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

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- 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:

(i) *Billboard Array*. A sparse 2-D array was installed at Sur Ridge off Point Sur, California, from July 1998 until August 1999 to receive the 3900-km-range transmissions from the low-frequency (75 Hz) acoustic source previously installed north of Kauai by the Acoustic Thermometry of Ocean Climate (ATOC) project. The 2-D array consisted of 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 Kauai source. Extensive measurements of the sound speed field between the Kauai source and the 2-D array were made. Analyses of these data are continuing.

(ii) *Kauai Source/SOSUS Receivers*. Transmissions from the Kauai source are being routinely 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.

(iii) *NPAL 2004 Experiment*. Preparations are in progress for a long-range ocean acoustic propagation experiment to be conducted during 2004. The experiment has two main components, or sub-experiments, named *SPICE04* and the *Long-range Ocean Acoustic Propagation EXperiment (LOAPEX)*. These components share a pair of closely spaced vertical receiving arrays that together will span a large fraction of the water column. SIO has primary responsibility for *SPICE04* and for the vertical receiving arrays. APL-UW has primary responsibility for *LOAPEX*.

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

WORK COMPLETED

Kauai Source Operations. Transmissions from the Kauai source resumed in January 2002, following completion of the environmental review process required to obtain the necessary authorizations. The permits and other authorizations allow source transmissions to continue for five years, at which time the source and cable will be abandoned in place.

SOSUS Receiver Operations. Acquisition and archiving of transmissions from the Kauai source and of ambient noise data continued throughout FY03. Transmissions are also being recorded from a 250-Hz source installed on Hoke Seamount by the Naval Postgraduate School.

NPAL Data Analysis Workshop. The Sixth NPAL Data Analysis Workshop was held in Borrego Springs, California, on 17–19 March 2003.

SPICE04 and LOAPEX Preparations. Planning and equipment preparations are well underway for the experiment to be conducted in 2004. Ship scheduling considerations led to a revised experiment geometry, with the VLA moorings located to the northeast of Hawaii instead of to the northwest (Fig. 1), as had been originally proposed. 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.

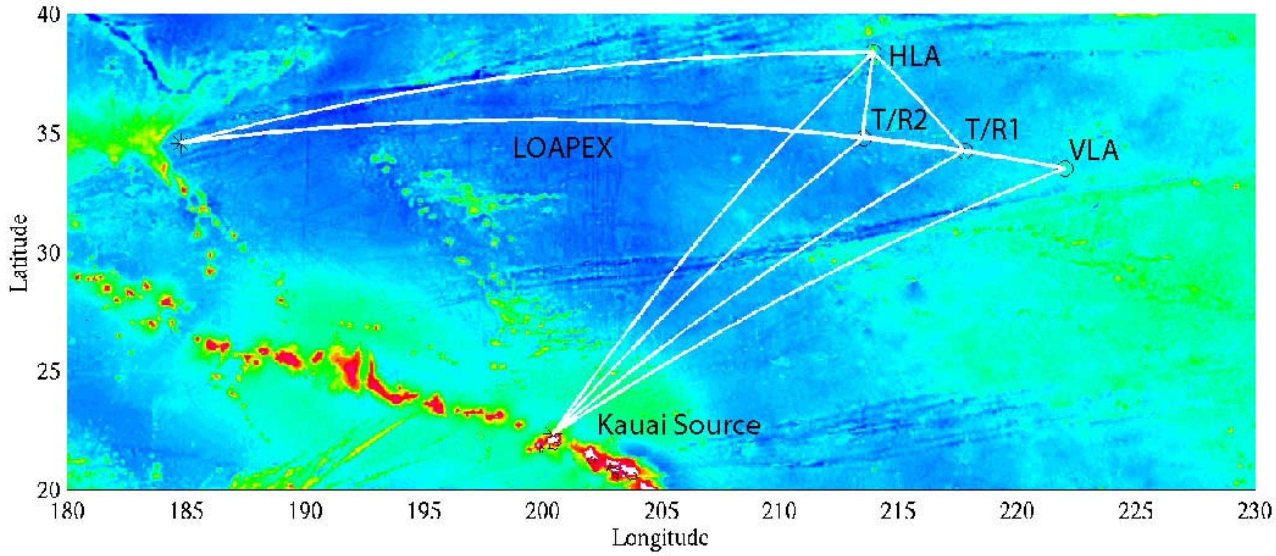

Fig. 1. Tentative 2004 NPAL experiment geometry. The two VLA moorings are located northeast of Hawaii. The LOAPEX ship track extends roughly westward from the VLAs to a maximum range of about 3500 km. The 250-Hz transceivers (T/R1 and T/R2) are located roughly 400 and 800 km from the VLAs along the LOAPEX track. The towed horizontal line array (HLA) is shown close to Kermit Roosevelt Seamount, approximately north of T/R2.

RESULTS

Kauai Source/SOSUS Receiver Data. 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 (Dushaw, 2003; Howe *et al.*, 2003). 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. The paths to the east, particularly those paths to the California coast (Kauai to SOSUS receiver f), show cooling (longer travel times) relative to earlier ATOC data (Fig. 2). A path to the northwest (Kauai to SOSUS receiver k) showed modest warming (shorter travel times) until early 2003, when a rapid cooling event occurred. Acoustic travel times can be readily computed from modern ocean general circulation models that have many layers in the vertical. The acoustic data not surprisingly show similarities and differences when compared to travel times computed from state-of-the-art efforts from the ECCO (Estimating the Circulation and Climate of the Ocean) Consortium, as provided by the Jet Propulsion Laboratory. The ECCO model assimilates data from satellite altimetry and other sources.

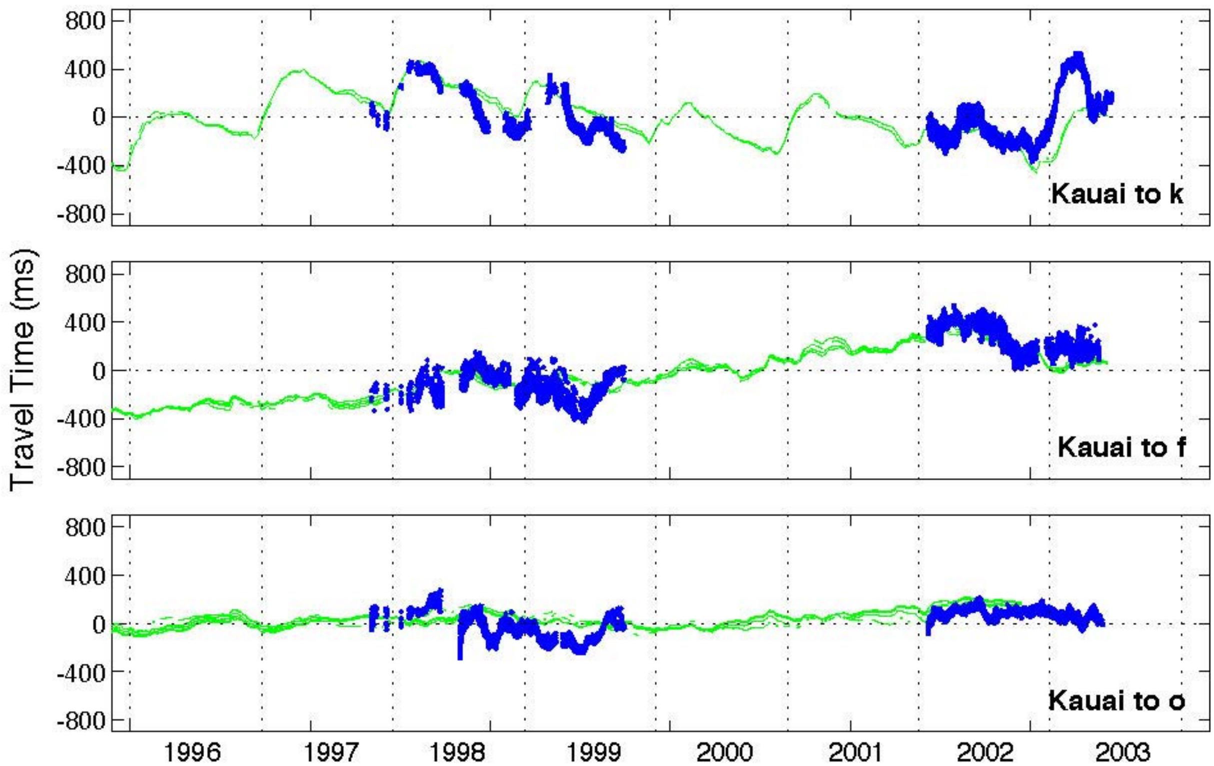

Fig. 2. Travel time variations for transmissions from the Kauai source to SOSUS receivers k, o, and f (dark blue lines), compared with the travel times calculated from the ECCO state estimates (light green lines). Each line represents a different ray path, which samples the ocean in a different way; typically 6-12 ray arrivals are resolved on each path.

SOSUS Receiver Data: Ambient Noise. Ocean ambient sound data collected from 1994 to 2001 using a U. S. Navy receiver on the continental slope off Point Sur, California, were calibrated using ambient noise data from the NPAL 2-D receiving array. The resulting data set was compared with long-term averages of earlier measurements made with the identical SOSUS receiver over the period from 1963 to 1965. This comparison shows that the 1994 to 2001 levels exceed the 1963 to 1965 levels by about 10 dB between 20 and 80 Hz and between 200 and 300 Hz, and about 3 dB at 100 Hz. Increases in (distant) shipping sound levels may account for this (Andrew *et al.*, 2002b). Ambient noise data collected on the SOSUS receivers have also been used to assess the contributions made by whales to low-frequency ambient sound (Andrew *et al.*, 2002a) and, in turn, to study the distribution of blue whales in the northeast Pacific (Burtenshaw *et al.*, 2003).

2-D Array Data. Analyses of data collected on the 2-D array have been hampered by relatively low signal-to-noise ratios and by difficulty matching the observed arrivals with predictions. The unexpectedly low SNR are due to the high shipping noise environment encountered off Pt. Sur. Processing the receptions using a RAKE correlator, which optimally combines coherent and incoherent processing in accord with the properties of the received signal, has dramatically improved the effective SNR (Fig. 3), making it possible to generate high-quality time series of travel times for the resolved ray arrivals. Comparison of the improved receptions with parabolic and ray simulations has shown that it is essential to consider ray paths that interact with the surface and seafloor near the Kauai source in order to correctly identify the observed arrivals. Rays with high launch angles that reflect off the

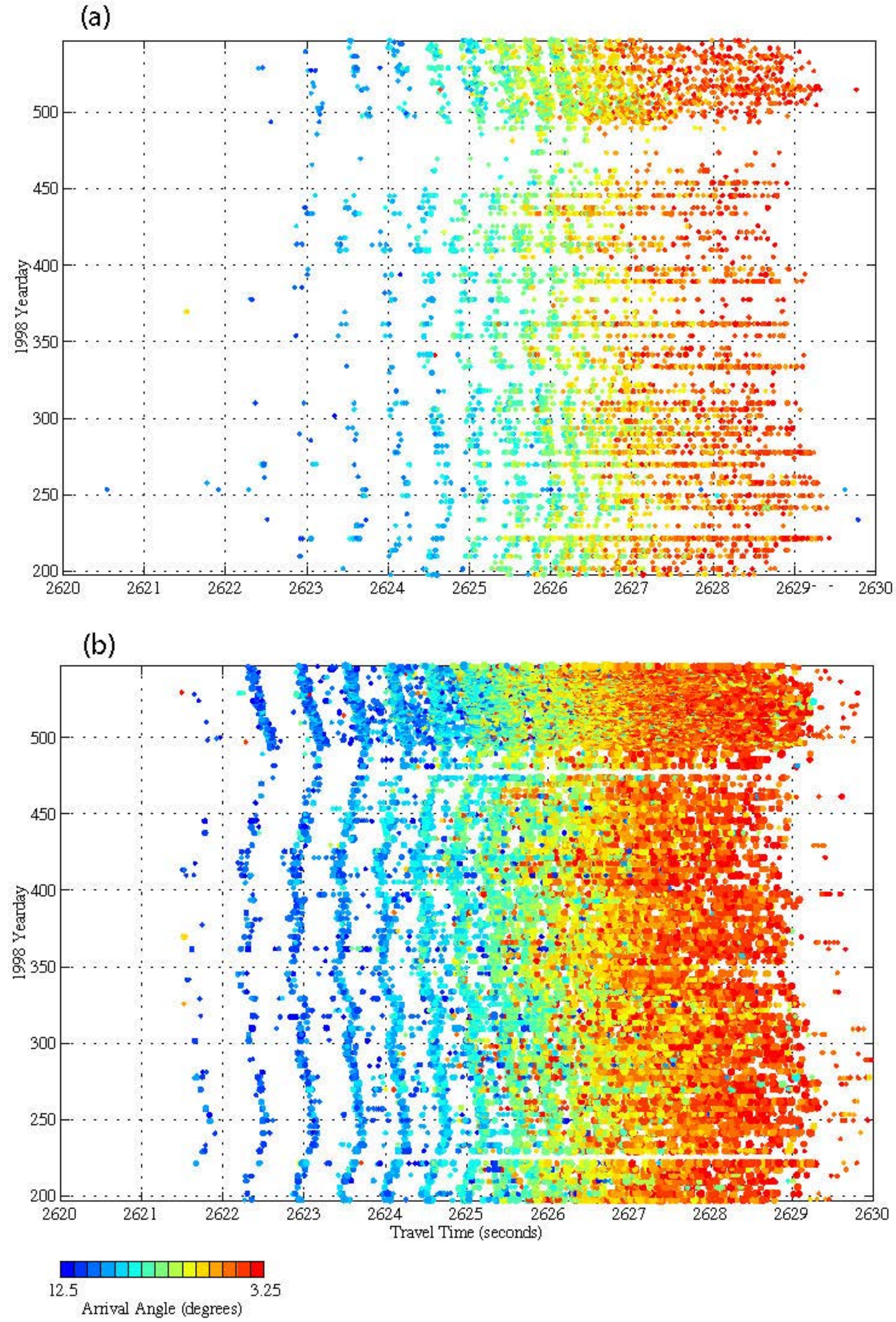

Fig. 3. Dot plots generated for the center mooring of the NPAL 2-D array using (a) standard coherent processing and (b) a RAKE correlator assuming a coherent bandwidth of 5 Hz, coherence time of 600 s, and a depth coherence of 800 m.

surface reflect off the bottom in front of the source and are converted to lower-angle rays due to the bottom slope. These lower angle rays then propagate as purely refracted or refracted-surface reflected rays to the 2-D array. The resulting arrivals overlap in angle with the purely refracted arrivals, but arrive slightly later in time due to the extra path length near the source. This class of rays also accounts for the earliest arriving resolved arrivals that show up most clearly in the dot plots, because it includes rays with shallower turning points than are possible for purely refracted arrivals (Fig. 3). Analyses of the acoustic fluctuations and coherence properties of the resolved arrivals are proceeding now that the signal-to-noise ratios have been improved and the observed arrivals can be matched with predictions

Ocean Spice. Using a closely sampled 1000 km hydrographic section in the eastern North Pacific, Dzieciuch *et al.* (2003) separated 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. Numerical transmission experiments show significant scatter within the mixed layer from the spicy fronts; beneath the mixed layer the major contribution to the sound-speed finestructure is due to internal waves (the traditional view). The SOFAR overture is associated with a triplication of the channel dispersion at the transition from reflected to near-surface refracted energy. The overture has a definitive start time and depends crucially on mixed layer processes and other near-surface oceanography, suggesting that remote monitoring of upper ocean processes with an abyssal source at surface-conjugate depth may be feasible.

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 is currently completing development of a new acoustic data acquisition system for use in the 2004 NPAL experiment. (Development 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.) 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, although it could also be used as a general-purpose acoustic data acquisition system. We are now in the process of integrating the STAR into the Webb Research Corporation (WRC) sweeper source to create a new generation of acoustic transceivers. WRC plans to manufacture and sell the combined system, which will be much more cost-effective and significantly easier to use than the current generation of acoustic transceivers used 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 (Orincon) are supported by ONR Code 321OA to make horizontal line array measurements during the 2004 NPAL experiment.

(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 (WHOI), S. Flatté (UCSC), F. Henyey (APL-UW), 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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HONORS/AWARDS/PRIZES

Bruce Cornuelle, Scripps Institution of Oceanography, Medwin Prize in Acoustical Oceanography, Acoustical Society of America, 2002.

Bruce Cornuelle, Scripps Institution of Oceanography, Fellow, Acoustical Society of America, 2002.

Walter Munk, Scripps Institution of Oceanography, The Prince Albert I Medal, International Association for the Physical Sciences of the Oceans (IAPSO), Mar del Plata, Argentina, 24 October 2001.

Walter Munk, Scripps Institution of Oceanography, 2002 Reischauer Laureate, Japan Society of San Diego and Tijuana, San Diego, California, 09 October 2002.

Peter Worcester, Scripps Institution of Oceanography, Fellow, Institute of Electrical and Electronics Engineers, 2003.