

North Pacific Acoustic Laboratory

Robert C. Spindel

Applied Physics Laboratory, College of Ocean and Fishery Sciences

University of Washington

Seattle, WA 98105-6698

phone: (206) 543-1310 fax: (206) 543-3521 email spindel@apl.washington.edu

Awards: N00014-97-1-0259 and N00014-97-1-0623 (AASERT)

Peter F. Worcester

Scripps Institution of Oceanography, University of California at San Diego

La Jolla, CA 92093-0225

phone: (858) 534-4688 fax: (858) 534-6251 email pworchester@ucsd.edu

Award: N00014-97-1-0258

<http://atoc.ucsd.edu>

LONG-TERM GOALS

The ultimate limits of long-range sonar are imposed by ocean variability and the ambient sound field. Scattering from internal waves limits the temporal and spatial coherence of the received signal. Low frequency noise is dominated by shipping and ultimately, by wave-breaking processes. The resulting “granularity” of the noise field can be exploited for detection and localization purposes. Our ultimate objective is to understand the fundamental limits to signal processing imposed by these ocean processes, to enable advanced signal processing techniques, including matched field processing and other adaptive array processing methods, to capitalize on the three-dimensional character of the sound and noise fields.

OBJECTIVES

The objective of this research is to understand the basic physics of low-frequency, broadband propagation and the effects of environmental variability on signal stability and coherence. In particular, it focuses on 3-D wave front coherence (horizontal, vertical, and temporal), on the details of signal energy redistribution through mode scattering, on signal and noise variability on ocean-basin scales, and on environmental processes such as internal waves that most affect long-range coherence.

APPROACH

The North Pacific Acoustic Laboratory (NPAL) program takes advantage of the acoustic network installed by the Acoustic Thermometry of Ocean Climate (ATOC) program, as well as instrumentation developed for that network and data previously obtained using it. Existing network components include two low-frequency (75 Hz), broadband acoustic sources installed on Pioneer Seamount off central California and north of Kauai, 14 U. S. Navy SOSUS arrays instrumented to receive the source transmissions, two autonomous vertical line arrays (AVLAs) installed near Hawaii and Kiritimati Island from November-December 1995 to August-September 1996, and an AVLA installed at OWS Papa from September 1998 to June 1999 (with NOPP funding). NPAL augmented the ATOC network

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE 30 SEP 1999		2. REPORT TYPE		3. DATES COVERED 00-00-1999 to 00-00-1999	
4. TITLE AND SUBTITLE North Pacific Acoustic Laboratory				5a. CONTRACT NUMBER	
				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) University of Washington, Applied Physics Laboratory, 1013 NE 40th Street, Seattle, WA, 98105				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					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a REPORT unclassified	b ABSTRACT unclassified	c THIS PAGE unclassified			

with a sparse billboard array installed at Sur Ridge off Point Sur, California, during July 1998 to receive the 3900-km-range transmissions from the Kauai source. The billboard array was fabricated by reconfiguring largely existing AVLA components developed for ATOC into four 700-m-long, 20-element vertical arrays and one 1400-m-long, 40-element vertical array, to allow measurement of the full 3-D signal wave front. The moorings were installed in a 3600-m line transverse to the acoustic path from the 75-Hz source north of Kauai.. The data previously collected by ATOC will be combined with data collected using the billboard array and the U. S. Navy SOSUS receivers:

- To study the temporal, vertical, and horizontal coherence of long-range, low-frequency resolved rays and modes and to compare the measurements to predictions;
- To study scattering/diffusion effects (mode scattering, steep ray scattering);
- To study horizontal multipathing;
- To study the effects of bottom interaction at the source;
- To measure directional ambient sound spectra and noise granularity;
- To improve basin-scale ocean nowcasts via assimilation of average temperature derived from acoustic travel-time data and of other data types into models; and
- To determine environmental limitations on signal processing.

CTD/XBT measurements were made between the Kauai source and the billboard array shortly after the billboard array was deployed and shortly before it was recovered to provide direct measurements of the sound speed field on the acoustic path. In addition, moored measurements were made at two locations on the acoustic path during most of the time that acoustic data were being collected.

This research is a joint effort involving B. Cornuelle, M. Dzieciuch, W. Munk, and P. Worcester at the Scripps Institution of Oceanography (SIO) and B. Dushaw, B. Howe, J. Mercer, and R. Spindel at the Applied Physics Laboratory (APL) of the University of Washington. We are collaborating in the analyses with a number of other investigators, including A. Baggeroer (MIT), J. Colosi (WHOI), and S. Flatté (UCSC).

WORK COMPLETED

Operation and maintenance of the Pioneer Seamount and Kauai acoustic sources, as well as the SOSUS receivers, continued during FY99. Pioneer Seamount source operations continued through 10 December 1998, at which time they were terminated in accord with various permit requirements. After failure of an attempt to recover the source during August 1999, recovery of the source and power cable is now scheduled for August 2000. Transmissions from the Kauai source continued through 3 October 1999, at which time they were also terminated in accord with various permit requirements. We are currently seeking new permits to allow continued operation of the Kauai source for an additional five years.

All five AVLA receivers comprising the NPAL billboard array were successfully recovered during August 1999. All six AVATOC data acquisition systems (two AVATOCs are required for the 40-element AVLA) were running upon recovery. We successfully obtained post-deployment time checks on all instruments. All eight acoustic transponders deployed to track the AVLA positions during their year-long deployment were also recovered. We are currently performing post-cruise calibrations of the

instrumentation, transferring the recorded data to a mass-store system, and beginning processing of the data.

Prior to recovery of the NPAL array, an environmental data cruise (IW99) was conducted during June-July 1999 along the path from the Kauai source to the NPAL receiving array. During the transect 13 CTD casts to the ocean bottom and 11 additional shallow CTD casts to 1500 m depth were made. XBTs with maximum depth of 760 m were deployed every 30 km, and 5 high-resolution XBT sections were performed with a maximum depth of 460 m. Each high-resolution section had XBT drops every 1.5 km for a 120 km range. Underway 150-kHz narrowband ADCP measurements were also made to observe the horizontal structure of the velocity field. Seabeam ocean depth data were collected along the acoustic path, and a two-pass survey (north and south tracks) was conducted from 25 km offshore of the billboard array to the SOSUS station. Seabeam data were also collected on the Pioneer Seamount to Hawaii AVLA path from about 20 km offshore to the Pioneer source. Finally, two moorings, each with upward-looking ADCPs, 6 temperature/conductivity/depth sensors, and 20 temperature sensors in the upper part of the water column, were successfully recovered. The moorings were installed during August 1998.

RESULTS

Although processing and analysis of the data collected on the NPAL billboard array are just beginning, continuing analysis of long-range acoustic propagation data collected as part of the ATOC project led to a number of publications during the past year.

Internal wave scattering. Analysis of propagation data from the ATOC Acoustic Engineering Test has shown that the early part of the arrival pattern at 75-Hz and 3250-km range consists of ray-like wave fronts that are resolvable, identifiable, and stable (Worcester *et al.*, 1999). The later part of the arrival pattern, containing energy that has propagated near the sound-channel axis, does not contain ray-like arrivals, due to scattering from internal-wave-induced sound-speed fluctuations. This result is not unexpected, given the earlier results from the SLICE89 propagation experiment at 250-Hz and 1000-km range. Detailed analysis of the raylike arrivals, however, yields the surprising result that the propagation is near the border between the unsaturated and partially saturated regimes, rather than in the saturated regime as predicted using traditional Λ , Φ methods (Colosi *et al.*, 1999a,b). Calculations of the diffraction parameter Λ appear to be sensitive to the broadband nature of the transmitted pulse.

Ocean temperature field estimates. Analysis of the vertical receiving array data from the ATOC Acoustic Engineering Test has also shown that the change over six days in range-averaged temperature can be estimated with an uncertainty of about 0.006°C (Worcester *et al.*, 1999). The vertical resolution is limited, however, even with a near-axial source and vertical receiving array, because of internal-wave-induced scattering of near-axial energy. The data also suggest that the currently accepted equation used to compute sound-speed from temperature and salinity requires refinement at high pressures.

Analysis of transmissions from the Pioneer Seamount source to the SOSUS arrays has shown that at 5-Mm range, travel time variations at tidal frequencies (about 50 ms peak-to-peak) agree well with predicted values, providing verification of the acoustic measurements as well as the tidal model (Dushaw *et al.*, 1999a). Ray-like receptions at our deepest receiver arrays, however, are still not

explained by present ocean models and propagation theories. On the longest and northernmost acoustic paths, the time series of resolved ray travel times show an annual cycle peak-to-peak variation of about 1 s and other fluctuations caused by natural oceanic variability. An annual cycle is not evident in travel times from shorter acoustic paths in the eastern Pacific. The low-pass-filtered travel times are estimated to an accuracy of about 10 ms. In order to linearize the subsequent inversions, the dominant annual cycle was removed by referencing the measured travel times to the Levitus monthly ocean atlas (Dushaw, 1999). This linearization results in a more accurate time series of range- and depth-averaged temperatures. Standard error bars for the 0 to 1000 m depth average are typically $\pm 0.012^{\circ}\text{C}$, while annual peak-to-peak temperature variation is about 0.4°C for this range- and depth-average temperature.

Finally, time series of temperature deduced from long-range acoustic transmissions in the Northeast Pacific Ocean performed as part of the ATOC project have been compared with other available data types (ATOC Consortium, 1998; Dushaw *et al.*, 1999b). In the upper 100 m, the annual cycle of heat content derived from satellite altimetry is considerably larger than that found from the acoustic data, Levitus climatology, and monthly maps of ocean temperature derived from XBTs of opportunity. Comparisons with the 12-year time series of temperature derived from the Hawaiian Ocean Timeseries (HOT) data set (monthly CTD casts) highlight the problem of mesoscale noise in sampling at a single point. To our surprise, thermal variability at 100-day time scales is observed in the acoustic data obtained between Hawaii and California from the Kauai source with no corresponding variability in the TOPEX data (and certainly not in the heavily smoothed XBT maps). This result indicates significant subsurface salinity-compensated temperature changes in the vicinity of Hawaii. Acoustic thermometry is complementary to altimetry and hydrography.

Ambient sound. Long-term ambient sound measurements made using single SOSUS hydrophones have provided estimates of the variability of ambient noise intensity at locations distributed across the North Pacific Ocean (Curtis *et al.*, 1999). Data on the probability density function of noise intensity is one of the fundamental pieces of information needed for the design of acoustic systems. The most distinctive feature in many of the long-term spectrograms is a blue/fin whale signature at 17-22 Hz with an annual cycle of 10 dB peak-to-peak. Noise in the 200–400-Hz band is found to be highly correlated with wind (not unexpected), and also, in some cases, with the noise in the 10-15-Hz band. An explanation for the latter observation is being sought.

IMPACT/APPLICATIONS

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

Estimates of basin-wide sound speed (temperature) fields obtained by the combination of acoustic, altimetric, and other data types with ocean general circulation models have the potential both to improve our ability to make the acoustic predictions needed for matched field and other sophisticated signal processing techniques and to improve our understanding of gyre-scale ocean variability on seasonal and longer time scales.

TRANSITIONS

None.

RELATED PROJECTS

(i) NPAL exploits the acoustic network, instrumentation, and data of the Acoustic Thermometry of Ocean Climate (ATOC) program (PI's: P. Worcester and R. Spindel, SERDP/DARPA).

(ii) NPAL also exploits data obtained as part of the dual-frequency Alternate Source Test performed for the "Ocean Acoustic Observatories" program to improve our understanding of the frequency dependence of horizontal and vertical coherence (PI's: Worcester, Mercer, and Spindel, ONR).

(iii) A consortium led by R. Spindel was funded by the National Ocean Partnership Program to conduct research closely related to NPAL in response to a proposal entitled "Monitoring the North Pacific for Improved Ocean, Weather, and Climate Forecasts." This program supported deployment of an acoustic receiver coupled to a nearby surface mooring via an acoustic modem in the central North Pacific at OWS Papa to record transmissions from the Pioneer Seamount and Kauai sources. A simple tomographic acoustic receiver (STAR) is under development to permit a broader application of acoustic tomographic methods by the oceanographic community.

(iv) An integral part of NPAL involves studying the possible effects of low-frequency sound on marine mammals, for which support was provided to C. Clark and W. Munk in response to a proposal entitled "Potential Effects of Low Frequency Sound on Distribution and Behavior of Marine Mammals" (SERDP/ONR). The Pioneer Seamount and Kauai sources were only permitted to transmit in conjunction with marine mammal research.

(v) A consortium led by J. Orcutt was funded by the National Ocean Partnership Program to conduct research partially in support of NPAL objectives. The grant, entitled "Ocean Acoustic Observatory Federation," provides for limited maintenance and improvements to the San Nicholas Island and Barber's Point SOSUS receivers. This grant also supported deployment of L-CHEAPO acoustic data loggers near the Kauai source as part of the Marine Mammal Research Program, enabling transmissions to continue until October 1999. Finally, this effort supported deployment of a 250-Hz acoustic source on Hoke Seamount off California for acoustic remote sensing of the California Current and the study of acoustic propagation through it.

PUBLICATIONS

ATOC Consortium (A. B. Baggeroer, T. G. Birdsall, C. Clark, J. A. Colosi, B. D. Cornuelle, D. Costa, B. D. Dushaw, M. Dzieciuch, A. M. G. Forbes, C. Hill, B. M. Howe, J. Marshall, D. Menemenlis, J. A. Mercer, K. Metzger, W. Munk, R. C. Spindel, D. Stammer, P. F. Worcester, and C. Wunsch), "Ocean climate change: Comparison of acoustic tomography, satellite altimetry, and modeling," *Science*, **281**, 1327–1332 (1998).

Colosi, J. A., and the ATOC Group (A. B. Baggeroer, T. G. Birdsall, C. Clark, J. A. Colosi, B. D. Cornuelle, D. Costa, B. D. Dushaw, M. A. Dzieciuch, A. M. G. Forbes, B. M. Howe, D. Menemenlis,

J. A. Mercer, K. Metzger, W. H. Munk, R. C. Spindel, P. F. Worcester, and C. Wunsch), "A review of recent results on ocean acoustic wave propagation in random media: Basin scales," *I.E.E.E. J. Oceanic Eng.*, **24**, 138–155 (1999a).

Colosi, J. A., E. K. Scheer, S. M. Flatté, B. D. Cornuelle, M. A. Dzieciuch, W. H. Munk, P. F. Worcester, B. M. Howe, J. A. Mercer, R. C. Spindel, K. Metzger, T. G. Birdsall, and A. B. Baggeroer, "Comparisons of measured and predicted acoustic fluctuations for a 3250-km propagation experiment in the eastern North Pacific Ocean," *J. Acoust. Soc. Am.*, **105**, 3202–3218 (1999b).

Curtis, K. R., B. M. Howe, and J. A. Mercer, "Low-frequency ambient sound in the North Pacific: Long time series observations," *J. Acoust. Soc. Am.* (in press, 1999).

Dushaw, B. D., "Inversion of multimegameter range acoustic data for ocean temperature," *IEEE J. Oceanic Eng.*, **24**, 215–223 (1999).

Dushaw, B. D., B. M. Howe, J. A. Mercer, R. C. Spindel, and the ATOC Group (A. B. Baggeroer, T. G. Birdsall, C. Clark, J. A. Colosi, B. D. Cornuelle, D. Costa, B. D. Dushaw, M. A. Dzieciuch, A. M. G. Forbes, B. M. Howe, D. Menemenlis, J. A. Mercer, K. Metzger, W. H. Munk, R. C. Spindel, P. F. Worcester, C. Wunsch), "Multimegameter-range acoustic data obtained by bottom-mounted hydrophone arrays for measurement of ocean temperature," *I.E.E.E. J. Oceanic Eng.*, **24**, 202–214 (1999a).

Dushaw, B. D., and the ATOC Group (A. B. Baggeroer, T. G. Birdsall, C. Clark, J. A. Colosi, B. D. Cornuelle, D. Costa, B. D. Dushaw, M. A. Dzieciuch, A. M. G. Forbes, B. M. Howe, D. Menemenlis, J. A. Mercer, K. Metzger, W. H. Munk, R. C. Spindel, P. F. Worcester, C. Wunsch), "A comparison of acoustic thermometry, XBT, TOPEX, and HOT observations of ocean temperature in the Northeast Pacific Ocean," Proc. International Conference on the Ocean Observing System for Climate, St. Raphael, France, 18–22 October 1999 (in press, 1999b).

Livingston, E.S. , A. Tolstoy, and P. F. Worcester, "Guest editorial," Special Issue on Long-range Propagation, *I.E.E.E. J. Oceanic Eng.*, **24**, 133–137 (1999).

Worcester, P. F., B. D. Cornuelle, M. A. Dzieciuch, W. H. Munk, B. M. Howe, J. A. Mercer, R. C. Spindel, J. A. Colosi, K. Metzger, T. G. Birdsall, and A. B. Baggeroer, "A test of basin-scale acoustic thermometry using a large-aperture vertical array at 3250-km range in the eastern North Pacific Ocean," *J. Acoust. Soc. Am.*, **105**, 3185–3201 (1999).