Estimating the density of Blainville's beaked whale (*Mesoplodon densirostris*) in the Tongue of the Ocean (TOTO) using passive acoustics

D. Moretti, N. DiMarzio, R. Morrissey, J. Ward, S. Jarvis
Naval Undersea Warfare Center Division
Code 71, Bldg. 1351
Newport, RI 02841 USA

***Abstract*-Techniques to detect and localize marine mammals including Blainville's beaked whales (*Mesoplodon densirostris*) using the bottom-mounted hydrophones of the Atlantic Undersea Test and Evaluation Center have been developed. A series of verification tests using these passive acoustics techniques to determine the presence and position of vocalizing animals are being conducted. These acoustic "sightings" are verified by a team of surface observers. Based on Woods Hole Oceanographic Institution tag data and the ongoing verification tests, vocalizations associated with *M. densirostris* appear to be distinct in type, frequency, and repetition rate. Group size estimates have been derived from these tests and from previous long-term observations. By acoustically mapping the distribution of animals and applying estimates of average group size an initial density estimate for *M. densirostris* is derived.**[*]

I. INTRODUCTION

In 2003 Johnson et al., from the Woods Hole Oceanographic Institution (WHOI), placed DTAGs on two Cuvier's beaked whales (*Ziphius cavirostris*) and two Blainville's beaked whales (*Mesoplodon densirostris*) and recorded their high-frequency clicks [1]. The DTAG sampled at 96 kHz. The energy band of the far-field *M. densirostris* clicks was found to span from about 25 kHz up to the 48 kHz limit of the DTAG recorder, with a characteristically sharp cutoff in energy below 25 kHz. *M. densirostris* click durations were ca. 250 µs, and the inter-click intervals (ICI) ranged from 0.2 to 0.4 seconds [1]. Beaked whale clicks are also highly directional. A Directionality Index (DI) exceeding 25 dB was estimated from DTAG data on Z. *cavirostris* [2,3].

In September 2004, calls closely matching those from the WHOI DTAG were detected and recorded at the Atlantic Undersea Test and Evaluation Center (AUTEC) (Fig. 1). Subsequent analysis by WHOI indicated a high correlation between the AUTEC calls and the *M. densirostris* calls from the DTAG. AUTEC is located in the Tongue of the Ocean, Bahamas, just east of Andros Island. The hydrophone range consists of 82 operational bottom-mounted hydrophones, spaced approximately 2 nmi apart, at depths of approximately 2000 m. The whole range covers over 1500 km^2 (Fig. 2).

The ONR-funded program Marine Mammal Monitoring on Navy Ranges (M3R) has developed algorithms to passively detect and localize marine mammals on Navy undersea ranges. To test the algorithms, a number of species verification tests have been carried out at AUTEC in conjunction with the Bahamas Marine Mammal Survey (BMMS). The purpose of these tests is to visually verify the species of animals acoustically detected on the range. A variety of odontocete species have been verified. *M. densirostris* have been passively detected, localized, and visually verified on nine different occasions (Table 1).

In April 2005, during a species verification test conducted in collaboration with BMMS, all 82 hydrophones were recorded for approximately 6 days and nights. Both marine mammal detections and localizations were archived for 8 days. These archive files and recordings were analyzed to produce an initial density estimate for *M. densirostris* in the Tongue of the Ocean.

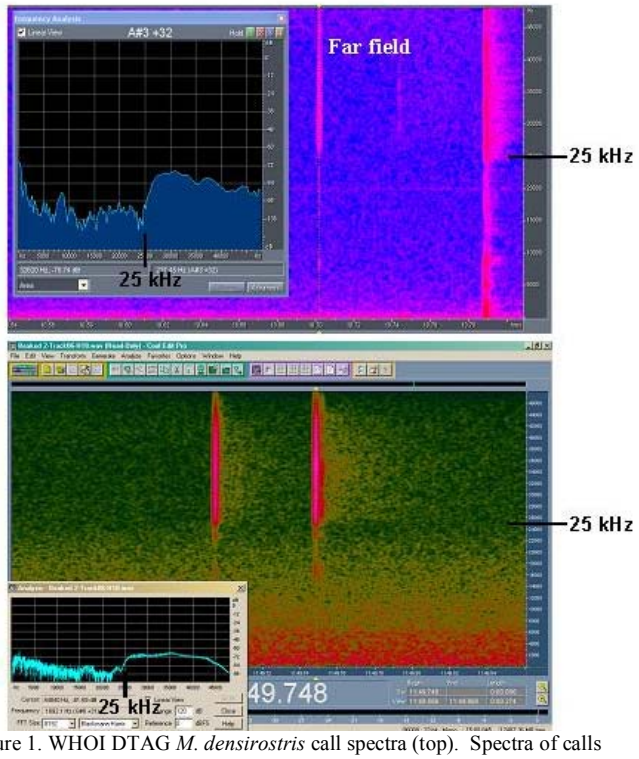

Figure 1. WHOI DTAG *M. densirostris* call spectra (top). Spectra of calls recorded at AUTEC (bottom).

[*] We would like to acknowledge our sponsors, Dr. Mardi Hastings and Dr. Robert Gisiner, at the Office of Naval Research.

1-4244-0115-1/06/$20.00 ©2006 IEEE

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
01 SEP 2006	**N/A**	**-**

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Estimating the density of Blainvilles beaked whale (Mesoplodon densirostris) in the Tongue of the Ocean (TOTO) using passive acoustics	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Undersea Warfare Center Division Code 71, Bldg. 1351 Newport, RI 02841 USA**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

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

13. SUPPLEMENTARY NOTES
See also ADM002006. Proceedings of the MTS/IEEE OCEANS 2006 Boston Conference and Exhibition Held in Boston, Massachusetts on September 15-21, 2006, The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**UU**	**5**	

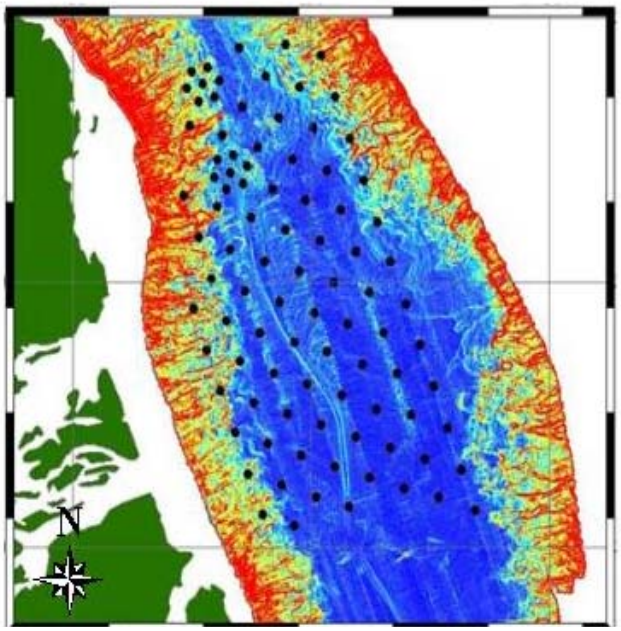

Figure 2. Location of AUTEC range in the Tongue of the Ocean (TOTO), Bahamas (top). AUTEC range hydrophone layout (bottom).

TABLE I
M3R VERIFIED *M. DENSIROSTRIS* SIGHTINGS IN THE TONGUE OF THE OCEAN

Date	Species	Encounter Duration (min)	# Animals
27-Apr-05	unknown *Ziphiidae*	1	1
27-Apr-05	*M. densirostris*	12	2-3
24-Sept-05	*M. densirostris*	33	2
24-Sept-05	*M. densirostris*	30	3
27-Sep-05	*M. densirostris*	120	2
27-Sep-05	*M. densirostris*	362	5
27-Sep-05	*M. densirostris*	118	4
6-Mar-06	unknown *Ziphiidae*	~5	2
6-Mar-06	*M. densirostris*	134	3

II. METHODS

The 82 AUTEC hydrophones were monitored for the presence of *M. densirostris* clicks over a 140-minute time window. Based on the presence and distribution of clicks, groups of animals were identified. For each 140-minute window, the number of animals on range was determined by multiplying the number of groups by an estimate of the average group size. The density was estimated by averaging all time windows and dividing by the total range area (1536 km^2).

This method makes 5 basic assumptions:

1. Vocalizing animals within the field of sensors are detected.
2. Animals vocalize within any 140-minute period.
3. Animals move no more than 4.8 km (1 hydrophone baseline) during the measurement time window.
4. Detections within the maximum hydrophone baseline (4.8 km) belong to the same group
5. The average *M. densirostris* group size is 4.1 animals.

M. densirostris DTAG data have shown vocalizations to be directional with a DI in excess of 25 dB [2,3]. When detected on the bottom-mounted AUTEC hydrophones, which are separated by approximately 4.8 km, the number of phones on which an animal vocalization is detected depends on the Signal to Noise Ratio (SNR) at the sensor. The SNR is a function of several factors, including the animal's orientation and depth, the sound velocity profile, and the background ocean noise.

Click source levels in excess of 210 dB re 1 µPa have been measured on recording tags placed directly on a pair of animals [2,3]. Propagation to a hydrophone using an AUTEC Sound Velocity Profile (SVP) measured September 29, 2005 during an M3R test is presented in Fig. 3.

Using the Impact Maritime Portable Acoustic Scoring System (IMPASS) ray trace model, direct path propagation to the sensor was predicted [4]. From the model, the SNR at the receiver was derived for a 210 dB on axis click along a direct path ray assuming a click bandwidth of 35 kHz (25-60 kHz) and receive level of 101.81 dB. This level assumes spherical spreading and accounts for absorption at 35 kHz.

Source Bandwidth = 35 kHz
Receiver Bandwidth = 57 Hz
Absorption at 35 kHz
Predicted Receive Level = 101.81 dB re µPa
Corrected Receive Level = 101.81 db +10log(57/35000)
= 73.93 dB re µPa
Ocean Noise SS3 = 38 dB re µPa
Corrected Noise Level = 38 dB + 10log57
= 55.5 dB
Receiver SNR = 73.93 dB-55.5dB = 18.42 dB re µPa

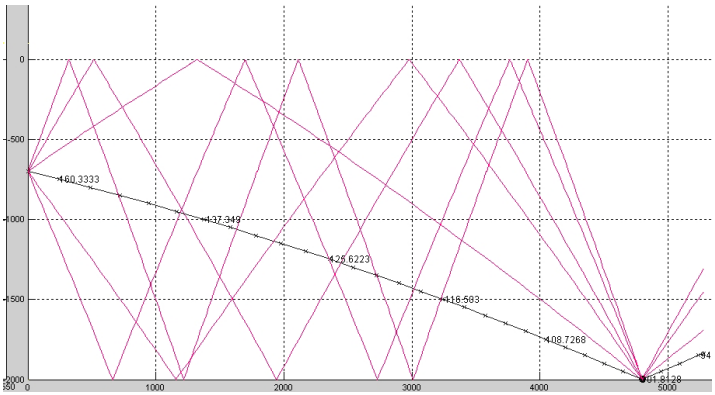

Figure 3. RayTrace for animal at 700 meters and hydrophone at a range of 4800 meters with the AUTEC 29 September 2005 SVP

A 210dB click directed at the receiver from a distance of 4.8 km provides 18.42 dB SNR (57 Hz noise bandwidth). This is sufficient SNR to assure signal detection at the receiver [5].

The maximum time between vocalizations for a group of animals was measured as 140 minutes using DTAG data [3]. A measurement window was established based on this time with the assumption that any group within the hearing radius of a hydrophone would vocalize and be detected.

Small groups of tagged *M. densirostris*, including adults and juveniles, have been observed diving as a cohesive group. During these observations, multiple vocalizing animals were recorded during the dive [1]. Data from a pair of tagged beaked whales show them diving in a coordinated manner, separating horizontally up to a maximum distance of 400 m at the deepest portion of the dive and ascending together [2]. Horizontal range speeds of Z. *cavirostris* in Hawaii varied from 0.84 km/hr to 1.85 km/hr during three dives [6]. Therefore, within a 140-minute exposure window, the animals within a group should remain within a hydrophone baseline (4.8 km).

It is assumed that detections within the maximum hydrophone baseline (4.8 km) belong to the same group. This method does not account for groups of animals collocated within a hydrophone array. If this occurs, the collocated groups are counted as a single group.

Globally *M. densirostris* group size is generally considered to range from one to seven [7]. Hauser noted *M. densirostris* group sizes between 2 and 4 individuals offshore central Abaco [8]. Generally, *M. densirostris* in tropical waters have been observed with group sizes from three to seven individuals [7]. Claridge (2004) reported group sizes in the Bahamas ranging from one to eleven animals with an average group size of 4.1, which was used for this analysis [9].

From the test conducted from 25 April to 2 May 2005, marine mammal detection reports were generated using a simple energy-based FFT detector which implements a noise-variable adaptive threshold for each bin of the FFT. If a signal was detected above the threshold the bin waa set to '1'. For this application a 2048-pt FFT with 50% overlap was used at a sample rate of 118.227 kHz. Detections were categorized as a click if at least 10 bins were set.

Clicks were classified as *M. densirostris* based on the following criteria:

1. The maximum signal energy is in the 24-48 kHz band [1,2,3,11].
2. Less than 10% of the bins in the 0-24 kHz band are set.
3. Greater than 1% of the bins in the 24-48 kHz band are set.

In addition, the extracted *M. densirostris* data were visually verified using a hard-limited spectrogram display.

Once *M. densirostris* clicks were isolated, 140-minute continuous data blocks from 8 different days were analyzed. These included blocks recorded both during the day and at night. For each day, the number of groups of animals was approximated. This number was multiplied by an average group size to derive the number of animals within the field of sensors.

The 140-minute measurement window was divided into 14 10-minute segments. For each segment, click count statistics were calculated. The hydrophone with the maximum number of clicks (red) and those with clicks 1 and 2 standard deviations (green, yellow) above the mean were color coded and displayed on a range sensor map (Fig. 5).

Each 10-minute sequential segment was examined to isolate groups of animals. For each cluster of hydrophones with beaked whale click counts at least 1 standard deviation above the mean, a circle with a radius of 4.8 km was drawn around

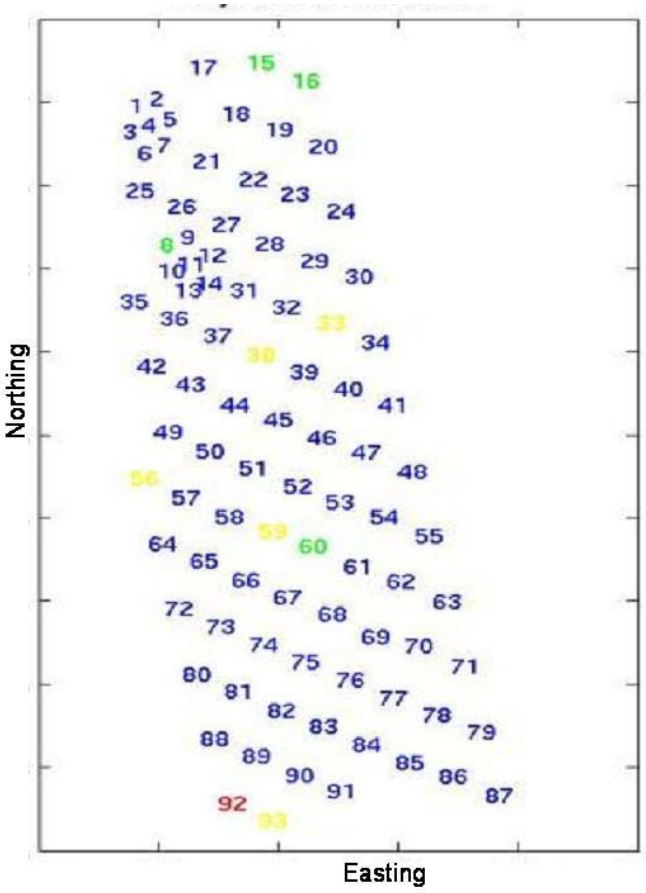

Figure 4. Range click count statistics for a 10-minute segment on 04/28/2005. Red (92) indicates the most active hydrophone. Green (15,16, 8, 60) and yellow (33, 38, 56, 59) represent hydrophones with activity 1 and 2 standard deviations above the mean, respectively.

the hydrophone with the maximum click count. This process was repeated for phones outside the circles until all phones were assigned to groups. All 14 10-minutes segments were analyzed in a like manner. The active hydrophones from each 10-minute segment were overlaid on a range plot. A blue circle was used to indicate each group of animals (Fig. 5).

Each group within every 10-minute segment was manually checked for the presence of *M. densirostris* clicks using a binary spectrogram display program (Fig. 6). Out of a total of 100 groups, 10 were incorrectly categorized as containing *M. densirostris* clicks. The signals in these rejected groups were believed to be associated with surface craft activities. Out of the 10 incorrectly categorized groups, 6 occurred in a single 140-minute analysis window. The clicks in all 90 final groups were visually verified as *M. densirostris* vocalizations.

The estimate of the number of animals present during each 140-minute window was calculated by multiplying the number of groups by an average group size of 4.1.

A density estimate was obtained by averaging the results from the 8 140-minute windows and dividing by the total range area, 1536 km^2.

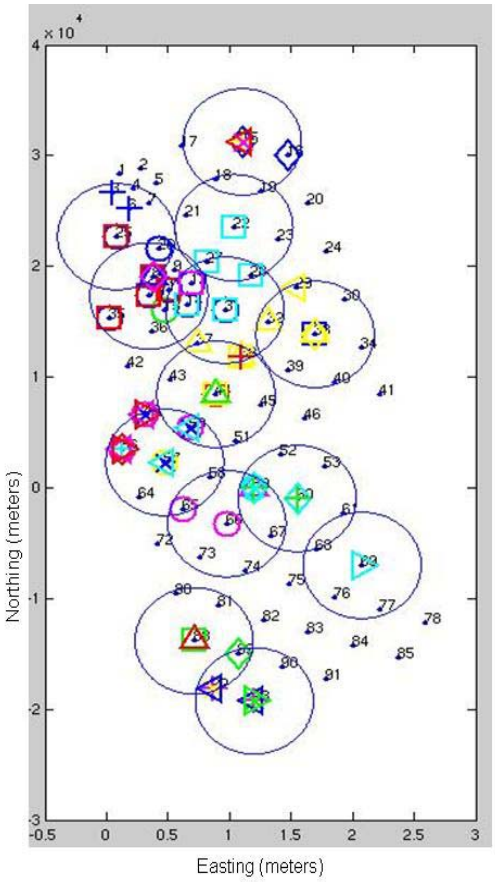

Figure 5. Final groups of *M. densirostris* for one 140-minute time window, indicated by large blue circles. For this 140-minute time window 13 (corrected to 12) groups of animals were estimated on the range. The group results for each 10-minute segment are plotted as different colored symbols.

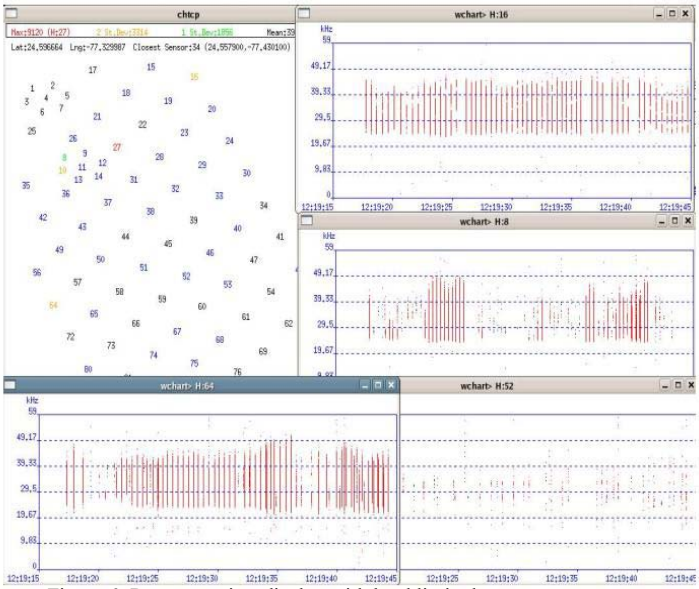

Figure 6: Range monitor display with hard limited spectrograms.

III. RESULTS

The results from each 140-minute window are presented in Table II. A maximum of 61.5 animals and a minimum of 24.6 animals were estimated for 8 140-minute periods collected over 8 days.

IV. SUMMARY

The described method provides an estimate of *M. densirostris* density for use in areas with multiple widely spaced sensors typical of the U.S. Navy undersea acoustic ranges. A density estimate of 30.029 animals per one thousand square kilometers during the period 4/25/2005-5/02/2005 was obtained.

TABLE II
FINAL ESTIMATE OF ANIMALS PER DAY AND AVERAGE OVER 5 DAYS WITH DENSITY ESTIMATE OVER THE 1,536 KM^2 SENSOR FIELD

Date	Start Time (GMT)	# Groups	Corrected # Groups	Average # Animals
04/25/2005	0602	12	12	49.2
04/26/2006	0206	9	8	32.8
04/27/2005	1859	15	13	53.3
04/28/2005	2104	13	12	49.2
04/29/2005	1218	15	15	61.5
04/30/2005	1049	15	15	61.5
05/01/2005	1840	15	9	36.9
05/02/2005	0402	6	6	24.6
Average Number of Animals Present = 46.125				
Average Density =30.029 animals per 1000 km^2				

This method makes basic assumptions regarding the average group size, animal movement, and signal detectability based primarily on WHOI data collected from recording tags.

Click classification was implemented automatically using a simple algorithm based on frequency distribution. *M. densirostris* groups were determined based on the distribution of these clicks. Visual screening of the data showed that 90% of the groups were correctly identified. The remaining 10% were believed to be associated with surface craft activity. Performance could be improved by incorporating a robust classification algorithm that takes advantage of the signal structure [11]. In addition, such an algorithm may make possible reliable automated density estimation.

The final estimate was obtained by applying the group size estimate reported by Claridge [9]. Direct observation in the TOTO from 7 confirmed *M. densirostris* sightings indicate an average group size of 3, which would reduce the estimate to 21.97 animals per 1000 square kilometers. Additional in-situ studies are required to better characterize *M. densirostris* average group size.

The method described assumes only one group is present within any array. If 2 or more groups are present, they will be counted as 1. This discrepancy may be resolved with the inclusion of click statistics into the estimate. Click counting methods are currently under investigation.

Extension of this method to other species requires an understanding of the dive and vocalization characteristics obtained from tagged animals and would indicate tag studies with additional species are highly desirable.

ACKNOWLEDGMENT

We would like to acknowledge our sponsors, Dr. Mardi Hastings and Dr. Robert Gisiner, at the Office of Naval Research. We would also like to thank the Bahamas Marine Mammal Survey and the Woods Hole Oceanographic Institution who provided observer support on the water and technical support on land. Special thanks to Rebecca LeBlanc for help with editing the paper. Finally thanks to the Atlantic Undersea Test and Evaluation Center (AUTEC) for access to their considerable infrastructure and ongoing support.

REFERENCES

[1] Johnson, M. and Tyack, P. "Measuring the behavior and response to sound of beaked whales using recording tags," National Oceanographic Partnership Program Report: Award Number: OCE-0427577, 2005.

[2] Zimmer, W. M. X., Johnson, M. P., Madsen, P. T., and Tyack, P. L. "Echolocation clicks of free-ranging Cuvier's beaked whales (*Ziphius cavirostris*)," J. Acoustical Soc. America, 117, 3919-3927, 2005

[3] Zimmer W., Johnson M., Madsen P., Tyack P., Aquilar de Soto N., "Passive acoustic detection of beaked whales", International Conference: The Effects of Sound in the Ocean on Marine Mammals, Lerici, Italy, 2-5 May 2005

[4] Deavenport, R.L., "NUWC Eigenray Tracking Program: Physics and Mathematics," Naval Undersea Warfare Center, NUWC-NPT Technical Memo 05-098, 25 August 2005

[5] Richards, M., Fundamentals of Radar Signal Processing, McGraw-Hill Electronics Engineering, New York, N.Y., 2005, Chapter 6

[6] Baird, R. W., D. L. Webster, D. J. McSweeney, A. D. Ligon, and G. S. Schorr, "Diving behavior and ecology of Cuvier's (*Ziphius cavirostris*) and Blainville's beaked whales (*Mesoplodon densirostris*) in Hawai'i" Report by Cascadia Research Collective to Southwest Fisheries Science Center, National Marine Fisheries Service under Order No. AB133F-04-RQ-0928, 2005

[7] Jefferson, T.A., Leatherwood, S., and Webber, M.A. FAO Species identification guide. "Marine mammals of the world," UNEP/FAO, Rome. 320 pp. 1993.

[8] Hauser, N., MacCleod, C., and Peckham, H. "Opportunistic survey for beaked whales and other marine mammals off of Central Abaco," Field Season Report: Center for Cetacean Research & Conservation, prepared for Dept. of Fisheries, Govt. of the Bahamas, 1-5. 2001.

[9] Claridge, D.E., "Fine-scale distribution and habitat selection of beaked whales," MSc Thesis, University of Aberdeen, Scotland, UK, 2006.

[10] Morrissey, R. P., J. Ward, N. DiMarzio, S. Jarvis, and D. J. Moretti, "Passive acoustic detection and localization of Sperm whales (*Physeter macrocephalus*) in the Tongue of the Ocean," Journal of Applied Acoustics, 2006. *In press.*

[11] S. Jarvis, N. DiMarzio, R. Morrissey and D. Morretti, Automated Classification of Beaked Whales and Other Small Odontocetes in the Tongue of the Ocean, Bahamas, Naval Undersea Warfare Center Division, Newport, RI, Oceans'06 MTS/IEEE-Boston, September 18-21, 2006