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

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 pworcester@ucsd.edu

Award Number: N00014-97-1-0258 and : N00014-97-1-0259
http://atoc.ucsd.edu, http://aogdb.ucsd.edu/npal

Thrust Category: Long-Range Propagation

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

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.

Environmental measurements include two CTD/XBT sections between the Kauai source and the 2-D array, one made shortly after the 2-D array was deployed and the second made shortly before it was recovered, to provide direct measurements of the sound speed field and its spatial variability from climatological scales down to the scales of internal gravity waves on the acoustic path. In addition, two environmental moorings were installed between Kauai and the 2-D array, instrumented with temperature, salinity, and velocity sensors, to provide information on the temporal variability of the sound-speed and current fields on the acoustic path.

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

Field Work

Acoustic Source Operations. The Pioneer Seamount source transmitted December 1995 until December 1998. Unsuccessful attempts to recover the source were made during August 1999 and August 2000. Another attempt is tentatively planned for October 2000. The Kauai source began operation in late October 1997, and continued through June 1999, after which the 2-D array was recovered.

2-D Array Operations. The 2-D array was deployed during July 1998 and recovered during August 1999. All five of the VLA's functioned satisfactorily throughout the year. The transmissions from the Kauai source are well above the ambient noise level at the 2-D array.

Environmental Observations. Two CTD/XBT/environmental mooring cruises were conducted (August 1998 and June, 1999). Two environmental moorings were successfully installed on the first and recovered on the second. A Seabeam 2000 system was used to measure bathymetry near the Kauai source, along the acoustic path, and near the 2-D array.

SOSUS Receiver Operations. Acquisition and archiving of acoustic data from the SOSUS arrays continued throughout FY99 and FY00.

Data Analysis

ATOC VLA Data. Worcester *et al.* (1999) presented detailed comparisons between measured and predicted arrival patterns at 3252-km range for 75 Hz transmissions. Colosi *et al.* (1999a and 1999b) presented analyses of travel-time variance, average pulse shape, and the probability distribution function (PDF) of intensity for identifiable time fronts from the same experiment and used a simple model to show that the wave propagation regime is sensitive to the broadband characteristics of the transmitted pulse.

2-D Array Data. Analysis of the 2-D array data following the recovery of the array during August 1999 has focused on the basic processing needed to make the data useful for further analyses:

- Hydrophone positions using a long baseline acoustic positioning systems have been calculated for all VLA's.

- The clock corrections needed to account for the long-term drifts of the system clocks in each of the VLA's have been computed from in situ Rubidium atomic frequency standards.

- Pulse compression and vertical beamforming has been performed for a number of receptions

The 2-D array data are now ready for analyses aimed at studying the signal coherence (horizontal, vertical, and temporal) of resolved rays and modes and at elucidating the properties of the ambient noise field.

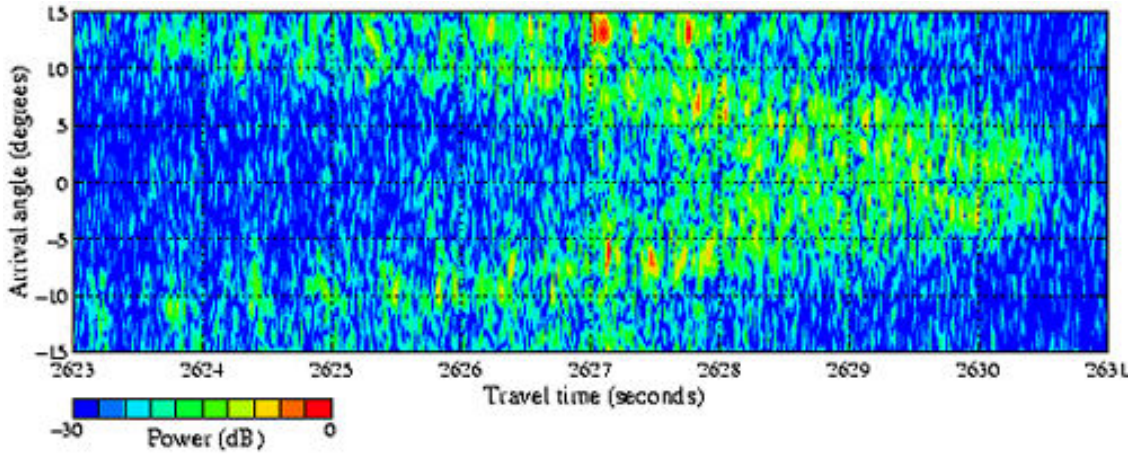

Fig. 1. A transmission from Kauai received on one of the 700m VLA's in the 2-d array at Sur Ridge. High angle arrivals (near 2627 sec.) are believed to be bottom reflections near the receiver.

Environmental Data. Analysis of the environmental data has included:

- Preparation of a preliminary summary of the IW98 cruise data report (CTD, XBT, shipboard ADCP, and bathymetry.
- Preparation of range-dependent sound speed fields suitable for propagation calculations from the CTD and XBT
- Processing the swath bathymetry data
- Calculating internal wave displacement frequency spectra from the moored thermistor data for summer and winter.

SOSUS Receiver Data. Dushaw *et al.* (1999) and Dushaw (1999) presented travel time data obtained on the SOSUS arrays and discussed how the data were used to estimate large-scale average temperatures. These papers presented the analyses underlying an earlier paper in which sea level measurements along the acoustic paths from the TOPEX/POSEIDON altimeter were combined with temperature estimated from the acoustic data and a general circulation model of the ocean (ATOC Consortium, 1998). A paper presenting results from the analysis of ambient sound data was also published in 1999 (Curtis *et al.*, 1999).

NPAL Data Analysis Workshops. The First NPAL Data Analysis Workshop was held in January, 2000, with 26 participants. The goals of were to specify the detailed scientific objectives, the data needs, and the analysis plans for all participants. A summary Workshop report (Worcester, 2000) has been produced. Science issues to be addressed by participants include:

- Signal fluctuations and signal coherence in space and time (Internal wave effects)
- Ambient noise variability and coherence
- Estimation of internal wave properties
- Inference of large-scale temperature structure

- Shadow-zone arrival analysis
- 3-D signal propagation effects and horizontal refraction
- Mean forward problem and the sound speed equation
- Bottom interactions

The Second (NPAL) Data Analysis Workshop is scheduled for October, 2000.

Kauai Source Permitting Effort

The environmental review process required to obtain the permits needed to continue operation for five additional years of the low-frequency sound source previously installed off the north shore of Kauai, Hawaii, for use in ATOC research began in spring 1999. The reuse of the source for the NPAL project would combine (i) a second phase of research on the feasibility and value of large-scale acoustic thermometry, (ii) long-range underwater sound transmission studies; and (iii) marine mammal monitoring and studies. We originally expected the permitting process to be completed by mid-2000, but it is now clear that it will not finish until mid-2001.

RESULTS

The past year was devoted to preparing the array data for analysis. For the 2-d array acoustic data this included correcting for clock errors and hydrophone movement, pulse compression and beamforming. For the environmental data this included processing swath bathymetry, CTD and XBT data, and producing internal wave displacement frequency spectra from the moored thermistor data. The data is now ready for distribution to collaborating investigators (See NPAL Data Analysis Workshop, above.).

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. (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."

(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). In addition, the ambient sound data collected as part of NPAL is being used in the ONR project "Baleen Whale Calls and Seasonal Ambient Noise" (J. Hildebrand, M. McDonald, B. Howe).

(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, and for deployment acoustic data loggers near the Kauai source as part of the Marine Mammal Research Program. This effort also 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.

(vi) An ONR effort led by J. Zittel to improve passive and active performance in shallow seas, Ocean Acoustic Observatory, Phase II, addresses closely related issues.

REFERENCES

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," *Scienc*e, **28**1, 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, recent results on ocean acoustic wave propagation in random media: Basin scales," *IEEE J. Oceanic En*g., **2**4, 138–155 (1999).

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 (1999).

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.*, **106**, 3189-3200 (1999).

Dushaw, B. D., “Inversion of multimegameter range acoustic data for ocean temperature,” *IEEE J. Oceanic Eng*., **2**4, 215–223 (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,” *IEEE J. Oceanic En*g., **2**4, 202–214 (1999).

Livingston, E.S. , A. Tolstoy, and P. F. Worcester, “Guest editorial,” Special Issue on Long-range Propagation, *IEEE J. Oceanic En*g., **2**4, 133–137 (1999).

Mercer, J., Dushaw, B. D., Howe, B. M., and R. C. Spindel, “Acoustic monitoring in the Northeast Pacific at megameter ranges (U),” U.S. Navy J. Underwater Acoustics (U), **49**, 4, 781-788, Oct., 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*., **10**5, 3185–3201 (1999).

Worcester, P. F. (1998). *Report on the Office of Naval Research Long-Range Propagation Workshop, 3–4 March 1997*, Scripps Institution of Oceanography Reference Series 98-8, University of California, San Diego, La Jolla, CA (1998).

Worcester, P. F. ,“Report on the First North Pacific Acoustic Laboratory (NPAL) Data Analysis Workshop,” Borrego Springs, CA, January 6-7, 2000, 20 pp (2000).