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Long-Term Observations in Acoustics – the Ocean Acoustic Observatory Federation

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Federation

The Ocean Acoustic Observatory Federation (OAOF) includes several laboratories and universities: the Institute of Geophysics and Planetary Physics (IGPP) and the Marine Physical Laboratory (MPL) at the Scripps Institution of Oceanography, the Pacific Meteorological and Environmental Laboratory (PMEL) of NOAA, the Naval Postgraduate School (NPS), and the Applied Physics Laboratory at the University of Washington (UW/APL). The OAOF integrates the previously independent activities of its member institutions in the collection of long time series from acoustic arrays in the Pacific. The funded activities include the outfitting and operation of retired Sound Surveillance System (SOSUS) stations, research in earthquake and volcano seismicity, the monitoring of marine mammal behavior, the use of acoustic methods for ocean acoustic tomography and thermometry, and the development of a fundamental understanding of the coupling of elastic waves from volcanoes and earthquakes into the ocean sound channel.

During the course of the NOPP-funded grant, we intend to install, operate and maintain high-quality recording systems at SOSUS arrays at Pt. Sur, Barbers Point, and San Nicolas. While the arrays have been in operation for decades, there is no legacy from the SOSUS systems in the form of long time series of ocean signals and noise. The OAOF will initiate and maintain records which are of great scientific interest now and well into the future. We are exploiting the data under current Navy guidelines for data classification and

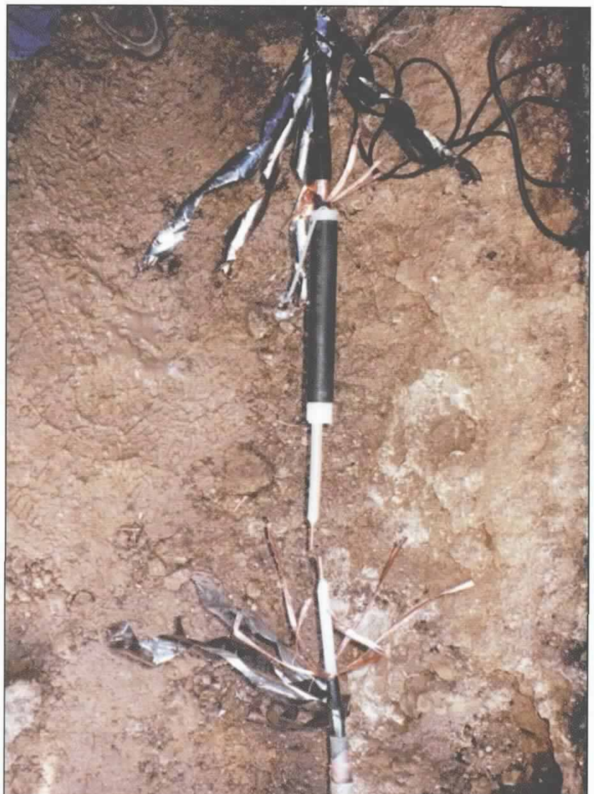


Figure 1: The SOSUS cable at Pt. Sur with the central conductor and various insulators and shields exposed.

declassification. In addition to these retired arrays, the OAOF, through PMEL, continues to make use of data received in real time from several operational arrays in the northeast Pacific to locate earthquakes, volcanoes, and marine mammals.

The California current system marks the eastern boundary of the subtropical gyre of the North Pacific. We have deployed an acoustic source on Hoke Seamount and are using the arrival structure of the low-power, encoded signals to infer temperature variability of the California current system. Finally, we are using recordings of earthquakes on the various SOSUS arrays to develop a fundamental understanding of how sources deep within the Earth are coupled, at low phase velocities, into the ocean's sound channel.

The scientists involved in the Federation bring a great variety of scientific and engineering expertise to this NOPP-supported program. The NOPP is an ideal funding mechanism for supporting this research in that the results are of considerable interest to several agencies including ONR, NSF, and NOAA. Furthermore, NOPP was expressly interested in the collection of long time series for data relevant to ocean processes. Single agencies have been unable to provide the infrastructure support necessary for such long-term research.

SOSUS Maintenance

The SOSUS arrays were installed in the 1950's and 1960's and now require considerable maintenance. We have found that cable repairs, at sea and on land, are not only possible, but less expensive than costs incurred by the Navy. A recent repair was conducted at Barbers Point.

During this past year, the Naval Air Station at Barbers Point was closed and the shore station for the associated SOSUS arrays was fenced off to maintain security. Unfortunately, when the fencing was done, one of the post holes was driven directly through the cable which supports the array. UW/APL, which has upgraded all the amplifiers and isolation electronics for the retired and some active arrays, undertook the needed repair in preparation for installing a Federation continuous recording system at the site similar to that already operating at Pt. Sur (see below). The cable had to be exposed in a 4x4x25 foot trench and repairs to the cable were made using some old SOSUS cable found in a nearly forgotten site in the jungle. Although the cable is basically coaxial, there are several layers (about 10) that include lead and mu metal. These layers were fabricated from raw materials (Figure 1). The cable has been repaired and the new recording system will be installed in the near future. We anticipate an at-sea repair to the array at Pt. Sur this summer at a cost of approximately $110,000 and more of these will need to be done during the next several years at other arrays.

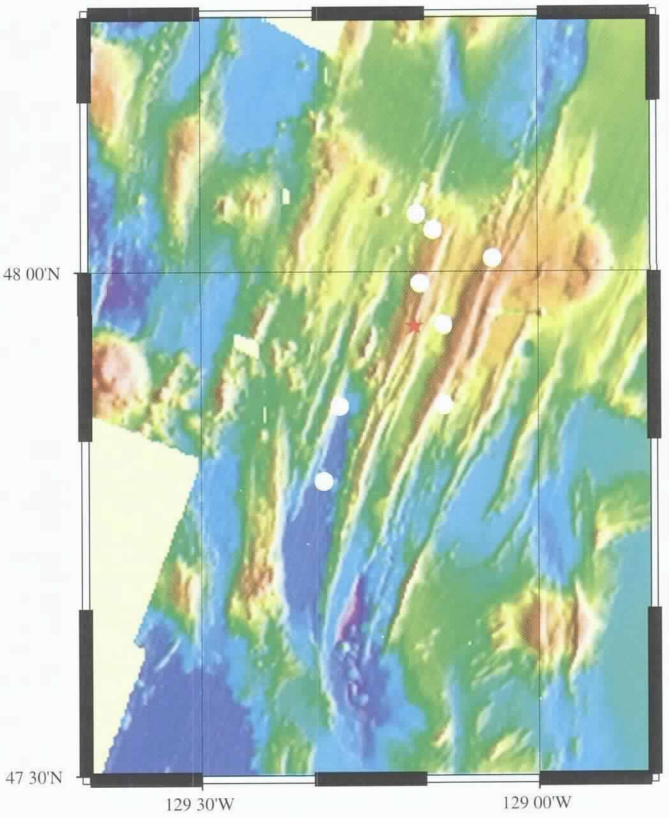


Figure 2: Eight epicenters on the Endeavor Segment of the Juan de Fuca Ridge. The red star is the mean location of these large earthquakes.

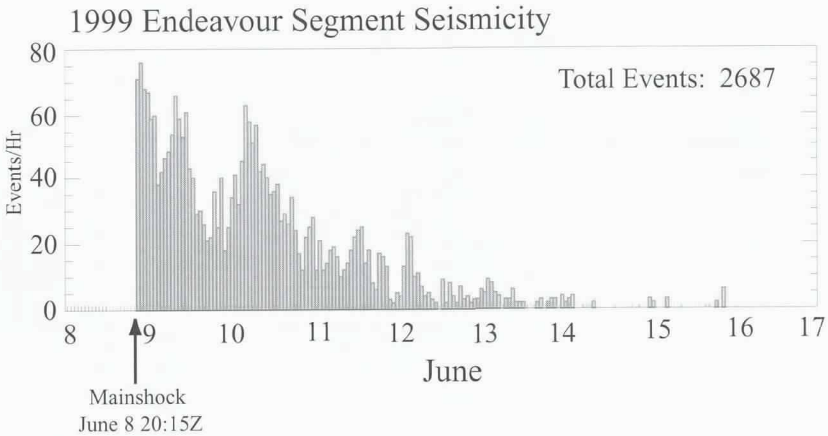


Figure 3: Histogram, by day, of earthquakes for the period 8-17 June 1999. The largest events are plotted in Figure 2.

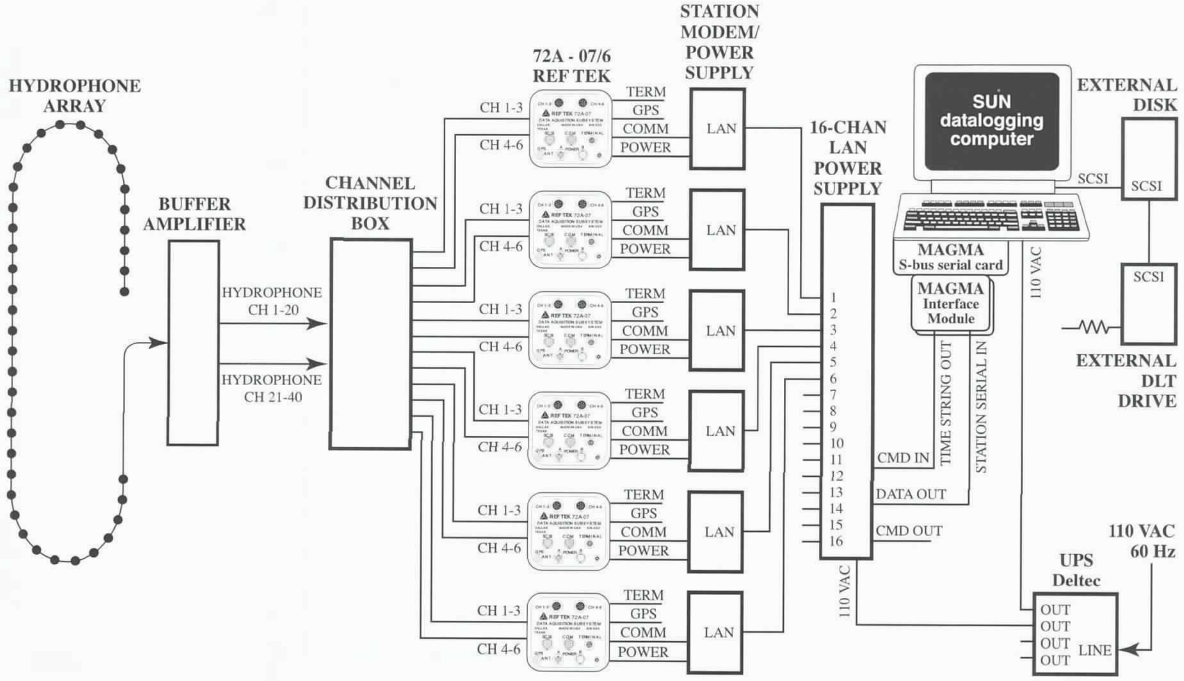
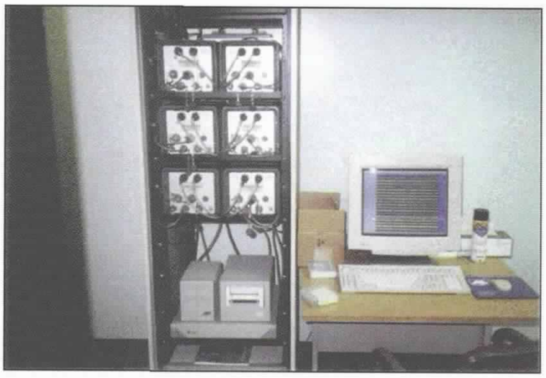


Figure 4: The Ocean Acoustic Observatory Federation SOSUS array recording system based on commercial off-the-shelf (COTS) hardware. The high-resolution (24-bit) system cost, for a single array, is approximately $100,000.

Earthquake and Volcano Monitoring

NOAA/PMEL has been using several SOSUS stations in the northeast Pacific for several years now to locate earthquakes and volcanoes on the Juan de Fuca ridge as part of the NOAA Vents program (e.g. Fox and Dziak, 1999). Seismic stations on land are far too insensitive for this task and, furthermore, are biased by the ocean-continent differences and asymmetry. Since its inception, the NOPP Federation grant has been providing the funding to continue these measurements. Figure 2 is an epicenter map showing the distribution of the eight largest (M≈4) earthquakes detected (white dots) and the mean location of these events (red star). The distribution of seismic events in time is shown in the histogram in Figure 3 (Johnson et al., 2000). The earthquakes were followed 4 to 11 days later by a significant increase in fluid temperatures at the along-axis hydrothermal vent field, which evolved into large-scale temperature oscillations. This extreme temperature instability in the tectonically-disturbed hydrothermal system may indicate either geyser-like behavior driven by the temporary formation of a sub-surface gas phase, or may be due to the episodic propagation of a cracking front associated with cold seawater penetrating into the newly-exposed hot crustal rocks. This facility has been invaluable to the NSF RIDGE program in developing an understanding of the episodicity of volcanic activity at mid-ocean ridges and has provided the informa-



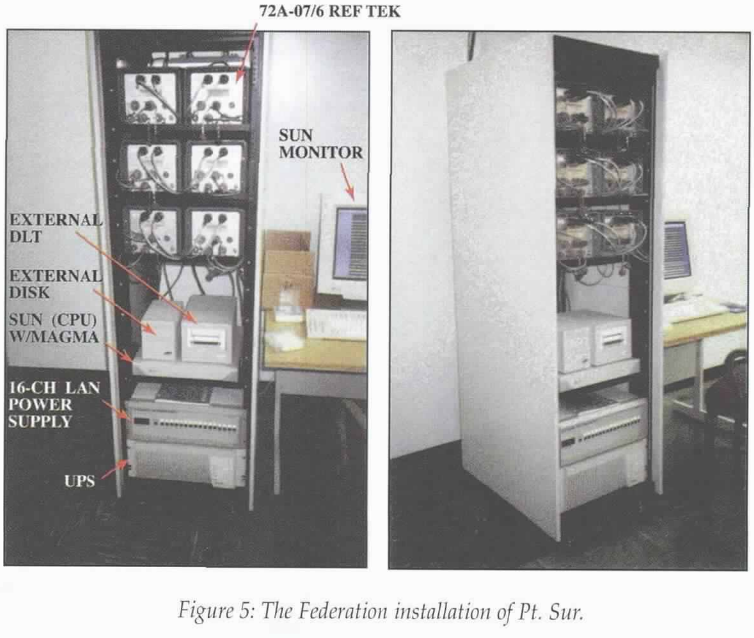


Figure 5: The Federation installation of Pt. Sur.

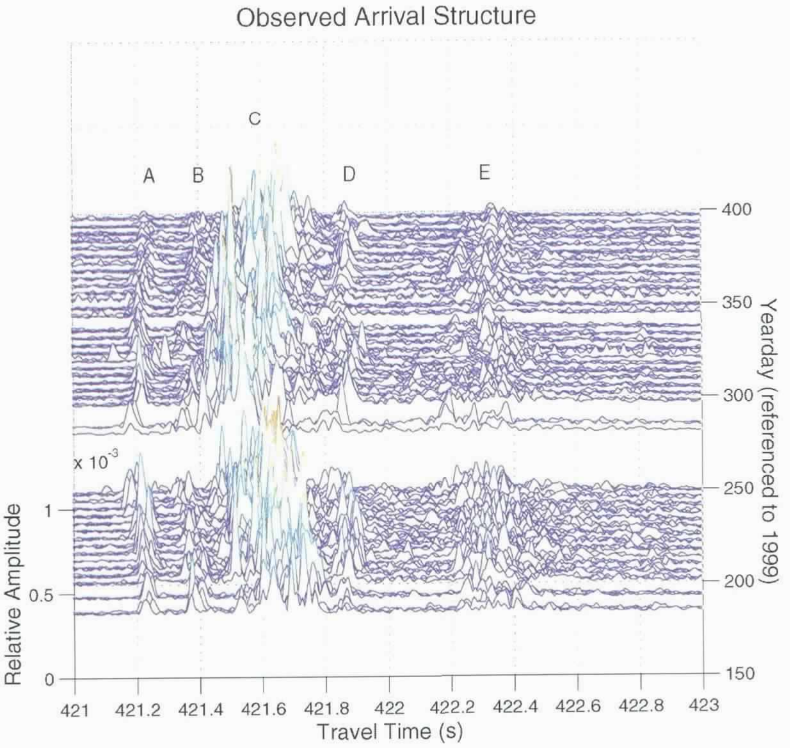


Figure 6: Arrivals from an acoustic source on Hoke Seamount to the SOSUS array at Pt. Sur.

tion needed to respond quickly to volcanic eruptions for detailed measurements and sampling. The facility has become critically important to the basic research community. Maintaining the ability to make these measurements on a long-term basis is essential.

SOSUS Station Upgrades and Recording

Modern electronics have greatly increased reliability and enhanced quality while at the same time, decreased costs. The loss of operational goals for the systems and this electronics revolution, have decreased the operations and maintenance costs for SOSUS by orders of magnitude.

The Federation, through Scripps, has developed a high resolution recording system to digitize and record the output from SOSUS arrays. The installation at Pt. Sur is maintained by the Naval Postgraduate School and the data are archived at the Scripps Marine Physical Laboratory (MPL). Additional installations will be completed in the near future at Barbers Point (see above) and at San Nicolas Island. Figure 4 is a schematic of the recording system based on commercially available equipment also used widely in the NSF's global seismic network and the portable instrument PASSCAL program. The core of the system comprises six REF TEK® digital acquisition systems (DAS; see http://www.reftek.com/). Each DAS digitizes six channels at 200 samples/s with a resolution of 24 bits and a dynamic range of 132 dB. The buffer amplifier, designed, constructed and installed by UW/APL provides isolated connections to each hydrophone for a variety of purposes. The output of each of the DAS is placed on a local area network (LAN) and operations and recording are managed by a low-end SUN workstation. The data are recorded on DLT (digital linear tape) tape and are shipped weekly to SIO/MPL; Figure 5 shows the physical installation. Similar systems are used in seismic applications on continents and have proven to be highly reliable. The software which operates the system is another commercial product—Antelope®. Antelope (see http://www.kinemetrics.com/index.html) is a UNIX distributed, open system which makes use of a relational database to manage the real time data. While the application for SOSUS data collection is operated as a closed, local system, the software is normally used to provide real time data using ordinary Internet connections including wireless and satellite applications. The reliability of all these systems can be enhanced enor-

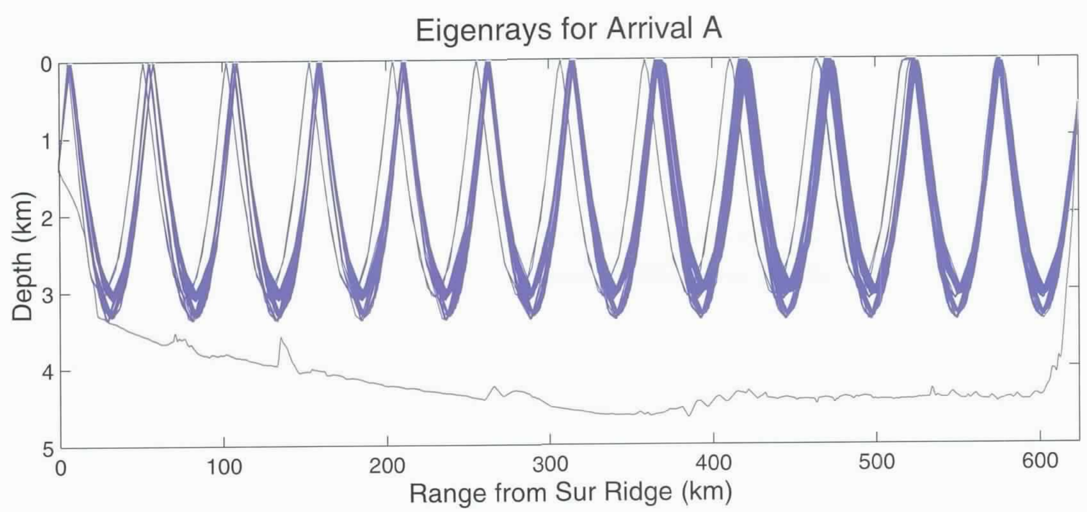


Figure 7: Ray geometry for Group A arrivals in Figure 6.

mously by the use of low-cost satellite telemetry. Only the data classification complicates this transition.

Acoustic Tomography

Acoustic methods can be used to infer average temperature profiles over great distances because sound speed increases with temperature. The determination of travel times to milliseconds accuracy over baselines of thousands of kilometers has allowed temperature estimates to be made to millidegree accuracy.

Early in 1999 an HLF-5 acoustic source was installed on Hoke Seamount southwest of Pt. Sur (Onofre et al., 2000). The source was configured to transmit M-sequence signals every fourth day (Morvillez, 1997). During the transmission days, the signals are sent at 4-hr intervals. The pulse-compressed signals are shown in Figure 6 and span the interval from year day 185 (5 July 1999) to year day 397 (2 February 2000). Electrical power problems were experienced at Pt. Sur from year day 250 to 300. There are five groups of arrivals (A, B, C, D, and E) and the initial arrival, which samples the upper 3 km of the water column, decreased by 80 ms from year day 200 through 255 (the summer months). This decrease in travel time may be due in part to clock drift in the autonomous source, which cannot be corrected until after recovery of the instrument. If entirely due to temperature, this decrease corresponds to a 0.06°C increase in the path-averaged water temperature. Cooling of the ocean interior began near year day 300 as indicated by the increase in travel time. The cooling appears to occur in two steps, one in November and then in January 2000. The predicted structure is very similar to that observed including the five different arrival groups. Figure 7 depicts the ray geometry for the A bundle, responsible for the arrivals in A. All of the eigenrays have similar geometry although the interactions of the rays with the continental margin, on which the SOSUS array is deployed, give rise to micro-multipaths which broaden the times of arrival in A. An inversion scheme is being developed which can account for the phase interference of the multipaths.

Excitation and Propagation of T-Phases

Research groups at SIO (e.g. deGroot-Hedlin and Orcutt, 1999) and UW/APL (Park, Soukup, Odom; e.g. Park and Odom, 1999) have been pursuing complementary paths to understanding the excitation and propagation of T-phases. Although T-phases were first identified almost fifty years ago, their excitation has not been adequately explained. We have found that realistic T-phase recordings can be computed by expressing the acoustic energy in terms of several low order modes excited by energy scattered from the seafloor. Once the energy is in the sound channel, it is able to propagate with very little loss across great distances. The oceans thus provide a window on seismicity, tectonics, and volcanic behavior simply not available on the continents.

We have synthesized T-phases by breaking the seafloor near an earthquake into a grid of points and computing the travel time and amplitude for each point. The amplitude is split into three parts—spread-

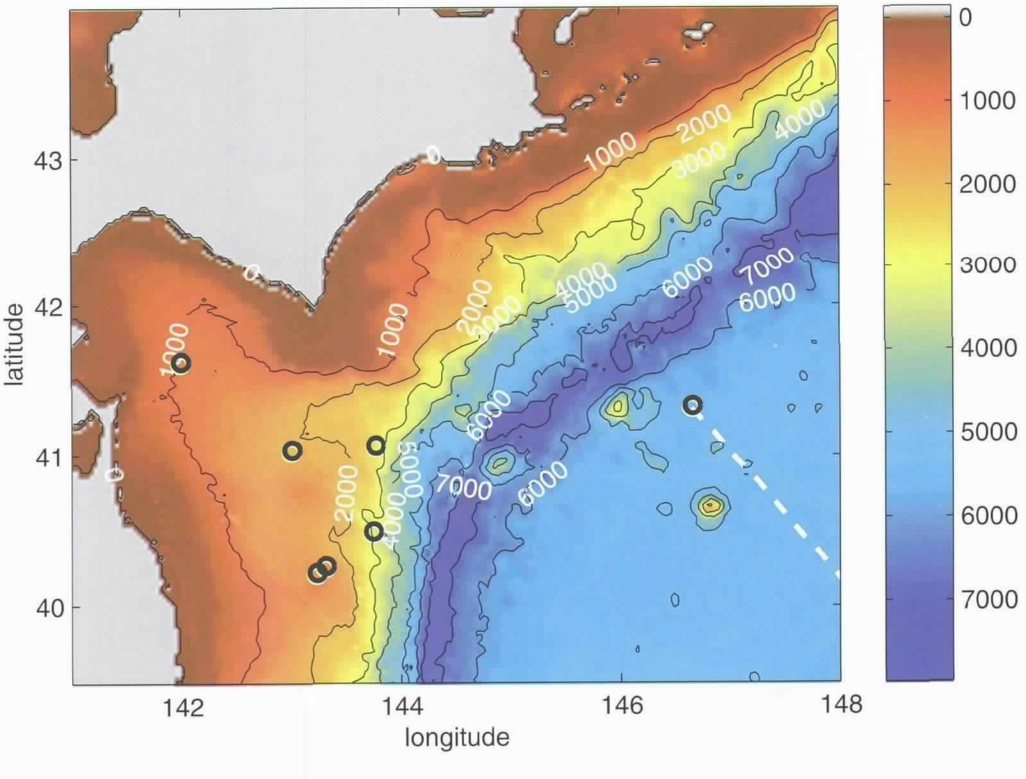


Figure 8: Bathymetry in the northwest Pacific with a ray path drawn from the epicenter to a SOSUS hydrophone. The depth of the source is 80 km.

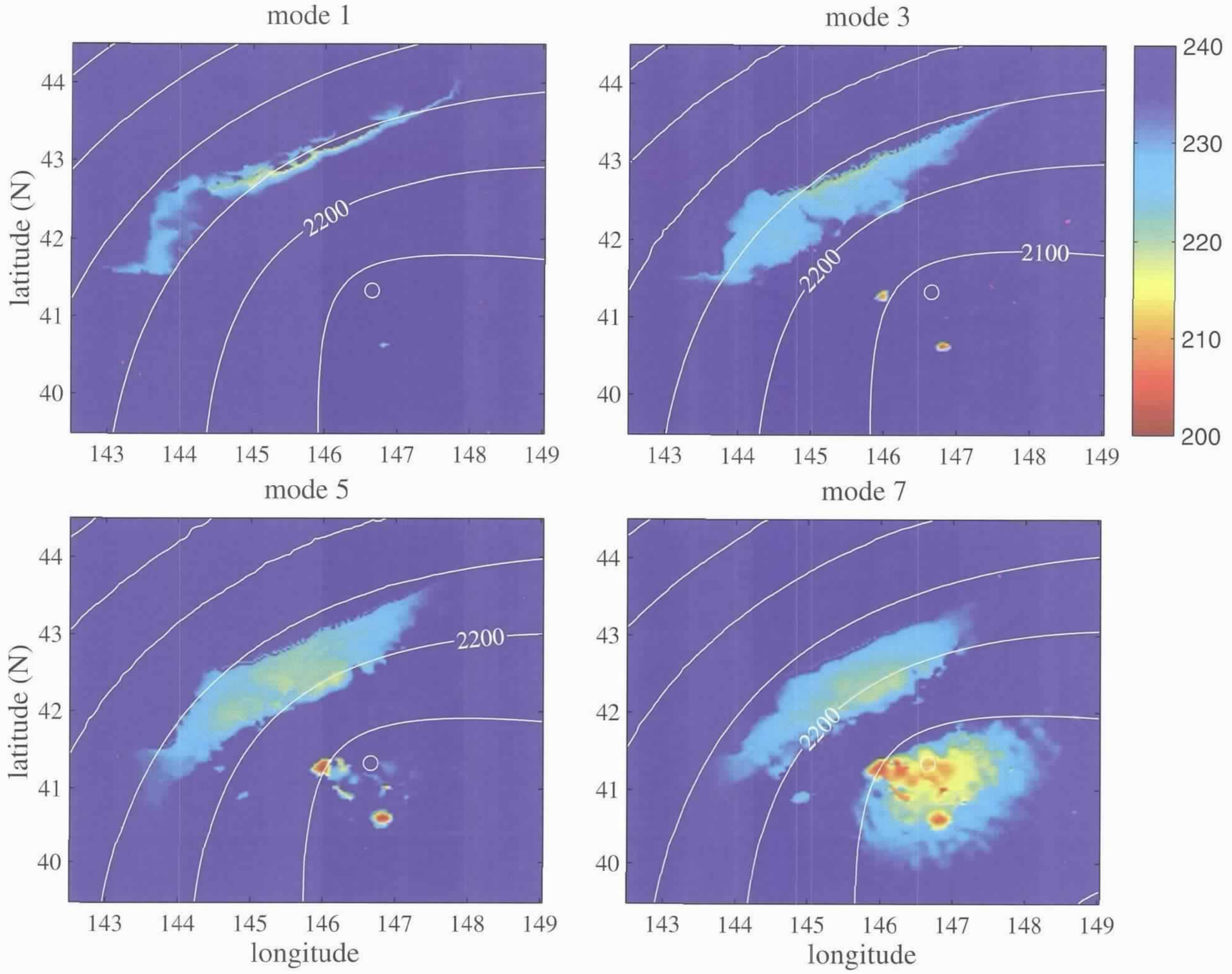
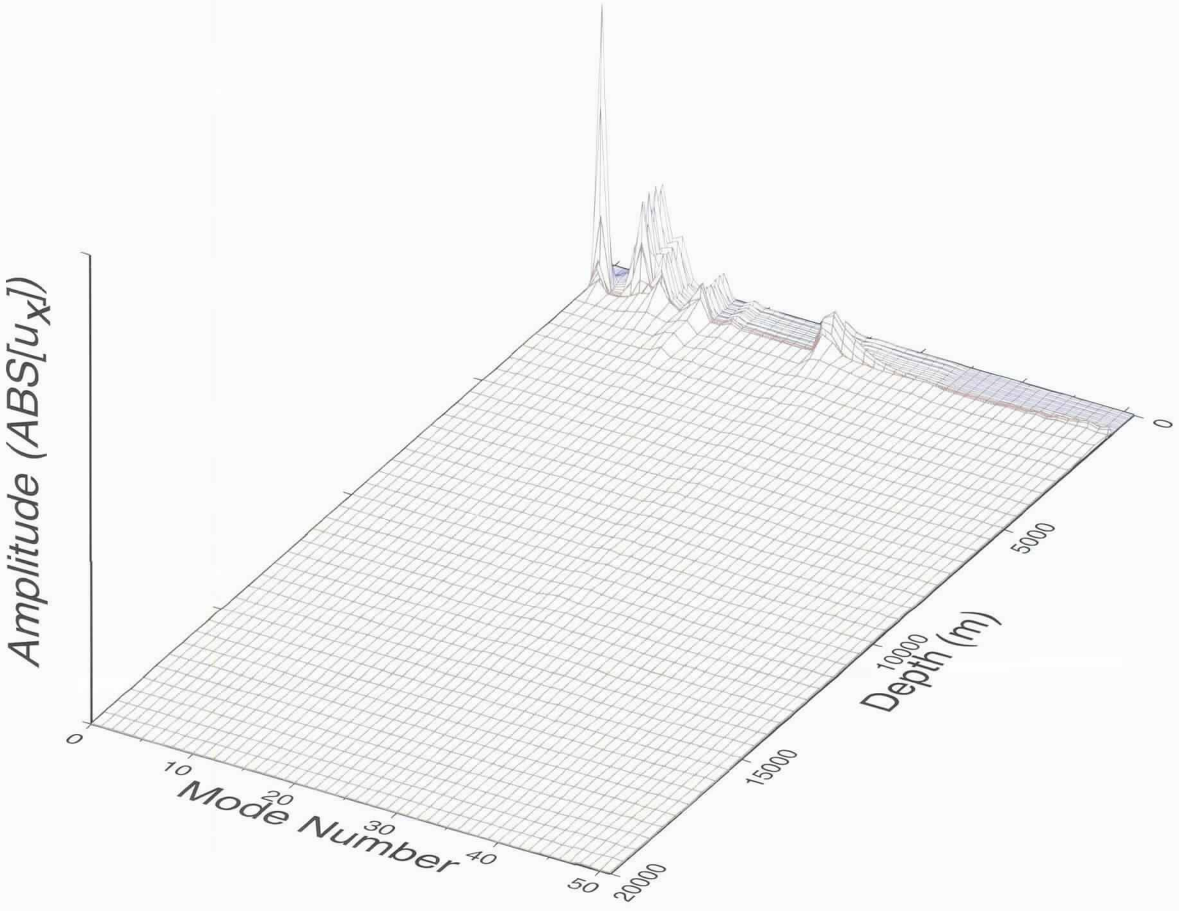


Figure 9: The excitation of several low-order modes by scattering from the seafloor. Only the highest order modes are excited at the seafloor immediately above the source.

ing losses in the crust and mantle, the efficiency of seismic-to-acoustic coupling at the seafloor, and the transmission loss from the seafloor to the receiver. The acoustic energy can be expressed in terms of modes in the water column. The amplitude of the lower order modes is a maximum in the sound channel and decays rapidly with depth. Only higher order modes have significant amplitudes at depth. Generally, the lower order modes are excited only when the bathymetry is shallow and actually extends into the sound channel. However, even in deep water higher order modes are excited and can propagate to great distances. This is most easily shown in a test example.

Figure 8 shows the bathymetry near an earthquake epicenter while Figure 9 shows the excitation of several low order modes from that event. Note that the gravest modes are excited by scattering from shallow topography while the higher order modes are excited even in the deep ocean. This is precisely the behavior anticipated in the paragraph above. The resultant wavetrains are considerably extended in time and show the excitation of both slope (shallow bathymetry, lower modes) and abyssal (great depth, higher modes) waveforms. These computations, however, are highly simplified, especially with respect to the behavior of the earthquake source and the propagation of elastic waves. The team at UW/APL has developed a scattering model which couples modes excited by a standard earthquake source to modes propagating in the ocean including the propagation of both shear and compressional elastic waves—the complement of the research at Scripps. Figure 10 shows the result of multiplying the scattering matrix with the matrix representing the modes excited by the earthquake. The lowest order modes at the far left corner, 1 and 2, are only very weakly excited because they have very small amplitudes at the bottom while some of the higher order modes with large amplitudes at greater depths, are well excited. During the coming year, the combination of the codes developed within the Federation will allow, for the first time, the



Model: vel_model98x2 (5 Hz) **Event:** 950709_0618_Blanco_TFZ
Moment Tensor: T = (5°,267°), N = (59°,167°), P = (31°,360°), depth z = 9.0 km

Figure 10: Ocean modes excited by an earthquake source on the Blanco transform fault in the north Pacific at a depth of 9 km.

prediction of amplitudes and travel times of T-phases arriving at a SOSUS station. This will open up many new opportunities for research using T-phases and contribute substantially to our ability to monitor potential nuclear explosions using these tools.

Conclusions

The Federation has shown that data collection from retired SOSUS arrays in the Pacific is practical, inexpensive and able to provide unique data relevant to a variety of scientific problems. The maintenance of these arrays remains problematic beyond the lifetime of this grant including the continuation of the earthquake and volcano monitoring on the Juan de Fuca Ridge. In addition, the data collected remain classified which restricts greatly the number of scientists who are able to work closely with the data collected. Nevertheless, the data collected by this project represent the only legacy of the long-term investment in SOSUS and are invaluable for understanding many ocean processes from volcanoes to ocean climate. The NOPP, as it contemplates an Integrated Ocean Observing System (IOOS), must consider a mechanism whereby such long term measurements can be sustained.

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