APL - North Pacific Acoustic Laboratory

PI James A. Mercer
Applied Physics Laboratory, University of Washington
1013 NE 40th Street, Seattle, WA 98105
phone: (206) 543-1361 fax: (206) 543-6785 email: mercer@apl.washington.edu

CO-PI Rex Andrew
Applied Physics Laboratory, University of Washington
1013 NE 40th Street, Seattle, WA 98105
phone: (206) 543-1250 fax: (206) 543-6785 email: rex@apl.washington.edu

CO-PI Bruce Howe
Applied Physics Laboratory, University of Washington
1013 NE 40th Street, Seattle, WA 98105
phone: (206) 543-1250 fax: (206) 543-9141 email: howe@apl.washington.edu

Grant Number: N00014-03-1-0181
http://npal.apl.washington.edu
http://npal.ucsd.edu

LONG-TERM GOALS

The ultimate limitations to the performance of long-range sonar are due to ocean sound speed perturbations and the characteristics of the ambient acoustic noise field. Scattering and diffraction resulting from internal waves and other ocean processes limit the temporal and spatial coherence of the received signal, while the ambient noise field is in direct competition with the received signal. Research conducted in the North Pacific Acoustic Laboratory (NPAL) program at the Applied Physics Laboratory (APL-UW) and the Scripps Institution of Oceanography (SIO) is directed toward a complete understanding of the basic physics of low-frequency, long-range, broadband acoustic propagation, the effects of environmental variability on signal stability and coherence, and the fundamental limits to signal processing at long-range imposed by ocean processes. The long-term goal of NPAL is to optimize advanced signal processing techniques, including matched field processing and adaptive array processing methods, based upon knowledge about the multi-dimensional character of the sound and noise fields and their impact on long-range ocean acoustic transmissions.

OBJECTIVES

The scientific objectives of the North Pacific Acoustic Laboratory are:

1. To study the spatial and temporal coherence of long-range, low-frequency resolved rays and modes and their range dependency.

2. To explore the range and frequency dependence of the higher order statistics of resolved ray and mode arrivals and of the highly scattered finale observed in previous experiments.

Report Documentation Page		*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE **30 SEP 2006**	2. REPORT TYPE	3. DATES COVERED **00-00-2006 to 00-00-2006**
4. TITLE AND SUBTITLE **APL - 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 N.E. 40th St.,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**	**Same as Report (SAR)**	**13**	

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

3. To understand the un-predicted large amount of acoustic energy scattered into the geometric shadow zone beneath deep caustics (shadow-zone arrivals) as measured with the NPAL network of bottom-mounted SOSUS receivers, the LOAPEX vertical line array, and ocean bottom seismometers.

4. To define the characteristics and determine the relative causes of ambient noise on ocean basin scales.

5. To elucidate the roles of internal waves, ocean spice, and internal tides in causing fluctuations in acoustic receptions.

6. To improve basin-scale ocean sound-speed predictions via assimilation of acoustic travel-time and other data into numerical ocean-dynamic models.

APPROACH

NPAL employs a combination of experimental measurements, data analysis, and simulations to address the objectives outlined above. These activities are funneled through two primary avenues. The NPAL network, operated and maintained by APL-UW, provides an actual laboratory for real-time propagation measurements at a selection of basin-scale distances, the capability to test various transmission signals, and ambient noise measurements at various locations in the Pacific Ocean. The network consists of an acoustic source near the Island of Kauai, HI controlled from Seattle, WA, the legacy SOSUS hydrophone receiver network in the Pacific Ocean, and a data processing and archive center at the Applied Physics Laboratory. Figure 1 illustrates the NPAL network.

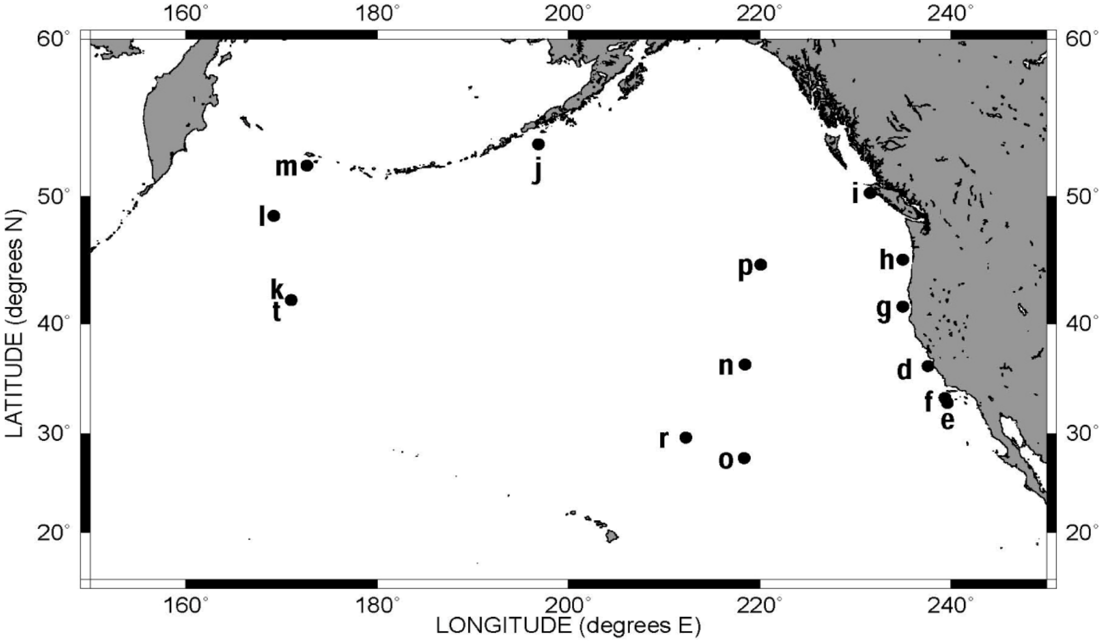


Figure 1. The NPAL network. A transducer near the Island of Kauai (near bottom of Figure) transmits periodically to receivers indicated by black dots and letters. The receivers also collect ambient noise spectral data. The entire network is controlled and monitored from APL-UW.

The second avenue includes highly focused, relatively short-term experiments.

The most recent NPAL experimental effort actually consisted of three coordinated experiments. APL-UW conducted the Long-range Ocean Acoustic Propagation EXperiment (LOAPEX), SIO was responsible for the SPICE04 experiment, and MIT and OASIS performed the Basin Acoustic Seamount EXperiment (BASSEX).

The approach of NPAL also includes collaboration with a number of researchers from several other institutions who provide further analysis of NPAL experimental data and theoretical development. The collaboration is enhanced by holding yearly NPAL conferences usually near Seattle or San Diego.

WORK COMPLETED

The major focus of this year's work has been the processing and preliminary analysis of data from the LOAPEX effort. Figure 2 illustrates the major assets employed during LOAPEX and the experiment geometry.

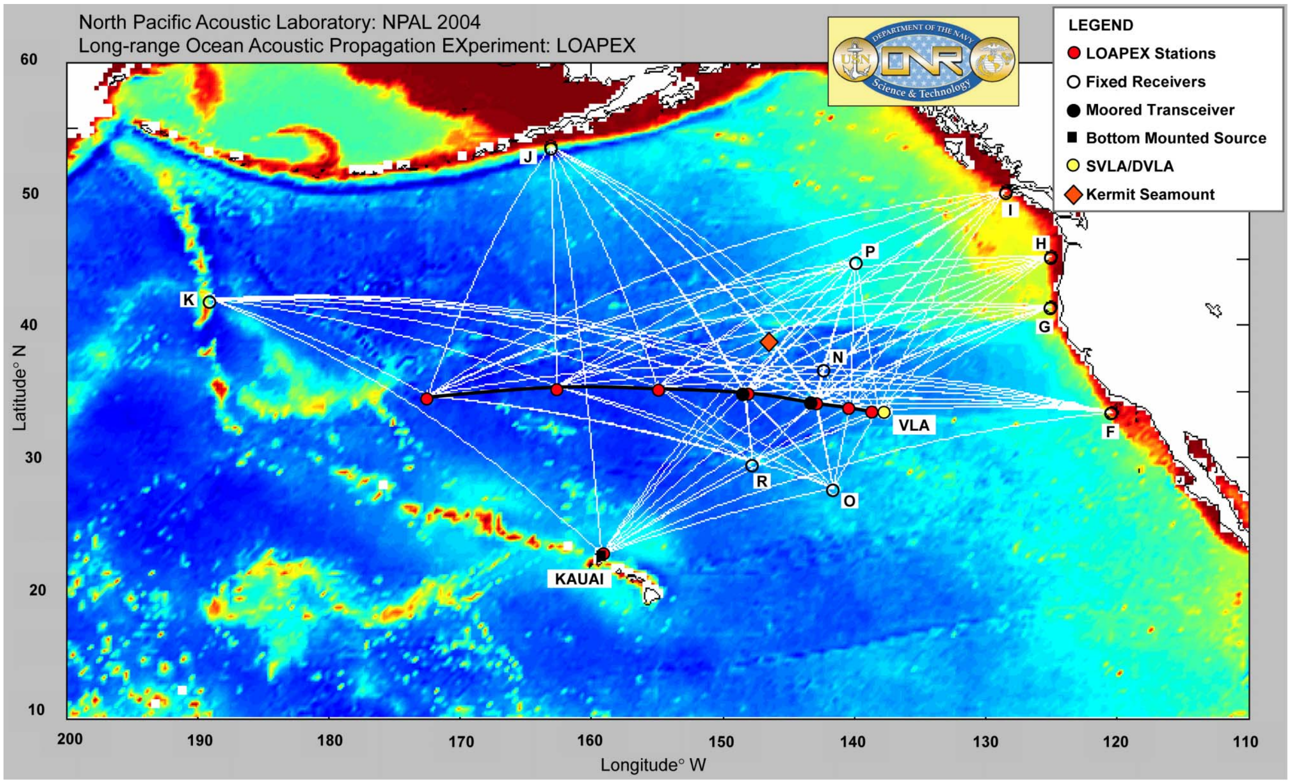


Figure 2 The LOAPEX geometry and assets. Seven red dots along the black cruise path indicate stations from which a low-frequency acoustic source was suspended at various depths from the R/V MELLVILLE. An eighth station was taken near the Kauai acoustic source. The open circles labeled with alphabetical letters represent permanent hydrophone arrays of the NPAL network. The red diamond locates the area of seamounts that were studied during BASSEX. The yellow dot shows the location of two vertical line arrays. The white lines indicate the geodetic paths between source locations and receivers.

SOSUS Data Network. Transmissions from the eight LOAPEX source stations were recorded on the network of SOSUS receivers. In addition to giving near-real-time feedback on the quality of the transmissions, the data from the SOSUS receivers will provide information on the range dependency of horizontal and temporal coherence as well as higher order statistics of the propagation. Figure 3 illustrates the reception of a single M-Sequence at the receiver indicated with the letter "R" in Figure 2. A single LOAPEX transmission usually consisted of at least 44 consecutive sequences allowing some coherent processing in the future. Movies have been made in which each frame is a processed M-Sequence arrival. The movies highlight the temporal fading and splitting of deterministic ray bundles.

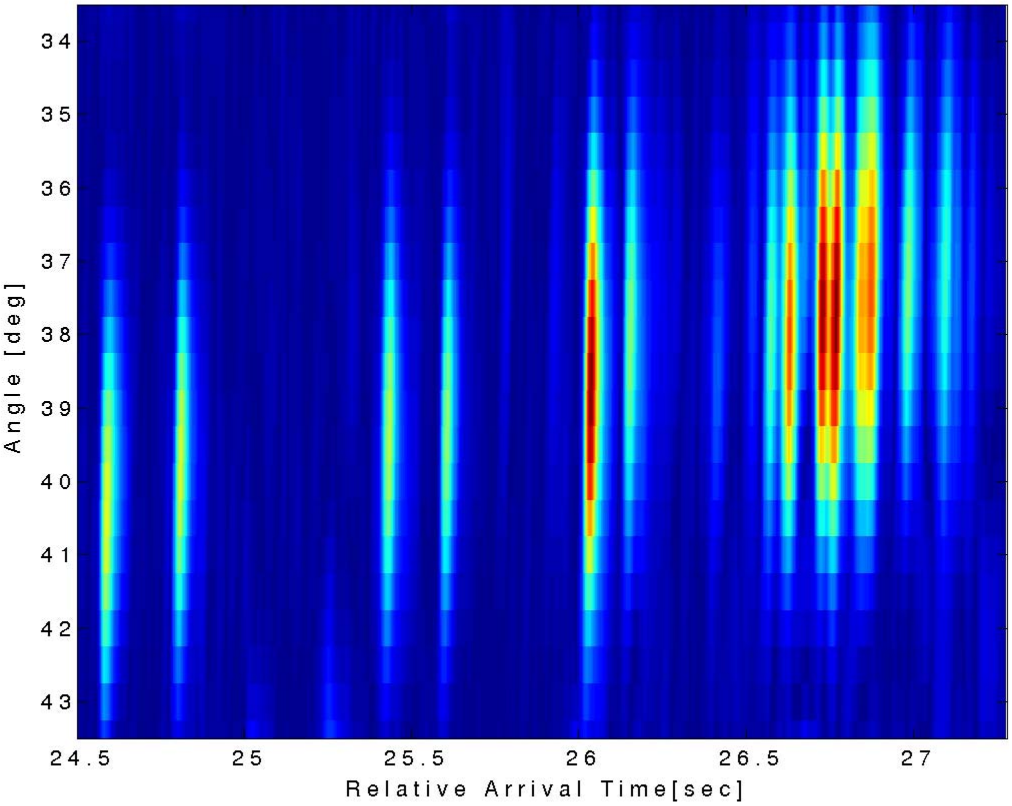


Figure 3 A single M-Sequence processed on the receiver indicated by the letter "R" in Fiugre 2. The vertical scale is the relative conic arrival angle in degrees and the horizontal scale is a reduced arrival time window in seconds.

The collection of LOAPEX data on the SOSUS receivers was very successful. Figure 4 illustrates the number of transmissions received at each SOSUS site from each transmission station. Approximately 100 hours of transmissions were completed during LOAPEX and the data collection at the SOSUS sites was about 99% complete.

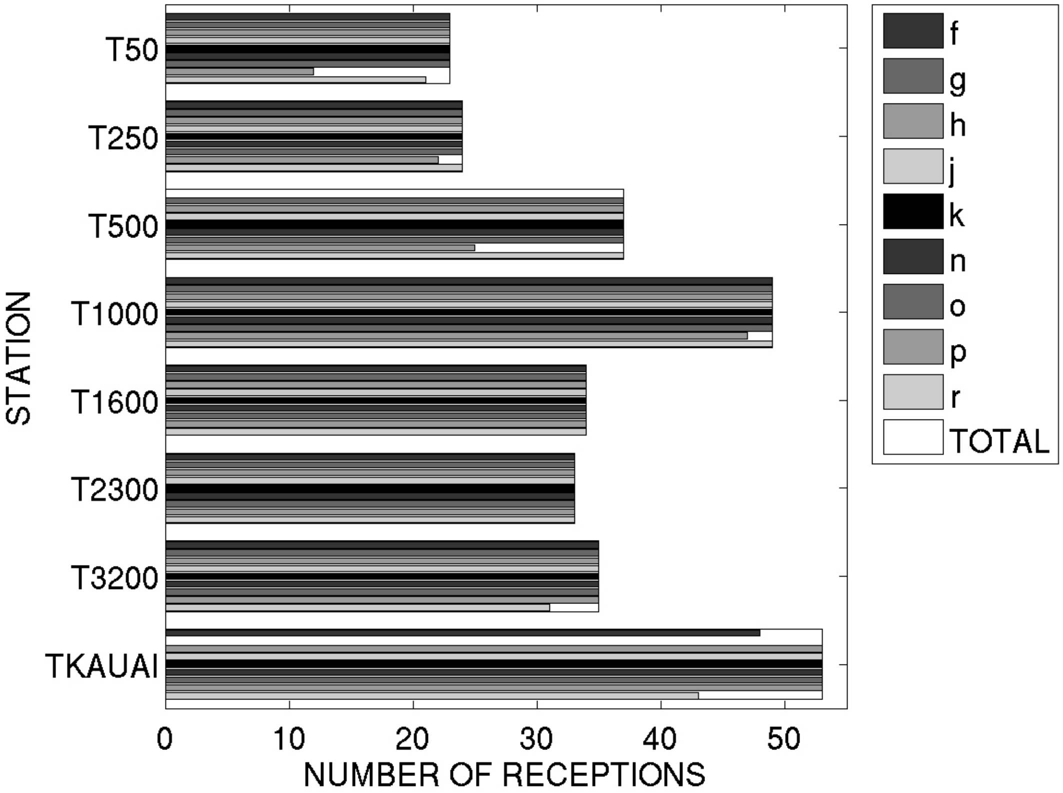


Figure 4 Number of successful receptions at each of the nine SOSUS receivers from each of the eight source stations. The letters in the key correspond to the letters in Figure 2, and the station labels, T50 e.g., refer to the distance in km from the VLA shown in Figure 2, and TKAUI is the eighth station near the Island of Kauai The length of each bar is the total number of transmission receptions possible at each receiver site.

In addition to the collection of LOAPEX data the SOSUS sites continued their routine collection of transmissions from the Kauai acoustic source and the collection of ambient noise data. The processing and presentation of data for sites “R” and “F” was simplified with the declassification of their cable routes, hydrophone element locations, and array orientations.

Kauai Transmissions. After approximately nine years of continuous scheduled transmissions the Kauai acoustic source ceased operation on 17 September in accordance with the existing Letter of Authorization (LOA) and the regulations set forth by the National Oceanic and Atmospheric Administration. Working with other NPAL collaborators, a “Kauai finale” schedule was defined for the end of the permitted period of operation. The permit allowed up to 2 months per year of operation at an 8% duty cycle (vice the normal 2%). The final schedule featured a single 2 hour transmission once each day. During tests of this new schedule, we learned that our transmit software would not support 2 hours of continuous transmission so the code in question was modified, tested and remotely loaded into the computer on Kauai.

In addition, APL-UW worked closely with Mike Brown at RSMAS to transmit a special coded signal for his research. Brown provided the digital content, and APL-UW modulated the content using BPSK (Binary Phase Shift Keying) and a carrier frequency of 75 Hz to produce the basic waveform. Spectral energy below 20 Hz was removed to avoid stimulating a mechanical resonance in the transducer. The waveform was run through our transmitter simulator to estimate the output level, and then the waveform level was adjusted so as to attain an RMS level of 195 dB re 1μPa @ 1 m. This RSMAS signal was transmitted one day per week, every four hours for 20 minutes during the final two-month period.

LOAPEX Source Motion. Three primary factors determine the received coherence of a fixed signal: 1) the range between the source and receiver; 2) the degree of variability in the intervening ocean; and 3) the motion of the source and the receiver. The first two items are determined by the experimental geometry. Source and receiver motion is not an issue for the bottom-mounted source near Kauai or for the bottom-mounted horizontal hydrophone arrays, but it is an issue for the suspended source and the VLAs. To better understand this issue for the conditions in LOAPEX a Doppler simulation study was completed. The conclusions of that study are that

- Doppler-induced intensity fluctuations are a few tenths of a dB, rarely more than 0.5 dB.

- Doppler-induced travel time fluctuations are a few milliseconds, rarely more than 5 ms.

- Sequence summing does not produce the same processing gain against Doppler induced fluctuations as against white noise.

- Doppler processing is necessary for coherence studies in order to separate incoherence due source-receiver motion from that due to ocean variability.

A significant effort was put forth to collect data that would allow the precise determination and verification of the LOAPEX suspended source location and velocity during transmissions. A goal was set to measure the absolute source position at one-second intervals to one tenth of the acoustic wavelength, or about 2 m. The primary method of achieving this goal was met by the application of a numerical finite-difference dynamic cable prediction model combined with a suite of navigation instrumentation. The analysis of this data is complete and the desired goal has been achieved. The analysis is part of a Master's thesis completed by Michael Zarnetske (Zarnetske, 2005).

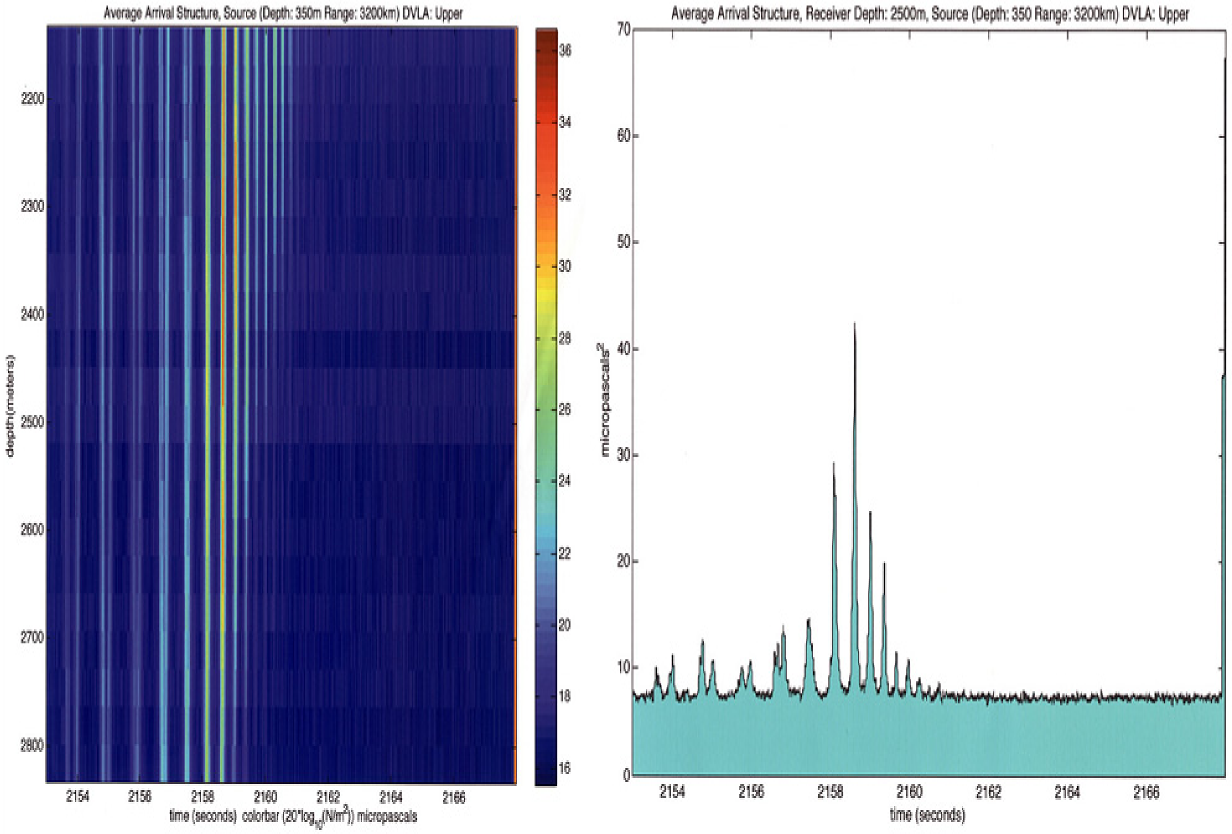
RESULTS

VLA data. The yellow dot in Figure 2 shows the location of two Vertical Line Arrays (VLAs) installed by the Scripps Institution of Oceanography. The Shallow VLA (SVLA) consisted of two 700 m subarrays covering the depth interval from 350 m to 1750 m, and was positioned about the sound channel axis to optimize resolution of acoustic modes 1-10 at 75 Hz. The Deep VLA (DVLA), roughly 3 nm due east of the SVLA, consisted of three 700 m subarrays and spanned depths from 2150 m to 4250 m. The DVLA was positioned as deep as possible to span many of the lower caustics in the predicted arrival pattern and thus provide information regarding the deep shadow zone. The positions of both VLAs were tracked with a surveyed set of six bottom-mounted acoustic transponders that were interrogated by transducers mounted on the arrays. Unfortunately, all of the data from the middle section of the DVLA were lost due to a water leak into its pressure case.

After Scripps processed the SVLA and DVLA navigation data and made it available to the NPAL community, it was learned that the navigation data were problematic. First, there is only one navigation solution every *other* hour for the upper DVLA subarray instead of every hour. This is possibly because the AVATOC (electronics pressure case) for the upper DVLA subarray was dropped on deck during recovery, incurring the loss of approximately half the VLA data. Second, there are gaps of consecutive solutions missing for all subarrays. Some gaps are much longer than a tidal period, the predominant period of VLA motion. Subsequent analysis by David Horwitt of Scripps revealed that the software "schedulers" in the SVLA and DVLA AVATOCs dropped navigation tasks during task "collisions," and that, unfortunately, the highest number of task "collisions" occurred during the periods scheduled for LOAPEX transmitter receptions.

Initial attempts to use Fourier interpolation proved inadequate for bridging the longer VLA navigation gaps. It was determined that the VLA motion is highly correlated with the tidal currents derived from Egbert's tidal prediction algorithms and software (Egbert et al., 2002). This has led to a new approach which shows considerable promise. Position solutions are modeled as a second order autoregressive process, with (noisy) Egbert predictions as the forcing function, and the missing solutions are estimated using least squares. This approach has the advantage of using the samples both prior to (as would be the case with a Kalman filter) and after a gap. With the navigation data at hand, there is no need to adopt a causal processing methodology for estimating the missing data. Once the VLA sensor location solutions are estimated onto a uniform time grid (at 1 hour periods), these solutions will be integrated into a non-causal multi-channel re-sampling filter that also uses the location solution for the ship-suspended transmitter (already available on a 1 second time grid) to remove motion-induced delay and dilation effects from the raw data.

Although a significant portion of the VLA data is missing, the data that were recorded will be very useful. Michael Kalnoky, a student has begun looking at the data received on the upper subarray of the DVLA. Figure 5 is an example of processed results of receptions on the upper subarray of the DVLA when the LOAPEX source was suspended to a depth of 350 m and at a range of 3,200 km. 15 transmissions were incoherently averaged. In Figure 5a each hydrophone of the subarray was processed independently and the "accordion" arrival structure is evident. The tail of the "accordion" is not present due to the shallow source depth. In Figure 5b the arrival structure for the hydrophone at a nominal depth of 2500 m is shown. There is no correction for source motion or VLA motion in this data. The initial effort will be to quantify second moment statistics which should not be sensitive to unknown Doppler in the acoustic data.



(a) (b)

Figure 5 (a) Arrivals on the upper subarray of the DVLA from the LOAPEX source at a depth of 350 and a range of 3,200 km, and (b) arrival times for the hydrophone at a nominal depth of 2500 m.

Ocean Bottom Seismometers. Although not shown in Figure 2, four Ocean Bottom Seismometers (OBSs) were deployed during LOAPEX in a rectangular pattern with each OBS about 2 km from the base of the DVLA. A calibration correction code for the OBS hydrophone channel data was obtained, and then, in collaboration with Ralph Steven at the Woods Hole Oceanographic Institution, the correction was applied to some of the OBS data. It was learned that either 1) the hydrophone files contain the geophone sensor data, and vice versa, or 2) the hydrophone channels suffer from considerable self-noise and the SVLA and DVLA hydrophone calibrations are considerably in error. It was also learned that one of the OBSs had a pressure-induced failure in an electrical cable, rendering its data useless. Requests have been forwarded to Jeff Babcock at SIO/OBSIP to verify the calibration and self-noise of the LOAPEX 2004 OBS instruments.

*Shadow Zone arrivals***.** The APL-UW NPAL computer cluster, although slow by modern standards, was used to run Monte Carlo PE acoustic propagation simulations. Hundreds of realizations of propagation were computed through a range-independent deep water waveguide with superimposed anomalies modeled by an in-house internal wave code based upon the Garrett-Munk (GM) model. Figure 6 shows a comparison between prediction and one actual reception on the DVLA.

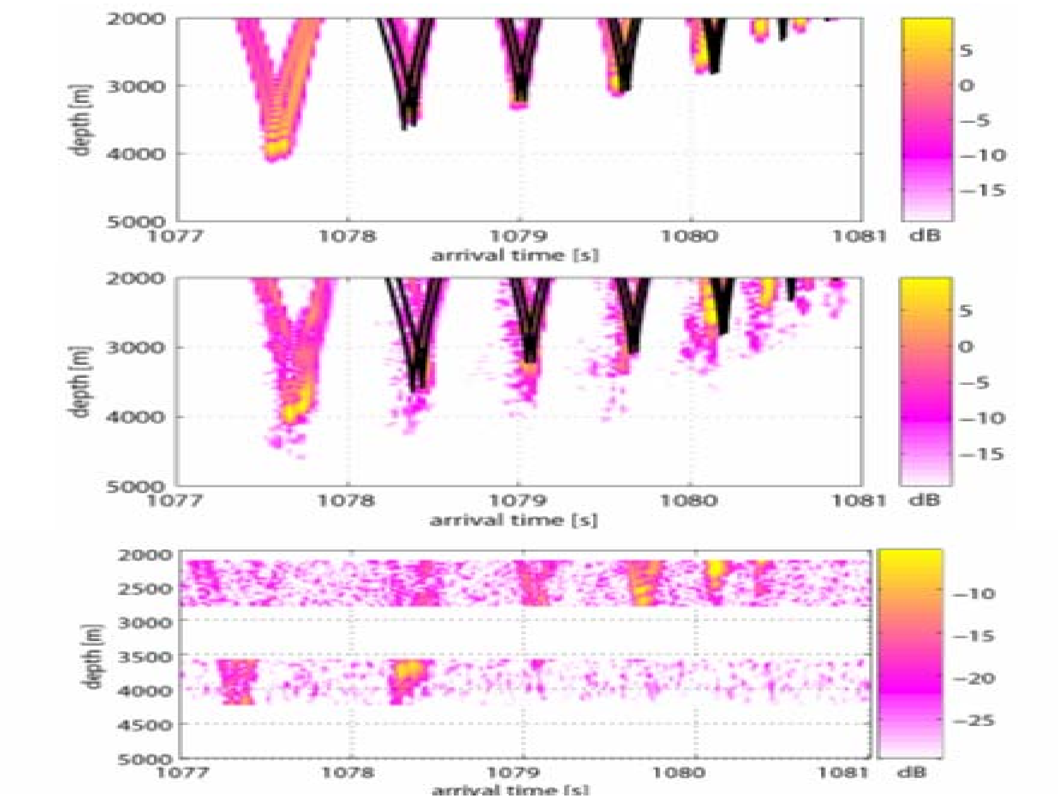


Figure 6 Comparison of predictions and actual data for the shadow zone problem. Top panel: deterministic PE calculation with a superimposed ray solution. Middle panel: a realization of a "stochastic" PE calculation with the same ray solution superimposed. Bottom panel: an example wavefront captured on the DVLA upper and lower subarrays.

It is unfortunate that the DVLA was not able to be deployed to full ocean depth and it is clear that the failure of the middle portion of the DVLA will hinder remaining comparisons with model results.

Ambient Noise. A meeting with Roy Gaul and David Knobles resulted in an exchange of intriguing ideas concerning ambient noise above and below the critical depth and the contribution of distant shipping. Although ambient noise collections were not explicitly scheduled for LOAPEX on the VLAs, many samples were inadvertently collected when the Scripps transmitter software failed several months before the completion of the experiment. Autospectra were estimated for each reception for each channel on each SVLA and DVLA subarray using the Welch method with no overlap, a Kaiser window, and a block size of 1024 points. Appropriate system calibration functions were applied to convert to in-water spectral density units of $\mu Pa^2/Hz$. Some receptions used a sample rate of 1000 Hz and an integration time of 123 s, while other receptions used 1200 Hz and 300 s. To render all the spectra onto the same frequency grid, all the estimates were interpolated onto the common grid of 1 Hz, 2 Hz, etc., using cubic splines. Figure 7 shows an omni-directional spectrogram, revealing baleen whale signals (most likely finback or blue whales) appearing in the vicinity of the VLA late in the year on their annual migratory route.

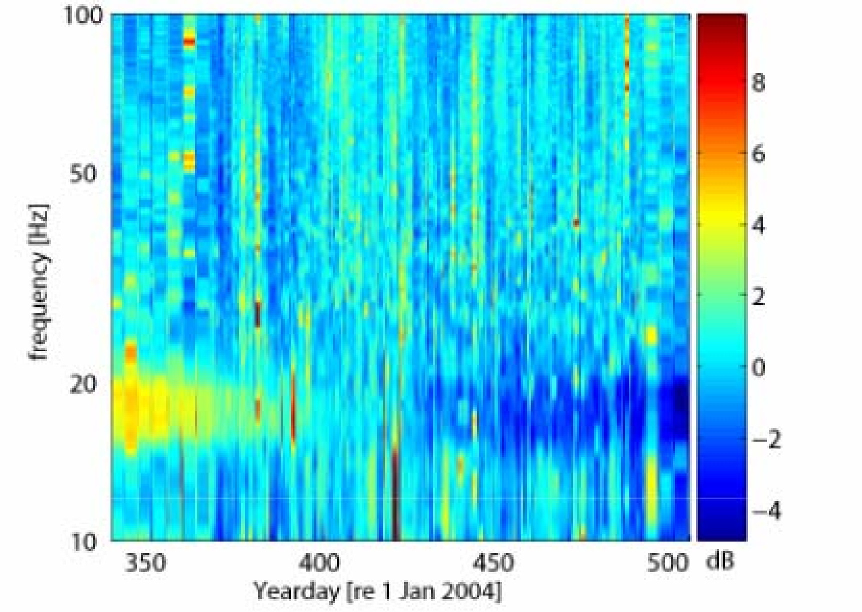


Figure 7 Ambient noise spectrogram from SVLA-lower channel 19. Median autospectrum removed to enhance low-level dynamic range features. The highlighted energy below about 20 Hz from the start of the spectrogram to about day 375 is due to whales.

A second example uses these “datasets of opportunity” to measure distant shipping noise. There was an experiment known as CHURCH OPAL conducted in 1976 at a location approximately 637~km north of the VLA site (Gaul et al., in press). The CHURCH OPAL data have recently been recovered and are being reanalyzed to separate the contributions from wind and shipping. Conversations with Gaul and Knobles, and the existence of these data, motivated a similar analysis. It was determined that the VLA site was closer to a shipping lane than the CHURCH OPAL site. This was based upon the HITS (Emery et al., 2001) shipping density database. The closer proximity to the shipping lane was borne out in the acoustical record, which seems to have considerably more loud transient events (ostensibly due to the transit of nearby ships) than the published CHURCH OPAL data.

In an effort to identify and disregard the datasets contaminated by nearby ships, we learned that the numerous channels on all SVLA and DVLA subarrays suffered from occasional gain anomalies. It was desirable to use a “clean” channel devoid of anomalies, but the number of spectra that would need to be reviewed precluded manual classification of “clean” and “dirty” channels. Instead, an automated procedure was devised that worked reasonably well. For a given data collection, the autospectra from all channels on a specific array segment should be similar to within a decibel or two. A cursory inspection had revealed this to be the case; the spectra from an overwhelming majority of channels were indeed very similar to one another. An average spectrum, $S_{ave}(f)$ was defined by the 50th percentile spectral level at each frequency across all channels. Anomalous channels could then be detected by setting a threshold on the mean squared error between the spectra $S_j(f)$ from channel j, $j=1,2,\ldots,20$, and $S_{ave}(f)$. It turned out that channel 12 on the DVLA lower subarray was identified in this manner as a “clean” channel over the entire dataset. This channel corresponds to a hydrophone at a nominal depth of 3962 m, which is fortunately reasonably close to the depth (3960 m) of one of the CHURCH OPAL sensors.

An auxiliary analysis next showed that ship traffic noise in the vicinity of 50 Hz is not significantly biased by sea surface noise. Although surface wind speed varies with time and location over the ocean, the dominant noise contribution depends on the wind speed at the receiver location. These "local" wind speeds were extracted from the National Center for Environmental Prediction (NCEP), National Center for Atmospheric Research reanalysis hind cast database for the time of each collection. All receptions were then grouped according to the prevailing local wind speed at the collection time. Figure 8 shows the 50th percentile spectrum for each group. The contributions of wind-related mechanisms are evident above about 120 Hz; below 120 Hz, however, there is a broad maximum, peaking at about 50 Hz, that shows no dependence on wind speed. This feature is the traffic noise; 50 Hz is clearly a frequency where the shipping component dominates over wind-related components, except possibly for winds 35 knots and greater.

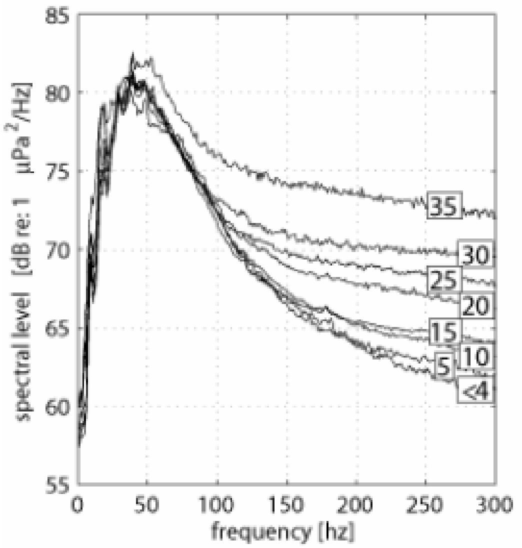


Figure 8 Median ambient noise autospectra versus wind speed, LOAPEX DVLA channel 12 at 3962 m. Wind speeds are in knots.

The median level at 50 Hz (with levels corresponding to wind speeds of 35 knots and above removed) was 80.36 dB for the LOAPEX record, with a standard error of +/- 0.05 dB. Future work with Gaul and Knobles is planned to produce a similar measure from the CHURCH OPAL dataset for comparison.

Student Advising. Supervision was provided for the on-going graduate research projects of Michael Kalnoky (LOAPEX intensity statistics) and Andrew White (LOAPEX ambient noise measurements), both from the University of Washington. In addition, one PI is on the Ph.D. committee for Jinshan Xu who is at the Woods Hole Institution of Oceanography. A part-time undergraduate student from Harvey Mudd, Nick Alger, has produced a preliminary objective map "snapshot" of the NE Pacific Ocean from the LOAPEX acoustic transmissions.

IMPACT/APPLICATIONS

This research has the potential to affect the design of long-range acoustic systems, whether for acoustic surveillance or remote sensing of the ocean interior. The data from the NPAL network, and the special NPAL experiments, indicate that existing systems do not begin to exploit the ultimate limits of acoustic coherence at long ranges in the ocean.

Estimates of basin-wide sound speed (temperature) fields obtained by the combination of acoustic, altimetry, and other data types with ocean general circulation models have the potential 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

The Seaglider autonomous vehicle, developed by APL-UW and the Department of Oceanography at the University of Washington, has matured to the point where a cost center has been established to allow regular production of the Seaglider for other institutions and various agencies of the government. Seagliders were deployed for the UPS Monterey Bay 2006 (MB06) experiment and demonstrated gateway functionality (transferring files with data/commands to and from sub-sea platforms via satellite and acoustic communications), long baseline navigation, and ambient sound monitoring.

RELATED PROJECTS

(i) D. Rudnick (SIO) was supported by ONR Code 322PO to make SeaSoar and Underway CTD (UCTD) measurements, and to provide UCTD hardware for use during LOAPEX.

(ii) A. Baggeroer (MIT) and K. Heaney (OASIS) were supported by ONR Code 321OA to make horizontal line array measurements during BASSEX using LOAPEX transmissions.

(iii) A large number of additional investigators are involved in ONR-supported research related to the NPAL project and participate in the NPAL Workshops, including J. Beron-Vera (UMiami), M. Brown (UMiami), J. Colosi (NPS), S. Flatté (UCSC), F. Henyey (APL-UW), V. Ostachev (NOAA/ETL), R. Stephen (WHOI), S. Tomsovic (Washington State), A. Voronovich (NOAA/ETL), K. Wage (George Mason Univ.), M. Wolfson (APL-UW), and G. Zaslavsky (NY Univ.).

REFERENCES

Egbert, Gary, A. Bennett, M. Foreman, TOPEX/Poseidon tides estimated using a global inverse model, *J. Geophys. Res.*, **99**, No C12, pp. 24,821 - 24, 852, 2002.

Emery, L., M. Bradley, T. Hall, Data Base Description (DBD) for the Historical Temporal Shipping Data Base (HITS), version 4.0, Technical Report TRS-301, Planning Systems Inc., Slidell, LA, 2001.

Gaul, R. D., D. P. Knobles, J. A. Shooter and A. F. Wittenborn, Ambient Noise Analysis of Deep Ocean Measurements on the Northeast Pacific, *IEEE J. Ocean. Eng.*, in press.

Zarnetske, Michael, Long-range Ocean Acoustic Propagation EXperiment (LOAPEX): Preliminary analysis of source motion and tidal signals, Master of Science thesis in the School of Oceanography, University of Washington, Seattle, WA, 2005.

PUBLICATIONS

Approval from PMW 180 to release an APL Technical Memo entitled "Dynamic Ambient Noise Model Comparison with Point Sur, California, In-Situ Data," C. V. Leigh and A. I. Eller, has been received. This work compares the omni-directional ambient noise predicted by the DANM code for the Pt. Sur site against NPAL measurements from several months in 1998. The prediction matched the actual ambient noise levels within a few decibels below 100 Hz, primarily in the upper ship traffic noise band.

Zarnetske, Michael, Long-range Ocean Acoustic Propagation EXperiment (LOAPEX): Preliminary analysis of source motion and tidal signals, Master of Science thesis in the School of Oceanography, University of Washington, Seattle, WA, 2005.