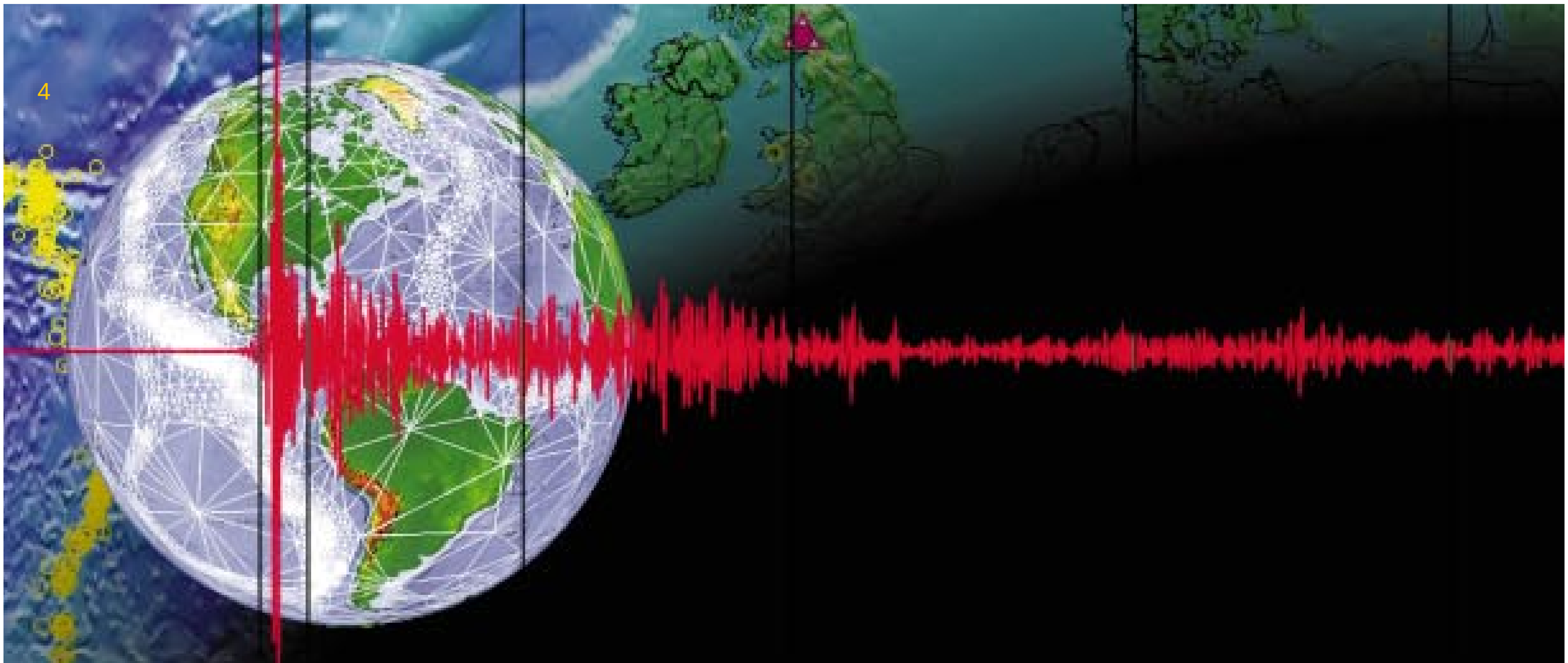


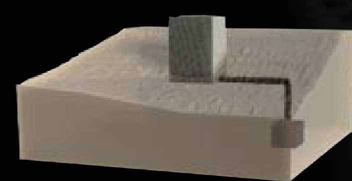
Forensic Seismology Supports the Comprehensive Test Ban Treaty

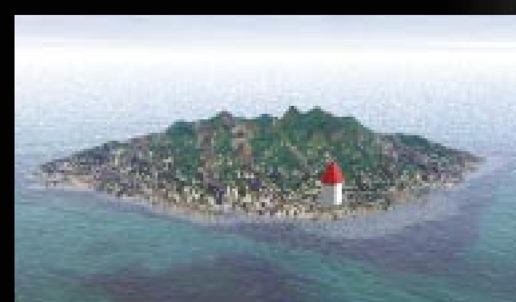
Some 53 years after the first nuclear explosion, a team of Livermore researchers is helping the nation prepare for the Comprehensive Test Ban Treaty by developing methods to detect clandestine nuclear tests.

THE nearly worldwide condemnation of India's and Pakistan's unexpected nuclear tests in May was a telling indicator of the determination of nearly all nations to put an end to nuclear testing. That determination is embodied in the Comprehensive Test Ban Treaty (CTBT), signed in 1996 following a half-century of passionate discussions, various proposals, and international research to ensure that attempts to evade the treaty would be detected.

The CTBT forbids all nuclear tests, including those intended for peaceful purposes, and creates an international monitoring network to search for evidence of clandestine nuclear explosions. The agreement—signed by President Clinton but still to be ratified by the U.S. Senate—is of profound interest to dozens of scientists at Lawrence Livermore. They have worked over the past several years to support American diplomats in achieving this international agreement backed by sound monitoring and verification measures. Lawrence Livermore scientists have developed monitoring technologies in support of nuclear treaties and have outstanding credentials in providing technological support to treaty negotiations and verification. (See the box on p. 7.)

The CTBT's International Monitoring System will consist of a





network of automated scientific instrumentation stations, secure communications links, and the International Data Center based in Vienna, Austria. The monitoring stations (many of which already exist) will consist of 170 seismic stations to record underground pressure waves, 60 infrasound stations to record low-frequency sound waves in the air, 11 hydroacoustic stations to record underwater sound waves, and 80 radionuclide stations to record airborne radioactive gases or particles (Figure 1).

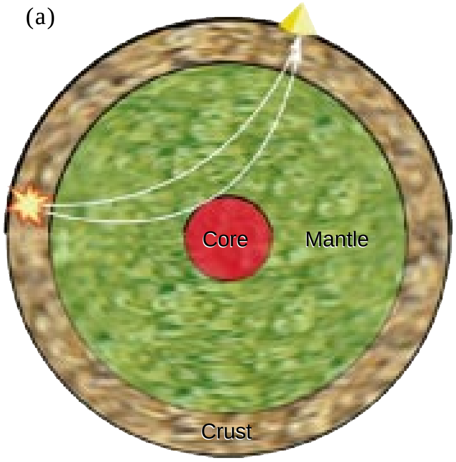
Each day, these stations will transmit enormous amounts of data via satellite to the International Data Center in Vienna, which in turn distributes it to national data centers around the world. Computers at the international center will process the raw data, associate segments of the data stream with specific events, and estimate the location of those events. Analysts will then review the processed data and send a daily bulletin to all parties to the treaty.

In turn, national data centers will have the responsibility to make judgments about the true nature of any suspect events. These national centers will have access to all raw data available at the international center. They will also have the right to use their own computer analyses, informational databases, and data gathered by their own technical resources. Most importantly, each nation will apply its own criteria for distinguishing between compliance and noncompliance.

The U.S. National Data Center at Patrick Air Force Base in Florida is the facility responsible for American monitoring of the treaty. The U.S. Department of Energy, in light of its extensive experience in making seismic and other measurements of nuclear tests, is providing data analysis, algorithms, and technology needed for the national center to reach the low monitoring thresholds required to meet the U.S. goals. DOE's research program focuses on advances in methods to precisely detect, locate, and characterize events in key areas of interest. The program draws upon the strengths of major universities, private contractors, and DOE laboratories such as Lawrence Livermore, Los Alamos, Sandia, Environmental Measurements, and Pacific Northwest.

At Lawrence Livermore, a team of about 30 researchers has been helping to prepare the National Data Center for monitoring compliance with the future CTBT. Most team members are geologists, geophysicists, and seismologists from the Earth and Environmental Sciences Directorate, while others are from the Computation, Engineering, and Chemistry and

Figure 1. The CTBT's International Monitoring System will consist of automated radionuclide, infrasound, seismic, and hydroacoustic stations. Together, they will monitor for evidence of clandestine nuclear explosions.



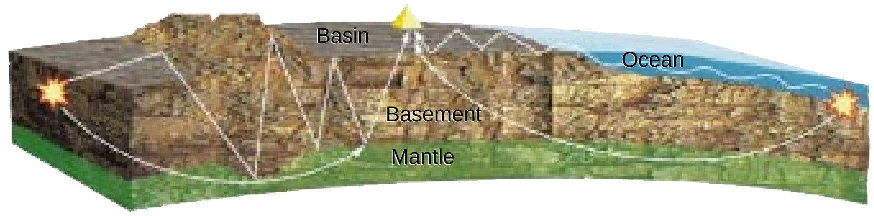


Figure 2. (a) Seismic signals from most nuclear tests under the current Threshold Test Ban Treaty (banning nuclear explosions above 150 kilotons) travel thousands of miles through Earth's relatively homogeneous lower mantle and core and are detected by far-away seismic stations. (b) Under the CTBT, a nation attempting to conceal a test would presumably detonate a much less powerful warhead. Signals from such an event would be confined to Earth's upper mantle and crust, a region that readily distorts the signals.

Materials Science directorates. The team's work supports the Laboratory's Nonproliferation, Arms Control, and International Security Directorate, which helps prevent the proliferation of weapons of mass destruction and assists in U.S. arms control matters.

For the CTBT, Livermore is carrying out field experiments, at sites ranging from the deserts of Jordan to the former Soviet nuclear test site in Kazakhstan, to document how regional geology affects the transmission of seismic signals. At the same time, Livermore specialists are developing powerful computer algorithms that calculate the degree to which measurements collected by seismic and hydroacoustic stations are altered by regional geology and how they compare with previous data from, say, regional earthquakes and mining operations (activities that can mimic small nuclear explosions). Finally, Livermore experts provide technical advice and expertise to U.S. negotiators and developed methods for international teams to use for on-site inspections. (See the box on p. 10.)

"Our goal is to achieve a very high level of confidence in the nation's ability to detect any clandestine nuclear explosion," says Livermore program leader Jay Zucca, a seismologist. Zucca notes that while DOE is the sponsor of this work, the primary user for the Livermore research program is the U.S. National Data Center. Livermore is also working closely with representatives of the Provisional Technical Secretariat (the international organization created by the treaty for its implementation) in Vienna in establishing the International Monitoring System and data center.

Meeting Monitoring Challenges

Zucca points out that under the current Threshold Test Ban Treaty (banning explosions exceeding 150 kilotons), determining accurate explosive yield is the critical issue. Most nuclear tests near the threshold treaty's limit generate seismic magnitudes of about 6 or greater on the Richter scale. Seismic signals from these tests travel thousands of miles through Earth's relatively homogeneous core and mantle and are readily picked up by far-away seismic stations for relatively straightforward characterization (Figure 2a).

Under the CTBT, however, the critical issues will be to determine that a nuclear explosion—no matter its size—took place and to pinpoint its location accurately. A nation attempting to conceal a test could attempt to minimize the seismic signals. Such signals from a small nuclear test could be well below magnitude 4, with resulting measurable signals traveling 1,000 miles or less. What's more, the signals would likely be confined to Earth's upper mantle and crust, an extremely heterogeneous environment that distorts, and even blocks, parts of the signals (Figure 2b).

Accurately locating and characterizing signals at these so-called regional distances pose a significant challenge, says seismologist Bill Walter. "It's a much harder job because we can't use global models of Earth. We have to calibrate region by region, seismic station by seismic station." Successfully meeting the regional distance challenge, says seismologist Marv Denny, has been the most difficult aspect of the Livermore effort over the past several years.

Denny says that complicating the task is the huge number of events that, at first cut, can resemble a small nuclear detonation. Stations will be recording a constant stream of background noise that includes earthquakes, lightning, meteors, sonic booms, navy armament testing, mining explosions, construction activities and other industrial operations, nuclear reactor operations and accidents, natural radioactivity, and even strong wind and ocean waves.

"As we consider the possibility of smaller and smaller clandestine tests, the

The Road to a Comprehensive Test Ban Treaty

Awed by the destructive power of nuclear weapons, scientists and others began discussing banning further weapons tests shortly after Trinity, the first test of a nuclear explosive in 1945. Since then, a succession of treaties has slowly narrowed the lawful testing environments. For example, the Limited Test Ban Treaty, ratified in 1963, banned nuclear explosions in the air, oceans, and space, while the Threshold Test Ban Treaty, ratified in 1988, limited underground nuclear weapon tests to 150 kilotons.

The Comprehensive Test Ban Treaty was signed by President Clinton and other heads of state on September 24, 1996, at the United Nations, following two years of international negotiations. In signing the treaty, President Clinton used the same pen President John F. Kennedy used to sign the Limited Test Ban Treaty. Following the signing ceremony, the President told the United Nations General Assembly that the treaty "points us toward a century in which the roles and risks of nuclear weapons can be even further reduced—and eventually eliminated."

As of mid-1998, the treaty has been signed by 149 nations and ratified by 13 nations. The treaty will not enter into force until ratified by the 44 nations named in the treaty that possess nuclear reactors. The U.S. has signed but not ratified the treaty; three other named nations—India, Pakistan, and North Korea—have neither signed nor ratified the treaty.

Under the treaty, each nation undertakes "not to carry out any nuclear weapon test explosion or any other nuclear explosion, and to prohibit and prevent any such nuclear explosion at any place under its jurisdiction or control." Each party also undertakes "to refrain from causing, encouraging, or in any way participating in the carrying out of any nuclear weapons test explosion or any other nuclear explosion."

Other articles of the treaty describe the international monitoring system, on-site inspections, confidence-building measures, organization of the treaty's executive council and the technical secretariat, and measures to redress violations. (The main text of the treaty may be viewed at *http://www.acda.gov/treaties/ctbt.htm*.)

An international organization, the Preparatory Commission in Vienna, Austria, was established in November 1996 to create the international monitoring and verification regime.

number of background events, both natural and human made, becomes immense," says Walter. For example, more than 200,000 earthquakes similar in seismic magnitude to a small nuclear explosion occur in the world every year. Many of these background events can be disregarded because of their depth or similarity to other events known to be nonnuclear. However, many will not be identified so readily. As a result, the National Data Center will require a set of tools, largely data-processing software, modeling capability, and reference databases, to perform what Walter terms "forensic seismology" to separate a weak potential nuclear test from background noise.

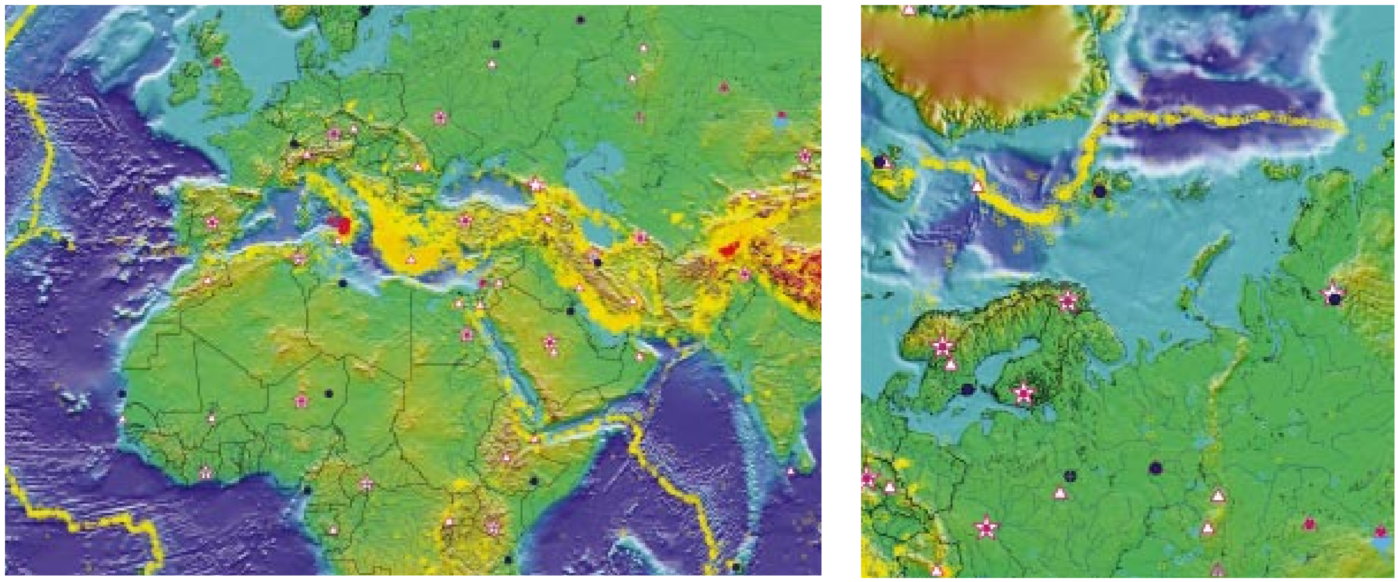
One essential tool will be a comprehensive database that includes seismic patterns and the location of mines and seismically active regions. This database must also include information on how Earth's crust and mantle affect the travel time and amplitude of seismic signals as they make their way to international stations. "We want to be sure that data relayed by individual stations are interpreted in light of their regional settings so that the location and nature of an event are properly determined," says Zucca.

Building the Knowledge Base

The DOE is assembling such a database, called the Knowledge Base, to manage, store, and retrieve vital information about major areas of the world. "A key Livermore product for the National Data Center is our contribution to the Knowledge Base," says Zucca. While the Knowledge Base includes information from all four sensor technologies, it is dominated by hydroacoustic and seismic data, considered the most essential for interpreting events in their regional context.

The Livermore team has been assigned by DOE to focus largely on the Middle East and North Africa (called MENA) and the western part of the former Soviet Union, which includes the former Soviet test site at Novaya Zemlya, near the Arctic Sea (Figure 3). The work has entailed collecting and organizing large quantities of geological, geophysical, seismological, and human-activities data within these areas. The task is complicated by the geological diversity of MENA and by the lack of "ground truth," that is, seismic data from well-documented earthquakes, mine explosions, or explosions carried out for seismic calibration purposes.

Obtaining needed ground truth has prompted several avenues of research. Geologist Jerry Sweeney, for example, is researching published literature for reports of earthquake aftershock studies from Iran, Algeria, and Armenia. Other researchers have deployed temporary stations in areas awaiting the construction of permanent international stations to record background seismic activity so that they can determine how the regional geology affects the seismic readings. Last April, engineer and seismologist Dave Harris traveled to Jordan to set up two temporary seismic stations in cooperation



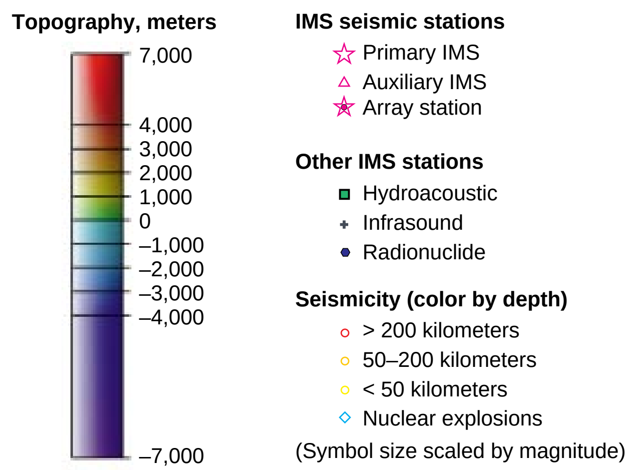
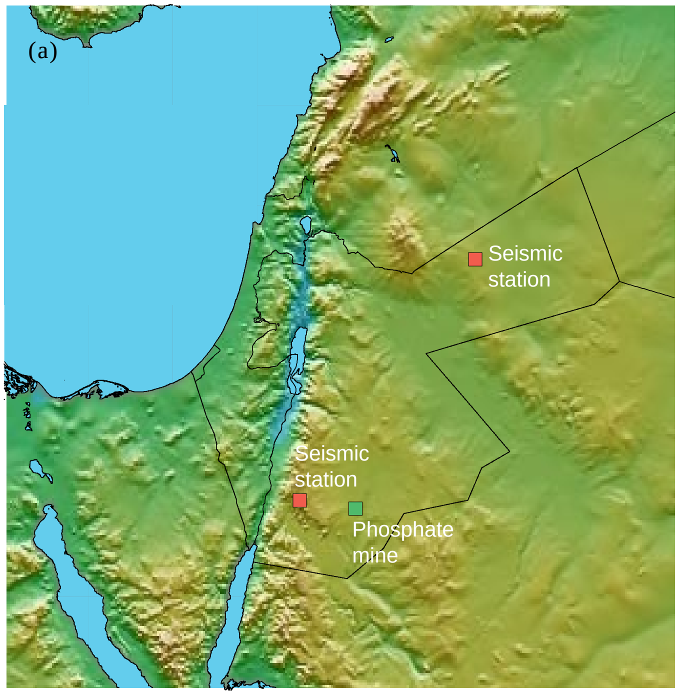


Figure 3. Livermore researchers are focusing on (a) the Middle East and North Africa and (b) the western part of the former Soviet Union, which includes the former Soviet nuclear test site at Novaya Zemlya. The locations of seismic, hydroacoustic, infrasound, and radionuclide monitoring stations for the International Monitoring System (IMS) are shown for both areas. The historic seismic record is plotted using a scale determined by the depth of the seismic signal. Past nuclear explosions (many of them for peaceful purposes) are denoted by blue diamonds. (Maps created by Livermore scientist Bill Walter.)

with the Jordanian Natural Resources Authority to record the seismic signatures of earthquake activity and nearby phosphate mining operations (Figure 4). “These extra stations provide additional constraint on the locations of earthquakes in the region and provide us with higher quality ground truth,” explains Harris.

Aiding the MENA effort is an ongoing Livermore study of earthquakes and underground explosions around the Nevada Test Site. Livermore researchers are comparing seismograms of underground nuclear tests conducted in 1992 (the last year of American nuclear testing) with several moderate local earthquakes in the same year. They also participated in a DOE test at the site in 1993 (called the Non-Proliferation Experiment) involving a kiloton of chemical explosive. The test revealed that seismic signals from an underground chemical blast closely mimic the signals that would be expected from an underground nuclear test.

Zucca notes that potential treaty violators might be tempted to detonate a nuclear device in the center of a large underground cavity, a technique called decoupling. The seismic signal from such a test is reduced by a factor of up to 70 through a muffling effect that reduces the amplitude of the signal. A 1-kiloton nuclear explosion, for example, would produce a magnitude in the range of approximately 2.5 to 3 on the Richter scale when tested in a large underground cavity. Seismic signals of the lower magnitude are produced frequently in a large number of mine explosions worldwide, and many thousands of earthquakes are in this range.



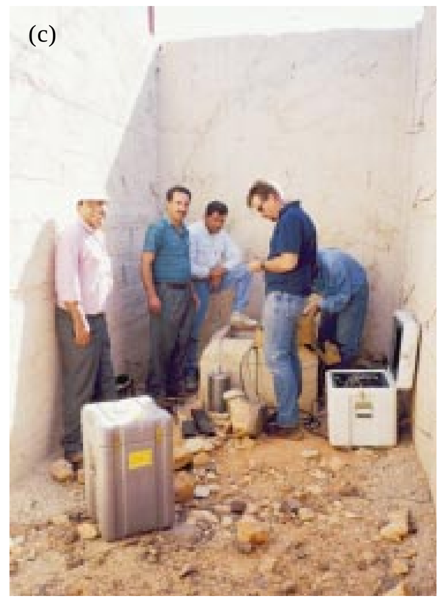


Figure 4. Livermore and Jordanian researchers recently established two temporary seismic stations in Jordan to record the seismic signatures of background earthquake activity and of explosions from phosphate mining activities from operations at the Eshidiyah phosphate mine. (a) Map of the area showing the location of the phosphate mine and seismic stations. (b) Outside view of the seismic station nearest the mine. (c) Inside view of the seismic station.

Livermore scientists have investigated the signal effects possible with blasts conducted in cavities formed from different rock types. Researchers have also attempted to gain a more complete understanding of the seismic signals caused by routine mining operations. They have joined with colleagues from the U.S. Geological Survey and Russian scientists to calibrate seismic wave propagation in regions of the former Soviet Union. Livermore scientists have also monitored different types of seismic signals from operations in mines located in Wyoming, Colorado, and Nevada.

Determining Underwater Events

While seismic network research is progressing along many fronts, several Livermore specialists have devoted their energies to advancing hydroacoustic monitoring technology. They have combined fundamental research on detecting the propagation of underwater sound waves with contributions to the Knowledge Base's storehouse of underwater signals from earthquakes, volcanoes, shipping activity, and chemical explosions from military testing. "A lot of background underwater events have to be taken into account," says seismologist Phil Harben, although he notes that they are not as pervasive as land activities such as mining.

Aiding Livermore's understanding of ocean signals is an automated data-acquisition facility on San Nicolas Island off southern California. Data from this station permit researchers to check computer models and conduct research on the sensitivities of island seismic stations and offshore hydrophones to water-borne signals.

The database of nuclear explosions at sea is limited to a few tests carried out years ago by the agencies preceding the DOE. Because data are so limited, Livermore scientists have developed a calculational capability to predict the effects of underwater nuclear explosions. They used this capability to provide diplomats with options for hydroacoustic networks. They also provided analyses showing the economic advantages of fixed hydroacoustic stations (connected by cable to recording sites on land) over unmoored, floating buoys. On the basis of this work, a network of six hydrophones and five island seismometers was chosen as the international system to detect and locate underwater explosions and, in some cases, explosions in the low atmosphere.

The network takes advantage of the fact that underwater explosions generate acoustic waves (in the frequency range of 1 to 100 hertz) that can travel completely across an ocean basin—in some cases, more than

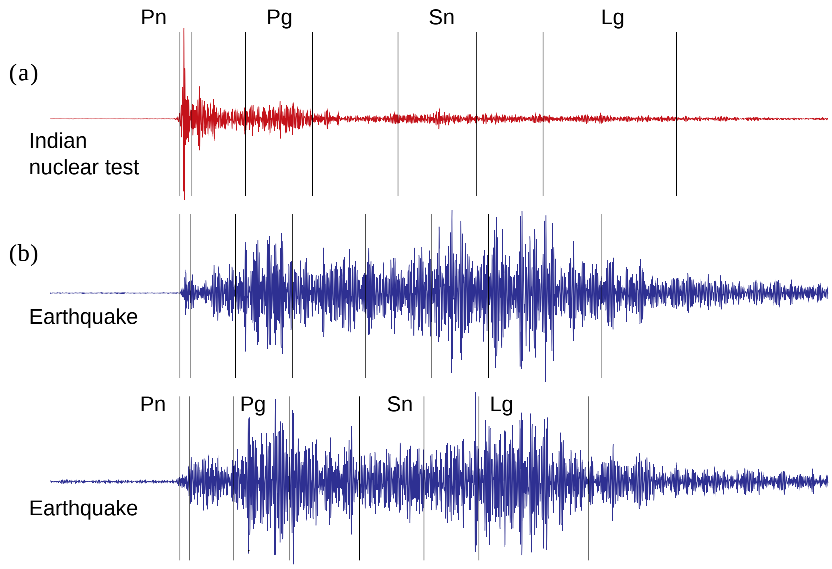


Figure 5. An international monitoring station in Pakistan detected the Indian nuclear test of May 11, 1998, about 740 kilometers away. (a) Analysis of the seismogram showed a P-wave-to-S-wave ratio strongly indicative of an explosion and not (b) nearby earthquakes.

When Monitoring Stations Aren't Enough

Under the terms of the Comprehensive Test Ban Treaty, a nation suspecting another of conducting a nuclear test may request that the treaty's 51-member Executive Council conduct an on-site inspection to determine the nature of the suspect event. The requesting nation may introduce evidence acquired on its own to strengthen its case to the organization. On-site inspections must be approved within 96 hours of receiving an inspection request because of the need to observe short-lived nuclear phenomena that are produced by a nuclear test.

Over the past decade, Lawrence Livermore experts have led the U.S. development of on-site inspection technologies and procedures; many of these procedures were eventually incorporated into the text of the treaty. Livermore seismologist Jay Zucca serves as the U.S. point of contact for the On-Site Inspection Experts Group that meets regularly in Vienna.

Zucca explains that a clandestine explosion may not necessarily form a telltale crater. In such a case, an inspection team will search for other evidence. For example, the team may deploy portable seismic equipment to detect very small aftershocks, collect samples of soil gases and water to look for radioactive materials, or search for an underground explosion cavity or rubble.

Livermore researchers have shown that low-frequency aftershocks associated with nuclear explosions may also be caused by mining operations. They compared aftershocks from the 1993 Non-Proliferation Experiment at the Nevada Test Site (in which 1 kiloton of chemical explosive was fired in an underground cavity) with those from routine operations at the Henderson Mine in Colorado. Although the events from both sources are similar, there are subtle differences in the aftershock signals. They were interested in the Henderson Mine because the caving operation is similar to the chimney formation following an underground nuclear event.

Also as part of the Non-Proliferation Experiment, Livermore experts found that very small amounts of rare radioactive gases such as xenon-133 and argon-37 generated in underground nuclear detonations can migrate toward the surface along natural fault lines and earth fissures in a time frame consistent with an on-site inspection. The technology used in these tests can be an extremely sensitive way to detect nearby underground nuclear explosions that do not fracture the surface. (See January/February 1997 *S&TR*, pp. 24–26.)

10,000 miles. The acoustic waves travel along the SOFAR (sound fixing and ranging) channel, described by Harben as “a wave guide for ocean acoustic energy that depends on temperature, density, and depth.” However, waves traveling in this channel can be blocked or weakened by land masses and regions of shallow or cold water. Livermore modeling of the properties of this channel during CTBT negotiations was important in determining the global distribution of hydroacoustic stations.

Refining Algorithms

A major effort of the National Data Center will be the automated analysis of data obtained from the international center, supplemented by data provided by other U.S. resources. Final reviews will be provided by analysts working with Knowledge Base data such as reference seismograms from historic nuclear events conducted in the area of a suspect event. Key to the automated process will be several algorithms for determining the location and nature of an event. Livermore experts are using data gathered for the Knowledge Base—for example, underground signal travel times to each international station—to refine the algorithms.

As part of their algorithm work, an interlaboratory team headed by Livermore seismologist Craig Schultz made a fundamental advance in the field of kriging, a geostatistical estimating process. The advance enables the team to develop estimates of the level of confidence in the regional seismic properties derived from a few geographically isolated observations. Zucca describes the work as one of the key breakthroughs for the functioning of the Knowledge Base. It is likely, he says, that the approach taken by Schultz’s team for the algorithms will be adopted by seismologists everywhere for their own applications.

Key algorithms provide discriminants, characteristic features of a waveform (peak-to-peak distance, height, width, or some ratio). A particularly useful discriminant, for example, is the ratio of P-wave amplitude to S-wave amplitude. The P (or primary) wave is a compressional wave that is the first to arrive at a station. The S wave or shear wave has a slower propagation speed and arrives behind the P wave. The seismogram from the Indian nuclear test of May 11, 1998, as recorded by an international monitoring system station in Pakistan about 740 kilometers away, showed a P-to-S ratio strongly characteristic of an explosion and not an earthquake (Figure 5).

Zucca points out that the Indian test successfully demonstrated the capability of the international network. Based on Livermore’s work at other sites and current examination of events in this area, he is confident a potential nuclear explosion in key areas of interest can be detected and identified down to much smaller magnitudes. In other words, says Zucca, the world will soon have strong international monitoring and analysis capabilities to help determine international compliance with the Comprehensive Test Ban Treaty.

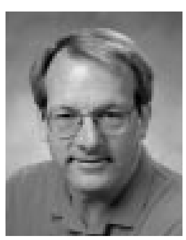
—Arnie Heller

Key Words: Comprehensive Test Ban Treaty (CTBT), discriminants, International Data Center, Knowledge Base, MENA (Middle East and North Africa) region, National Data Center, Nevada Test Site, SOFAR (sound fixing and ranging) channel, Threshold Test Ban Treaty (TTBT).

Editor’s Note: On p. 4, the image of the globe is courtesy of Sandia National Laboratories, the image of the radionuclide monitoring devices was provided by Pacific Northwest National Laboratories, and the image of the infrasound monitor was created at Los Alamos National Laboratory.

For more information contact Jay Zucca (925) 422-4895 (zucca2@llnl.gov). Information on DOE’s overall CTBT program may be found at **www.ctbt.rnd.doe.gov**.

About the Scientist



JOHN J. (JAY) ZUCCA, leader of Livermore’s Comprehensive Test Ban Treaty Program, joined the Laboratory in 1984. He has worked primarily for the Laboratory’s Treaty Verification Program, concentrating on seismic instrumentation development, on-site inspection, and regional seismology. He was a member of the U.S. delegation to the Nuclear Testing Talks (Threshold Test Ban Treaty) and a member of the U.S. delegation to the Conference on Disarmament for the Comprehensive Test Ban Treaty. He is currently a member of the U.S delegation to the Preparatory Commission for the CTBT. Zucca received his B.S. from the University of California at Berkeley and his Ph.D. from Stanford University. He completed postdoctoral positions at the U.S. Geological Survey in Menlo Park and the University of Karlsruhe in Germany.