REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)* 30 Nov 2015	**2. REPORT TYPE** Final Technical Report	**3. DATES COVERED** *(From - To)* 01 Sep 2010 - 30 Sep 2014

4. TITLE AND SUBTITLE
ASW Research at WHOI and SIO

5a. CONTRACT NUMBER

5b. GRANT NUMBER
N00014-10-1-0990

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
The Regents of the University of California San Diego: UCSD
Office of Contract and Grant Administration
9500 Gilman Drive
La Jolla, CA 92093-0210

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
875 North Randolph Street
Arlington, VA 22203-1995

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

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

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This was a collaborative award to SIO and WHOI. Most of the funding supported cruises to the Philippine Sea and the North Pacific targeting ocean-acoustic bottom interaction, deep seafloor arrivals and bottom diffracted surface reflected acoustic paths. We observed bottom diffracted surface reflected arrivals in the Philippine Sea similar to arrivals observed in the North Pacific and were able to further constrain the conditions under which they occur.

15. SUBJECT TERMS
bottom interacting ocean acoustics, acoustic tomography, underwater sound

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Peter Worcester
unclassified	unclassified	unclassified	unlimited	5	**19b. TELEPHONE NUMBER** *(Include area code)* 858-534-4688

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

June 7, 2016

FINAL TECHNICAL REPORT

ASW Research at WHOI and SIO

ONR Grant N00014-10-1-0990
Period of Performance: 01 September 2010 – 30 September 2014

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This project was a collaborative effort between Scripps Institution of Oceanography (ONR Grant N00014-10-1-0990, PI: Peter Worcester) and Woods Hole Oceanographic Institution (ONR Grant N00014-1-0987, PI: Ralph Stephen). The Final Report submitted by WHOI for ONR Grant N00014-10-1-0987 included the contributions made by SIO on ONR Grant N00014-10-1-0990. A copy of that final report is attached.

This final report augments the final report previously submitted by WHOI. It briefly summarizes the SIO contributions and provides up-to-date lists of the publications supported at least in part by this grant.

Part A. "Ocean bottom seismometer augmentation of the NPAL 2010-2011 Philippine Sea Experiment (OBSAPS)" – R. A. Stephen (WHOI) and P. F. Worcester (SIO)

A near-seafloor DVLA and array of six ocean bottom seismometers (OBS) were deployed in the Philippine Sea during April-May 2011, immediately following recovery of the 2010–2011 NPAL Philippine Sea Experiment (PhilSea10) moorings, to study the relationship between the acoustic field in the water column and the seismic field in the seafloor for both ambient noise and signals transmitted by a J15-3 source (Stephen *et al.*, 2011; Worcester *et al.*, 2013). The experiment was motivated in part by unexpected arrivals observed on OBSs at 5000-m depth in the northeast Pacific Ocean from broadband signals transmitted by a ship-suspended 75-Hz source during the 2004 Long-range Ocean Acoustic Propagation Experiment (LOAPEX) (Stephen *et al.*, 2012, 2013). These arrivals were named Deep Sea Floor Arrivals (DSFAs).

SIO (Worcester) and WHOI (Kemp) provided the near-seafloor DVLA. The OBSIP (Ocean Bottom Seismometer Instrumentation Pool) group at SIO provided the OBS instruments. WHOI provided the J15-3 source. R. Stephen (WHOI) was Chief Scientist on the cruise.

Analysis of the OBSAPS data is continuing. To date, the following refereed publications and formal technical reports that were supported at least in part by this grant have appeared:

Stephen, R. A., Bolmer, S. T., Udovydchenkov, I. A., Dzieciuch, M. A., Worcester, P. F., Andrew, R. K., Mercer, J. A., Colosi, J. A., and Howe, B. M. (**2012**). "Analysis of Deep Seafloor Arrivals Observed on NPAL04," *WHOI Technical Report WHOI-2012-09* (Woods Hole Oceanographic Institution, Woods Hole, MA), 88 pp.

Stephen, R. A., Bolmer, S. T., Udovydchenkov, I. A., Worcester, P. F., Dzieciuch, M. A., Andrew, R. K., Mercer, J. A., Colosi, J. A., and Howe, B. M. (**2013**). "Deep seafloor arrivals in long range ocean acoustic propagation," J. Acoust. Soc. Am. **134**, 3307–3317.

Stephen, R. A., Kemp, J. N., McPeak, S., Bolmer, S. T., Carey, S. D., Aaron, E., Campbell, R. C., Moskovitz, B., Calderwood, J., Cohen, B., Worcester, P. F., and Dzieciuch, M. A. (**2011**). "Ocean Bottom Seismometer Augmentation of the Philippine Sea Experiment (OBSAPS) Cruise Report," *WHOI Technical Report WHOI-2011-04* (Woods Hole Oceanographic Institution, Woods Hole, Massachusetts), 183 pp.

Worcester, P. F., Dzieciuch, M. A., Mercer, J. A., Andrew, R. K., Dushaw, B. D., Baggeroer, A. B., Heaney, K. D., D'Spain, G. L., Colosi, J. A., Stephen, R. A., Kemp, J. N., Howe, B. M., Van Uffelen, L. J., and Wage, K. E. (**2013**). "The North Pacific Acoustic Laboratory deep-water acoustic propagation experiments in the Philippine Sea," J. Acoust. Soc. Am. **134**, 3359–3375.

Part A – Renewal. "Bottom interacting acoustics in the North Pacific (OBSANP)" – P. F. Worcester (SIO) and R. A. Stephen (WHOI)

The OBSANP experiment was conducted in the northeast Pacific Ocean during June-July 2013, returning to the location of the 2004 LOAPEX experiment at which Deep-Sea Floor Arrivals (DSFAs) were first observed, but with 12 OBSs (instead of four) and a DVLA extending up 1000 m from the seafloor (Stephen *et al*., 2014). The goals were the same as those of the OBSAPS experiment, except that the additional instrumentation allows DSFAs to be characterized at a location where they are known to occur, but at shorter ranges, for more azimuths, and with more frequencies than were available during the 2004 LOAPEX experiment.

In addition, SAIC ultra-low-noise hydrophones were deployed on two of the long-period OBS to study the relationship between deep ocean ambient noise and surface winds for acoustic frequencies below roughly 30 Hz (Farrell *et al*., 2016).

SIO (Worcester) and WHOI (Kemp) provided the near-seafloor DVLA. The OBSIP (Ocean Bottom Seismometer Instrumentation Pool) group at SIO provided the OBS instruments. SIO (Worcester) provided the SAIC ultra-low-noise hydrophones. WHOI provided the J15-3 source (McPeak *et al*., 2013). P. Worcester (SIO) was Chief Scientist on the cruise.

Analysis of the OBSANP data is continuing. To date, the following refereed publications and formal technical reports that were supported at least in part by this grant have appeared:

Farrell, W. E., Berger, J., Bidlot, J.-R., Dzieciuch, M. A., Munk, W. H., Stephen, R. A., and Worcester, P. F. (**2016**). "Wind sea behind a cold front and deep ocean acoustics," J. Phys. Oceanogr. **46**, 1705–1716.

McPeak, S. P., D'Spain, G. L., Stephen, R. A., von der Heydt, K., and Worcester, P. F. (**2013**). "OBSANP Data Acquisition System: Operator's Manual and System Overview," *WHOI Technical Report WHOI-2013-06* (Woods Hole Oceanographic Institution, Woods Hole, Massachusetts), 54 pp.

Stephen, R. A., Worcester, P. F., Udovydchenkov, I. A., Aaron, E., Bolmer, S. T., Carey, S. D., McPeak, S. P., Swift, S. A., and Dzieciuch, M. A. (**2014**). "Ocean Bottom Seismometer Augmentation in the North Pacific (OBSANP) – Cruise Report," *WHOI Technical Report WHOI-2014-03* (Woods Hole Oceanographic Institution, Woods Hole, Massachusetts), 241 pp.

Part B. "WHOI/SIO investigation 3D ocean sound fields in areas of complex seafloor topography and active ocean dynamics" – T. F. Duda (WHOI) and B. D. Cornuelle (SIO)

The goal of the work was to understand the combined effects of complex bathymetry and ocean sound speed variability on sound propagation in order to allow sonar to adapt to or exploit variability in such areas. Time-dependent 3-D acoustic simulations were performed in areas where time-dependent water column structure can change the interaction of sound with complex seafloor features such as canyons and ridges. For this, 3-D acoustic simulations were run for realistic environments computed by internal tide-resolving regional ocean circulation models. The hypothesis was that combining state of the art regional ocean models with state of the art acoustic models can provide useful information and allow insight into the 4-D acoustic field variation of the real ocean.

The work was divided into three parts: (1) ocean modeling focused on the Southern California Bight (SIO); (2) further development of 3-D acoustic codes (WHOI); and (3) study of time-varying 3-D acoustic field structure in slope and canyon regions, done in collaboration. The Southern California Bight model used the MITgcm z-level model with uniform horizontal resolution down to 500 m in some cases and 115 –200 z-levels in order to resolve the topography and the internal tides. The models matched barotropic tides well, but internal tide variability depended strongly on the size of the domain due to the inward propagation of remotely generated super-inertial internal tides at the open boundaries.

To date, the following refereed publication that was supported at least in part by this grant has appeared:

Ponte, A. L., and Cornuelle, B. D. (**2013**). "Coastal numerical modelling of tides: Sensitivity to domain size and remotely generated internal tide," Ocean Modell. **62**, 17–26.

Part C and Part C – Renewal. "Deep water acoustic propagation in the Arctic (ACOBAR)" – P. F. Worcester (SIO), J. F. Lynch (WHOI), and J. N. Kemp (WHOI)

The European Union ACOBAR (ACoustic technology for OBserving the interior of the ARctic Ocean) project was conducted in Fram Strait during 2010–2012. The goal was to develop an observing system based upon underwater acoustic methods, including ocean acoustic tomography, passive listening, acoustic navigation, and acoustic communications to/from underwater platforms. The Nansen Environmental and Remote Sensing Center (NERSC) in Bergen, Norway, led the project. A triangle of three 250-Hz tomographic transceivers (A, B, C) and a vertical line array (VLA) receiver (D) located in the center of the triangle were moored in Fram Strait for two years.

With support from NERSC, SIO participated in the 2010 ACOBAR deployment cruises. With support from both ONR and NERSC, SIO helped recover, refurbish, and redeploy one of the acoustic transceivers (A) and the VLA receiver in 2011. The battery packs in these instruments were not adequate for the full two-year duration of ACOBAR. SIO and WHOI both participated in the final recovery of the ACOBAR system during September-October 2012. One of the ACOBAR transceiver moorings (C) failed shortly after deployment, but the remaining instruments functioned normally. SIO has subsequently participated in the processing and analysis of the ACOBAR data set.

Analysis of the ACOBAR data is continuing. To date, the following refereed publications that were supported at least in part by this grant have been submitted or appeared:

Geyer, F., Sagen, H., Hope, G., Babiker, M., and Worcester, P. F. (**2016**). "Identification and quantification of soundscape components in the Marginal Ice Zone," J. Acoust. Soc. Am. **139**, 1873–1885.

Mikhalevsky, P. N., Sagen, H., Worcester, P. F., Baggeroer, A. B., Orcutt, J., Moore, S. E., Lee, C. M., Vigness-Raposa, K. J., Freitag, L., Arrott, M., Atakan, K., Beszczynska-Möller, A., Duda, T. F., Dushaw, B. D., Gascard, J. C., Gavrilov, A. N., Keers, H., Morozov, A. K., Munk, W. H., Rixen, M., Sandven, S., Skarsoulis, E., Stafford, K. M., Vernon, F., and Yuen, M. Y. (**2015**). "Multipurpose acoustic networks in the Integrated Arctic Ocean Observing System," Arctic **68**, 11–27.

Sagen, H., Geyer, F., Sandven, S., Babiker, M., Dushaw, B. D., Worcester, P. F., Dzieciuch, M. A., Cornuelle, B. D., and Beszczynska-Möller, A. (**2016**). "Resolution, identification, and stability of broadband acoustic arrivals in Fram Strait," J. Acoust. Soc. Am., submitted.

REPORT DOCUMENTATION PAGE	***Form Approved*** **OMB No. 0704-0188**

1. REPORT DATE *(DD-MM-YYYY)* 08-01-2015	**2. REPORT TYPE** FINAL	**3. DATES COVERED** *(From - To)* Sep 2010 - Sep 2014

4. TITLE AND SUBTITLE Collaborative Research: ASW Research at WHOI and SIO	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER N00014-10-1-0987
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Ralph A Stephen Peter F. Worcester Timothy F. Duda James F. Lynch	**5d. PROJECT NUMBER**
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER 1, 2, 3, 4 and 5
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Woods Hole Oceanographic Institution, 569 Woods Hole Road (MS#14), Woods Holoe, MA 02543-1041 Scripps Institution of Oceanography, University of California, San Diego, La Jolla, CA 92093-0225	**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSOR/MONITOR'S ACRONYM(S)**
	11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT
DISTRIBUTION STATEMENT A: Distribution approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This was a collaborative award to WHOI and SIO that covered five projects with four Principal Investigators. Most of the funding supported two cruises, one in the Philippine Sea and one in the North Pacific, targeting ocean-acoustic bottom-interaction, deep seafloor arrivals and bottom-diffracted surface-reflected acoustic paths. We observed bottom-diffracted surface-reflected arrivals in the Philippine Sea similar to arrivals observed in the North Pacific and we were able to further constrain the conditions under which they occur. One project developed a stable and reliable three-dimensional acoustic code and simulations were run for realistic environments computed by ocean flow models. Another project developed a simple scattering theory to quantify time-spread from ocean surface scattering. Some funding also provided cruise support for an experiment in the FRAM straight.

15. SUBJECT TERMS
bottom-interacting ocean acoustics, acoustic tomography, underwater sound

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT** SAR	**18. NUMBER OF PAGES** 30	**19a. NAME OF RESPONSIBLE PERSON** RALPH A STEPHEN
a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** U			**19b. TELEPONE NUMBER** ***(Include area code)*** 508-540-7745

Collaborative Research: ASW Research at WHOI and SIO

FINAL REPORT

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Award Numbers (WHOI): N00014-10-1-0987 and N00014-12-M-0394
Award Number (SIO): N00014-10-1-0990
http://msg.whoi.edu/msg.html

INTRODUCTION

This was a collaborative award to WHOI and SIO that covered five science categories with various Principal Investigators. Separate final reports are being submitted for each science category with the corresponding WHOI project numbers and WHOI funding as follows:

Science Category 1: Ocean Bottom Seismometer Augmentation to the Philippine Sea (OBSAPS) Experiment - Ralph Stephen
  - 13098700, Part A - Task 1: Phil Sea OBS Exp't, $447,136
  - 13098701, Part A - Task 2A: Mooring Operations, $45,546
  - 13098702, Part A - Task 2B: Mooring Fabrication, $26,887
  - 13098703, Part A - Task 2C: Instrumentation Prep, $3,698
  - 13098706, Supplement, $25,799

Science Category 2: Investigation 3D Ocean Sound Fields - Tim Duda
  - 13098704, Part B - Investigation 3D Ocean Sound Fields - $325,584

Science Category 3: Deep Water Acoustic Propagation - Jim Lynch
  -13098705, Part C - Deep Water Acoustic Propagation - $102,149

Science Category 4: Ocean Bottom Seismometer Augmentation in the North Pacific (OBSANP) Experiment - Ralph Stephen
  - 13098707, Part A - Task 1: NPAL13 Cruise, Source and Science, $567,429
  - 13098708, Part A - Task 2a: Mooring Design and Build, $45,392
  - 13098709, Part A - Task 2b: Mooring Field Operations, $93,316
  - 13098710, Part A - Task 2c: Mooring Operations, Aquadopp, $2,744
  - 13098711, Part A - Task 2d: Mooring Fabrication, $42,119

Science Category 5: Fram Strait Cruise Support - Peter Worcester - FINAL REPORT WILL BE SUBMITTED FROM SCRIPPS

- 13098712, Part C - Task 1: Fram Strait Cruise Support, $53,024

Science Category 1

Ocean bottom seismometer augmentation of the NPAL 2010-2011 Philippine Sea Experiment

FINAL REPORT

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Award Numbers: N00014-10-10987, N00014-10-10994 and N00014-10-1-0990
Award Number (SIO): N00014-10-1-0990
http://msg.whoi.edu/msg.html

LONG-TERM GOALS

This project, OBSAPS, addresses the coherence and depth dependence of deep-water ambient noise and signals. Seafloor signals are studied in the band from 50-400Hz and seafloor ambient noise is studied in the band from 0.03 - 80Hz. On NPAL04 we observed a new class of arrivals in long-range ocean acoustic propagation that we call Deep Seafloor Arrivals (DSFAs) because they are the dominant arrivals on ocean bottom seismometers (Mercer *et al.*, 2009; Stephen *et al.*, 2009; Stephen *et al.*, 2008). They either were undetected or very weak on the deepest DVLA hydrophone located near the conjugate depth about 750m above the seafloor. Ongoing analysis of the NPAL04 data indicated that these Deep Seafloor Arrivals were actually Bottom-Diffracted Surface-Reflected (BDSR) arrivals from a near-by seamount (Stephen *et al.*, 2012; 2013). One goal is to see if DSFAs and BDSR arrivals would be observed in the Philippine Sea at relatively short ranges of 50km or less and, if so, to study their characteristics and physical mechanism.

OBJECTIVES

The objective here is to understand the relationship between seafloor pressure and seafloor particle motion for both ambient noise and short- and long-range signals. What is the relationship between the seismic (ground motion) noise on the seafloor and the acoustic noise in the water column? What governs the trade-offs in contributions from local and distant storms and in contributions from local and distant shipping? How effective is seafloor bathymetry at stripping distant shipping noise from the ambient noise field?

APPROACH

Originally the OBSAPS DVLA (O-DVLA) was to be deployed at the location of the PhilSea10 DVLA, following its recovery. Because of fouling problems at this site, the OBSAPS site was moved about 8.7km to the southwest: Lat: 21deg 19.559'N Lon: 125deg 56.325'E. The O-DVLA consisted of one 1000-m DVLA section, with a D-STAR at the top. The O-DVLA consisted of 15 hydrophone modules from 12m above the seafloor to near the conjugate depth (852m above the seafloor). A current meter was deployed at the bottom of the DVLA.

Each OBS had a three-component seismometer and hydrophone or differential pressure gauge. Four OBSs were L-CHEAPOS sampling at 1000sps suitable for the frequency band from 1-400Hz, and two OBSs were broadband instruments sampling at 200sps and suitable for the frequency band from 0.03 to 80Hz. The L-CHEAPO short period OBSs are pretty much the same units we had in 2004. Some critical differences are that the 2011 OBSs acquired three components of particle motion plus acoustic pressure and they sampled at 1000sps. (The 2004 OBSs had only a vertical geophone and hydrophone and sampled at 500sps.) We do not expect that the system noise levels for the geophone or hydrophone channels will be significantly different from the 2004 experiment which was system noise limited (Stephen *et al.*, 2008). We did attach autonomously recording hydrophone modules (identical to the ones in the O-DVLA, to three of the short-period OBSs. The broadband OBSs will provide seafloor ambient noise data for comparison with other deep-water, broadband data sets in the Pacific such as the Hawaii-2 Observatory (H2O) (Duennebier *et al.*, 2002; Stephen *et al.*, 2006) and the Ocean Seismic Network Pilot Experiment (OSNPE) (Stephen *et al.*, 2003).

The source program was carried out using a J15-3 with a bandwidth from 50 to 400Hz, depths down to 100m, ranges to 250km and a variety of azimuths based on the known bathymetry. The main format of the transmission program was binary maximal-length sequences (m-sequences). The receptions can be time compressed using matched field processing to yield impulsive arrivals, that can be studied for multi-path effects and signal-to-noise ratios. For at least one azimuth we had no bathymetric blockage along a line out to 250km, similar to NPAL04, where we can look for DSFA's in a clean wave guide. At least one other path will had bathymetric blockage for comparison. Many radial lines and a "Star of David" at one CZ range were shot to study the range and azimuth dependence of the bottom interaction within one CZ. We also stayed at fixed locations for durations up to four hours to study the temporal variability of the arrival structure and to permit stacking to improve signal-to-noise ratios.

WORK COMPLETED

The cruise was carried out from April 29 to May 16, 2011. We prepared a cruise report with some quick look results (Stephen *et al.*, 2011) and we prepared a technical report on the J15-3 control and acquisition system (McPeak *et al.*, 2011). We also collaborated with Ilya Udovydchenkov on analysis of short range bottom interaction on the NPAL04 experiment (Udovydchenckov *et al.*, 2012) and we prepared materials for Peter Worcester's overview paper on the Philippine Sea Experiments (Worcester *et al.*, 2013).

RESULTS

A cruise report with some quick look results (Stephen *et al.*, 2011) was submitted as a WHOI Technical Report on September 1, 2011. Figures 1, 2 and 3 show some sample results.

Figure 1 compares signal-to-noise ratios, between the hydrophone module on the North short-period OBS and the shallowest hydrophone module on the O-DVLA - 852m above the seafloor, as a function of range for a single line from 50km SW of the O-DVLA to 50km NE of the O-DVLA. Good SNR's were acquired on both sensors at center frequencies of 77.5, 155, and 310Hz. At all three frequencies there are ranges where the signal is undetectable in the background noise (either ambient or system generated). There are also instances when the deep hydrophone has better SNR than the shallow hydrophone.

Figure 2 shows one example of a potential DSFA arrival. Potential DSFA arrivals are identified by two characteristics: a) they arrive much later than the PE predicted arrival (by 2-7sec) and b) their SNR is highest on the seafloor receivers and decreases with increasing height above the seafloor. The relative amplitude of the three arrivals at the North OBS is quite different between the vertical component geophone and the co-located (within 1m) hydrophone module.

Samples of power spectral density of the vertical component channels on the three short-period OBSs (one flooded) and the two long period OBSs are compared in Figure 3. The long-period instruments resolve the noise notch between 0.01 and 0.2Hz.

IMPACT/APPLICATIONS

Clearly the ability of Navy systems to detect and identify ships and submarines by acoustic techniques will depend on at least the following factors: i) the system noise of sensors used to detect the acoustic field, ii) the true field noise for a given sensor type and location, and iii) accurate knowledge of how sound travels in the ocean including bottom interaction if necessary. The observation of deep seafloor arrivals on NPAL04 showed that there is a significant bottom path for coherent sound propagation that was previously unrecognized and is still poorly understood. If this path is as ubiquitous as we expect it will have significant consequences for the performance of any ASW system that uses seafloor receivers, for predictions of long- and short-range propagation to seafloor receivers, and for models of near seafloor ambient noise in the deep ocean.

TRANSITIONS

Transitions to 32ASW project "Behavior of very low frequency near bottom ambient noise in deep water".

RELATED PROJECTS

LOAPEX - ONR Award Number N00014-1403-1-0181
SPICEX - ONR Award Number N00014-03-1-0182
PhilSea09 and PhilSea10 - ONR Award Number N00014-08-1-0840
Bottom Interaction in Ocean Acoustic Propagation - ONR Award Number: N00014-10-1-0510 and N00014-14-1-0324

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HONORS/AWARDS/PRIZES

Ralph Stephen, WHOI, Edward W. and Betty J. Scripps Chair for Excellence in Oceanography, WHOI.

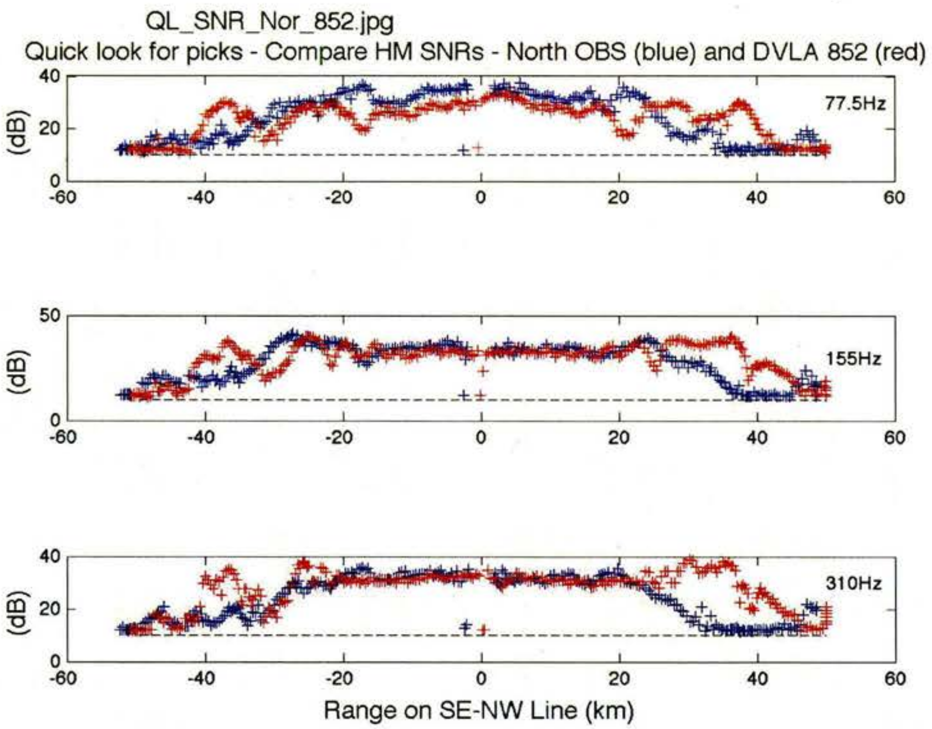

***Figure 1:** SNRs as a function of range are compared between the seafloor hydrophone module (on the North OBS) and the shallowest element on the O-DVLA (at 852m above the seafloor). Figure from Stephen et al (2011).*

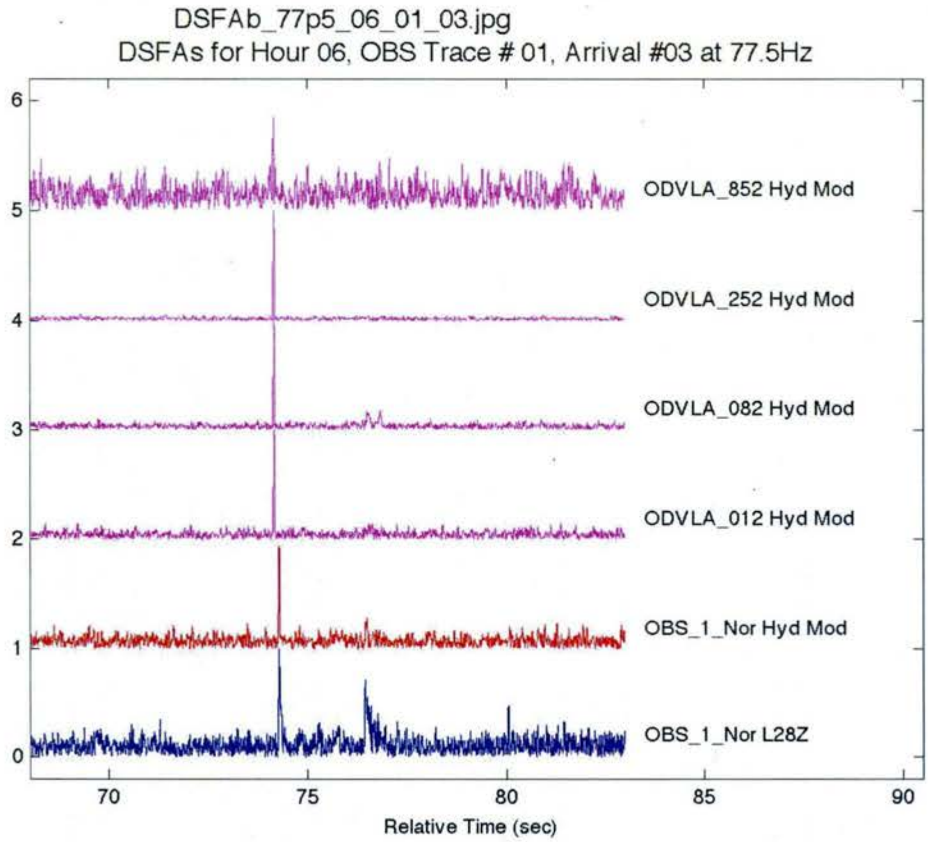

Figure 2 - DSFA Example #1: Here we compare receptions for a single 77.5Hz M-sequence on six OBSAPS receivers: (from bottom to top) the vertical geophone on the North OBS (blue), the hydrophone module on the North OBS (red), and the hydrophone modules on the O-DVLA at 12, 82, 252 and 852m above the seafloor (magenta). The range to the North OBS (bottom two traces) was 31.4km and the range to the O-DVLA (top four traces) was 30.3km. We call the large peak near 74sec the "PE predicted" arrival because it is consistently a large arrival across all of the receivers. The strong arrival about 3sec later on the vertical geophone on the OBS is a classic DSFA, although it is strange that this arrival is so weak on the co-located hydrophone module. There is a weak indication of this arrival on the O-DVLA up to at least 82m above the seafloor. There is also a weak indication of second DSFA on the geophone channel near 80sec. Figure from Stephen et al (2011).

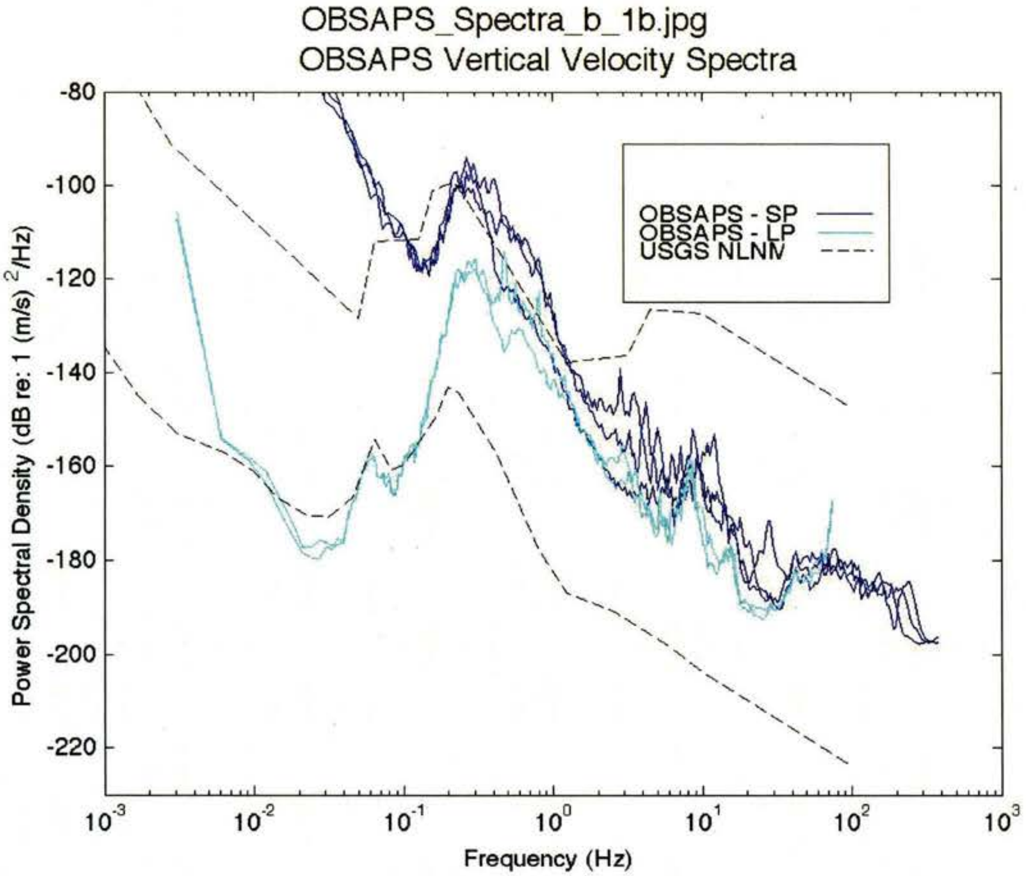

Figure 3: Samples of vertical particle velocity spectra for the three short-period and two long-period OBSs on OBSAPS. The discrepancy at the microseism peak needs to be fixed. Figure from Stephen et al (2011).

Science Category 2

Part B: WHOI/SIO investigation of 3D ocean sound fields in areas of complex seafloor topography and active ocean dynamics

Final Report

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Award N00014-10-1-0987

LONG-TERM GOALS

The goal is to more completely understand natural variability in ocean sound propagation in environments where sound interacts with complex bathymetry, and where time dependence of the water column causes additional temporal variability. With better understanding there is increased potential to tailor sonar methods to adapt to or exploit the variability in such areas.

OBJECTIVES

Broad objectives of this project were (1) to improve the three-dimensional acoustic propagation modeling capability of the ocean acoustics community, (2) to couple this capability with regional ocean model fields, and (3) to determine which aspects of propagating sound-field structure can be effectively modeled with two-dimensional propagation models, which aspects require static three-dimensional models, and which aspects require time-dependent three-dimensional models. A focused objective was to analyze time-dependent three-dimensional acoustic simulation results in areas where time-dependent water columns structure can impact the geometry of sound interaction with complex seafloor features, such as near canyons and ridges. For this, three-dimensional simulations were run for realistic environments computed by ocean flow models. Improvement of the acoustic computational tools was another objective, with the improvements allowing more efficient work toward the objectives listed above.

APPROACH

The work required dynamical computational ocean modeling, computational acoustic propagation modeling, and coupling these together to investigate acoustic condition variability. To estimate effects of ocean variability on sound propagation, realistic ocean modeling was employed. Collaborators Bruce Cornuelle at Scripps Institution of Oceanography and Scripps Postdoc Aurelien Ponte, under an ONR grant concurrent with this one, used the MITgcm ocean model (Marshall et al., 1997) with realistic tidal forcing (from one to six tidal constituents) and realistic bathymetry to model internal tides in the Southern California Bight area (Ponte and Cornuelle, 2013). The resulting time-dependent ocean fields excluded variability from wind forcing, eddies and thermohaline features, and small-scale nonhydrostatic internal waves, isolating the internal tides of the area.

The acoustic modeling was performed by Timothy Duda and Ying-Tsong Lin at Woods Hole with a fluid-seabed type three-dimensional parabolic equation propagation model. The model was improved from previous versions under this under this grant, and coupled with the ocean model. The ocean and acoustic models are not dynamically interactive; the acoustic model takes ocean model fields as input, and computes the acoustic field from specified point sources placed within the model domain. Frequencies from 50 to 700 Hz have been modeled. The acoustic computing grid is scaled by the acoustic wavelength, so that higher acoustic frequencies use more memory and run more slowly for a specified environmental domain. The acoustic code can be set up by the user to fill memory (slowest run speed), or to use a reduced domain size to speed up the computation.

Acoustic field output of the propagation model was then analyzed to determine relationships between acoustic field scintillation, acoustic phase variability, internal-tide strength, bathymetric slope, water depth, and bathymetric slope geometry, over the modeled frequency band. Duda and Lin performed this work.

WORK COMPLETED

The development of the stable and reliable three-dimensional acoustic was one main goal of this project. Another was interfacing of the acoustical code with the dynamical ocean model of the Southern California area. The code has been finished and transitioned to follow-on projects. The codes are all written in the MATLAB language. Reports on the methods used and the performance have been published (Lin, Duda and Newhall, 2013, and Duda, 2013). The third goal was to analyze the acoustical output. Analysis has been presented at multiple professional meetings.

A robust interfacing protocol has been developed to enable linking of the code with time-stepped three-dimensional output fields from dynamical ocean models. The simple protocol involves demanding the user to supply a model-interfacing translator meeting a specific design, and also including an open input field where the user can type the filename of the translator, so the code can access the translator and thus the data.

Acoustic propagation modeling was completed for time-series of internal-tide fields within multiple domains. Three domains are shown with boxes in Figure 1. These are “Coronado Canyon” at the south, “Inshore North”, and ‘Inshore-North 2” at Nine-Mile Bank. The last two are rotated from each other but otherwise similar. Other domains are “Basin” 1, 2, 3 and 4 in the Santa Cruz Basin near 119.5 W, 33.6 N. Statistics of acoustic phase and transmission loss-variability at these locations were examined and compared. It was found that three-dimensional bottom-reflection effects played a role in defining the acoustic behavior over many sloping areas, effects that are not modeled with two-dimensional acoustic models (such as common N by two-D modeling in radial vertical slides from a point source). Statistical analysis of some Coronado Canyon results are shown in Figure 2.

This project saw a majority of effort in 2011 and 2012. The work and some findings from the work were described in two conference presentations in addition to five of the publications listed in the Publications section. (Note that these five publications followed conference presentations.) The two presentations were

(1) Shallow-water acoustic studies with regional ocean models. Timothy F. Duda, Ying-Tsong Lin, Weifeng Gordon Zhang, Aurelian L. Ponte, Bruce D. Cornuelle and Pierre F. J. Lermusiaux, J. Acoust. Soc. Am. 129, 2509 (2011) ; http://dx.doi.org/10.1121/1.3588286

(2) Spatiotemporal variability of underwater sound fields near steep slopes. Timothy F. Duda, Ying-Tsong Lin, Weifeng Gordon Zhang, Aurelien Ponte and Bruce D. Cornuelle, J. Acoust. Soc. Am. 131, 3391 (2012); http://dx.doi.org/10.1121/1.4708792

RESULTS

It was found that the area of largest internal tides, the Santa Cruz Basin, did not produce the largest acoustic scintillation indices. Instead, beams of strong scintillation (strong TL variability) were found where sound reflected obliquely off of steep slopes into deep water. In this situation, a reflected beam of sound would wobble as the internal tide evolved, leading to stronger variations in the beam than in the surrounding area. The effect of the slopes was verified by re-running the acoustics with smoothed bathymetry, verifying that the greater the bathymetric detail, the stronger the wobbling-beam effects.

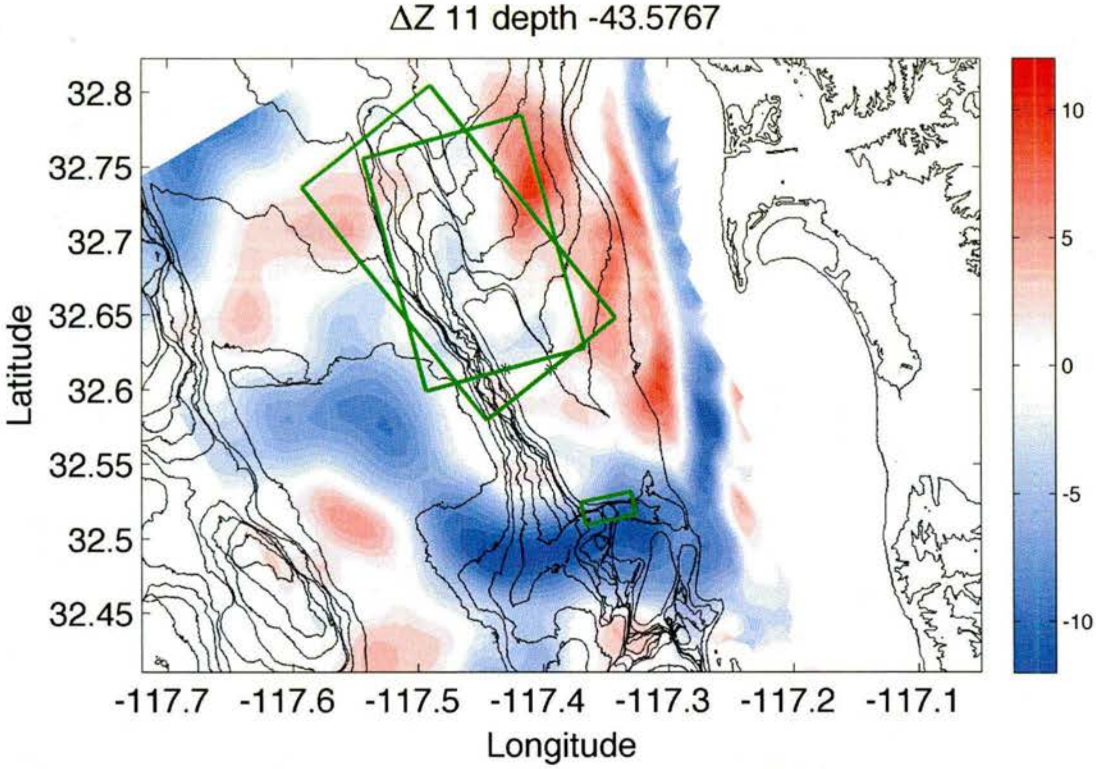
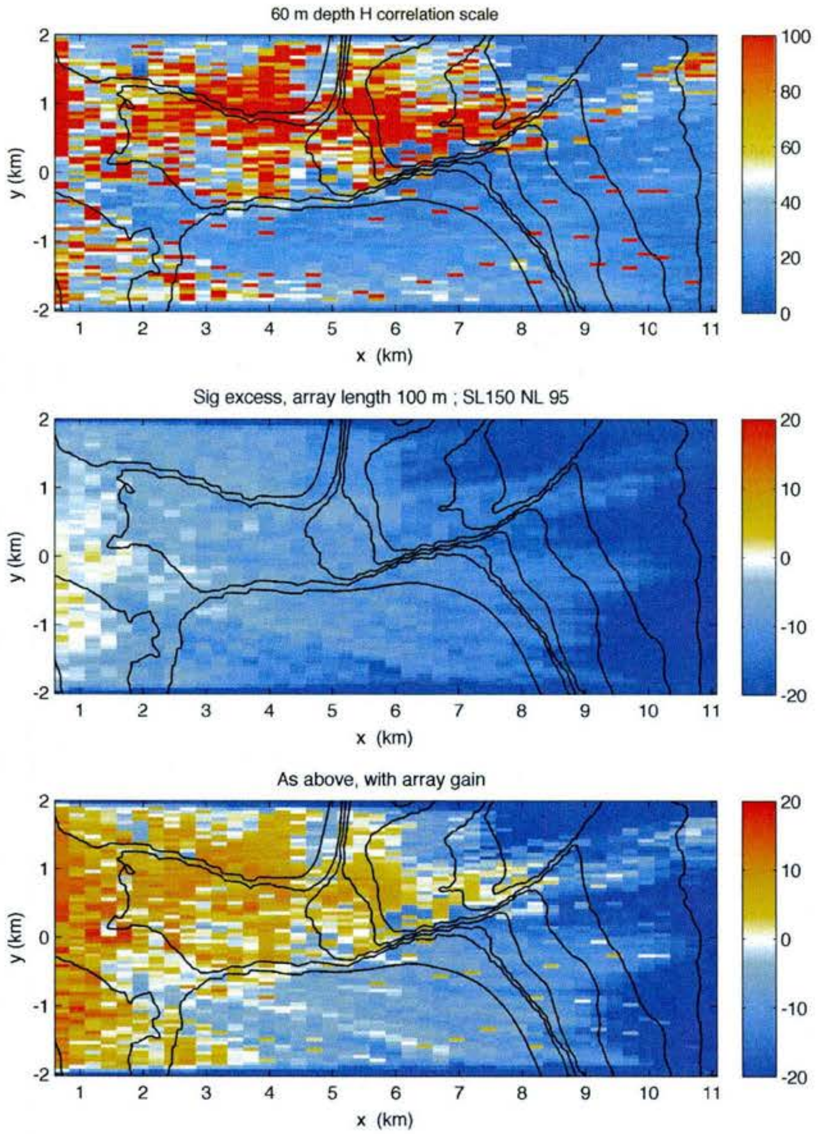


Figure 1. A snapshot of internal tide displacement amplitude, in meters, of the water residing at 43.5 meters mean depth beneath the surface is shown in color. The water depth and land elevation are contoured at 100-m increment from 120--m depth to 100-m elevation. The outline of the San Diego coastline can be seen at the right, including Sam Diego Bay. The green box near 117.35 W and 32.5 N shows the location of sound-field modeling analyzed statistically in Figure 2. The larger boxes show two domains extending northward from Nine-Mile Bank into deep water, rotated with respect to each other for numerical testing of performance over steep slopes. The evolving internal tide field looks a little bit like a complicated surface wave field scaled down in wavenumber so that the scale lengths are tens of kilometers rather than tens of meters.


60 m depth H correlation scale

Sig excess, array length 100 m ; SL150 NL 95

As above, with array gain

Figure 2: Analysis of horizontal coherence of a 300-Hz acoustic signal propagated westward down Coronado Canyon in California with the three-dimensional computational model. The x axis points slightly south of west. Bathymetry is shown in 100-m contours, with the 800-m depth contour at the right of all panels, and the 200-m contour enclosing the shallow area in the lower center and left center of all panels. (top) The horizontal correlation scale lengths of fields beamformed using 100-m long synthetic horizontal arrays at 60-m depth are shown in color. (middle) The modeled signal excess is shown in color for the same synthetic arrays, source level 150 dB and uncorrelated omnidirectional noise level 95 dB. (bottom) The signal excess fpor the synthetic arrays after beamforming, computed from a theoretical expression involving the data of the top two panels is shown. Various methods of estimating the key statistic of the upper panel using a reduced computational load are being examined. The most reliable, but computationally intense, way is to compute the array performance (lower panel) is to collect field statistics for many snapshots of the time-dependent ocean.

In general, scintillation indices were lower than observed in nature, implying that smaller-scale internal waves, which can develop from internal tides as well as from other sources, are responsible for much of the acoustic fluctuation. This result supports our idea of pushing ocean dynamical models to include smaller-scale features, one goal of our related MURI project. (See Related Projects section.)

RELATED PROJECTS

Related projects are

(1) Experimentally-Based Ocean Acoustic Propagation and Coherence Studies, ONR Award N00014-11-1-0194 to Dr. Timothy F. Duda

(2) Ocean Acoustic Propagation and Coherence Studies, ONR award N00014-14-1-0223 to Dr. Timothy F. Duda

(3) Integrated Modeling and Analysis of Physical Oceanographic and Acoustic Processes, DoD MURI grant (ONR award N00014-11-1-0701) to Dr. Timothy F. Duda, Woods Hole Oceanographic Institution

The third of these has goals of modeling acoustic conditions in complex environments using two- and three-dimensional acoustic models operating on fields computed using dynamical ocean models. That project is a large-scope direct follow-on to the project reported here.

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Science Category 3

Deep Water Acoustic Propagation

FINAL REPORT

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LONG-TERM GOALS

The long term goal is to enable acoustic tomography and similar acoustic measurement techniques to operate in interesting high-latitude locations.

OBJECTIVES

Our objective was to quantify ocean surface scattering effects that degrade ones ability to resolve the acoustic multipath arrivals, be they rays or modes, which form the usual data set for tomographic inversions.

APPROACH

Our approach was to concentrate on how scattering in open water areas, which are common in the Marginal Ice Zone, and increasingly important deeper in the traditionally ice covered areas, produces spreading of the acoustic arrivals, versus distance and multipath angle. We particularly focused on using simple approximations, which give reasonably good answers without needing large calculations and computer resources.

WORK COMPLETED

We have devised a simple theory, which uses very basic descriptors of the surface wave field as input, to give good estimates of the time spreading of an acoustic pulse.

RESULTS

The simple scattering theory we have devised gives a very reasonable estimate of the time spread of a pulse. This theory, which is based on using (plus or minus) the rms slope of the surface, convolved with the ray incident angle and number of surface interactions, reproduces data from two shallow water experiments rather well, and can be just as easily applied to the deep water Arctic application.

IMPACT/APPLICATIONS

Surface time spread is a computationally intensive quantity to predict with acoustic theories such as coupled modes or parabolic equation. Thus, it is often neglected when designing acoustic experiments, which leads to an overly optimistic view of what the resolution of the overall system is. With the simpler approximation available, this spread can now be easily incorporated, both in the design and the data analysis phases of an experiment.

RELATED PROJECTS

This theory is being applied both to Acoustic Communications experiments and to our ONR BRC project looking at reverberation and scattering from fish schools. In the former case, the surface degrades multipath resolution for acomms. In the latter case, the surface time spread looks like reverberation, which competes with that produced by the fish schools and shoals.

Science Category 4

Ocean Bottom Seismometer Augmentation in the North Pacific (OBSANP) Experiment

FINAL REPORT

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Award Numbers (WHOI): N00014-10-1-0987 and N00014-12-M-0394
Award Number (SIO): N00014-10-1-0990
http://msg.whoi.edu/msg.html

LONG-TERM GOALS

This award category was originally titled "Bottom Interacting Acoustics in the North Pacific (NPAL13)" but to avoid confusion with other projects we have change the title to "Ocean Bottom Seismometer Augmentation in the North Pacific (OBSANP)". The OBSANP cruise to the NPAL04 site was carried out on R/V Melville, San Diego to Seattle, June 12 –July 11, 2013.

This project addresses the coherence and depth dependence of deep-water ambient noise and signals. Seafloor signals are studied in the band from 15 - 400Hz and seafloor ambient noise is studied in the band from 0.03 - 400Hz. On NPAL04 we observed a new class of arrivals in long-range ocean acoustic propagation that we call Deep Seafloor Arrivals (DSFAs) because they are the dominant arrivals on ocean bottom seismometers (Mercer *et al.*, 2009; Stephen *et al.*, 2009; Stephen *et al.*, 2008). We recently resolved that many of the DSFAs observed on NPAL04 are diffracted energy from a near-by seamount that is reflected from the sea surface (bottom-diffracted surface-reflected - BDSR - paths) (Stephen *et al.*, 2012; 2013). This diffracted energy is a relatively weak signal on hydrophones on the DVLA, more than 750m above the seafloor, but it is by far the strongest signal on vertical geophones on the seafloor for signals out to 3200km range. One goal of OBSANP is to study these BDSR paths at shorter ranges and at more azimuths than were available from the 2004 experiment. This work is relevant to the Navy because it seeks to quantify and understand the signal propagation and noise floors that are necessary to evaluate and exploit seismo-acoustics for operational ASW systems.

OBJECTIVES

The objective here is to understand the relationship between seafloor pressure and seafloor particle motion for both ambient noise and short- and long-range signals. What is the relationship between the seismic (ground motion) noise on the seafloor and the acoustic noise in the water column? What governs the trade-offs in contributions from local and distant storms and in contributions from local and distant shipping? How effective is seafloor bathymetry at stripping distant shipping noise from the ambient noise field? By returning to the NPAL04 site with more OBSs, a deep DVLA extending from the seafloor to 1000m above the seafloor, and a towable, controlled source (J15-3) our goals were to further define the characteristics of DSFAs, to understand the conditions under which they are excited and to understand their propagation to the seafloor.

In addition to studying DSFAs we acquired ambient noise data over a 15day period. Although it has been recognized for a long time that acoustic noise in the 0.1 to 30Hz band is a function of surface gravity wave conditions (McCreery *et al.*, 1993; Webb and Cox, 1986), recent studies indicate that seafloor ambient noise in deep water (~5,000m) in the 1-30Hz band carries significant information about even very short ocean surface waves (wavelengths from 6m to a centimeter) (Duennebier *et al.*, 2012; Farrell and Munk, 2008; 2010). Since our ship was in the vicinity of the seafloor sensors during the whole recording period we have direct observations of sea surface conditions to compare with the seafloor ambient noise data.

APPROACH

During the LOAPEX/NPAL04 experiment in 2004 sources, centered near 68 and 75Hz, were deployed at three depths, 350m, 500m and 800m, and at seven ranges, 50km, 250km, 500km, 1000km, 1600km, 2300km and 3200km. All of the source stations were intentionally located along the same geodesic, that is at the same azimuth to the receivers. Oddly DSFAs were only observed at 500km range and greater. We returned to the site to fill-in these gaps: a) to extend the frequency range to cover M-sequences from 77.5 to 310Hz, b) to include hydrophones and three component geophones on the seafloor and a DVLA extending from the seafloor to 1000m above the seafloor, c) to have continuous tows and station stops for a controlled source in the upper 100m, d) to include radial tows at a variety of azimuths as well as arcs and circles around the receivers and around Seamount B.

WORK COMPLETED

On the OBSANP cruise (R/V Melville, San Diego to Seattle, June 12 –July 11, 2013) we deployed twelve OBSs and a near-seafloor DVLA in the vicinity of the NPAL04 site (Figure 1) and we carried out a two week transmission program using J15-3s (Worcester and Stephen, 2013) (Stephen *et al.*, 2014). The near-seafloor DVLA, which had 32 Hydrophone Modules distributed along one 1000-m DVLA section (Figure 2), was deployed at the location of the Deep VLA during NPAL04.

The four short period (SP1 to SP4) and four long period OBSs (LPA to LPD) in the immediate vicinity of the ODVLA were aligned with respect to the LOAPEX (NPAL04) source geodesic. Each of the four short-period OBSs, at 2km range from the ODVLA, had a hydrophone module attached. Two short period OBSs also with hydrophone modules attached (SP7 and SP8) were located as near as possible to the tops of Seamounts B and C respectively to measure directly the incident field at these features. Two short period OBSs without hydrophone modules (SP5 and SP6) fall on a line between Seamount B and the ODVLA. The four long period OBSs (LPA to LPD) were distributed about the ODVLA at 4km range. Two of these, LPA and LPC, acquired data from SAIC low-noise hydrophones in addition to the three inertial channels on the Trillium seismometers and the differential pressure gauge.

J15-3 operations on OBSANP were quite successful with no down-time due to equipment failure and essentially two weeks of scheduled transmissions. We transmitted primarily m-sequences at various frequencies spanning 20 to 310Hz with the source at depths from 60m to100m. The m-sequences fall into four categories: 1) multi-frequency, short range (<1/2CZ) tows at 77.5, 155 and 310Hz; 2) single frequency, long range (up to 250km, ~3-1/2CZ) tows at 77.5Hz, 3) multi frequency station stops at 1/2, 1-1/2, 2-1/2 and 3-1/2CZ at 77.5, 102.3,155, 204.6, and 310Hz) and 4) low frequency transmissions (19.375, 25.575, 38.75 and 51.15Hz) at short ranges (< 1/2CZ) that would provide field data for modeling with SPECFEM3D. We also tested Minimum Shift Keying (MSK) format m-sequences, which are an alternative to our usual phase shift keying (PSK) format and could potentially have improved properties for some applications.

In the first phase of the transmission program we carried out a "pin cushion" pattern of station stops spanning 1/2CZ ranges to the ODVLA and Seamount B (Figure 3). This pattern was designed to insonify Seamount B at a variety of sagittal and azimuthal angles and to distinguish bottom-diffracted from bottom-reflected energy.

We attempted to replicate the LOAPEX results as closely as possible by carrying out a series of long- and short-range tows and station stops along the LOAPEX geodesic out to 250km range (Figure 4). On LOAPEX DSFAs were observed using the ATOC source at ranges of 500km and greater, so we could not duplicate the 2004 results directly. These transmissions will, however, fill-in the long-range propagation story for short ranges along the same path.

In order to obtain a comprehensive view of propagation and scattering within 1/2CZ to receivers on and near the seafloor we carried out a series of radial line tows out to 50km range at eight azimuths and half of a "Star of David" pattern over the seamounts across 1/2CZ ranges (Figure 5.) This pattern is very similar to the OBSAPS experiment in the Philippine Sea in 2011, so propagation and scattering characteristics at the two sites can be compared.

In the fourth phase we occupied two station stops within 1/2CZ of both the ODVLA and Seamounts B and C in order to carry out source tests that will be useful in subsequent experiments (Figure 6). We transmitted identical m-sequences in both MSK and PSK formats. We had not done MSK format transmissions in the past but they have smoother phase than the PSK format and this could be an advantage for some types of sources. Also, although the J15-3 is not recommended for use below 100Hz, we tested the source with CW and m-sequence transmissions down to 20Hz. Source levels are quite low at these frequencies but we are at very short ranges from the receivers and we are optimistic that we will see useful returns. Full three-dimensional bottom-interaction problems with shear, that can be studied using codes like SPECFEM3D, are more tractable at these low frequencies.

We prepared a cruise report with some quick look results (Stephen *et al.*, 2014) and we prepared a second technical report on the J15-3 control and acquisition system (McPeak *et al.*, 2013).

RESULTS

We are in the initial stages of data reduction, analysis and interpretation of the two weeks of data on 83 channels. The signal-to-noise of the 77.5Hz time compressions is good out to at least 50km (Figure 7).

IMPACT/APPLICATIONS

Clearly the ability of Navy systems to detect and identify ships and submarines by acoustic techniques will depend on at least the following factors: i) the system noise of sensors used to detect the acoustic field, ii) the true field noise for a given sensor type and location, and iii) accurate knowledge of how sound travels in the ocean including bottom interaction if necessary. The observation of deep seafloor and bottom-diffracted surface reflected arrivals on NPAL04 showed that there is a significant path for coherent sound propagation to the deep seafloor that was previously unrecognized and is still poorly understood. If this path is as ubiquitous as we expect it will have significant consequences for the performance of any ASW system that uses seafloor receivers in deep water, for predictions of long- and short-range propagation to seafloor receivers, and for models of near seafloor ambient noise in the deep ocean.

TRANSITIONS

Transitions to 32ASW project "Behavior of very low frequency near bottom ambient noise in deep water". On the OBSANP cruise we acquired data to support projects of Bill Farrell, Walter Munk and Jon Berger at SIO.

RELATED PROJECTS

LOAPEX - ONR Award Number N00014-1403-1-0181,
SPICEX - ONR Award Number N00014-03-1-0182,
PhilSea09 and PhilSea10 - ONR Award Number N00014-08-1-0840,
OBSAPS - ONR Award Numbers N00014-10-10994 and N00014-10-1-0990,
Bottom Interaction in Ocean Acoustic Propagation - ONR Award Numbers: N00014-10-1-0510 and N00014-14-1-0324

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HONORS/AWARDS/PRIZES

None

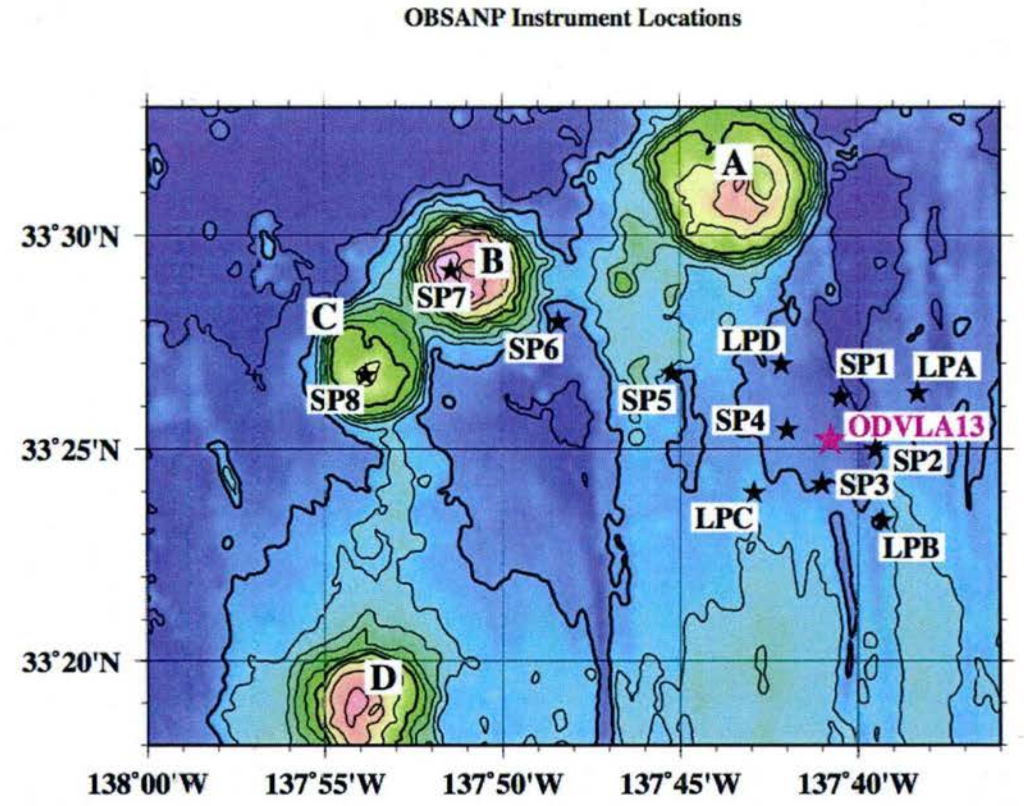

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Figure 1: Locations of the eight short period OBSs (SP*), the four long period OBSs (LP*), and the ODVLA13 with respect to the bathymetric relief. [OBSANP_Ralph_Instruments.jpg]

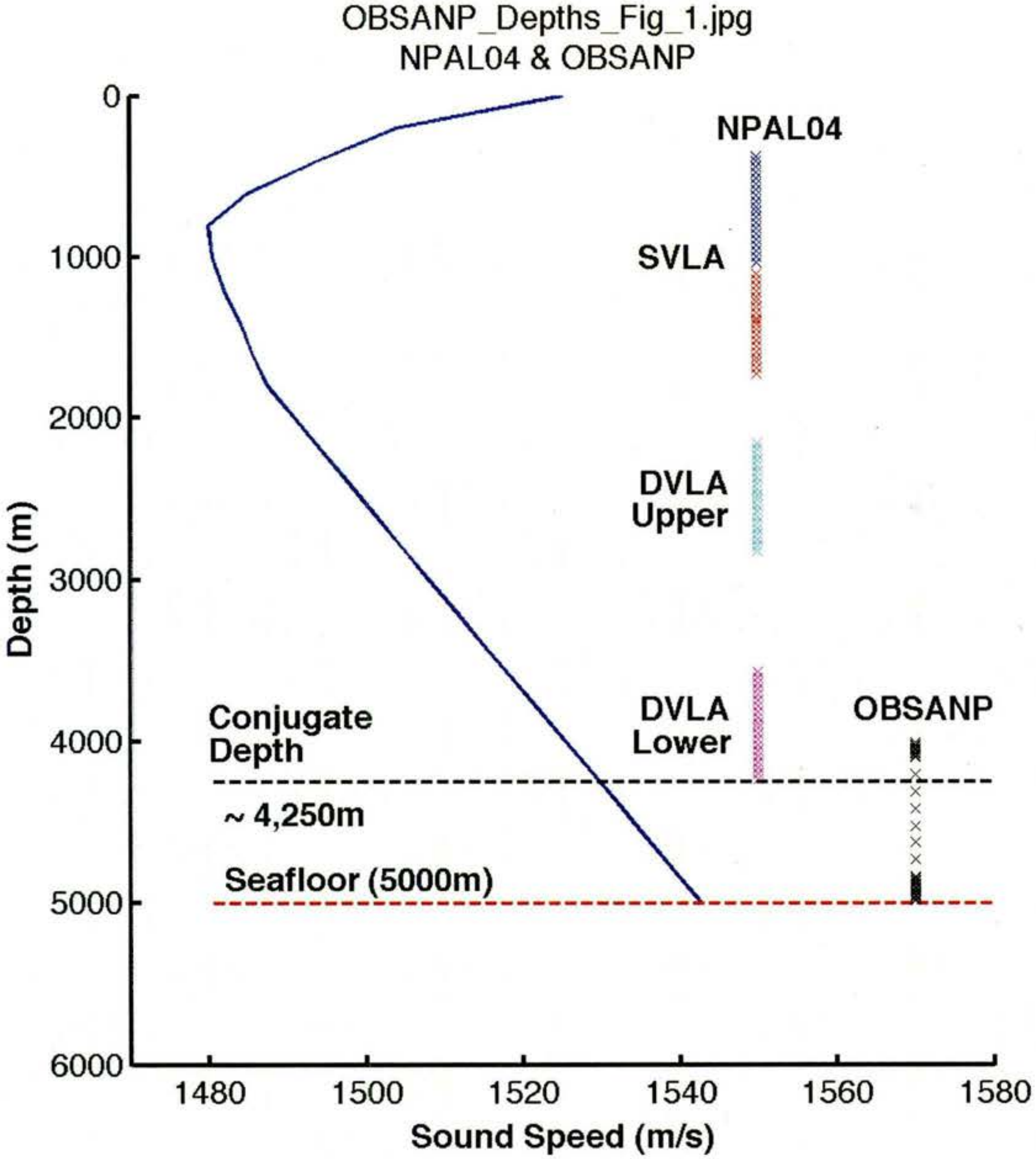


Figure 2: The OBSANP DVLA (black x's) is designed to span from the seafloor to the conjugate depth. There are 16 elements at 10m spacing (half wavelength at 75Hz) at the bottom and ten elements at 10m spacing at the top. The two mini-arrays are separated by 6 elements at 105m spacing. The shallow and deep VLA's deployed on NPAL04 are shown for comparison. A nominal sound speed profile from NPAL04 is shown.

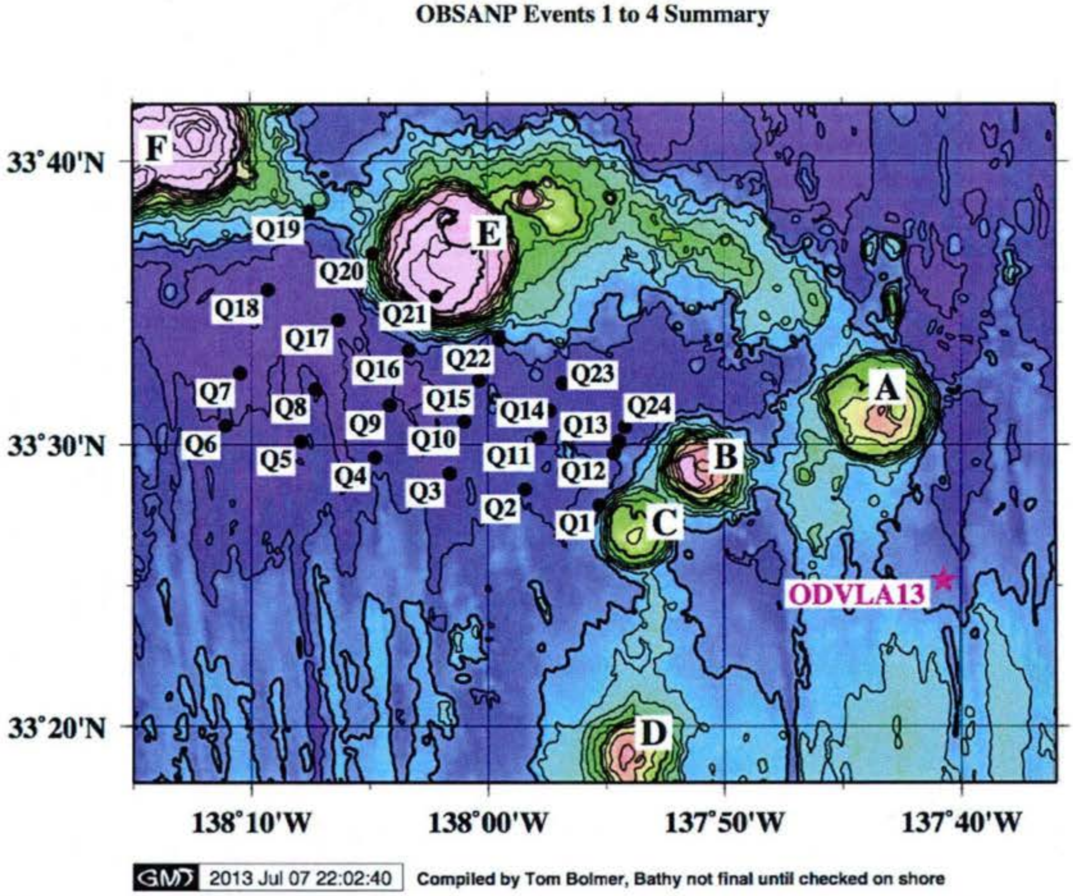


Figure 3: A "pin cushion" of station stops was designed to insonify Seamounts B and C at a variety of sagittal and azimuthal angles. The stations span 1/2CZ from the DVLA and the seamounts. Q1 to Q6 are on the LOAPEX geodesic. Q13 to Q18 are collinear with Seamount B and the DVLA. [OBSANP_Ralph_Event_1_4_Summary.jpg]

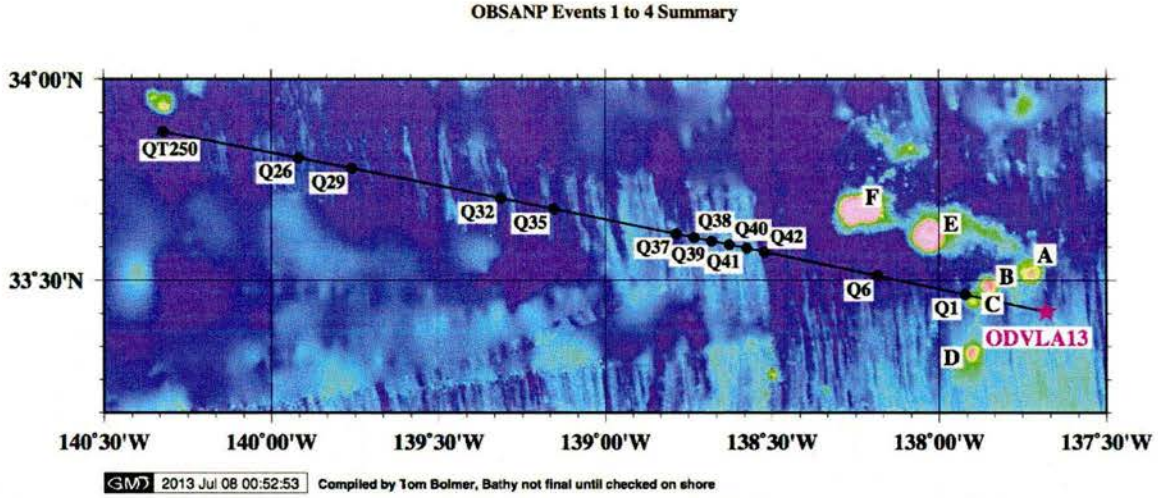


Figure 4: In an attempt to replicate the 2004 LOAPEX results we transmitted continuously out to 250km range on the LOAPEX geodesic and then occupied station stops at ½, 1-1/2, 2-1/2 and 3-1/2 CZ's from the DVLA. Stations between Q1 and Q6 are shown in Figure 3. [OBSANP_Ralph_Event_1_4_Summary.jpg]

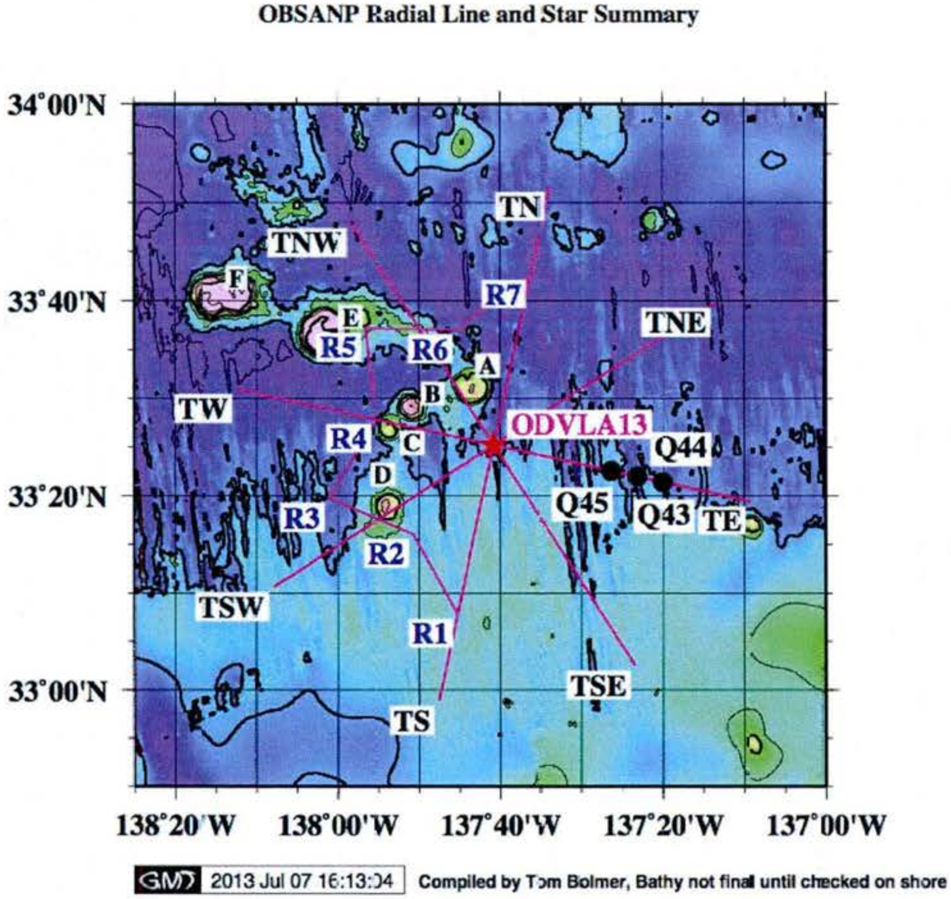
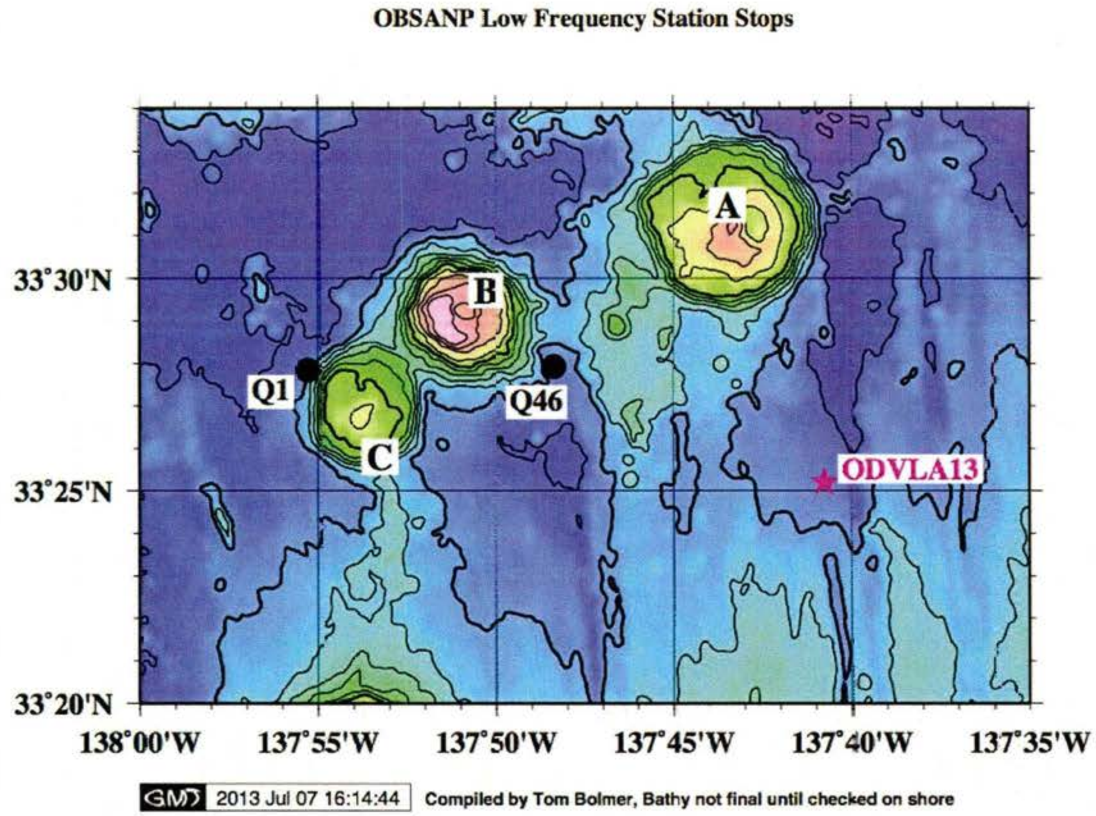


Figure 5: Phase 3 of the transmission program carried out a comprehensive survey (out to 50km) around the DVLA. [OBSANP_Ralph_Spokes_Star.jpg]



OBSANP Low Frequency Station Stops

Figure 6: Q1 and Q46 were the locations of the MSK and low frequency tests. It is conceivable that 20Hz scattering from Seamounts B and C could be modeled using a fully elastic, three-dimensional propagation code such as SPECFEM3D. [OBSANP_Ralph_Q1_Q46.jpg]

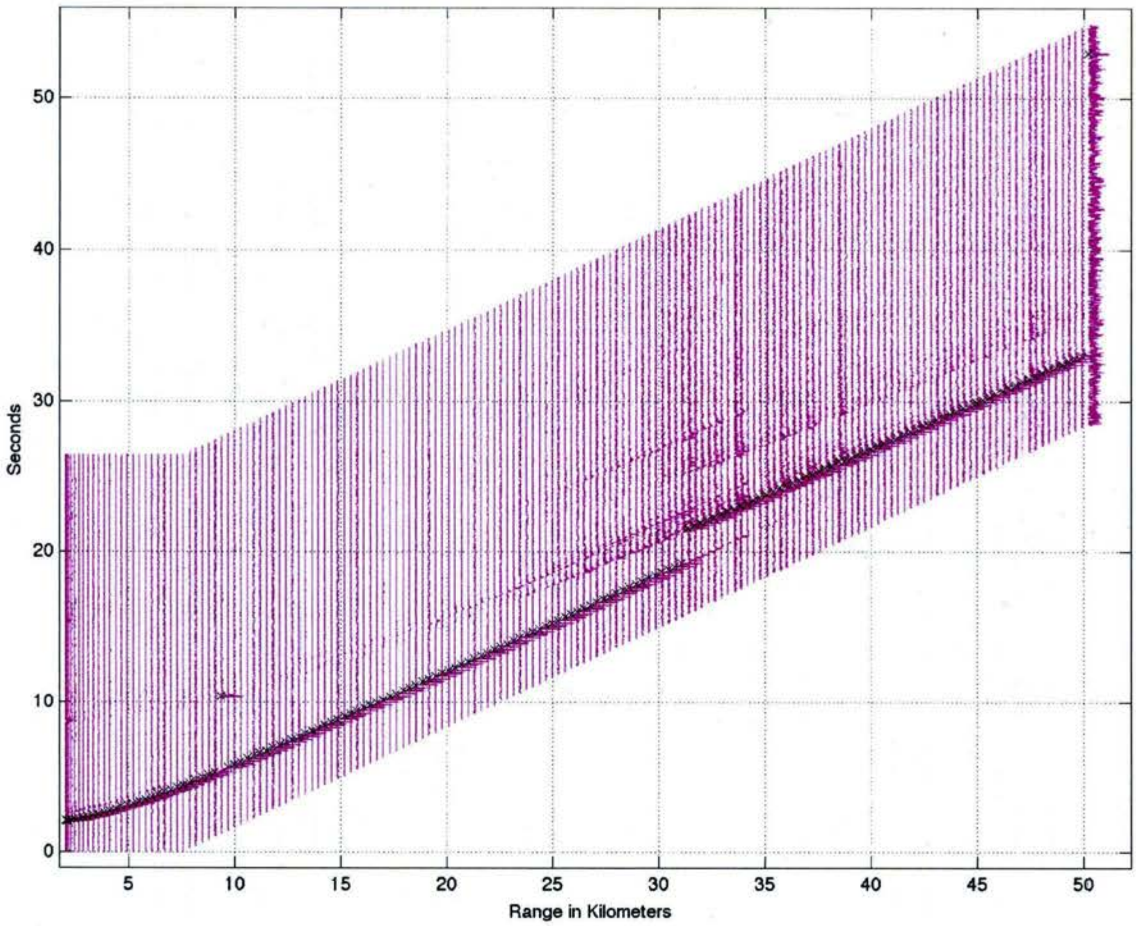


Figure 7: Example of 77.5Hz time compressions for transmissions on the North radial line to the hydrophone module on SP2. Good signal-to-noise is obtained for transmissions out to 50km range. [N_HM_OBS_SP2_775.jpg]