North Pacific Acoustic Laboratory: Deep Water Acoustic Propagation in the Philippine Sea

Peter F. Worcester
Scripps Institution of Oceanography, University of California, San Diego
La Jolla, CA 92093-0225
phone: (858) 534-4688 fax: (858) 534-6251 email: pworcester@ucsd.edu

Co-Investigators
Bruce D. Cornuelle
Scripps Institution of Oceanography, University of California, San Diego
La Jolla, CA 92093-0230
phone: (858) 534-4021 fax: (858) 534-9820 email: bcornuelle@ucsd.edu

Matthew A. Dzieciuch
Scripps Institution of Oceanography, University of California, San Diego
La Jolla, CA 92093-0225
phone: (858) 534-7986 fax: (858) 534-6354 email: mdzieciuch@ucsd.edu

Walter H. Munk
Scripps Institution of Oceanography, University of California, San Diego
La Jolla, CA 92093-0225
phone: (858) 534-2877 fax: (858) 534-6251 email: wmunk@ucsd.edu

Award Numbers: N00014-03-1-0182, N00014-08-1-0840
http://npal.ucsd.edu

LONG-TERM GOALS

The North Pacific Acoustic Laboratory (NPAL) program is intended to improve our understanding of (i) the basic physics of low-frequency, broadband propagation in deep water, including the effects of oceanographic variability on signal stability and coherence, (ii) the structure of the ambient noise field in deep water at low frequencies, and (iii) the extent to which acoustic methods, together with other measurements and coupled with ocean modeling, can yield estimates of the time-evolving ocean state useful for acoustic predictions. The goal is to determine the fundamental limits to signal processing in deep water imposed by ocean processes, enabling advanced signal processing techniques to capitalize on the three-dimensional character of the sound and noise fields.

OBJECTIVES

The series of long-range, deep-water acoustic propagation experiments conducted over the last 20 years in the North Pacific Ocean during the NPAL program reflect the background sound-speed field, the relatively low level of eddy variability, the small-scale sound-speed fluctuations caused by internal tides, internal waves, and density-compensated temperature and salinity variations (spice), and the noise sources found in the relatively benign northeast and north central Pacific Ocean. The experiments in the North Pacific have for the most part, although not entirely, also been at long ranges of 500 km or more. Simulations suggest that at these long ranges the detailed physics of the scattering processes tend to become less important, as the signals undergo multiple scattering.

Our experimental efforts have now shifted to the oceanographically complex and highly dynamic northern Philippine Sea, with differing background sound-speed profiles, much higher eddy energy levels, differing internal wave and spice fields, and differing sources of ambient noise. Our efforts have also shifted to include measurements at shorter ranges, so that the detailed physics of the scattering processes can be better elucidated.

A short-term Pilot Study/Engineering Test was conducted in the Philippine Sea during April-May 2009. A large-scale, one-year-long, acoustic propagation experiment in the Philippine Sea, for which six acoustic transceivers and a water-column-spanning Distributed Vertical Line Array (DVLA) receiver were deployed during April 2010, is now in progress. The specific objectives are to (i) understand the impacts of fronts, eddies, and internal tides on acoustic propagation in this highly variable region, (ii) determine whether acoustic methods, together with satellite, glider and other measurements and coupled with ocean modeling, can yield estimates of the time-evolving ocean state useful for making improved acoustic predictions and for understanding the local ocean dynamics, (iii) improve our understanding of the basic physics of scattering by small-scale oceanographic variability due to internal waves and spice, and (iv) characterize the ambient noise field, particularly its variation over the year and its depth dependence.

APPROACH

A water-column-spanning Distributed Vertical Line Array (DVLA) receiver was developed for the 2009 NPAL Philippine Sea Pilot Study/Engineering Test (PhilSea09) and the 2010–2011 NPAL Philippine Sea Experiment (PhilSea10) (Worcester et al., 2009). The NPAL experiments previously conducted in the North Pacific were constrained by the lack of vertical line array receivers capable of spanning the full water column in deep water. Such arrays are required to enable the separation of high-order acoustic modes using spatial filtering and to fully characterize the acoustic time fronts found in deep water propagation. The new DVLA uses a novel approach with distributed, self-recording Hydrophone Modules with timing and scheduling provided by a small number of specially modified versions of our Simple Tomographic Acoustic Receiver (STAR) data acquisition system and controller, called D-STARs. The enabling technologies for this approach are (i) the availability of flash memory modules that can store several gigabytes of data and be located in a small pressure case at each hydrophone, making it unnecessary to transfer acoustic data from the hydrophone to the central controller for storage, and (ii) inductive modems that allow low-bandwidth communication for command, control, and time synchronization between the D-STAR controllers and the Hydrophone Modules over standard 3 x 19 jacketed oceanographic mooring wire. The DVLA is modular, made up of 1000-m long subarrays, each of which has one D-STAR and roughly 30 distributed, internally-recording Hydrophone Modules that clamp on the mooring wire.

A prototype DVLA consisting two 1000-m subarrays, one spanning the sound-channel axis and one spanning the surface conjugate depth, was deployed for PhilSea09. Each subarray had 30 Hydrophone Modules. It recorded transmissions from a near-axial 225–325 Hz Teledyne Webb Research Corporation (WRC) swept-frequency source moored 185.126 km from the DVLA. The strategy was to instrument a single acoustic path, approximately between the locations of T1 and the DVLA, in the larger array planned for PhilSea10 (Fig. 1). Both moorings remained in place for about one month, while coordinated, ship-based components of the experiment were conducted by A. Baggeroer (MIT), G. D'Spain (MPL-SIO), K. Heaney (OASIS), and J. Mercer (APL-UW). The objectives were (i) to obtain an initial look at deep-water acoustic propagation and ambient noise in the northern Philippine Sea, with special emphasis on issues of interest to the ONR Undersea Surveillance Program and on using long duration transmissions to study temporal variability, and (ii) to test the equipment planned for use in 2010–2011 under actual operating conditions.

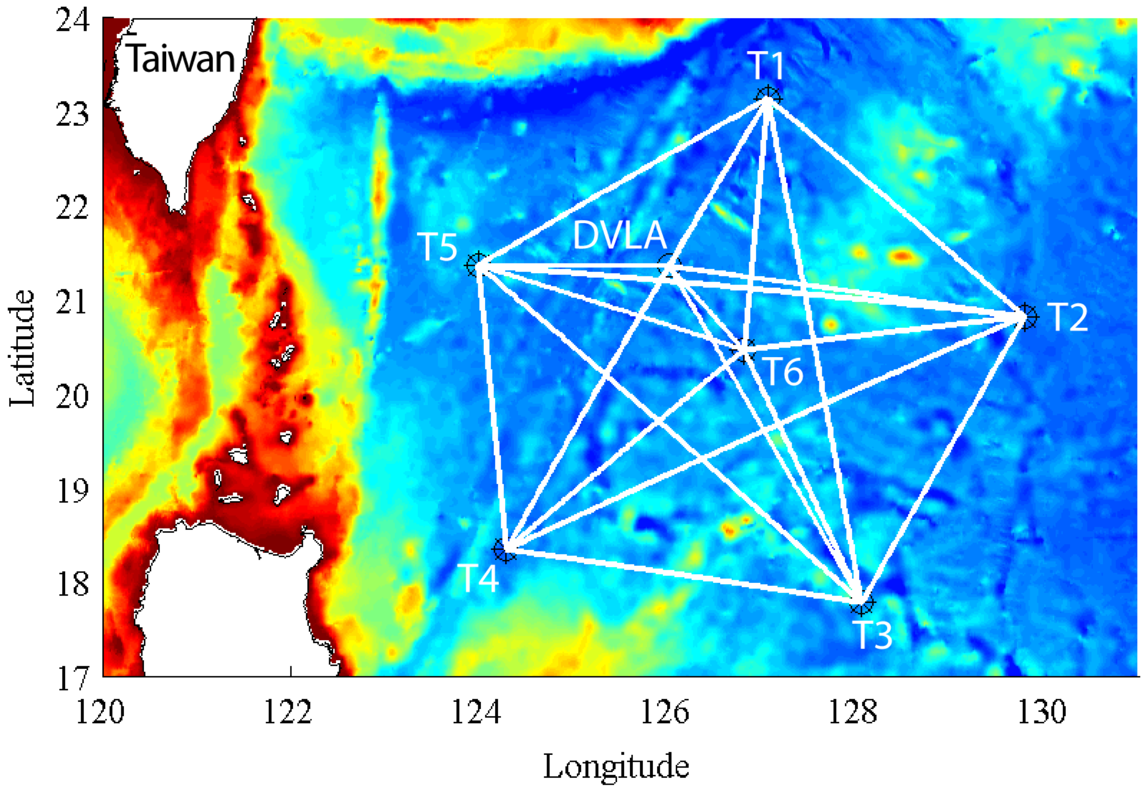

Figure 1. Overall mooring geometry of the 2010–2011 Philippine Sea Experiment, consisting of five 250-Hz acoustic transceivers arranged in a pentagon with a sixth transceiver in the center (T1, T2, … T6) and a new DVLA receiver. The array radius is approximately 330 km.

A full water-column spanning DVLA consisting of five 1000-m subarrays and 150 Hydrophone Modules was deployed within a six-element ocean acoustic tomography array for PhilSea10 (Fig. 1). Transmissions from the tomographic sources to the DVLA will be used to study acoustic propagation and scattering in this strongly range-dependent, deep-water region. The tomographic measurements, when combined with satellite, glider, and other in situ measurements and with ocean models, will help characterize the baroclinic and barotropic structure of the rapidly varying environment in the northern Philippine Sea, providing an eddy-resolving, 4-D sound-speed field for use in making acoustic predictions. Following deployment of the moorings, coordinated, ship-based transmissions to the DVLA were made by J. Mercer (APL-UW) during May 2010 and by A. Baggeroer (MIT) and K. Heaney (OASIS) during July 2010. B. Howe (U. Hawaii) will deploy Acoustic Seagliders in the interior of the array during November 2010. As part of a recently funded augmentation to PhilSea10, following recovery of the DVLA during April 2011, a deep DVLA consisting of one 1000-m subarray located immediately above the seafloor will be deployed in the same location. On a subsequent cruise during May 2011, R. Stephen (WHOI) will deploy six Ocean Bottom Seismometers (OBS) around the deep DVLA and transmit to the OBS and DVLA with a ship-suspended source.

WORK COMPLETED

2009 NPAL Philippine Sea Pilot Study/Engineering Test (PhilSea09). Analysis of PhilSea09 data continued throughout FY10. Our efforts included processing and analysis of the 225–325 Hz swept-frequency source transmissions recorded on the DVLA, analyses of the omnidirectional and directional properties of the ambient noise recorded on the DVLA, calibration of the precision thermistors in the 60 Hydrophone Modueles deployed during PhilSea09, and analysis of the resulting temperature data.

The ray paths associated with the time fronts in the 225–325 Hz receptions have been identified and tracking of the time series for each of the time fronts is nearly complete. Once the time series of travel times are available, the fluctuations in the resolved ray arrivals will be characterized, including the vertical and temporal coherences. Swept-frequency transmissions made every five minutes over periods of up to 72 hours during PhilSea09 will allow the long-timescale temporal fluctuations in the signals to be quantified. Earlier NPAL experiments have not included transmissions at such high repetition rates.

2010–2011 NPAL Philippine Sea Experiment (PhilSea10). Following completion of PhilSea09, engineering efforts focused on the acquisition, construction, preparation, and testing of the acoustic transceivers, DVLA components (D-STARs and Hydrophone Modules), and other equipment needed for PhilSea10, culminating in the mooring deployment cruise on the *R/V Roger Revelle*. The six tomographic moorings have WRC swept-frequency acoustic sources, with integrated STAR controller and data acquisition systems, at a nominal depth of 1050 m. Five of these sources transmit linear frequency-modulated (LFM) signals with center frequencies of approximately 250 Hz and bandwidths of approximately 100 Hz. One WRC source (T2) transmits at somewhat lower frequencies, with a LFM signal from 140–205 Hz. Each WRC acoustic source includes a STAR controller and data acquisition system to provide precise timing and scheduling for the source transmissions and to record the transmissions from the other WRC sources. Each transceiver has a four-element vertical hydrophone array located above the source. The DVLA has 150 Hydrophone Modules non-uniformly distributed in depth, with smaller separations near the sound-channel axis (20 m) and the surface conjugate depth (40 m). All moorings and associated equipment were successfully deployed during April 2010. Baggeroer and Heaney reported that all six sources were still transmitting during their cruise in July 2010.

Ancillary data collected during the mooring deployment cruise included multibeam bathymetric data on a subset of the acoustic paths and full-ocean-depth Conductivity-Temperature-Depth casts.

Ocean and acoustic modeling. A regional, high-resolution ocean circulation model has been implemented for the northern Philippine Sea, in preparation for a model-based analysis of the area in which the acoustic travel times, together with satellite, glider and other measurements, will be assimilated into the model. The MITgcm has been configured with 50 vertical levels and 1/12° resolution in a domain covering 17–27° N and from the western boundary to 140° E (Fig. 2). It is forced by surface fluxes from NCEP and NOGAPS products, meant to approximate the real forcing as well as possible. Assimilated HYCOM 1/12° output is used for initial and boundary conditions. Sound-speed profiles taken from the model (sampling section shown in Fig. 2) were used to trace rays weekly from early April 2009 to late May 2010. The ray arrival pattern showed variability somewhat similar in magnitude to the observations during PhilSea09, but did not agree even qualitatively. The ray arrivals changed with time, as paths were created and destroyed by ocean changes. For identified tracked rays, ray paths changed by less than 30 m in the upper ocean and by up to 100 m in the deep ocean. Work is underway to allow the integral of sound speed along the ray path to be used as a constraint in the ocean model, in preparation for model-based analysis of the northern Philippine Sea.

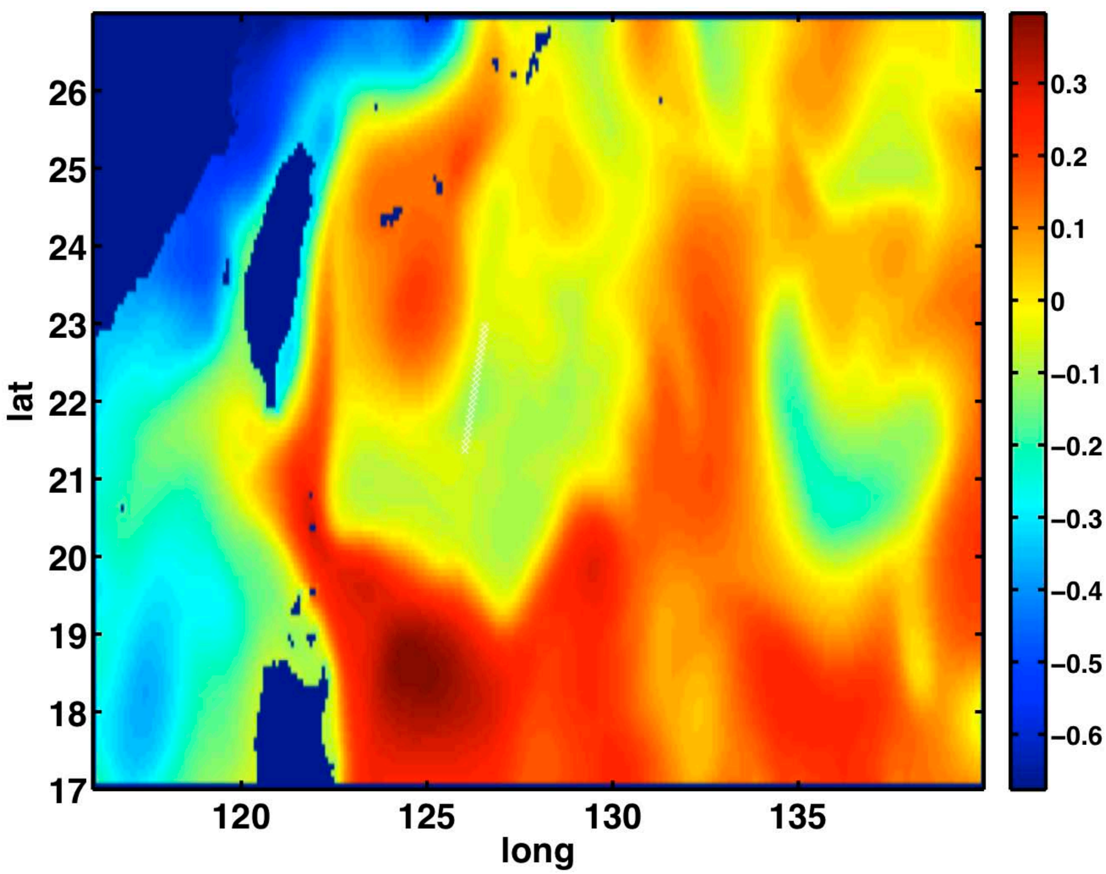

Figure 2. Sea surface height anomaly (m) on 23 April 2009 from a regional implementation of the MITgcm ocean circulation model in the northern Philippine Sea. The sharp zonal gradient in sea-surface height immediately east of Taiwan is associated with the northward-flowing Kuroshio Current. The features in the interior of the northern Philippine Sea are associated with the energetic mesoscale eddy field in the area. The white line at about 22°N, 125°E is the acoustic propagation path from the moored source to the DVLA during PhilSea09.

RESULTS

2009 NPAL Philippine Sea Pilot Study/Engineering Test (PhilSea09). Processing of the LFM transmissions from the 225–325 Hz WRC swept-frequency source on mooring T1 as recorded on the DVLA yielded acoustic time fronts with high signal-to-noise ratios (Fig. 3). As might be expected given the relatively short range (185.126 km), there is little evidence of a highly-scattered near-axial finale in the time fronts that is seen at longer ranges.

The DVLA was also programmed to record during periods when no transmitted signals were present in order to characterize the low-frequency ambient noise field. The *minimum* omnidirectional ambient noise levels during PhilSea09 decrease significantly below the surface conjugate depth at frequencies from 50 to 500 Hz. Similar behavior had previously been observed in the central North Pacific (Gaul et al., 2007). The minimum noise levels presumably correspond to times when there are no nearby ships, wind speeds are low, and surface conditions are calm, so that there is little locally generated noise.

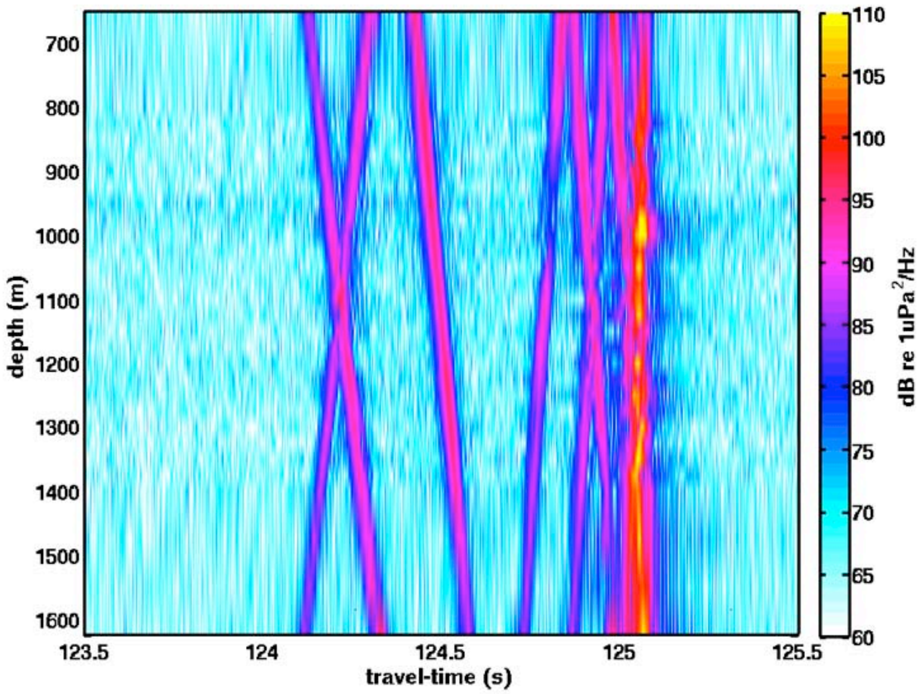

Figure 3. Acoustic time front on the DVLA subarray spanning the sound-channel axis for a transmission from the acoustic source on mooring T1, at a range of 185.126 km, during PhilSea09. The recording was made on 5 April 2009 at 18:02:00 UTC.

In addition, the DVLA allowed the angular distribution of the ambient noise to be determined, both at the sound-channel axis and below the surface conjugate depth (Fig. 4). The near-axial subarray had 25 hydrophones spaced 25 m apart ($\lambda/2$ at 30 Hz), and the deep subarray had 20 hydrophones spaced 5 m apart ($\lambda/2$ at 150 Hz). As a result, the vertical resolutions differ for the two depths. In an attempt to roughly equalize the angular resolutions of the arrays, Fig. 4 shows the vertical noise structure at 50 Hz for the upper array (3° angular resolution) and at 150 Hz for the lower array (6° angular resolution). The vertical distribution of the ambient noise at the upper array is symmetric about the horizontal and falls off quickly above ±15°, similar to the behavior seen in comparable measurements at other locations. The vertical noise distribution at the lower array is asymmetric about the horizontal and differs from that at the sound-channel axis. The different structures cannot be explained by differences in array angular resolution alone. To the best of our knowledge, the vertical structure of the ambient noise field below the surface conjugate depth has not previously been reported.

IMPACT/APPLICATIONS

This research has the potential to affect the design of deep-water acoustic systems, whether for sonar, acoustic communications, acoustic navigation, or acoustic remote sensing of the ocean interior. The data indicate that existing systems do not begin to exploit the ultimate limits to acoustic coherence at long range in the ocean.

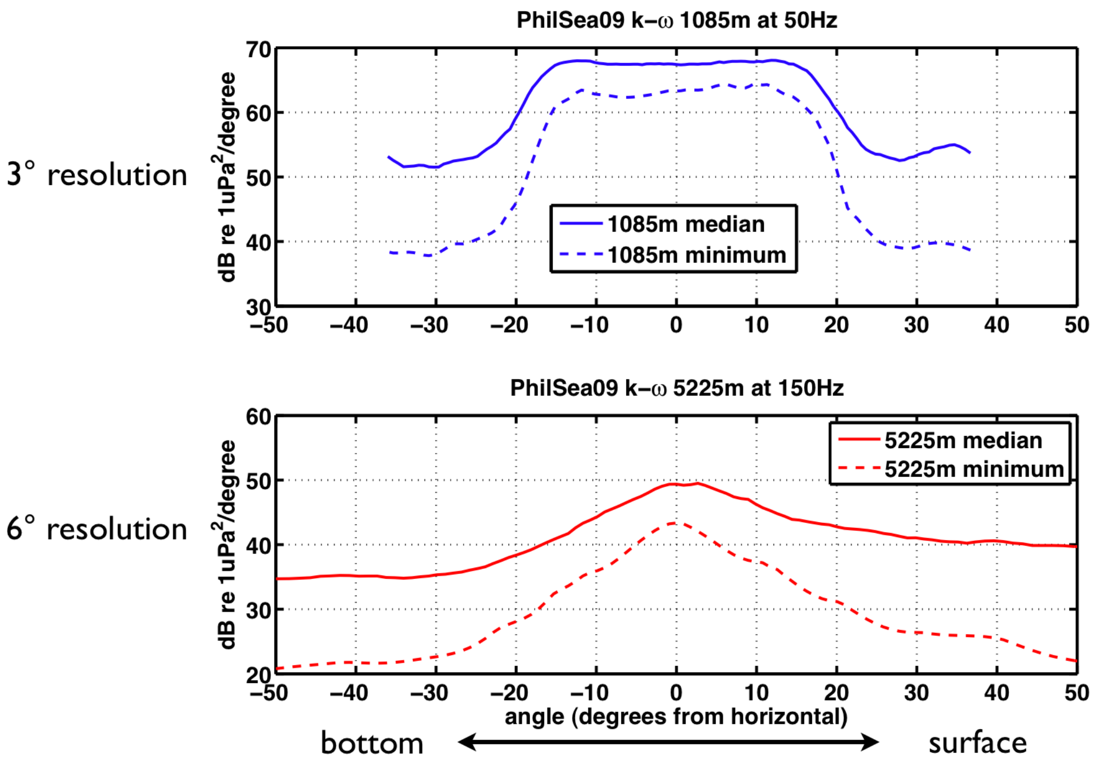

Figure 4. Vertical ambient noise distributions at 1085 m depth (near the sound channel axis) at 50 Hz and at 5225 m depth (below the surface conjugate depth) at 150 Hz. The median and minimum noise levels over the approximately one-month duration of PhilSea09 are shown.

RELATED PROJECTS

A large number of investigators and their students are currently involved in research related to the NPAL project, including R. Andrew (APL-UW), A. Baggeroer (MIT), M. Brown (UMiami), T. Chandrayadula (NPS), J. Colosi (NPS), B. Dushaw (APL-UW), G. D'Spain (SIO), K. Heaney (OASIS), F. Henyey (APL-UW), B. Howe (Univ. Hawaii), J. Mercer (APL-UW), V. Ostachev (NOAA/ETL), B. Powell (Univ. Hawaii), I. Rypina (WHOI), R. Stephen (WHOI), I. Udovydchenkov (WHOI), L. Van Uffelen (SIO), A. Voronovich (NOAA/ETL), K. Wage (George Mason Univ.), and M. Wolfson (APL-UW).

REFERENCES

Gaul, R. D., D. P. Knobles, J. A. Shooter, and A. F. Wittenborn (2007), Ambient noise analysis of deep-ocean measurements in the Northeast Pacific, *IEEE J. Ocean. Eng.*, **32**(2), 497–512.

Worcester, P. F., S. Carey, M. A. Dzieciuch, L. L. Green, D. Horwitt, J. C. Lemire, and M. Norenberg (2009), Distributed Vertical Line Array (DVLA) acoustic receiver, in *Proc. 3rd International Conference on Underwater Acoustic Measurements: Technologies and Results*, edited by J. S. Papadakis and L. Bjørnø, pp. 113–118, Foundation for Research and Technology Hellas (FORTH), Nafplion, Greece.

PUBLICATIONS

Dushaw, B. D., P. F. Worcester, and M. A. Dzieciuch (2010), On the predictability of mode-1 internal tides, *Deep-Sea Research Part I***.** [submitted, refereed]

Dushaw, B. D., W. W. L. Au, A. Beszczynska-Möller, R. E. Brainard, B. D. Cornuelle, T. F. Duda, M. A. Dzieciuch, A. M. G. Forbes, L. Freitag, J.-C. Gascard, A. N. Gavrilov, J. Gould, B. M. Howe, S. R. Jayne, O. M. Johannessen, J. F. Lynch, D. Martin, D. Menemenlis, P. N. Mikhalevsky, J. H. Miller, S. E. Moore, W. H. Munk, J. Nystuen, R. I. Odom, J. A. Orcutt, T. Rossby, H. Sagen, S. Sandven, J. Simmen, E. Skarsoulis, B. Southall, K. M. Stafford, R. Stephen, K. J. Vigness-Raposa, S. Vinogradov, K. B. Wong, P. F. Worcester, and C. Wunsch (2010), A global ocean acoustic observing network, in *Proceedings of OceanObs'09: Sustained Ocean Observations and Information for Society (Vol. 2),* Venice, Italy, 21–25 September 2009, Hall, J., Harrison, D. E. and Stammer, D., Eds., ESA Publication WPP-306. [in press, refereed]

Farrell, W. E. and W. H. Munk (2010), Booms and busts in the deep, *J. Phys. Oceanogr.*, **40,** 2159–2169. [published, refereed]

Munk, W. H. (2009), An inconvenient sea-truth: Spread, steepness and skewness of surface slopes, *Annual Review of Marine Science*, **1,** 377–415. [published, refereed]

Rainville, L., T. M. S. Johnston, G. S. Carter, M. A. Merrifield, R. Pinkel, P. F. Worcester, and B. D. Dushaw (2010), Interference pattern and propagation of the M_2 internal tide south of the Hawaiian Ridge, *J. Phys. Oceanogr.*, **40**(2), 311–325. [published, refereed]

Sagen, H., S. Sandven, A. Beszczynska-Moeller, O. Boebel, T. F. Duda , L. Freitag, J. C. Gascard, A. N. Gavrilov, C. M. Lee, D. K. Mellinger, P. N. Mikhalevsky, S. E. Moore, A. K. Morozov, M. Rixen, E. Skarsoulis, K. M. Stafford, E. Tveit, and P. F. Worcester (2010), Acoustic technologies for observing the interior of the Arctic Ocean, *Proceedings of OceanObs'09: Sustained Ocean Observations and Information for Society (Annex)*, Venice, Italy, 21–25 September 2009, J. Hall, D. E. Harrison, and D. Stammer, Eds., ESA Publication WPP-306. **[**in press, non-refereed]

Skarsoulis, E., G. Piperakis, M. Kalogerakis, H. Sagen, S. A. Haugen, A. Beszczynska-Möller, and P. F. Worcester (2010), Tomographic inversions from the Fram Strait 2008–9 experiment, in *Proceedings of ECUA 2010, European Conference on Underwater Acoustics*, Istanbul, Turkey, 5–9 July 2010. [in press, non-refereed]

Van Uffelen, L. J., P. F. Worcester, M. A. Dzieciuch, D. L. Rudnick, and J. A. Colosi (2010), Effects of upper ocean sound-speed structure on deep acoustic shadow-zone arrivals at 500- and 1000-km range, *J. Acoust. Soc. Am.*, **127**(4), 2169–2181. [published, refereed]

Worcester, P. F. and B. D. Dushaw (2010), A decade of acoustic thermometry in the North Pacific, *Proceedings of OceanObs'09: Sustained Ocean Observations and Information for Society (Annex)*, Venice, Italy, 21–25 September 2009, J. Hall, D. E. Harrison, and D. Stammer, Eds., ESA Publication WPP-306. **[**in press, non-refereed]

HONORS/AWARDS/PRIZES

Walter Munk, Crafoord Prize in Geosciences 2010 (Royal Swedish Academy of Sciences), "for his pioneering and fundamental contributions to our understanding of ocean circulation, tides and waves, and their role in the Earth´s dynamics."

Walter Munk, Österreichisches Ehrenzeichen für Wissenschaft und Kunst (The Austrian Decoration for Science and Art) 2010 (The National Council of the Republic of Austria)