# North Pacific Acoustic Laboratory

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## LONG-TERM GOALS

The ultimate limits of long-range sonar are imposed by ocean variability and the ambient sound field. Scattering due to internal waves and other ocean processes limits the temporal and spatial coherence of the received signal. The objectives of the North Pacific Acoustic Laboratory (NPAL) program are to understand the basic physics of low-frequency, long-range, broadband 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 is 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 scientific objectives are:

- To study 3-D coherence (horizontal, vertical, and temporal) of long-range, low-frequency resolved rays and modes
- To explore the range and frequency dependence of the fluctuation statistics of resolved ray and mode arrivals and of the highly scattered finale observed in previous experiments
- To understand the surprisingly large amount of acoustic scattering into the geometric shadow zone beneath caustics previously seen with bottom-mounted SOSUS receivers (shadow-zone arrivals)
- To elucidate the relative roles of internal waves, ocean spice, and internal tides in causing acoustic fluctuations
- To document the spatial and temporal variability of ambient noise on ocean basin scales

- To improve basin-scale ocean nowcasts via assimilation of acoustic travel-time and other data into models

**APPROACH**

NPAL employs a combination of experiment, data analysis, and simulations to address the issues outlined above. Previous NPAL-related research is summarized in Worcester and Spindel (2004).

The principal experimental effort during the current phase of NPAL is a long-range ocean acoustic propagation experiment with three main components, named *SPICE04, LOAPEX (Long-range Ocean Acoustic Propagation EXperiment),* and *BASSEX (Basin Acoustic Seamount Scattering EXperiment)* (Fig. 1). *SPICE04* and *LOAPEX* share a pair of closely spaced vertical receiving arrays that together span a large fraction of the water column. The acoustic signals transmitted during *SPICE04*and *LOAPEX* will also be received on a towed horizontal array during *BASSEX* to study acoustic scattering and diffraction from Kermit Roosevelt seamount. SIO is responsible for *SPICE04* and for the vertical receiving arrays. APL-UW is responsible for *LOAPEX*. MIT and OASIS are responsible for *BASSEX*. The geometry was chosen to keep the *SPICE04* and *LOAPEX* paths entirely within the subtropical gyre. The VLA moorings are located between the Subarctic and Northern Subtropical Fronts and to the west of the complicated California Current region.

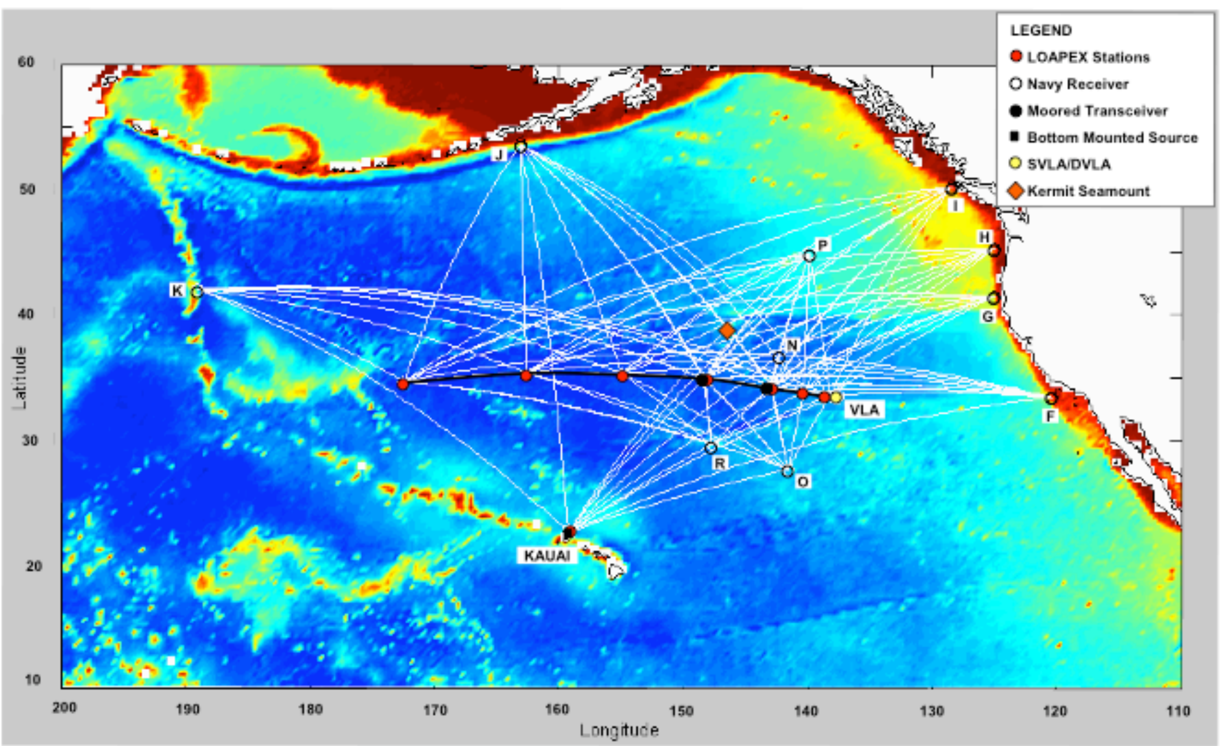


***Fig. 1. Overall geometry of the 2004 NPAL experiment. The 250-Hz moored transceivers (black) are located 500 and 1000 km west of the SVLA/DVLA receivers (yellow). The LOAPEX transmission stations (red) extend roughly westward from the VLAs to a maximum range of about 3200 km. A final LOAPEX station is located near the Kauai source. The BASSEX towed array will be deployed close to Kermit Roosevelt Seamount (orange), as well as in the vicinity of the Kauai source. U. S. Navy SOSUS receivers that will receive the various transmissions are shown in white.***

In addition, the transmissions during *SPICE04* and *LOAPEX*, as well as the continuing transmissions from the ATOC/NPAL source north of Kauai, are being recorded at the U. S. Navy SOSUS receivers in the North Pacific. APL-UW has primary responsibility for continued operation of the Kauai source and SOSUS receivers. Ambient noise data are also being recorded at the SOSUS receivers.

Theoretical issues raised by NPAL and other long-range propagation data are being addressed by a number of our collaborators.

**WORK COMPLETED**

*SPICE04.* Two autonomous vertical line array (VLA) receivers and two 250-Hz broadband acoustic transceiver moorings were deployed from the *R/V Roger Revelle* during a research cruise from San Diego to Honolulu, 26 May-18 June 2004 (Fig. 2). Recovery is tentatively scheduled for June-July 2005.

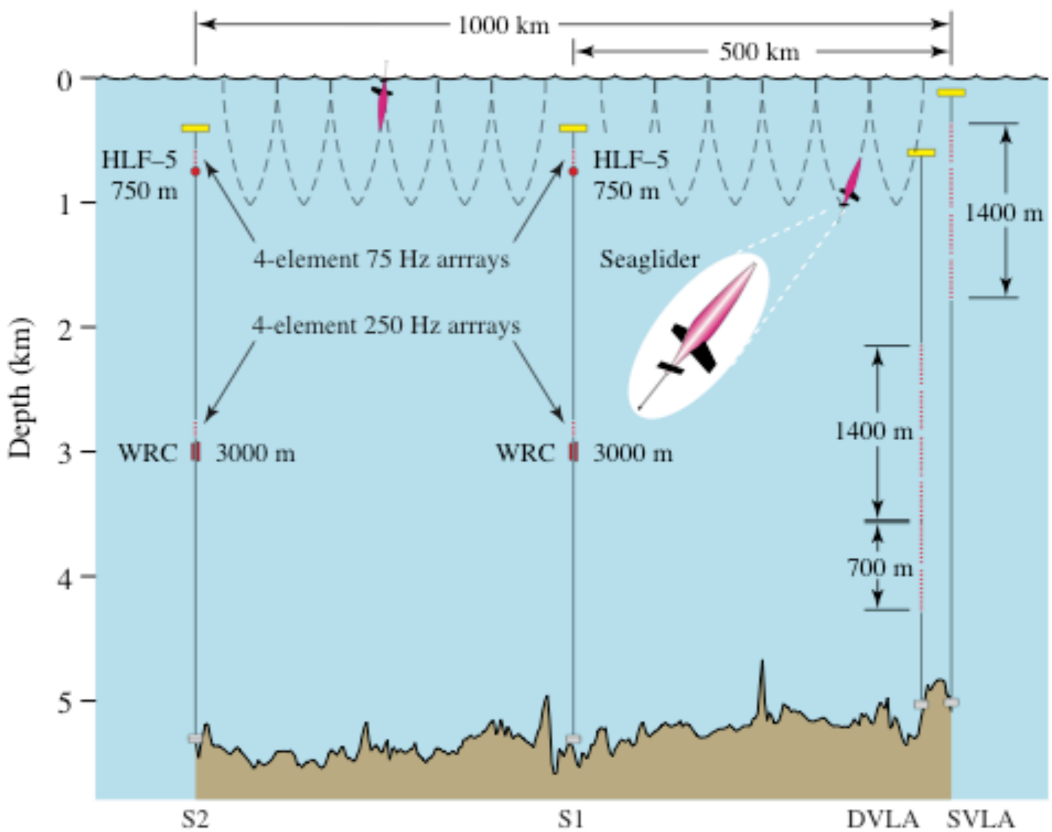


***Fig. 2. SPICE04 experimental geometry. Two transceiver moorings (S1 and S2) were deployed 500 and 1000 km from two autonomous vertical line array receivers (SVLA and DVLA). One receiving array has a 1400-m aperture spanning the sound-channel axis (Shallow VLA), and the other has a 2100-m aperture spanning a number of lower turning points (Deep VLA). The Seaglider shown is just one method used to obtain the necessary environmental data.***

The moored transceivers consist of newly-developed STAR (Simple Tomographic Acoustic Receiver) data acquisition systems combined with either a Hydroacoustics, Inc., HLF-5 source or a Webb Research Corporation (WRC) sweeper source. The STAR is both a four-channel receiver and an acoustic source controller. It has been designed to provide the precise time keeping and acoustic positioning needed for acoustic propagation and ocean acoustic tomography experiments. A prototype STAR was tested at sea for approximately two weeks during February 2004. The data are stored internally in the moored data acquisition systems and will not be available for analysis until after recovery.

During the deployment cruise CTD and Underway CTD (UCTD) measurements were made along the path between the VLAs and moored sources, as well as between mooring S2 and the Kauai source. There will be a SeaSoar cruise during March 2005 to measure upper ocean structure along the acoustic path between the source moorings and VLAs (D. Rudnick, SIO). The goal is to separate the sound-speed finestructure into two component fields: (i) isopycnal tilt dominated by internal waves and (ii) "spicy" (cold-fresh to hot-salty) millifronts associated with upper ocean stirring, so that the relative roles of internal waves and spice in the scattering of the NPAL transmissions can be evaluated.

*LOAPEX*. *LOAPEX* is being conducted from the *R/V Melville* during a research cruise from San Diego to Honolulu, 10 September – 10 October 2004. A broadband low-frequency (75 Hz) source is being suspended from shipboard at seven stations at ranges varying from 50 km to 3200 km from the SVLA and DVLA receivers. There will also be an eighth station near the island of Kauai. Four ocean bottom seismometers and hydrophones were deployed adjacent to the SVLA and DVLA moorings to complement the VLA receivers (R. Stephen and J. Colosi, WHOI).

Two Seaglider autonomous undersea vehicles (AUV) were deployed during the *LOAPEX* cruise to measure ocean structure along the acoustic path between the *SPICE04* transceiver moorings and the VLAs. In addition, a combination of CTD, UCTD, and XBT measurements are being made during the *LOAPEX* cruise.

The low-frequency source system was tested off San Diego from the *R/V New Horizon* from 20–23 May 2004. Data obtained during the test helped determine the signals that could be transmitted during *LOAPEX* without damaging the Alliant TechSystems HX-554 source.

*Kauai Source Operations.* Transmissions from the Kauai source continued throughout FY04. The duty cycle has been increased to the maximum allowed, 8%, from 10 September until 8 November 2004, overlapping the times when the *LOAPEX* and *BASSEX* cruises are in progress. The permits and other authorizations allow source transmissions to continue through autumn 2006, at which time the source and cable will be abandoned in place.

*SOSUS Receiver Operations.* Acquisition and archiving of the transmissions from the moored 250-Hz sources as received at the U. S. Navy SOSUS receivers began when the transceiver moorings were deployed. The 75-Hz transmissions from each of the *LOAPEX* stations are also being recorded. Acquisition and archiving of Kauai source transmissions and of ambient noise data continued throughout FY04. Finally, transmissions were recorded from a 250-Hz source installed on Hoke Seamount by the Naval Postgraduate School.

*NPAL Data Analysis Workshop.* The Seventh NPAL Data Analysis Workshop was held in Borrego Springs, California, on 29–31 March 2004. Final planning for the 2004 NPAL experiment was done during the Workshop.

**RESULTS**

Thirteen papers giving recent results from NPAL-related research are scheduled for publication early in 2005 as a Special Section in the *Journal of the Acoustical Society of America* (Andrew *et al.*, 2004; Baggeroer *et al.*, 2004; Brown *et al.*, 2004; Colosi *et al.*, 2004; Heaney, 2004; Hegewisch *et al.*, 2004; Mobley, 2004; Morozov and Colosi, 2004; Smirnov *et al.*, 2004; Vera *et al.*, 2004; Voronovich *et al.*, 2004; Wage *et al.*, 2004; Worcester and Spindel, 2004). These papers are concerned with a wide range of topics, including statistical measures of amplitude and phase fluctuations at long ranges, the spatial and temporal coherence of the received signal, signal energy redistribution through mode scattering, horizontal refraction, the implications of the theory of ray chaos, the effects of bottom interactions, the characteristics of ambient noise on ocean-basin scales, and the potential impact of the low-frequency transmissions on marine mammals. The results are summarized by Worcester and Spindel (2004), who served as NPAL co-editors for the Special Section.

Summarized below are a few of the results from the papers for which SIO and/or APL-UW investigators are authors or co-authors, as well as additional results not included in the *JASA* Special Section.

*Horizontal Coherence.* NPAL data from U. S. Navy bottom-mounted horizontal arrays suggest horizontal coherence lengths of resolved wave fronts of 400–500 m at 75 Hz and ranges of 2000–3000 km, in accord with theoretical predictions (Andrew *et al.*, 2004). The data from the 2-d NPAL array deployed off Pt. Sur, California, during 1998–1999 exhibit similar horizontal coherence lengths, even though the measurement is coarser (Fig. 3) (Voronovich *et al.*, 2004). (The first lag distance is about 500 m, the distance between the two closest vertical arrays in the 2-d array.)

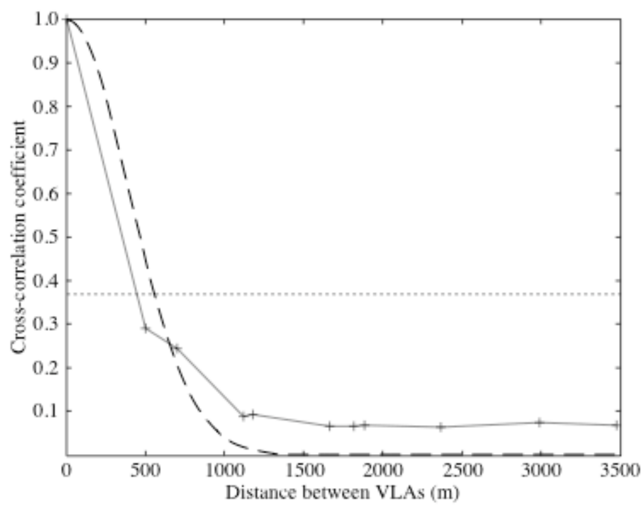


***Fig. 3. Horizontal correlation at the NPAL 2-d array for the 75 Hz transmissions from the ATOC/NPAL Kauai source at a range of 3889.8 km, averaged over depth. The solid line is data; the dashed line is a model prediction. (From Voronovich et al., 2004.)***

*Ambient Noise*. The 2-d NPAL array allowed measurement of the vertical directionality of the noise field as well as the coherence of noise sources near the array (Baggeroer *et al.*, 2004). The practical implication of sensor-to-sensor noise coherence is signal gain greater than the 10 log *N* achievable in an incoherent noise field. In general, coherence is low when no identifiable noise sources are present. When strong signals are present, such as 10–20 Hz whale tones, coherence was high across both dimensions of the array. Similarly, earthquake noise is strongly coherent across the array. Vertical beamforming of these strong signals indicates a highly directional spectrum at low grazing angles. There is very little directionality during periods when such signals are absent.

*Ocean acoustic tomography*. Geometric ray theory commonly used in ocean acoustic tomography to relate measured travel-time changes to ocean sound-speed changes is a high-frequency approximation. Skarsoulis and Cornuelle (2004) use wave-theoretic methods to derive the sensitivity kernel of travel times with respect to sound-speed variations for the case of finite frequencies. They find significant deviations from ray theory for the case of low acoustic frequencies. Low-frequency travel times are sensitive to sound-speed changes in Fresnel-zone-scale areas surrounding the rays, but not on the rays themselves, where the sensitivity is zero, for example. The use of wave-theoretic methods to evaluate travel-time sensitivity kernels could provide a tool to study finite frequency travel-time effects of ray and "wave" chaos.

*Acoustic Thermometry*. Acoustic measurements of large-scale, depth-averaged temperatures are continuing in the North Pacific using transmissions from the Kauai source to U.S Navy SOSUS receivers (Worcester and Spindel, 2004). Long-term trends in large-scale ocean temperature are easily visible in the acoustic time series because acoustic methods give integral measurements of large-scale ocean temperature that provide the spatial low-pass filtering needed to observe small, gyre-scale signals in the presence of much larger, mesoscale noise. Recent data along the paths from Kauai to the California coast show cooling relative to earlier ATOC data. A path to the northwest showed modest warming until early 2003, when a rapid cooling event occurred. This was followed by a much stronger annual cycle. The changing temperatures may be a manifestation of the Pacific Decadal Oscillation.

## 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 NPAL and 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 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

*Simple Tomographic Acoustic Receiver (STAR)*. SIO and Webb Research Corporation (WRC) collaborated to integrate the newly-developed STAR (Simple Tomographic Acoustic Receiver) four-channel receiver and source controller into the WRC sweeper sources used in the 2004 NPAL experiment. (Development of the STAR originally started with funding provided by the National Ocean Partnership Program, as one component of a multi-institutional proposal entitled "Monitoring the North Pacific for Improved Ocean, Weather, and Climate Forecasts," for which APL-UW was the lead institution.) We are currently seeking additional Small Business Innovative Research (SBIR) funding to complete the development and documentation of the combined system so that WRC can manufacture and sell it. The integrated STAR/WRC sweeper source system is much more cost-effective and significantly easier to use than the current generation of acoustic transceivers employed in long-range propagation and ocean acoustic tomography experiments.

**RELATED PROJECTS**

(i) D. Rudnick (SIO) is supported by ONR Code 322PO to make SeaSoar and Underway CTD (UCTD) measurements during the 2004 NPAL experiment.

(ii) A. Baggeroer (MIT) and K. Heaney (OASIS) are supported by ONR Code 321OA to conduct *BASSEX (Basin Acoustic Seamount Scattering EXperiment)* as part of the 2004 NPAL experiment. The acoustic signals transmitted during *SPICE04*and *LOAPEX* will be received on a towed horizontal line array to study acoustic scattering and diffraction from Kermit Roosevelt seamount.

(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 F. J. Beron-Vera (UMiami), M. Brown (UMiami), N. Cerruti (Washington State), J. Colosi (WHOI), S. Flatté (UCSC), F. Henyey (APL-UW), A. Morozov (WRC), V. Ostachev (NOAA/ETL), S. Tomsovic (Washington State), A. Voronovich (NOAA/ETL), K. Wage (George Mason Univ.), M. Wolfson (APL-UW), and G. Zaslavsky (NY Univ.).

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