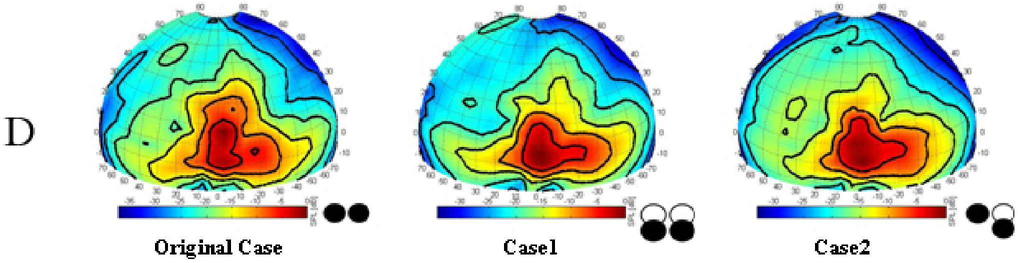
Original Case **Case1** **Case2**

Simulation moving the bursae with smooth melon



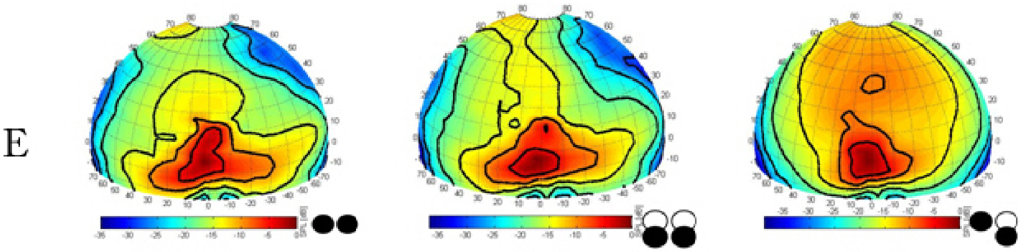
Original Case **Case1** **Case2**

Simulation moving the bursae with smooth melon and air spaces



Original Case **Case1** **Case2**

Simulation moving the bursae with smooth melon and a living dolphin



Original Case **Case1** **Case2**

Figure 2

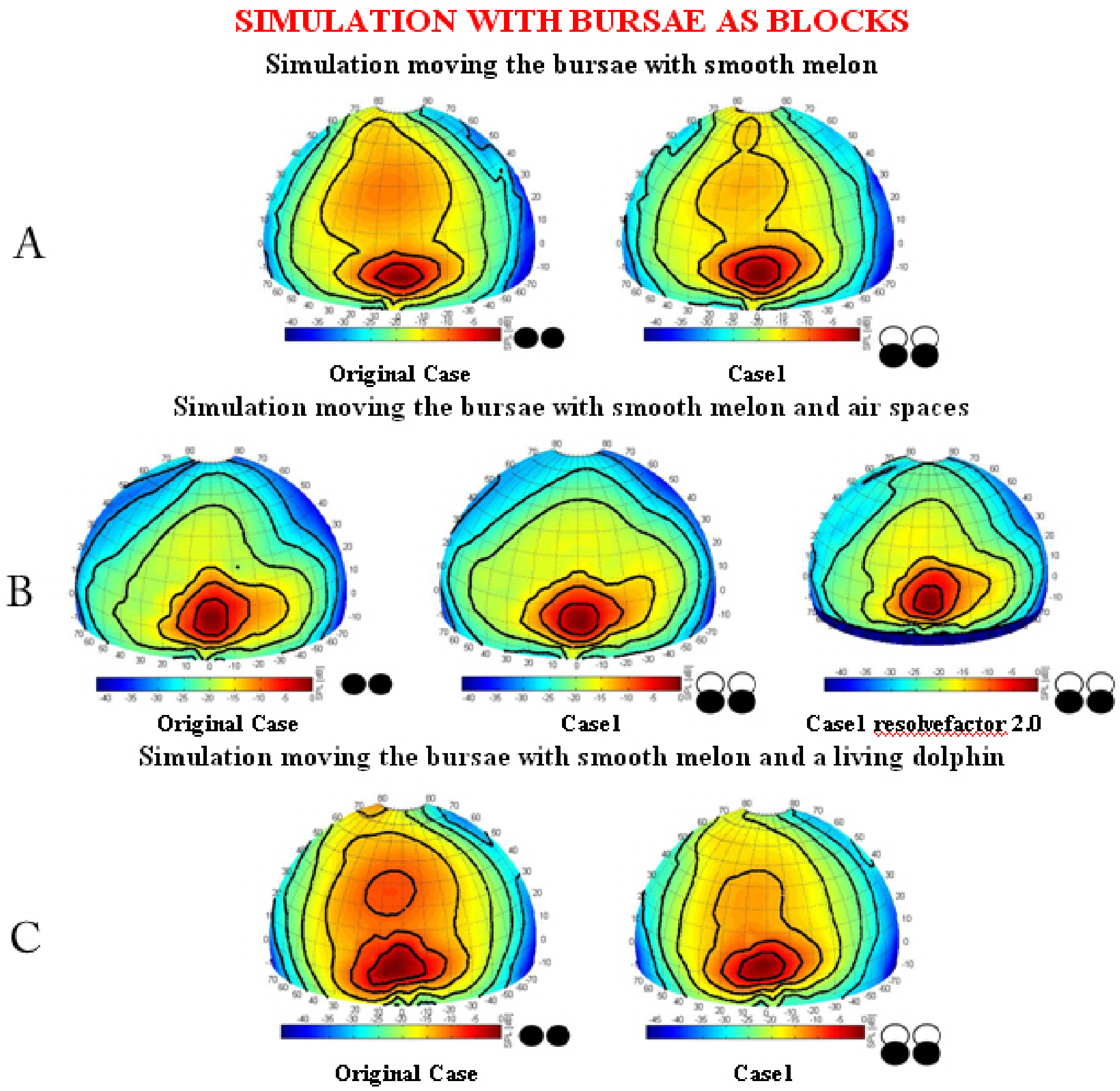


Figure 3

DISCUSSION

The simulations reveal three significant results.

(1) Small Changes in Relative Position of Fat Bodies Can Adjust Beam Direction

This is a new discovery, the first evidence that small changes in relative position of the fatty elements within the sound generation apparatus can produce small changes or adjustments in bottlenose dolphin biosonar beam direction. There are likely more discoveries ahead as we run additional simulations, for example adding the sound source on the left side of the nasal apparatus. The details of this apparatus have been described previously (Cranford, 1988; Cranford, 1999; Cranford, 2000; Cranford *et al.*, 1996; Cranford *et al.*, 2008b).

(2) Consistent Beam Direction

Biosonar beam formation in dolphins has been the subject of considerable research (Au, 1980; Au, 1993; Au *et al.*, 1978; Au *et al.*, 1986; Au *et al.*, 1993; Au *et al.*, 1995; Au *et al.*, 1987; Cranford *et al.*, 2008a; Diercks *et al.*, 1973; Evans and Prescott, 1962; Norris and Evans, 1966; Norris *et al.*, 1961; Schevill and Watkins, 1966). This previous work was primarily concerned with describing the dimensions of the biosonar beam under particular circumstances with a few target species. Sorting out the anatomic contributions to the formation of that beam has not been possible in the past. This can now be accomplished with the tools and techniques that we have brought to bear on this issue.

The sound transmission system within the delphinid's forehead contains several elements. The inherent flexibility of our FEM technique allows us to tease apart the contributions that these structures make to the formation of an echolocation beam. We have tested a few conformations for various elements. The primary finding that the beam emanates from the simulations in a consistent direction suggests that the skull is the primary structural element in the formation of the sound transmission beam. The other elements play an additive role in concentrating or "focusing" the outgoing beam.

The odontocete skull has been revamped during the evolution of the biosonar system (Miller, 1923). All of the soft tissues lie atop the skull and are anchored to it. The consistent beam direction in all of the simulations is to be expected because other studies have shown that a similar directional beam can be formed by the skull alone (Evans *et al.*, 1964; Romanenko, 1973; Romanenko, 1974).

(3) Evidence for Focusing in Stages

The idea of focusing in stages was put forth by Dr. Kenneth S. Norris more than 40 years ago (Norris, 1964; Norris, 1968; Norris, 1969; Norris, 1975). It is only by the development of our FEM techniques that we can now test and apparently verify his hypothesis.

FUTURE PLANS

We will continue to test adjustments or small changes in the configuration of the components of the nasal apparatus in order to tease apart the functional contributions of these anatomic components.

PEER REVIEWED PUBLICATIONS DURING THIS PROJECT

CRANFORD, T.W., P. KRYSL, AND M. AMUNDIN. **Accepted**. A new acoustic portal into the odontocete ear and vibrational analysis of the tympanoperiotic complex. *PLoS ONE*.

CRANFORD T.W., P. KRYSL, AND J.A. HILDEBRAND. **2008b**. Sound pathways revealed: simulated sound transmission and reception in Cuvier's beaked whale (*Ziphius cavirostris*). *Bioinspiration and Biomimetics* **3(016001)**: 1-10.

CRANFORD T.W., M. MCKENNA, M. SOLDEVILLA, S.M. WIGGINS, R. SHADWICK, J. GOLDBOGEN, P. KRYSL, J.S. LEGER, AND J.A. HILDEBRAND. **2008a**. Anatomic geometry of sound transmission and reception in Cuvier's beaked whale (*Ziphius cavirostris*). *The Anatomical Record* **291(4)**: 353-378.

CONFERENCE PRESENTATIONS DURING THIS PROJECT

CRANFORD, T.W., P. KRYSL, AND J.A. HILDEBRAND. **2009**. Knocking on the door of the inner ear in Cuvier's beaked whale. *18th Biennial Conference on the Biology of Marine Mammals*, Quebec City, Canada.

BARROSO, C., A. BERTA, AND T.W. CRANFORD. **2009**. Shape analysis of odontocete mandibles. *18th Biennial Conference on the Biology of Marine Mammals*, Quebec City, Canada.

ROMMEL, S.A., A.M. COSTIDIS, W.A. MCLELLAN, T.W. CRANFORD, AND D.A. PABST. **2009**. Vascular structures associated with the air sacs and fatty bodies in the ventral head of *Tursiops truncatus*, *Kogia spp*., and *Ziphius cavirostris*. *18th Biennial Conference on the Biology of Marine Mammals*, Quebec City, Canada.

PACINI, A.F., P.E. NACHTIGALL, T.W. CRANFORD, M. BREESE, D.A. LOOK, AND S. VLACHOS. **2009**. Comparison of hearing sensitivities and potential sound pathways for the bottlenose dolphin *Tursiops truncatus* and the false killer whale *Pseudorca crassidens*. *5th Animal Sonar Symposium*, September 14-18, Kyoto, Japan.

CRANFORD, T.W., P. KRYSL, AND J.A. HILDEBRAND. **2009**. "Rivers" of sound in Cuvier's beaked whale (*Ziphius cavirostris*): implications for the evolution of sound reception in odontocetes. *157th Meeting: Acoustical Society of America*, Portland, OR, May. *J. Acoust. Soc. Am.* 125 (4), Part 2: 2677.

KRYSL, P., T.W. CRANFORD, AND J.A. HILDEBRAND. **2009**. *Tursiops truncatus*: Vibration characteristics of the tympanoperiotic complex. *157th Meeting: Acoustical Society of America*, Portland, OR, May. *J. Acoust. Soc. Am.* **125 (4), Part 2**: 2677.

CRANFORD, T.W., P. KRYSL, AND J.A. HILDEBRAND. **2008**. Building on the shoulders of a giant: using technology to extend biosonar research pathways first blazed by Sam H. Ridgway. *156th Meeting: Acoustical Society of America*, Miami, FL, October. *J. Acoust. Soc. Am.* **124 (4), Part 2**: 2505.

AWARDS AND HONORS

Excellence in Science Communication Award (2009) – Society for Marine Mammalogy, *18th Biennial Conference on the Biology of Marine Mammals*, Quebec City, Quebec, Canada.

REFERENCES

AMUNDIN, M. Variable directionality in the high-frequency click emission of the Harbor porpoise. <u>In:</u> *Physiological Institute*: University of Odense, Denmark.

AMUNDIN, M. **1991a**. Helium effects on the click frequency spectrum of the harbor porpoise, *Phocoena phocoena*. *J. Acoust. Soc. Am.* **90**: 53-59.

AMUNDIN, M. **1991b**. Sound production in odontocetes with emphasis on the harbour porpoise *Phocoena phocoena*. <u>In:</u> *Department of Zoology*, p. 128. University of Stockholm, Stockholm, Sweden.

AU, W.W.L. **1980**. Echolocation signals of the Atlantic bottlenose dolphin (*Tursiops truncatus*) in open waters. <u>In:</u> R. G. BUSNEL AND J. F. FISH (eds.). *Animal Sonar Systems*, pp. 251-282. Plenum Publishing Corporation, New York.

AU, W.W.L. **1993**. The sonar of dolphins. Springer-Verlag, Inc., New York.

AU, W.W.L., R.W. FLOYD, AND J.E. HAUN. **1978**. Propagation of Atlantic bottlenose dolphin echolocation signals. *J. Acoust. Soc. Am.* **64**: 411-422.

AU, W.W.L., P.W.B. MOORE, AND D. PAWLOSKI. **1986**. Echolocation transmitting beam of the Atlantic bottlenose dolphin. *J. Acoust. Soc. Am.* **80**: 688-691.

AU, W.W.L., J.L. PAWLOSKI, T.W. CRANFORD, R.C. GISINER, AND P.E. NACHTIGALL. **1993**. Transmission beam pattern of a false killer whale. *J. Acoust. Soc. Am.* **93**: 2358-2359.

AU, W.W.L., J.L. PAWLOSKI, P.E. NACHTIGALL, M. BLONZ, AND R.C. GISINER. **1995**. Echolocation signals and transmission beam pattern of a false killer whale (*Pseudorca crassidens*). *J. Acoust. Soc. Am.* **98**: 51-59.

AU, W.W.L., R.H. PENNER, AND C.W. TURL. **1987**. Propagation of beluga echolocation signals. *J. Acoust. Soc. Am.* **82**: 807-813.

CRANFORD, T.W. **1988**. The anatomy of acoustic structures in the spinner dolphin forehead as shown by X-ray computed tomography and computer graphics. In: P.E. NACHTIGALL AND P.W.B. MOORE *(eds.). Animal sonar: processes and performance*, pp. 67-77. Plenum Publishing Corporation, New York.

CRANFORD, T.W. **1999**. The sperm whale's nose: sexual selection on a grand scale? *Mar Mam Sci* **15**: 1133-1157.

CRANFORD, T.W. **2000**. In Search of impulse sound sources in odontocetes. In: W.W.L. AU A.N. POPPER AND R.R. FAY *(eds.). Hearing by whales and dolphins*, pp. 109-156. Springer-Verlag, New York.

CRANFORD, T.W., M. AMUNDIN, AND K.S. NORRIS. **1996.** Functional morphology and homology in the odontocete nasal complex: implications for sound generation. *J. Morphol.* **228**: 223-285.

CRANFORD, T.W. AND M.E. AMUNDIN. **2003**. Biosonar pulse production in odontocetes: the state of our knowledge. *In:* J.A. THOMAS, C.F. MOSS AND M. VATER (*eds.*). *Echolocation in bats and dolphins*, pp. 27-35. The University of Chicago Press, Chicago.

CRANFORD, T.W., P. KRYSL, AND J.A. HILDEBRAND. **2008a**. Acoustic pathways revealed: simulated sound transmission and reception in Cuvier's beaked whale (*Ziphius cavirostris*). *Bioinsp. Biomim.* **3**: 1-10.

CRANFORD, T.W., M.F. MCKENNA, M.S. SOLDEVILLA, S.M. WIGGINS, R.E. SHADWICK, J. GOLDBOGEN, P. KRYSL, J.A. ST. LEGER, AND J.A. HILDEBRAND. **2008b**. Anatomic geometry of sound transmission and reception in Cuvier's beaked whale (*Ziphius cavirostris*). *Anat. Rec.* **291**: 353-378.

DIERCKS, K.J., R.T. TROCHTA, AND W.E. EVANS. **1973**. Delphinid sonar: measurement and analysis. *J. Acoust. Soc. Am.* **54**: 200-204.

DUBROVSKY, N. **2009**. A model of acoustic click production in the dolphin by analogy with a traveling-wave antenna. *Acoust Phys.* **55**: 441.

EVANS, W.E. AND J.H. PRESCOTT. **1962**. Observations of the sound production capabilities of the bottlenose porpoise: a study of whistles and clicks. *Zoologica* **47**: 121-128.

EVANS, W.E., W.W. SUTHERLAND, AND R.G. BEIL. **1964**. The directional characteristics of delphinid sounds. In: W.N. TAVOLGA (ed.). *Marine Bio-Acoustics*, **vol. 2**, pp. 353-372. Pergamon Press, New York.

KRYSL, P., T.W. CRANFORD, AND J.A. HILDEBRAND. **2008**. Lagrangian finite element treatment of transient vibration/acoustics of biosolids immersed in fluids. *Int. J. Numer. Meth. Engng.* **74**: 754-775.

MILLER, G.S. **1923**. The telescoping of the cetacean skull. *Smith. Misc. Coll.* **76**: 1-70.

MØHL, B., M. WAHLBERG, P.T. MADSEN, L.A. MILLER, AND A. SURLYKKE. **2000**. Sperm whale clicks: directionality and source level revisited. *J. Acoust. Soc. Am.* **107**: 638-648.

MOORE, P.W., L.A. DANKIEWICZ, AND D.S. HOUSER. **2008**. Beamwidth control and angular target detection in an echolocating bottlenose dolphin (*Tursiops truncatus*). *J. Acoust. Soc. Am.* **124**: 3324-3332.

NORRIS, K.S. **1964**. Some problems of echolocation in cetaceans. In: W. N. TAVOLGA (*ed.*). *Marine bio-acoustics*, pp. 317-336. Pergamon Press, New York.

NORRIS, K.S. **1968**. The evolution of acoustic mechanisms in odontocete cetaceans. In: E. T. Drake (*ed.*). *Evolution and Environment*, pp. 297-324. Yale University Press, New Haven.

NORRIS, K.S. **1969**. The echolocation of marine mammals. In: H.T. ANDERSEN (*ed.*). *The Biology of Marine Mammals*, pp. 391-423. Academic Press, New York.

NORRIS, K.S. **1975**. Cetacean biosonar: Part 1 - Anatomical and behavioral studies. In: D.C. MALINS AND J.R. SARGENT (*eds.*) *Biochemical and biophysical perspectives in marine biology*, pp. 215-234. Academic Press, New York.

NORRIS, K.S. AND W.E. EVANS. **1966**. Directionality of echolocation clicks in the rough-tooth porpoise, *Steno bredanensis* (Lesson). In: Museum of Natural History. *Second Symposium on Marine Bio-Acoustics*, pp. 305-316. Pergamon Press, New York.

NORRIS, K.S. AND G.W HARVEY. **1974**. Sound transmission in the porpoise head. *J. Acoust. Soc. Am.* **56**: 659-664.

NORRIS, K.S., J.H. PRESCOTT, P.V. ASA-DORIAN, AND P. PERKINS. **1961**. An experimental demonstration of echolocation behavior in the porpoise, *Tursiops truncatus*, Montagu. *Biol. Bull.* **120**: 163-176.

ROMANENKO, E.V. **1973**. Investigating generation of echolocation pulses in dolphins. *Zool. Zh.* **11**: 1698-1707.

ROMANENKO, E.V. **1974**. Investigating generation of echolocation pulses in dolphins. *JPRS* **61553**: 1-8. Joint Publications Research Service, Arlington, Virginia.

SCHEVILL, W.E. AND W.A. WATKINS. **1966**. Sound structure and directionality in *Orcinus* (killer whale). *Zoologica* **51**: 71-76.

SOLDEVILLA, M.S., M.F. MCKENNA, S.M. WIGGINS, R.E. SHADWICK, T.W. CRANFORD, AND J.A. HILDEBRAND. **2005**. Cuvier's beaked whale (*Ziphius cavirostris*) head tissues: physical properties and CT imaging. *J. Exp. Biol.* **208**: 2319-2332.

INITIAL DISTRIBUTION LIST

1.	Defense Technical Information Center 8725 John J. Kingman Rd., STE 0944 Ft. Belvoir, VA 22060-6218	2
2.	Dudley Knox Library, Code 013 Naval Postgraduate School Monterey, CA 93943-5100	2
3.	Erin Oleson National Marine Fisheries Service Pacific Islands Fisheries Science Center Honolulu, HI	1
4.	John Hildebrand Scripps Institution of Oceanography University of California La Jolla, CA	1
5.	John Calambokidis Cascadia Research Collective Olympia, WA	1
6.	Greg Schorr Cascadia Research Collective Olympia, WA	1
7.	Erin Falcone Cascadia Research Collective Olympia, WA	1
8.	Ching-Sang Chiu Naval Postgraduate School Monterey, CA	1
9.	Curtis A. Collins Naval Postgraduate School Monterey, CA	1
10.	Thomas A. Rago Naval Postgraduate School Monterey, CA	1
11.	Tetyana Margolina Naval Postgraduate School Monterey, CA	1
12.	Chris Miller Naval Postgraduate School Monterey, CA	1

13.	John Joseph Naval Postgraduate School Monterey, CA	1
14.	Katherine Whitaker Pacific Grove, CA	1
15.	Frank Stone CNO(N45) Washington, D.C.	1
16.	Jay Barlow Southwest Fisheries Science Center, NOAA La Jolla, CA	1
17.	CAPT Ernie Young, USN (Ret.) CNO(N45) Washington, D.C.	1
18.	Dale Liechty CNO(N45) Washington, D.C.	1
19.	Dave Mellinger Oregon State University Newport, OR	1
20.	Kate Stafford Applied Physics Laboratory University of Washington Seattle, CA	1
21.	Sue Moore NOAA at Applied Physics Laboratory University of Washington Seattle, WA	1
22.	Petr Krysl University of California La Jolla, CA	1
23.	Mark McDonald Whale Acoustics Bellvue, CO	1
24.	Ted Cranford San Diego State University San Diego, CA	1

25.	Monique Fargues Naval Postgraduate School Monterey, CA	1
26.	Mary Ann Daher Woods Hole Oceanographic Institution Woods Hole, MA	1
27.	Heidi Nevitt NAS North Island San Diego, CA	1
28.	Rebecca Stone Naval Postgraduate School Monterey, CA	1
29.	Melissa Hock Scripps Institution of Oceanography University of California La Jolla, CA	1
30.	Sean M. Wiggins Scripps Institution of Oceanography University of California La Jolla, CA	1
31.	E. Elizabeth Henderson Scripps Institution of Oceanography University of California La Jolla, CA	1
32.	Gregory S. Campbell Scripps Institution of Oceanography University of California La Jolla, CA	1
33.	Marie A. Roch San Diego State University San Diego, CA	1
34.	Anne Douglas Cascadia Research Collective Olympia, WA	1
35.	Julie Rivers COMPACFLT Pearl Harbor, HI	1
36.	Jenny Marshall Naval Facilities Engineering Command San Diego, CA	1

37.	Chip Johnson COMPACFLT Pearl Harbor, HI	1
38.	CDR Len Remias U.S. Pacific Fleet Pearl Harbor, HI	1
39.	LCDR Robert S. Thompson U.S. Pacific Fleet Pearl Harbor, HI	1
40.	Jene J. Nissen U. S. Fleet Forces Command Norfolk, VA	1
41.	W. David Noble U. S. Fleet Forces Command Norfolk, VA	1
42.	David T. MacDuffee U. S. Fleet Forces Command Norfolk, VA	1
43.	Keith A. Jenkins Naval Facilities Engineering Command, Atlantic Norfolk, VA	1
44.	Joel T. Bell Naval Facilities Engineering Command, Atlantic Norfolk, VA	1
45.	Mandy L. Shoemaker Naval Facilities Engineering Command, Atlantic Norfolk, VA	1
46.	Anurag Kumar Naval Facilities Engineering Command, Atlantic Norfolk, VA	1
47.	Merel Dalebout University of New South Wales Sydney, Australia	1
48.	Robin W. Baird Cascadia Research Collective Olympia, WA	1
49.	Brenda K. Rone National Marine Mammal Laboratory Seattle, WA	1

50.	Phil Clapham National Marine Mammal Laboratory Seattle, WA	1
51.	Laura J. Morse National Marine Mammal Laboratory Seattle, WA	1
52.	Anthony Martinez NOAA Southeast Fisheries Science Center Miami, FL	1
53.	Darlene R. Ketten Woods Hole Oceanographic Institution Woods Hole, MA	1
54.	David C. Mountain Boston University Boston, MA	1
55.	Melissa Soldevilla Duke University Durham, NC	1
56.	Brandon L. Southall Southall Environmental Associates, Inc. Santa Cruz, CA	1
57.	David Moretti NUWC Newport, RI	1
58.	Michael Weise Office of Naval Research, Code 32 Arlington, VA	1
59.	Dan Costa University of California, Santa Cruz Santa Cruz, CA	1
60.	Lori Mazzuca Marine Mammal Research Consultants, Inc. Honolulu, HI	1
61.	Jim Eckman Office of Naval Research Arlington, VA	1
62.	Ari Friedlaender Duke University Beaufort, NC	1

63.	CAPT Robin Brake U.S. Navy Washington, DC	1
64.	Mary Grady Southwest Fisheries Science Center La Jolla, CA	1
65.	Lisa Ballance Southwest Fisheries Science Center La Jolla, CA	1
66.	Angela D’Amico SPAWAR San Diego, CA	1
67.	Amy Smith Science Applications International Corporation McLean, VA	1
68.	Peter Tyack Woods Hole Oceanographic Institution Woods Hole, MA	1
69.	Ian Boyd University of St. Andrews St. Andrews, Scotland, UK	1