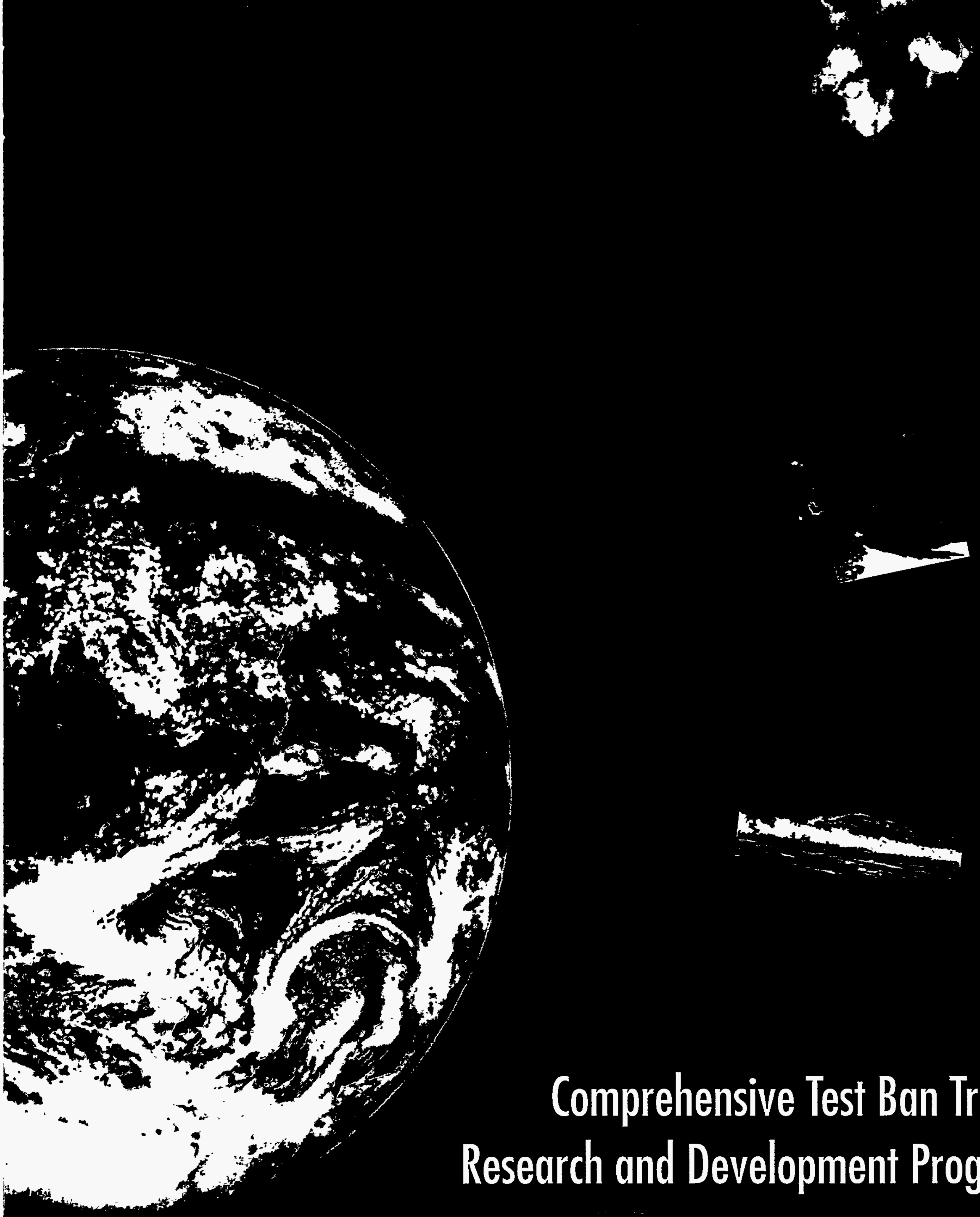

Comprehensive Test Ban Treaty Research and Development Program

U.S. Department of Energy

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> One of my administration's highest priorities is to negotiate a Comprehensive Test Ban Treaty. . . . I am committed to pursuing a comprehensive research and development program to improve our treaty-monitoring capabilities and operations.
>
> President Clinton
> August 11, 1995

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Research in Support the Comprehensive

The U.S. Department of Energy (DOE) has an active program* to provide technologies for monitoring and verifying a Comprehensive Test Ban Treaty (CTBT). DOE technologies will significantly increase the nation's capability to identify potential nuclear explosions with high confidence and with minimal false alarms. This report presents the highlights of the first year of this program.

The primary objectives of the CTBT monitoring system are to deter nuclear explosions in all environments (underground, underwater, or in the atmosphere) and, if such an explosion does occur, to detect, locate, and identify its source. The system is designed to provide credible evidence to national authorities to aid in resolving ambiguities and to serve as the basis for appropriate action.

To collect this evidence, we must develop technologies that can detect and identify the signals from a nuclear test against a background of hundreds of thousands of benign events. The monitoring system must have high sensitivity to detect the events of interest and, to minimize false alarms, it must identify those events with a high level of confidence.

All Environments Must Be Monitored

When a nuclear explosion occurs, a large amount of energy is released into the underground, underwater, or atmospheric environments, depending on where the explosion took place. The monitoring system will need to have sensors in all of these environments. When an explosion occurs on the interface between environments, signals may be detected on several systems, which can aid in interpretation. Appropriate technologies for international use include seismic, hydroacoustic, and infrasound signal detection, air sampling for radionuclide monitoring, and various techniques for on-site inspections.

Underground: The primary asset for detecting explosions in the underground environment is the global seismic network. This technology takes advantage of the seismic waves (in the frequency range of a few hundredths of a hertz to a few tens of hertz) that are created when an explosion is detonated underground. Because it will be important under the CTBT to be able to detect small explosions, seismic signals must be recorded at *regional* distances (less than 2000 kilometers from the source), since low-magnitude signals do not propagate well at teleseismic distances (more than 2000 kilometers). Seismic waves from these small events are trapped in the structurally complex crust and upper mantle of the earth, requiring new analysis

Joan B. Rohlfing

Director of the Office of Non-Proliferation and National Security

On August 11, 1995, President Clinton announced his decision to seek a true "zero-yield" Comprehensive Test Ban Treaty. The Department of Energy's national security mission and nuclear weapons design expertise uniquely qualify us to provide the science and technology necessary for monitoring and verification of a Comprehensive Test Ban Treaty. Improving treaty-monitoring and verification capabilities is a high priority within the Department. We look forward to meeting the challenges ahead.

Joan B. Rohlfing

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*See *Comprehensive Test Ban Treaty Research and Development FY95–96 Program Plan,* U.S. Department of Energy, Washington, DC, Report No. DOE/NN-0003 (November 1994).

# of Monitoring Test Ban Treaty

techniques to discriminate explosions from earthquakes.

Other monitoring techniques may also contribute in cases where an underground test is shallow or vents to the atmosphere. For example, air sampling for radioactive noble gases can help in detecting underground tests.

Underwater: The key assets for detecting and locating explosions in the oceans are hydroacoustic detectors placed beneath the sea surface and seismic detectors near shorelines. Underwater events generate acoustic waves (in the frequency range of 1 to 100 hertz) that can travel completely across an ocean basin. This very efficient propagation makes it possible to cover the ocean areas of the globe with a small number of detectors. In addition, radioactive gases produced in an underwater test will likely bubble to the surface and be carried by the wind to air-sampling systems.

Atmosphere: Atmospheric nuclear explosions can be detected by several methods. An explosion releases radioactive gases and particulates into the air. Wind can carry them thousands of kilometers to monitoring stations, where their radioactivity (gamma radiation) is measured. The explosion also generates heat and intense light as well as shock waves. Some of the explosion's energy produces sub-audible pressure waves (in the frequency range of a few hundredths of a hertz to a few hertz) that can travel several thousand kilometers and be detected at infrasound stations.

CTBT R&D Benefits from the Strengths of Many Organizations

The DOE draws on the strengths of not only the national laboratories but also university and private-sector contractors. By focusing these resources in a common direction, the CTBT R&D Program can develop and demonstrate appropriate technologies, computations, procedures, and integrated systems in a cost-effective and timely manner. DOE laboratories involved in the CTBT research and development are the Environmental Measurements Laboratory, Lawrence Livermore National Laboratory, Los Alamos National Laboratory, Pacific Northwest National Laboratory, and Sandia National Laboratories.

Customers Define the Product

The primary customer for the products of the CTBT R&D Program is the U.S. National Data Center. Under a CTBT, the Center will be responsible for monitoring for nuclear explosions in the atmosphere, underground, and in the oceans, and our R&D products are defined by those monitoring needs. We are also working closely with the prototype International Data Center and U.S. government agencies that may be assigned responsibilities under a CTBT. In addition, our experts are providing crucial support to the U.S. delegation negotiating the Comprehensive Test Ban Treaty.

Leslie A. Casey

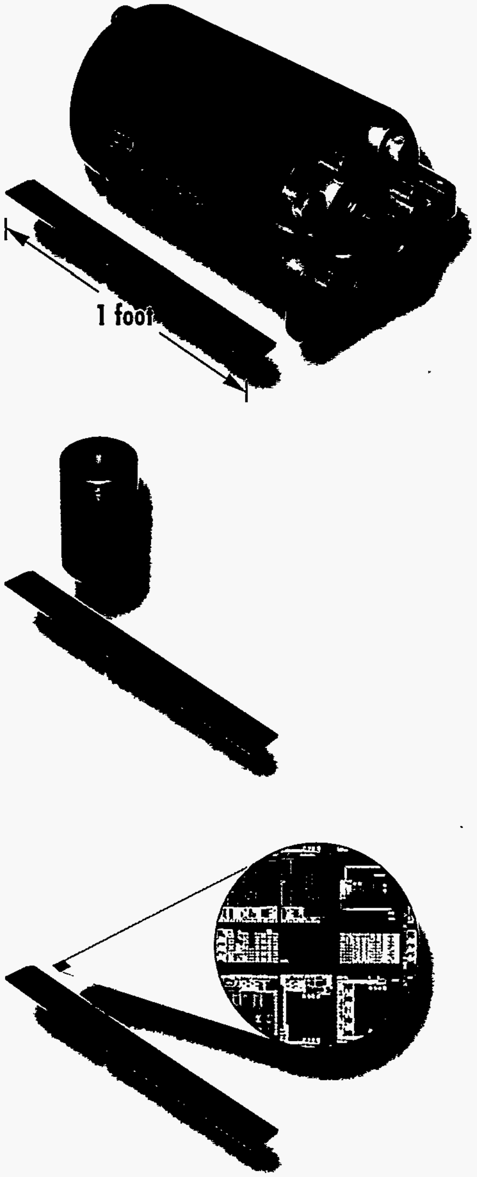
Manager of the CTBT Research and Development Program

The Department of Energy is responsible for the United States government's research and development for monitoring the proposed Comprehensive Test Ban Treaty. Our research will improve detection, location, and identification of nuclear explosions in all environments. We have completed the first year of a seven-year program; this report is a means of facilitating access to our research and development products. We hope that these products will spur progress toward treaty signature by increasing confidence in verifiability. I welcome your comments on our program or products at any time (phone 202-586-2151; fax 202-586-0485).

Leslie A. Casey

Monitoring the Underground Environment

Listening to the earth can help answer the big questions: Was it an earthquake? Was it an explosion? Was it nuclear?



Seismometers such as the large instrument at the top have been available for many years and will be used initially to monitor a CTBT. DOE is working with industrial partners to provide the next-generation seismometer, which will be smaller, lighter, and much cheaper. This smaller seismometer (middle) is planned to be commercially available in 1996. DOE's advanced micromachining techniques have the goal of producing an even smaller version (bottom), including the electronics to provide signal conditioning and analog-to-digital conversion all on one computer chip.

Finding the Needle in the Haystack

When energy is released on or under the ground from an explosion or an earthquake, seismic signals are generated. Seismometers are used to sense the signals, which can provide information about the size, location, and source of the energy. The CTBT R&D Program seeks to provide the tools to use this information to distinguish between earthquakes and explosions—and to determine when an explosion is not the result of normal mining or other industrial operations. This knowledge will enable the U.S. National Data Center, using the global network of seismic stations and arrays that will be part of the International Monitoring System under a CTBT, to reliably collect, relay, and evaluate seismic signals.

Tests of large-yield nuclear weapons produce seismograms that make them easy to identify. However, under a CTBT, potential violators may try to evade detection by detonating low-yield devices, because the signals are harder to detect. Furthermore, there are so many mining events and earthquakes worldwide that are similar in magnitude to a small nuclear explosion that a monitoring system designed to detect these small events will be flooded with signals. (More than 200,000 earthquakes at these levels occur in the world every year.) To provide a means of picking out the possible nuclear explosions from all the other signals, the CTBT R&D Program is developing improved instrumentation, as well as region-specific signal-analysis and discrimination procedures, to better locate and identify events.

Regionalization: Understanding What Is Normal Seismic Activity for a Region

Before we can detect unusual seismic activity in a specific region, we have to fully understand what is typical for that region. We are assembling and organizing large quantities of geologic, geophysical, and seismic data for regions of interest. We are also collecting associated data such as mine locations, blasting practices, and mine seismicity. For example, we have already identified the locations of thousands of mines in China and the Middle East.

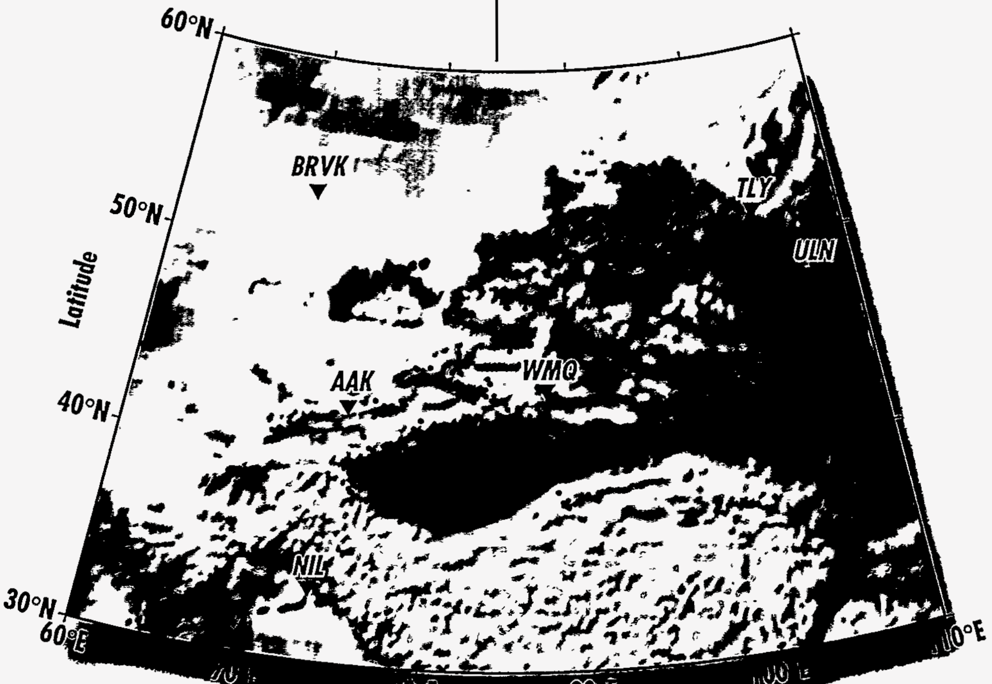
We are searching for all available source information and, where necessary, collecting new data in our effort to understand how the geophysical features in a region affect a seismic signal. In 1995 we processed data from the station at Urumqi in northwest China and from the MedNet regional network in the Middle East, and are including additional stations from other networks at regional distances (up to 2000 kilometers).

Our regional characterization efforts are aided by a DOE-funded external research program, consisting of contracts with university, government, and industrial research groups. The 1995 Annual Seismic Research Symposium on Monitoring a CTBT,* organized by the Air Force Phillips Laboratory, represented a first step at coordinating this research and integrating the various efforts into the overall DOE CTBT R&D Program. Since the meeting, a geophysical/geologic database has been delivered by one of the contractors, another contractor is scheduled to install a software system for identification research, and other data sets will be used for research to characterize seismic-wave propagation in the Middle East and North Africa.

External contractors representing universities and private industry are assisting in the collection and modeling of data. For example, Cornell University will take information about variations in the earth's crustal thickness (available from various sources) and synthesize a unified map of crustal thickness for the entire Middle East.

Our regionalization research includes analyzing seismograms to determine how signals travel and attenuate (weaken over distance), as well as how regional propagation affects the relative strengths of various parts of the signal. The key to this regional characterization is the development of discriminants.

Seismic recording stations (triangles) provide data for regional characterization of western China. The earthquakes that we have analyzed, using data from station WMQ at Urumqi, are shown in green. Clusters of underground nuclear explosions are shown in red. White indicates the highest elevations and brown the lowest.



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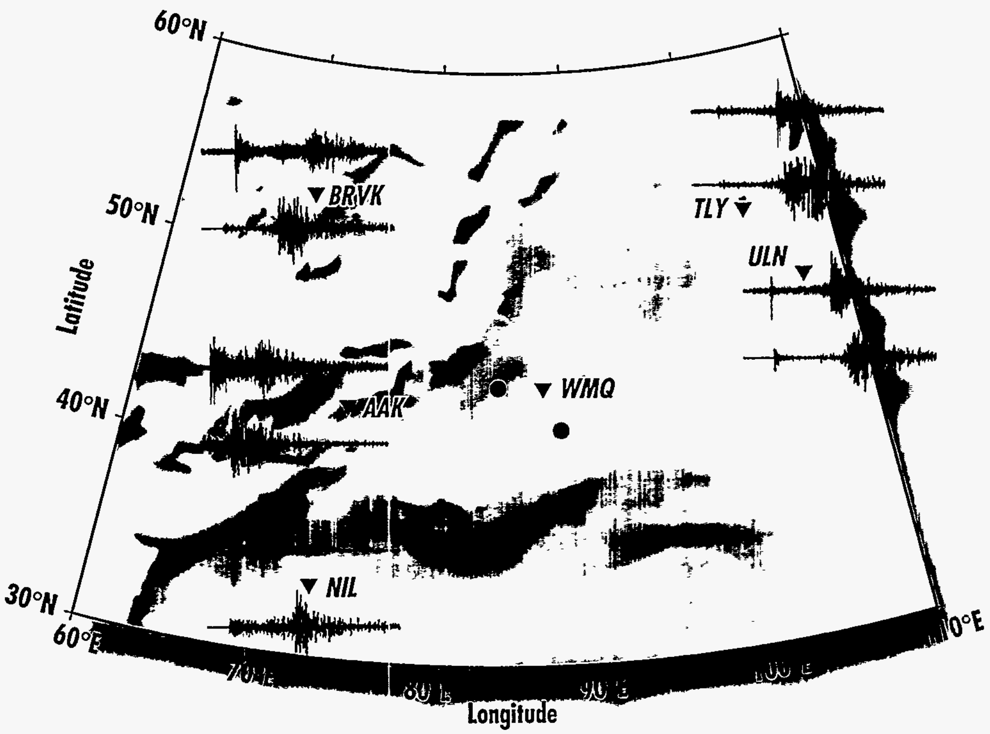
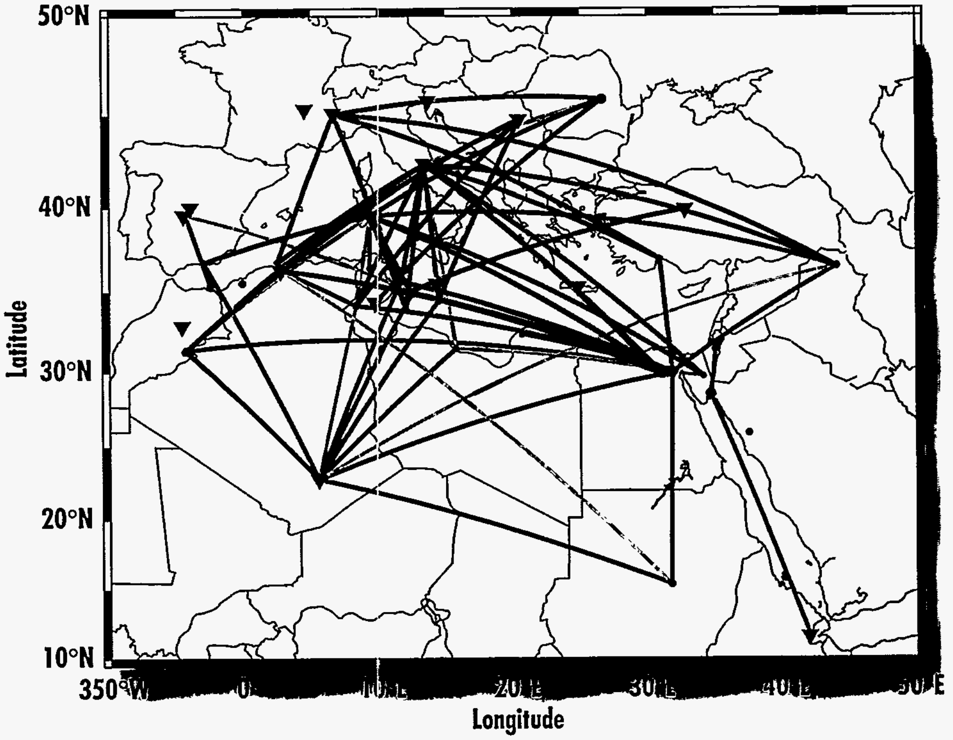
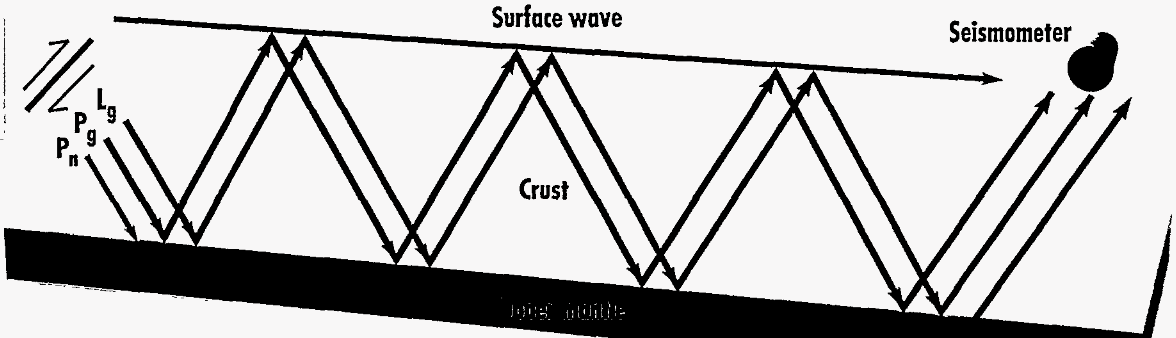
*See *Proceedings of the 17th Seismic Research Symposium on Monitoring a Comprehensive Test Ban Treaty*, U.S. Air Force Phillips Laboratory, Scottsdale, Arizona, Report No. PL-TR-95-2108 (1995).



Signals from an earthquake (blue dot) and an explosion (red dot) vary among stations in a network in western China. For example, at station NIL, the later part of the signal (the shear-wave component) is severely attenuated for the explosion. Here, the signals are superimposed on a map showing the depth to the boundary between the earth's crust and mantle: dark green indicates the greatest depths and yellow the shallowest. Such variations in crustal thickness typically contribute to the variations in signals at different stations, and must be taken into account when tuning a discriminant for a particular region.

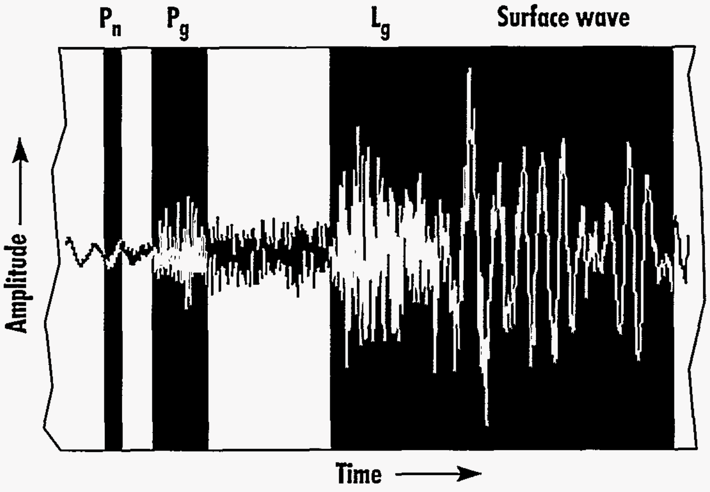


Regional shear waves are critical for determining the true nature of an event, so the effects on them as they propagate through different regions must be factored into monitoring techniques. Here, source-to-receiver travel paths for one kind of shear wave in the Middle East demonstrate the problem's complexity: red paths show blockage, green paths show partial transmission, blue paths show clear transmission.



Anatomy of a waveform

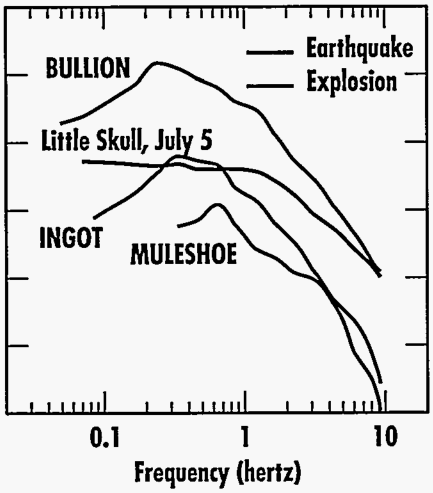
Various phases of a seismic signal can be exploited to develop discriminants that are characteristic of how signal components propagate through the earth. The first arrival is a compressional wave that propagates along the crust/mantle boundary (P_n); the intermediate segments are compressional (P_g) and shear waves (L_g) that propagate through multiple reflections in the crust. The final phase is a surface wave created by a complex interaction of compressional and shear waves at the free surface.



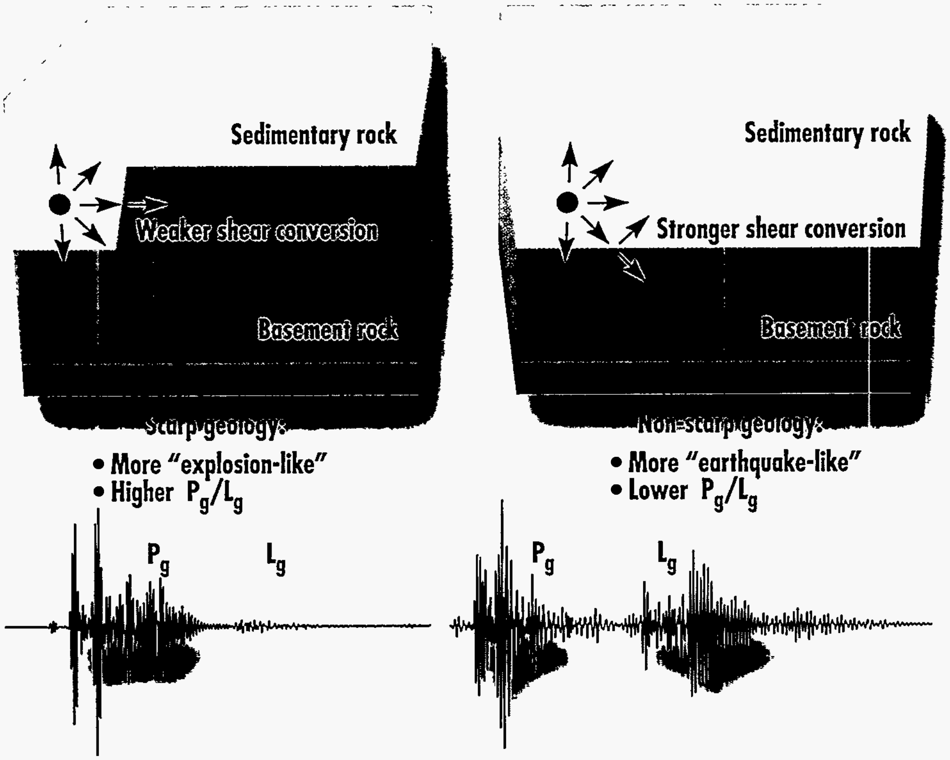
The P_g/L_g amplitude ratio is an example of an effective discriminant of earthquakes and explosions; it is a measure of the relative amounts of compressional and shear energy radiated from a seismic source. An earthquake occurs along a planar fault surface and therefore radiates significant shear energy relative to compressional energy, so it has a low P_g/L_g ratio. In contrast, an explosion is a spherical source; it radiates more compressional than shear energy and has a high P_g/L_g ratio. Because each of the phases used for discrimination propagates through different portions of the earth, the regional geology along the path can alter the effectiveness of each discriminant. A discriminant that is effective in one geologic region may not be effective in another.

A discriminant is typically some feature of a waveform (peak-to-peak separation, height, width, or ratio, for example) that can be shown to be characteristic of a source or of the attenuation of a signal due to the properties of the material it is traveling through. Because of geologic complexity, as many as ten such discriminants may be needed to adequately determine the source within a region.

The major drawback of most techniques designed to distinguish explosions from earthquakes is that the effects of propagation through the earth weaken the seismic signals in whole or in part, making it difficult to obtain measurements for small events at even moderate distances. Geologic structures can also completely block parts of the signal that are important for discrimination. For example, we know that regional shear waves do not propagate across the northern portion of the Tibetan Plateau. Another example is apparent in our 1995 results in the Middle East; the same regional shear waves travel freely across northern Africa but are almost completely blocked by the Mediterranean Sea. It is important to map out these propagation effects so that they can be factored into new discrimination techniques.



Coda-wave amplitudes in seismic spectra show differences in shape between explosions at the Nevada Test Site and an earthquake in southern Nevada. These spectra are so stable that a single seismogram can give a reliable measure of the source spectral shape for discrimination purposes.



An example of a study that addressed the influence of a fault scarp on a regional waveform. In this instance, when a nuclear device (the DIVIDER test) was detonated close to a scarp, the regional waveform appeared more explosion-like than waveforms from detonations in more conventional, flat-layered configurations. This result, which is supported by seismic observations, was not intuitively obvious until the waveforms were modeled using analysis techniques developed under the DOE CTBT R&D Program.

Discrimination: Distinguishing Possible Nuclear Explosions from Everything Else

We have begun to assess techniques for identifying the type of seismic event that has occurred in a region and to develop and evaluate techniques to discriminate between earthquakes and explosions. Using available data, we have analyzed approximately 140 earthquakes from western China, 15 underground nuclear explosions from a former Soviet Union test site, and one nuclear explosion from the Chinese test site. A number of techniques for discrimination have been evaluated. We have found that not all of these discriminants are directly transferable from one region to the next. For example, one discriminant we evaluated in 1995 appears to work well for a set of events in western China. It also performs well for the western United States, but does not provide as distinct separation of earthquakes and explosions as it does for China. In contrast, another discriminant works well for many Nevada Test Site explosions but performs poorly for China.

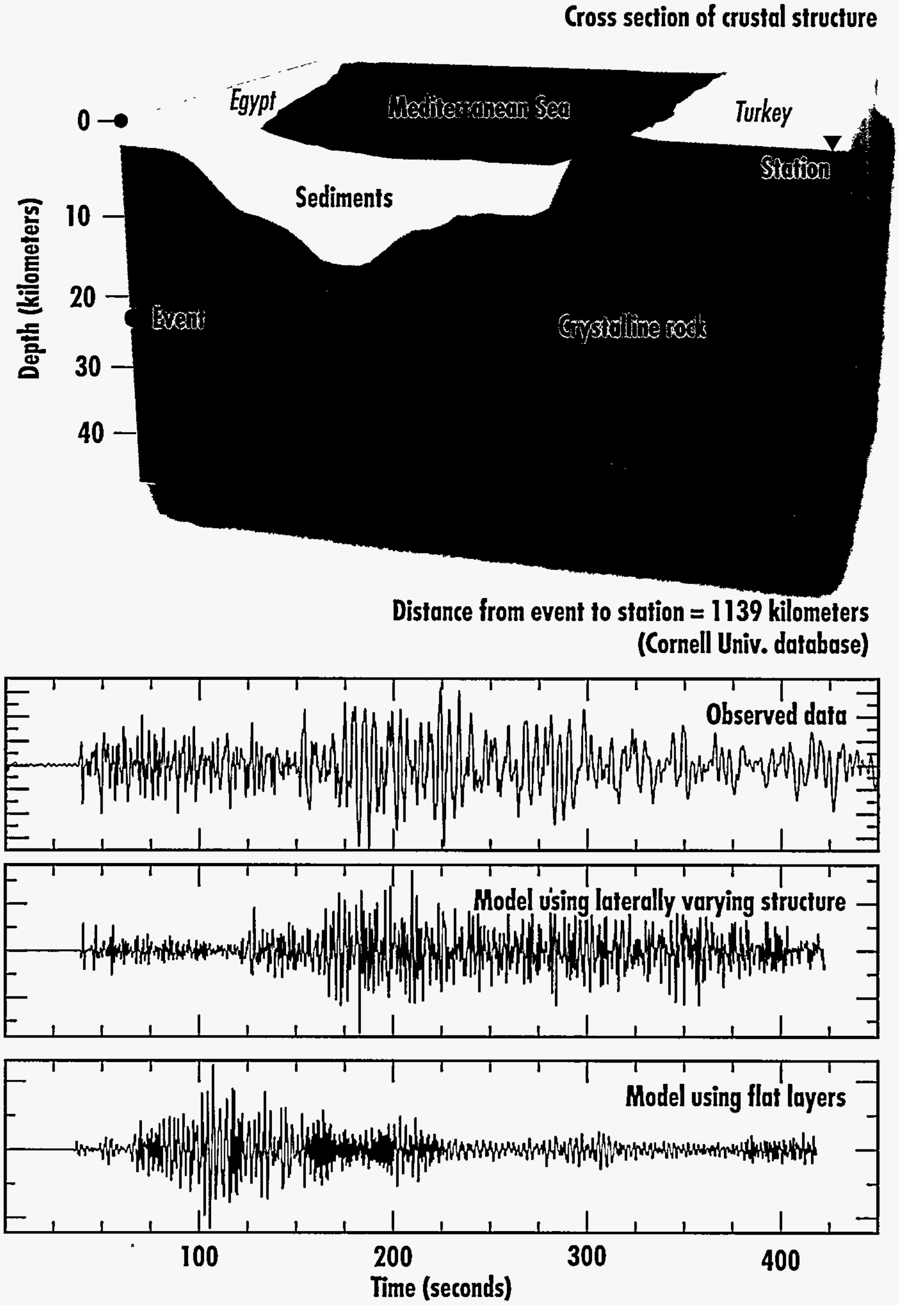
A research goal is to find discriminants that *are* transferable from region to region. One new discriminant that is showing promise works on the "coda waves" (late-arriving waves) of the main regional signal. The advantage of using coda waves is their stability, particularly in detecting differences in the frequency of the seismic wave emitted by the source (the *spectra*) for earthquakes and explosions. This is a very desirable feature, especially for smaller events, because there may be only one or two good recordings of a suspicious event in a noisy environment. In 1995 we delivered a research version of this discriminant to the U.S. National Data Center for evaluation.

The Signal Path: What the Signals Go Through to Get to the Monitoring Station and How That Affects Them

To design analytical tools and instruments for the seismic monitoring system, we first had to understand how underground geologic structures affect the seismic amplitudes as waves propagate, what types of structures can block the transmission of certain regional signals, and how these factors affect the reliability of our discrimination techniques.

One way to reach such understanding is through *modeling*. For example, a computer code incorporating the details of source physics and geologic complexities is used in a calculation that is then linked to a seismic-wave propagation code, which, in turn, can include such path characteristics as geologic structure and attenuation. Seismograms from these modeling calculations are compared with measurements, allowing quantitative analysis of issues such as (1) factors causing certain explosions to appear more or less like earthquakes, (2) the sensitivity of seismic signatures to source geometries and firing practices associated with mining, (3) the relative importance of near-source versus regional path characteristics in shaping the seismic waveform, (4) the level of detail required in source or regional characterization, and (5) the potential for nuclear test evasion through modification of the source configuration.

The earth's structure can vary dramatically over distances of hundreds to thousands of kilometers. We are trying to understand the effects of these structural



Modeling of waveforms using laterally varying earth structure, instead of flat layers, can give insight into observed seismic signals. Here a north–south cross section through the Mediterranean region shows great changes in earth structure. These simulations help us understand how seismic signals travel through a given region, which will help us determine the level of detail needed to characterize that region.

1

2 (750 milliseconds)

3 (1500 milliseconds)

4 (2250 milliseconds)

Mining events can provide useful information for calibrating the location capabilities of the seismic monitoring system. In a typical cast blast—here, at the Black Thunder Mine in Wyoming—unwanted material (overburden) overlying coal is explosively broken into rubble so it can be removed, exposing the coal for recovery.

changes on the regional seismograms. For example, in our work in 1995 in the area of the Mediterranean Sea, we have shown that models of waveforms that take into account this laterally varying earth structure come significantly closer to matching the observed data than do models that do not include this complexity.

The Signal Source: How the Physical Characteristics of the Source Affect the Signals

Besides distinguishing between earthquakes and explosions, successful treaty monitoring will require differentiating explosions related to mining operations from other types of explosions. Mining explosions are normally spread out in space and time compared with nuclear test explosions, which occur all at once. In addition, mining operations can trigger energetic rockbursts and mine collapses that might be mistaken for small-yield nuclear weapons tests. To gain a more complete understanding of these events and their corresponding seismic signals, we have undertaken a comprehensive program in cooperation with U.S. mining companies, including many field experiments, to characterize explosion sources.

We know that explosions associated with mining operations produce signals that will be detected by a worldwide seismological monitoring system. For

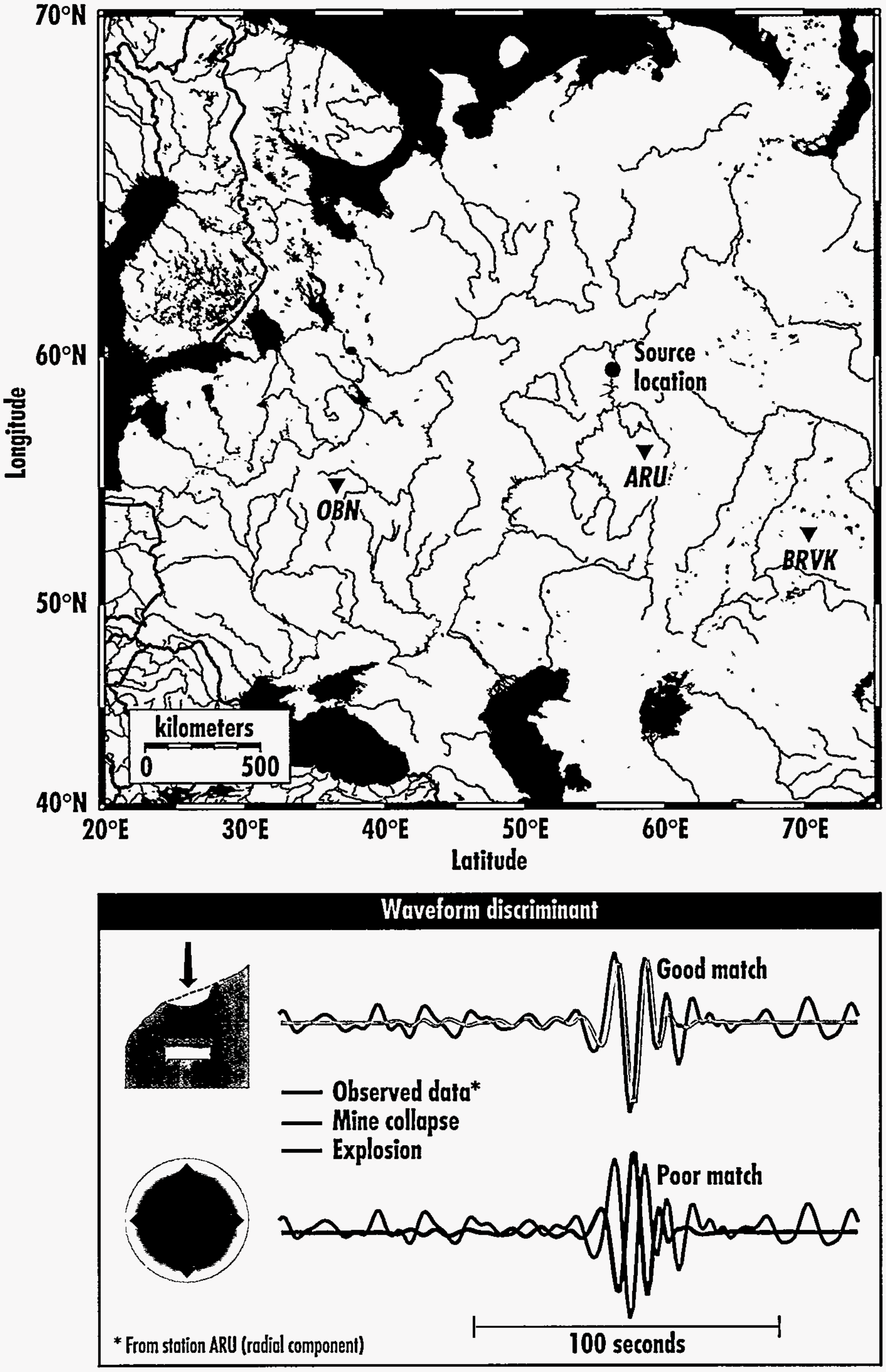
CTBT R&D seismic field experiments in 1995.

Objective	Type of rock	Location	Experiment name
Source geometry effects	Limestone	Indiana	Chinook
Blasting practices	Metamorphic	Northern Nevada	Carlin
Decoupling*	Porous alluvium	Nevada Test Site	KUCHEN
Blasting practices	Sedimentary (coal)	Wyoming	Black Thunder
Mine collapse	Meta-sedimentary hard	Michigan	White Pine
Mine collapse	Sedimentary	Colorado	Twentymile
Surface waves	Coal	Washington	Centralia

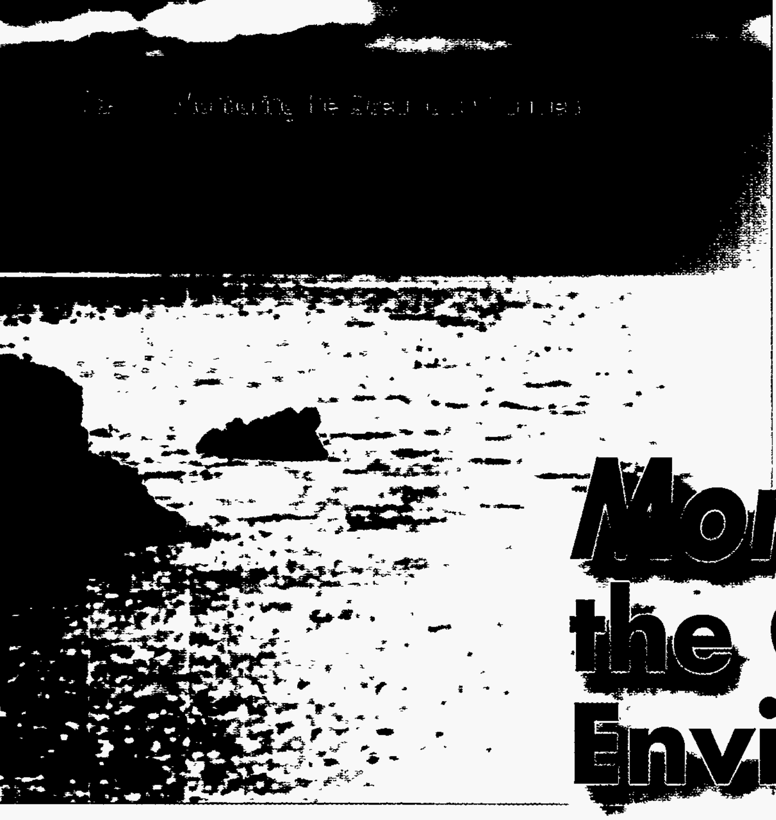
* Decoupling is a study of how well the energy from a nuclear test is transferred to the surrounding medium.

example, in 1995 three explosions at the Black Thunder Mine near Gillette, Wyoming, were detected by two nearby regional seismic stations, the Pinedale Seismic Research Facility and the South Dakota Regional Seismic Station. This demonstrates that, to some degree, these types of sources will trigger the monitoring system and may have to be identified. Mining events can provide useful information for calibrating the location capabilities of the monitoring system if we have *ground truth*—that is, an understanding of the physical features and activity characteristic of the location.

In addition, in 1995 we examined seismic data for several mine collapses that proved to be problems for some discrimination techniques. On first analysis, the events looked like explosions and thus fell into the category of false alarms—a concern for verification. We developed a new waveform-modeling technique to solve this problem.



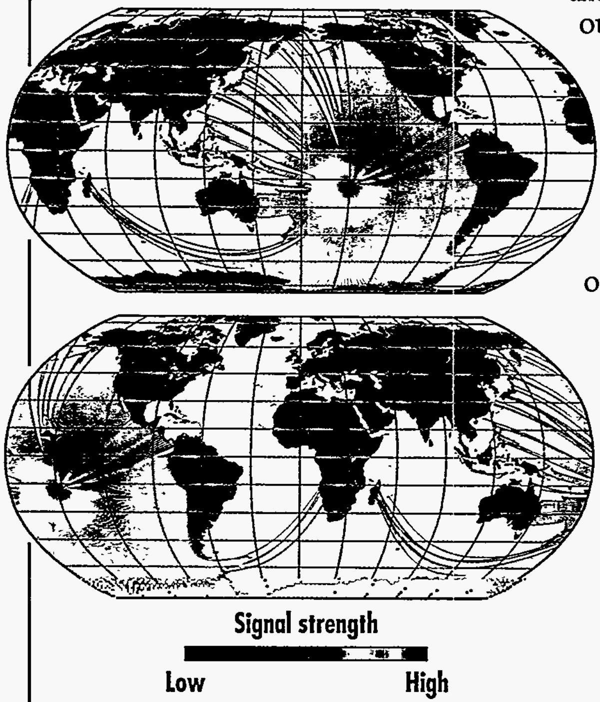
A seismic event of magnitude 4.7 (red dot) in Russia's Ural Mountains was identified as an explosion by the standard teleseïsmic discriminant. Our whole-waveform modeling techniques clearly showed that the event was a mine collapse.



Monitoring the Oceanic Environment

Nuclear tests conducted in the broad ocean areas pose a special problem for the International Monitoring System.

The broad ocean areas pose a major monitoring problem because they are large, sparsely populated, and not covered well by seismic networks. Oceans of the southern hemisphere present the greatest challenge. Fortunately, sound waves created by explosions travel to great distances trapped in an oceanic acoustic waveguide called the SOund Fixing And Ranging (SOFAR) channel. A network of hydrophones (underwater microphones) and additional seismometers on islands can sense signals in the SOFAR channel. The network can detect and locate underwater explosions and, in many cases, explosions in the low atmosphere. We focused our 1995 efforts on three areas: designing the International Monitoring System hydroacoustic network for wide ocean coverage, understanding how nuclear explosions generate underwater sound, and collecting a database of oceanic seismic events.



A ray-tracing diagram models the ability of one station to detect signals from explosions creating sound waves in the SOFAR channel. Here, good propagation characteristics in all directions are evident for the proposed station being modeled. The color scale indicates how strong the signal will be. Signal strength depends on the distance of the explosion from the sensor and on the presence of intervening islands or seamounts that block sound transmission. Such models allow us to predict the usefulness of a proposed station site.

Designing a Worldwide System for Oceanic Monitoring

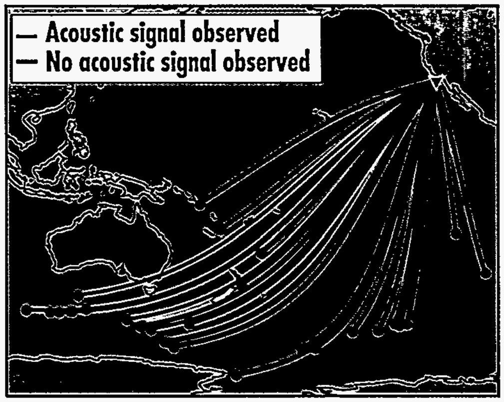
Although sound travels efficiently in the SOFAR channel for great distances (more than 15,000 kilometers), it can be blocked by land masses and regions of shallow water or be severely attenuated in the cold polar regions where the channel is less effective. Blocked regions and regions of low surface temperature must be considered when designing a hydroacoustic monitoring network.

In 1995, we worked with our counterparts from other countries to develop a network that provides coverage in the major oceans (the Atlantic, the Pacific, and the Indian) and the Antarctic region. Our goal was to use as few stations as possible to reduce the costs of developing and maintaining the network.

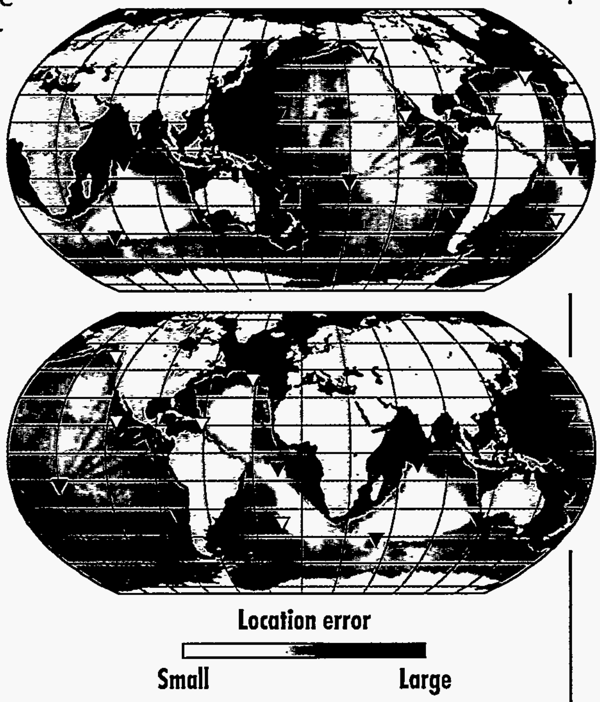
We are using computer models to assess the performance of individual sites and the performance of several trial network configurations. The Naval Research Laboratory is also conducting extensive ray-trace calculations for the DOE to estimate blockage for candidate stations. These calculations show the "field of view" of alternative sites, allowing us to select sites with widest coverage. In addition, we have developed a simple model for assessing the location performance of proposed networks.

Assessing Underwater Monitoring Performance with Real Data

We are also developing a database of hydrophone signals from underwater events such as earthquakes and chemical explosions. Our goal in this research is to calibrate monitoring conditions in specific oceans with existing stations. Since April 1993, we have operated a data-collection system at a hydrophone station in southern California that was previously used by the U.S. Navy. We can use data from these stations to examine blockage of acoustic signals from earthquakes along the Pacific–Antarctic ridge (a long submarine mountain range). The pattern of observed and absent signals from a large suite of earthquakes distributed along the ridge may be used to map shallow blocking features between the ridge and the station.



The pattern of observed or missed signals from earthquakes along undersea ridges shows regions of blockage. Here, the paths that undersea sound waves could take from known earthquakes to our recording station offshore from southern California are color-coded to show which paths actually showed signals and which did not. Paths with no observed signal traverse blocked regions. Blockage is apparent in the Chatham ridge region east of New Zealand and in the Tasman Sea between Australia and New Zealand. This technique allows us to map areas of poor sound transmission.



The proposed International Monitoring System hydroacoustic network provides acceptable location coverage in the wide ocean areas. (Seismic stations provide alternate coverage at the margins of continents and in the Arctic, where coverage is poor.) We calculated the predicted location errors of the network for all possible points in the world's oceans where explosions might be conducted. Red triangles indicate hydrophone stations; open triangles indicate new island seismic stations (T-phase stations; T-phases are the seismic signals created by ocean acoustic signals hitting steep shorelines.) The black triangle indicates an existing seismometer station incorporated into the network for this calculation. These calculations allow us to evaluate the overall performance of a proposed network.

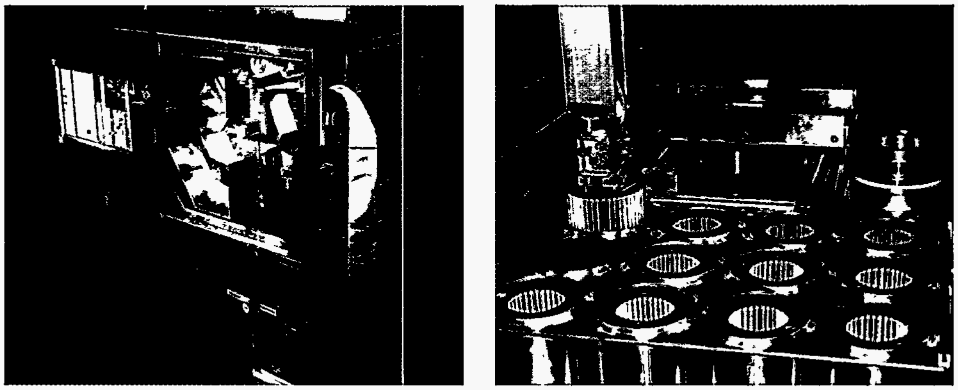
Monitoring the Atmosphere and Beyond

Complementary technologies will monitor the earth's envelope.

Nuclear Evidence: Radioactive Particles and Gases Carried by the Wind

To look for airborne radioactivity from nuclear tests, a network of air-sampling stations will be used to detect radioactive particles and gases (radionuclides). Our major contributions to this network lie in developing the instruments to collect and analyze the radionuclides and in modeling the performance and coverage of network options to support the negotiation process. DOE scientists are building a new generation of ultrasensitive equipment to automatically detect and identify subsurface and low-yield atmospheric tests. In 1995 we began field-testing two models of particulate samplers, and we conducted laboratory testing of a fully automatic prototype xenon gas detector.

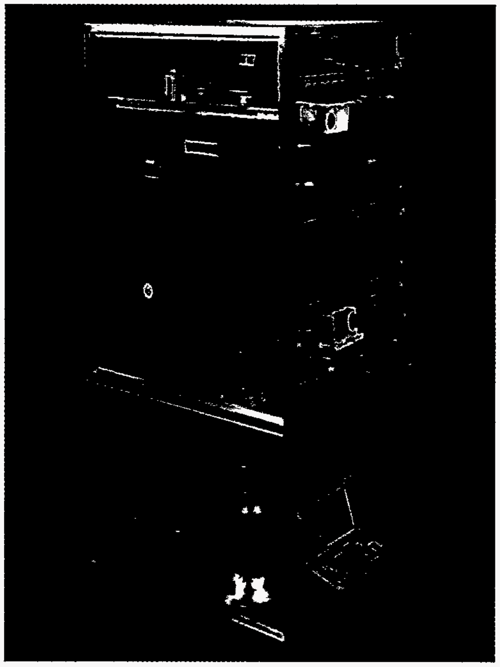
The particulate sampler measures radionuclides transported on airborne particles; it provides conclusive evidence of a nuclear test if such particles are collected and analyzed. The patterns of gamma rays emitted by particles



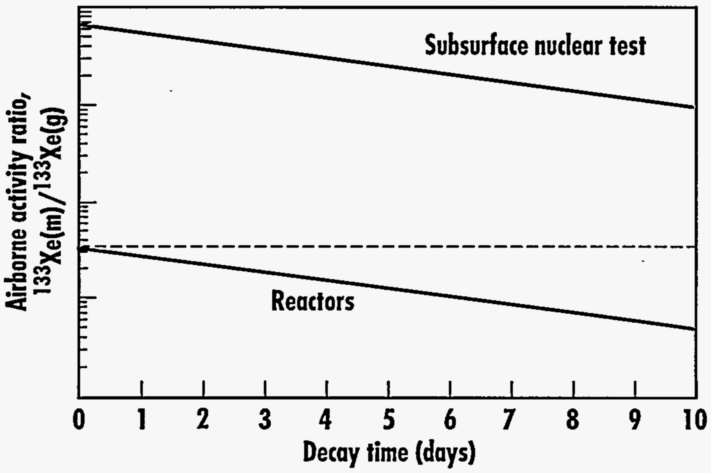
These fully automated particulate-collector and radionuclide analyzers are DOE prototypes that the U.S. National Data Center is evaluating for use in the International Monitoring System. They were field-tested at McClellan Air Force Base in Sacramento, California.

filtered from air are like detailed fingerprints, or signatures, of the source of the radioactivity. The new generation of particulate collectors and analyzers, by automating the filter changing and data reporting, will lower operations costs while ensuring quality control. By designing for ultrasensitive detection, we will need fewer stations to get nominal global coverage, further reducing network costs. Two different designs of particulate samplers began field tests in 1995; commercialization of an improved design will begin in 1996.

The xenon sampler/analyzer detects radioactive xenon gas. Under certain conditions, this may provide the only indication of a test: although radioactive particles carry definitive indication of a nuclear explosion, they may not escape from a subsurface test in sufficient quantities to be detected at the necessary distances, and those from a small atmospheric test may be washed out of the air by a rainstorm. However, xenon gas may escape into the atmosphere, even if no particles do. The automated xenon gas collector uses basic gas-separation techniques (such as sorbent beds and cryogenics) in unique combination for extraction from very large volumes of air. A beta-gamma coincidence counter detects the decays of the separated radioxenon with sensitivity one hundredfold greater than that of earlier counting technology. For CTBT applications, the new goal is to adapt the laboratory techniques into an automated system that is reliable (requiring only annual maintenance) and ultrasensitive (measuring quantities as low as 20 microbecquerels per cubic meter, or $\mu Bq/m^3$), and that provides near-real-time analyzing and reporting. The ultrasensitivity is required to compensate for reducing the number of radionuclide monitoring stations to achieve nominal global coverage at minimal cost. The coincidence-counting technique measures the ratios of different states of xenon radionuclides; these ratios distinguish nuclear tests from reactor releases. In 1995 an automated laboratory prototype demonstrated a sensitivity of 150 $\mu Bq/m^3$. The additional sensitivity needed will be achieved in the field prototype in 1996 by raising the xenon transfer efficiency to greater than 80% from the present 20%, using larger detectors to improve counting efficiency, and adding shielding to reduce background noise.



When the DOE's fully automated prototype xenon sampler/analyzer is completed in 1996, it will be able to detect (at great distances) even small amounts of radioactive xenon gas escaping from a subsurface nuclear detonation.



The xenon sampler/analyzer is designed to distinguish nuclear tests from other sources by determining the ratio of radioactive decays from two states of the radionuclide xenon-133. These two states have different origins. Subsurface nuclear tests release the metastable (m) state, which decays with a half-life of about two days. Reactor operations and medical diagnostic procedures commonly release the ground (g) state, which has a half-life of a little more than five days. The dashed line shows the ratio at which a remote nuclear test could be misidentified as a release from a nearby reactor. Radioxenon from reactors is unlikely to be mistaken for that vented from a nuclear test, because the vented radioxenon will decay away before it reaches the ratio from reactors.

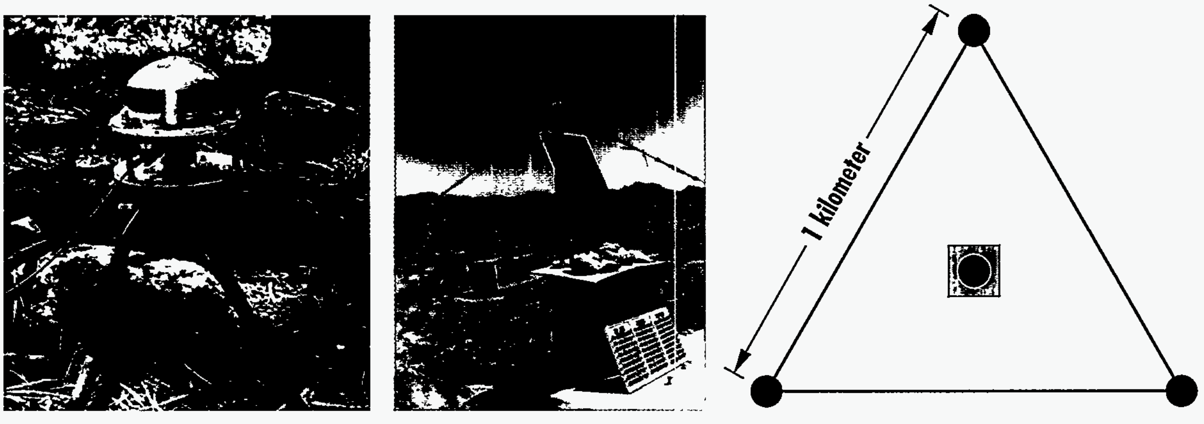
Infrasound: Pressure Waves in the Air

One method for detecting and locating atmospheric explosions is to monitor infrasound—air vibrations at frequencies too low to be perceived by human hearing. Explosions generate a strong shock wave that dissipates rapidly as it travels away from the explosion. Low-frequency components of the shock wave can continue through the earth's atmosphere to long ranges at signal amplitudes from a few pascals to less than one-tenth of a pascal (normal sea-level pressure is one hundred thousand pascals). These signals can be detected by arrays of microphones designed to pick up such low-frequency acoustic waves. Kiloton-size explosions can be detected at a few thousand kilometers with good signal-to-noise ratio.

Infrasound is not a new monitoring technology. Prior to the early 1970s, the United States operated a global network of stations. The original pre-1970s systems did not benefit from modern digital signal processing. As a result, no database of recent experience directly addresses certain questions of the proposed CTBT network performance, so simulations must be used with input from the older experience.

Designing an Infrasound Network to Provide Global Coverage. Our current focus in infrasound research is to estimate how effectively a CTBT network would perform in detecting and locating atmospheric nuclear explosions, which is an issue that is being dealt with by the U.S. delegation negotiating a CTBT in Geneva. We are collaborating with the U.S. National Data Center to estimate the performance of the proposed CTBT infrasound network using network-simulation computer codes. In 1995 we incorporated information on propagation physics, wind patterns, and recent explosion measurements into the simulation codes. These inputs are the primary data needed to determine the basic pressure-range

Infrasound signals can be detected by arrays of microphones. An infrasound microphone for frequencies of 0.1 to 10 hertz is shown here; the 16-meter-long hoses attached below the microphone reduce the effects of wind noise. (Ground cover or trees also help reduce noise.) Individual arrays and their recording/transmission equipment can be operated by solar panels with battery backup. A typical array will consist of four microphones; the exact configuration will depend on site conditions.



● Microphone with hoses

▨ Recording/transmission site

Typical array

curve, which is the starting point for estimates of detection capability. Another part of our 1995 work was devoted to recommending network sites to provide global coverage and reasonable location capability.

Evaluating the Detection Methods to Improve Our Data Analysis. Early this year, hardware upgrades were completed to allow data from two infrasound arrays to be sent to the U.S. National Data Center. These DOE arrays are at St. George, Utah, and Los Alamos, New Mexico. We reviewed and revised the seasonal wind normalization procedure. The data set for this procedure comes from earlier measurements of atmospheric nuclear tests taken at stations around the Nevada Test Site. This research will allow us to understand how middle-atmospheric wind (at 50-kilometer altitude) affects the signals so we can interpret them properly. It also allows us to better understand how signals move through the lowest 10 kilometers of the atmosphere.

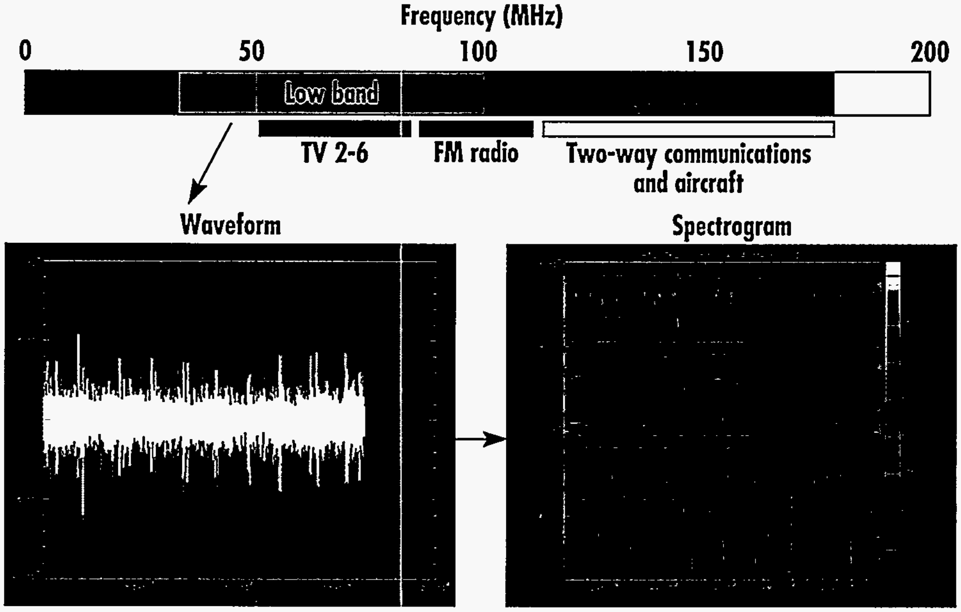
Also in 1995, a software package was written for analyzing the data and comparing the various detection methods used on infrasound data. Because of the nature of the infrasound wind noise, simple power detectors are poorly suited for the detection process, so some form of correlation analysis is needed. This work will continue in 1996 and will help define the best detectors for use in automated processing.

Space-Based Monitoring: The View from Space

As part of its national technical means, the United States has used satellite sensors for 35 years not only to detect and accurately locate any explosions that might occur in the atmosphere or in near-earth space, but also to identify whether they are nuclear and to characterize them. At present, the space-based monitoring research project has nuclear explosion sensors in secondary payloads operating on military satellite constellations for the Global Positioning System (GPS) and the Defense Support Program. In the future, we will continue to fly such sensors for national purposes.

To deal with emerging threats from nuclear proliferation, as well as the monitoring needs of a CTBT, we are developing a new generation of satellite sensors. The research emphasis is on monitoring low-technology, evasively tested nuclear devices. Low-technology devices are those that would be the initial products of a new nuclear weapons program. The new generation of sensors being developed for deployment on upcoming GPS flights includes a combined x-ray sensor/dosimeter, a high-speed sensor data downlink, an enhanced-sensitivity optical radiometer (called a bhangmeter), and an autonomous electromagnetic pulse sensor. Together, these new sensors are intended to enable the United States to identify likely CTBT violations with a high level of confidence and to recognize false alarms for what they are.

FORTÉ: A Space Flight Experiment. The FORTÉ space experiment is in the final stages of preparation for launch. This experiment is designed to test and validate advanced technologies for the new autonomous electromagnetic pulse sensor. It will collect and identify radio-frequency emissions of simulated nuclear detonations, under conditions that would hide

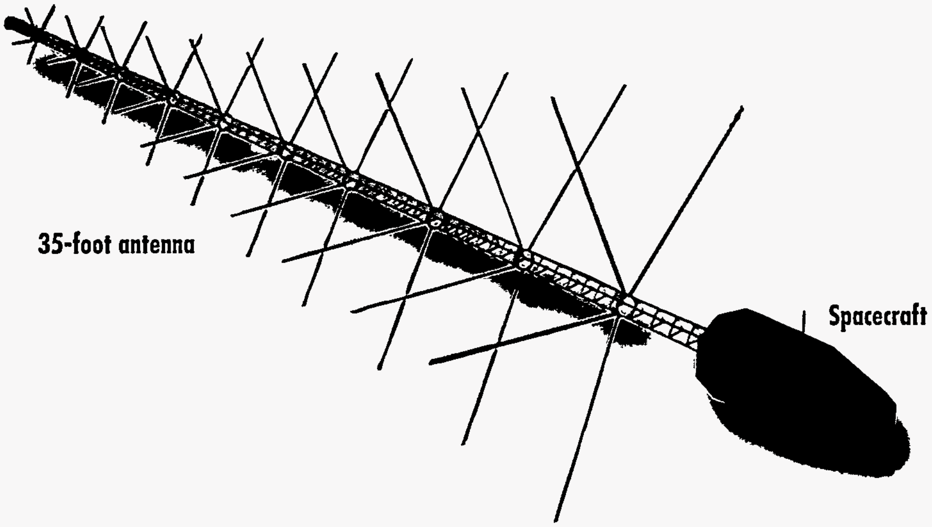


BLACKBEARD, the precursor space experiment to FORTÉ, has been collecting radio-frequency data from low-earth orbit for more than two years. Shown here are the waveform of a 100-microsecond reception of an electromagnetic pulse (EMP) simulator signal, and a spectrogram, the frequency spectrum of that essentially instantaneous signal as it is dispersed by the ionosphere. The collected EMP waveform is completely hidden by the much stronger broadcast television and radio background; FORTÉ on-board processing will produce spectrograms with exponential curves like the one shown that permit high-confidence recognition of space-based EMP signals received by the satellite radio equipment.

or distort the accompanying optical signatures if the detonations were real. This system will operate in the presence of daunting backgrounds of naturally occurring interference, such as lightning, and other interference such as the transmission signals from broadcast television and FM radio.

FORTÉ is a store-and-forward system that will collect data worldwide, evaluating and storing it on-board, and downlinking just the interesting parts to a single DOE ground station located in New Mexico. The FORTÉ on-board processing will significantly improve our ability to recognize electromagnetic pulse signals with a high level of confidence.

FORTÉ is a joint venture between two DOE national laboratories, supported by broad commercial participation. The U.S. Air Force Space Test Program is scheduled to launch FORTÉ in late 1996, pending resolution of performance issues regarding the Pegasus XL space launch system.



The FORTÉ spacecraft is constructed by a new process in which lightweight graphite composite pieces are snapped together, much as they would be in a toy model. The antenna deploys in space from a container drum no larger than a small wastebasket, providing coverage of a 900-kilometer-diameter spot on the earth's surface.

Preparing for On-Site Inspections

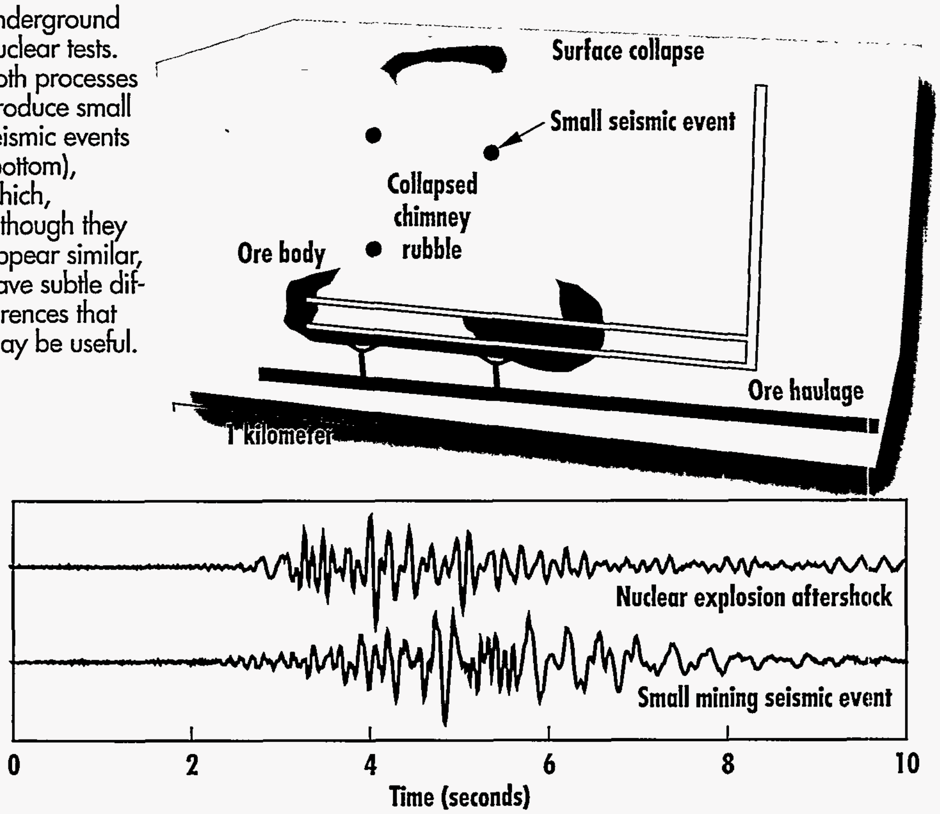
Inspection on-site may be required to prove the true nature of an ambiguous event.

Underground nuclear explosions leave behind evidence of their occurrence, but such evidence may be difficult to obtain remotely. Collapse craters, for example, occur over most of the nuclear tests at the Nevada Test Site; such craters are clear evidence of an underground explosion. However, if an explosion is buried deeply, it may not form a crater. In such a case, an inspection team will need to search on-site for other evidence of the explosion. For example, the team may deploy portable seismic equipment to look for very small explosion aftershocks, collect samples of soil gases, water, and soil to look for radioactive materials, or conduct geophysical soundings to search for the collapsed chimney rubble or underground explosion cavity. Our research has made significant advances in developing the technology to be used during an on-site inspection.

Using Aftershocks to Help Narrow the Search Pattern

Aftershocks—small but sudden movements of the earth's crust—are often artifacts of underground explosions. They are also characteristic of other events, such as earthquakes and mining activity, that stress and fracture the subsurface. Block-caving mining, which involves the collapse of large blocks of overburden into the excavated areas beneath, produces cavities similar to those resulting from an underground test and produces aftershocks that might be confused

Some mining practices mimic collapse processes that occur during a nuclear test. For example, in a block-caving mine (shown here in cross section), the ore body is undermined and the ore is allowed to fall into the cavity. A similar process occurs after some underground nuclear tests. Both processes produce small seismic events (bottom), which, although they appear similar, have subtle differences that may be useful.

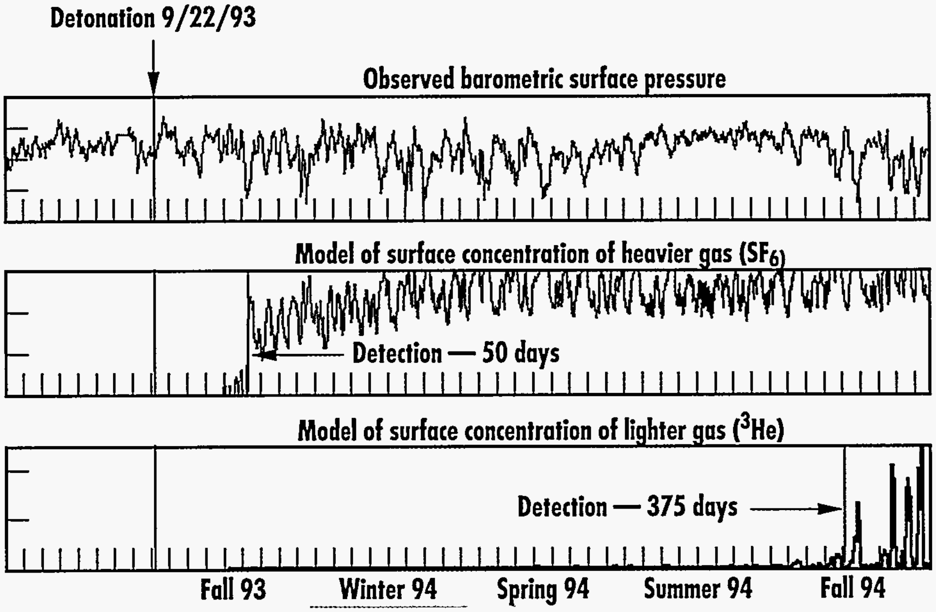


with those from an underground explosion. However, a detailed comparison of aftershocks from the one-kiloton Non-Proliferation Experiment at the Nevada Test Site with those from a block-caving mine shows subtle differences in the aftershock waveforms. Such differences are important for distinguishing between the aftershock signatures of explosions and of mining activity that can potentially be used to mask a clandestine test. We found that the rise in amplitude of the signature from the explosion aftershock is much quicker than the rise in amplitude from the mining aftershock. We also found that it is easier to locate the sources of aftershocks caused by an explosion than those caused by normal mining operations.

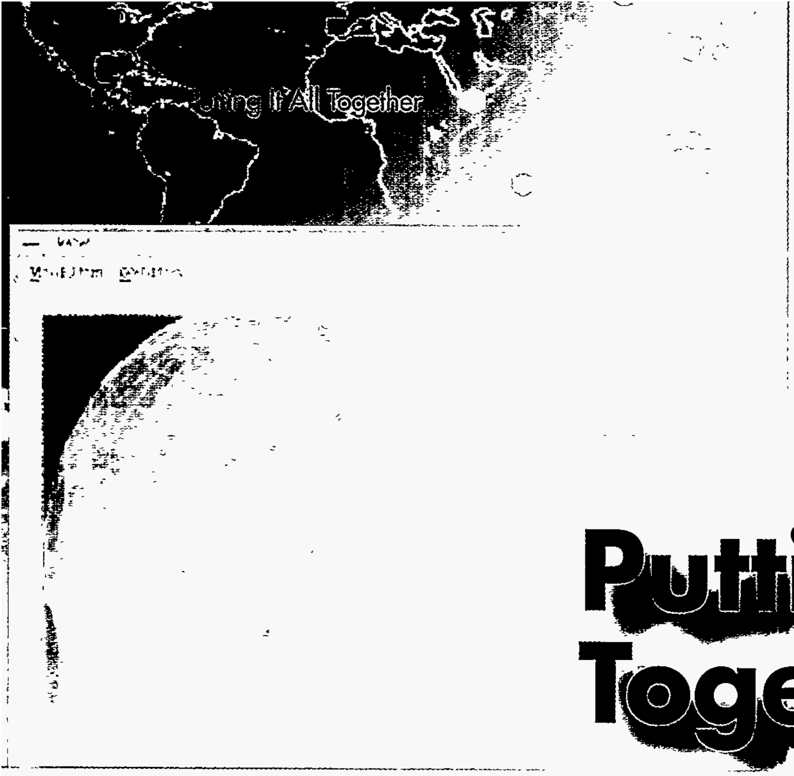
Radioactive Gas Seepage: Direct Evidence from Underground

Nuclear fission produces rare radionuclide gases such as xenon-133 and argon-37 that, when detected at a suspect site, may be interpreted as indicators of a nuclear event. In 1995 we obtained results that are valuable for predicting the ability of these radionuclides to reach the surface along natural faults and fractures following a very deep underground explosion. As part of the Non-Proliferation Experiment at the Nevada Test Site, we released two tracer gases during detonation at a depth of 400 meters beneath Rainier Mesa. We detected both tracers some time later at the surface along nearby faults and fractures. The first tracer was detected by gas sampling and chemical analysis about 50 days following the explosion. The other tracer was detected some 12 months later. Surprisingly, the less diffusive tracer was detected first.

Our computer simulations show that along faults and fractures this kind of behavior is to be expected. As a result of surface pressure variations associated with the weather on Rainier Mesa, the heavy gas (sulfur hexafluoride), which is less diffusive, reaches detectable concentrations at the surface long before the lighter, more diffusive gas (helium-3). Our estimates of the time when these gases would reach detectable concentrations along a fault are in agreement with what we actually observed. Furthermore, we found that the large barometric pressure drops associated with storms are important for moving gas quickly to the surface. Based on the results of this experiment, our simulations predict that the radionuclides of xenon-133 and argon-37 would be detectable within months following a deep underground one-kiloton nuclear detonation at the Rainier Mesa site. This is useful timing information for planning a successful on-site inspection, as well as a basis for predicting the success of an inspection using information about the geology and weather patterns at a suspected test site.



Different gases travel to the surface at different rates. Our tracer test results show that in complex geologic media, heavier gases travel to the surface faster—and thus are detected sooner—than lighter gases. (That is, the middle curve here crosses the detection threshold sooner than the bottom curve.) Our computer model based on these results allows us to predict the behavior of the tracer gases.



Putting It All Together . . .

An automated data-processing system will combine data from all of the monitoring technologies, facilitating analysis as a whole.

The utility of a monitoring system collecting data from underground, underwater, and the atmosphere is diminished if the data from the various technologies cannot be quickly and effectively combined and analyzed. The Department of Energy has thus taken on the task of developing the tools to support an automated data-processing environment that can accommodate these otherwise overwhelming amounts of multi-phenomenology data rapidly and in a user-friendly manner. If one or more of the technologies in the monitoring system detects a suspicious event but cannot confirm that the event was or was not nuclear, then other parts of the monitoring system may provide information to resolve the ambiguity.

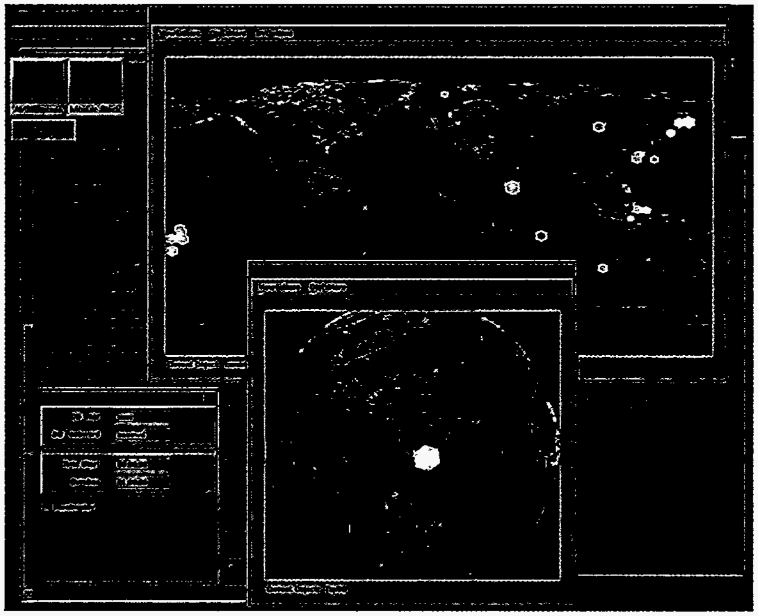
Also, because shrinking budgets mean smaller staffs, the data-processing system must automate the analysis as much as possible. To do so, we must develop computational techniques and other computer tools that will aid human decision-making by providing first-cut interpretations of the data. For those events that cannot be fully resolved through automated processing, tools must be developed to improve the ability of human analysts to interact with the computer-based data. Finally, tools must be developed to protect the International Monitoring System and its data from intentional or accidental corruption so that all parties to the treaty will have confidence in the integrity of the system.

Enhanced Processing to Handle Large Numbers of Events

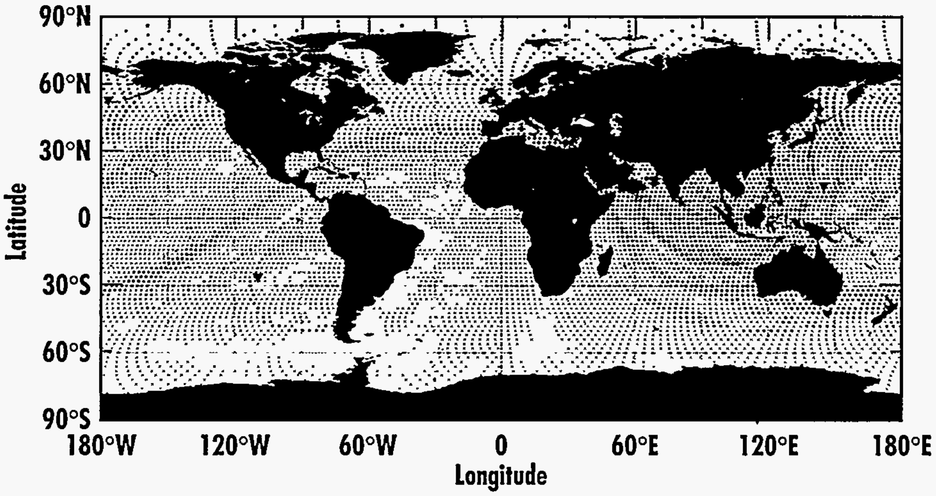
The International Monitoring System will generate an enormous amount of data to be analyzed, recording information on about ten times as many events as current systems do. For example, the system is expected to detect hundreds of earthquakes each day. Even with significant improvements in processing capabilities, not all of the analysis can be automated.

One way to address this problem is to examine the way information is conveyed from the computer to the analysts and identify methods of improving that transfer of information. In one of our data-visualization projects, we are exploring new methods of examining events and analyzing the sensor data and the results of the automated processing. For example, in 1995, we developed a time-varying display of the direction and amplitude of incoming seismic signals. We also developed a new graphics technique to quickly eliminate certain events from further review.

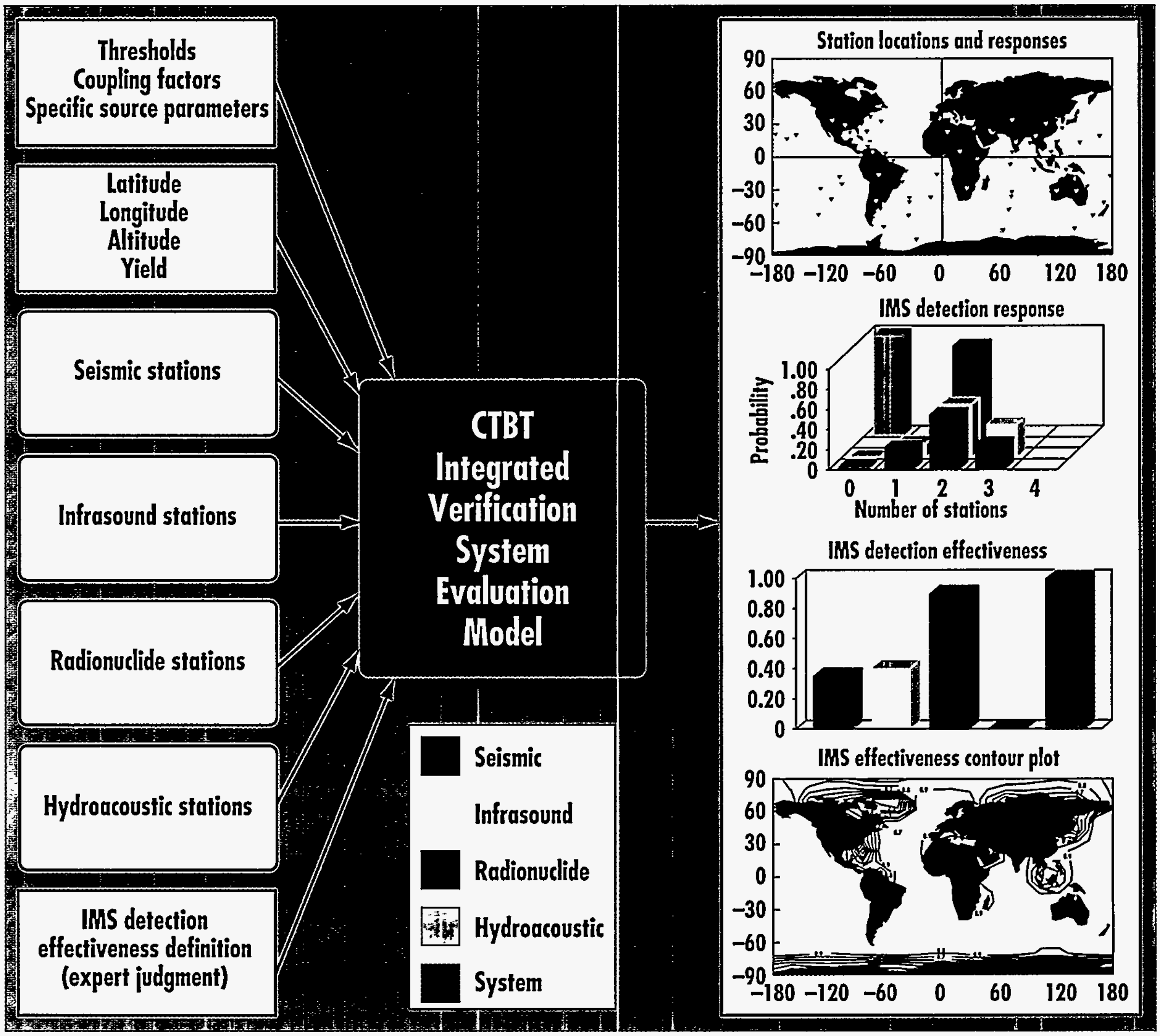
Another tool we have developed to process the exponentially larger number of signals is the Waveform Correlation Event Detector System (WCEDS), which detects the events directly in the signal data from the entire network. To do so, we divide the earth into a grid and assume that an event occurred at each grid point. Data from the grid points are then correlated against a master image based on events that occurred in the past. If the correlation between the current stack of data and the master stack is high enough, then an event is declared for that grid point. The WCEDS technique is expected to reduce the computational demands enough to allow real-time processing of the large quantity of data expected in a CTBT monitoring environment.



One of our products visually displays the location and approximate magnitude of an event (yellow) and the monitoring stations that detected it (pink). This display could help analysts quickly identify events that need further investigation.



Our Waveform Correlation Event Detector System will process the enormous amounts of data generated by the International Monitoring System using an innovative technique to break the problem down into many small parallel operations. Some results of our initial evaluation are shown here. The larger circles indicate higher correlation, that is, a higher likelihood that an event occurred at this location. The actual event was located in western China.



In our computer model (the Integrated Verification System Evaluation Model), user-defined inputs produce various graphics displays of the effectiveness of the monitoring system.

Our Computer Model Evaluates the International Monitoring System Performance

We developed a computer model (the Integrated Verification System Evaluation Model) to help evaluate the performance of the CTBT International Monitoring System. The model is fast, portable, and user-friendly. Users may alter the locations of each monitoring station and the type and location of the nuclear events. Such simulations allow the user to determine how well a potential monitoring system performs against a given test scenario. This model is the first to incorporate synergy among the various monitoring technologies.

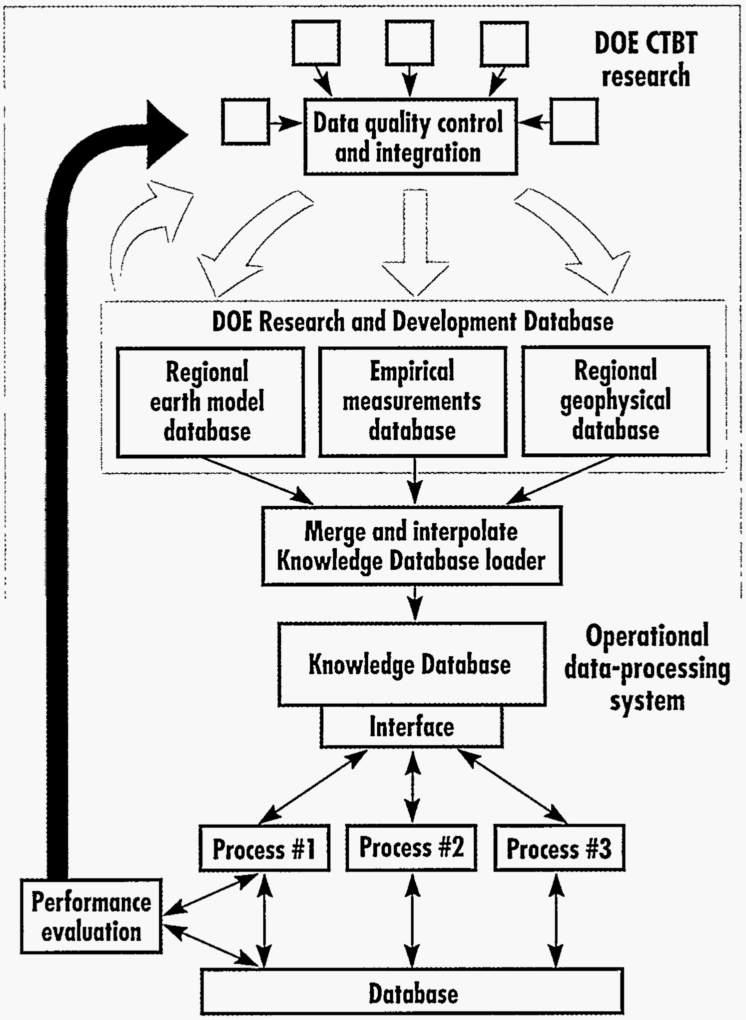
The original version of the model, which was initially distributed in 1995 within the U.S. government, estimates the monitoring system's performance for detecting tests in all environments, including interfaces (for example, the interface of air and land or air and water). The next version, due in early 1996, will incorporate location capability.

The Knowledge Database Structures Information for the User

The DOE CTBT R&D Program will produce a vast, complex set of information that will be needed to meet the challenges of monitoring a CTBT. However, our challenge does not end there. In many cases, research results remain unused or underused because they are included in reports or other outputs that are not directly suitable for the operational environment. Our goal is to address this interface need by developing a bridge between research and operations in the form of a CTBT Knowledge Database that contains the results of research in an accessible form.

The Knowledge Database is a framework for organizing, storing, and rapidly retrieving this information for use by automated processing routines and human analysts. It will contain the distilled information needed to allow processing routines to develop the high-fidelity solutions required in a CTBT environment. Accurate information such as regional seismic travel times, path blockages in the ocean, and atmospheric attenuation curves will be available in the Knowledge Database. Our database will also include *metadata*, or information about the data, which will improve the ability to trace how solutions were calculated and identify the confidence in an automated solution.

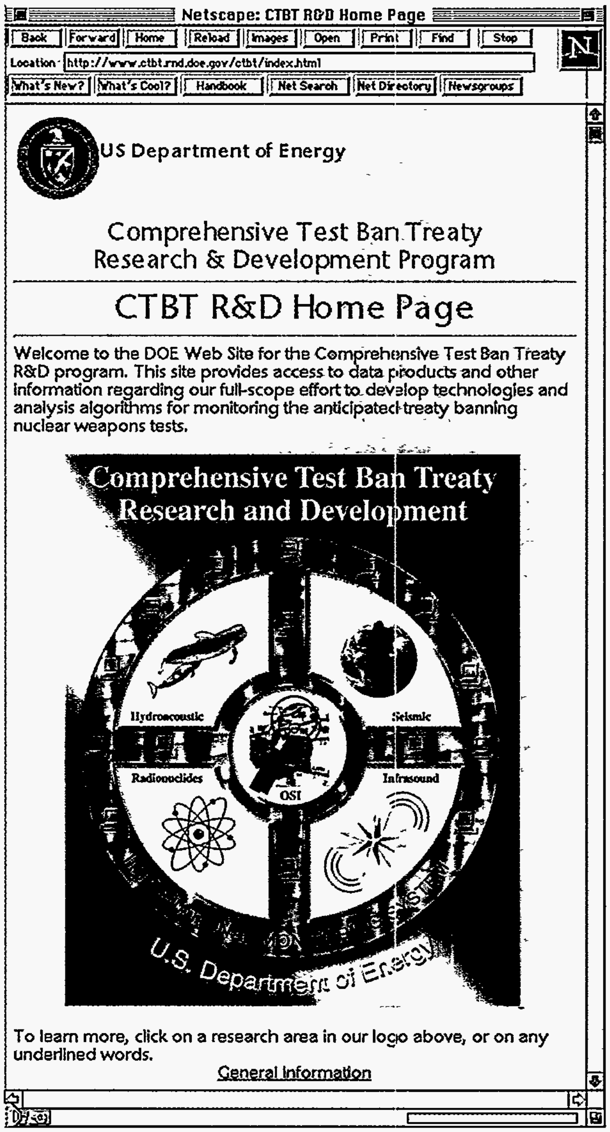
During 1995, we developed the conceptual requirements for the Knowledge Database and identified how the results from other research areas would be integrated to provide content for it. We are currently evaluating commercial technologies for storing the large quantities of data expected in this database and performing the initial design and prototype functions. When complete, the CTBT Knowledge Database will provide a wealth of diverse information derived from the DOE research for use in monitoring a Comprehensive Test Ban Treaty.



The Knowledge Database (orange) will organize and store the large quantity of key results from the DOE CTBT research and make them available on-line to the operational data-processing system.

CTBT R&D Home Page: Disseminating Research Results

As a communication tool, the Internet is unsurpassed in versatility and ease of use. The CTBT Research and Development Program has taken advantage of this capability by establishing a home page on the World Wide Web. Researchers, customers, and policy makers can quickly access CTBT R&D data products, research results, and useful information about the program. A key feature of the home page is a bibliography of publications where visitors can make on-line requests for copies of reports—for example, reports from our field tests (one-month "Quick Look" data reports, three-month Preliminary Analysis reports, and six-month Final Analysis reports). We invite you to visit our home page at http://www.ctbt.rnd.doe.gov/.



US Department of Energy

Comprehensive Test Ban Treaty
Research & Development Program

CTBT R&D Home Page

Welcome to the DOE Web Site for the Comprehensive Test Ban Treaty R&D program. This site provides access to data products and other information regarding our full-scope effort to develop technologies and analysis algorithms for monitoring the anticipated treaty banning nuclear weapons tests.

Comprehensive Test Ban Treaty
Research and Development

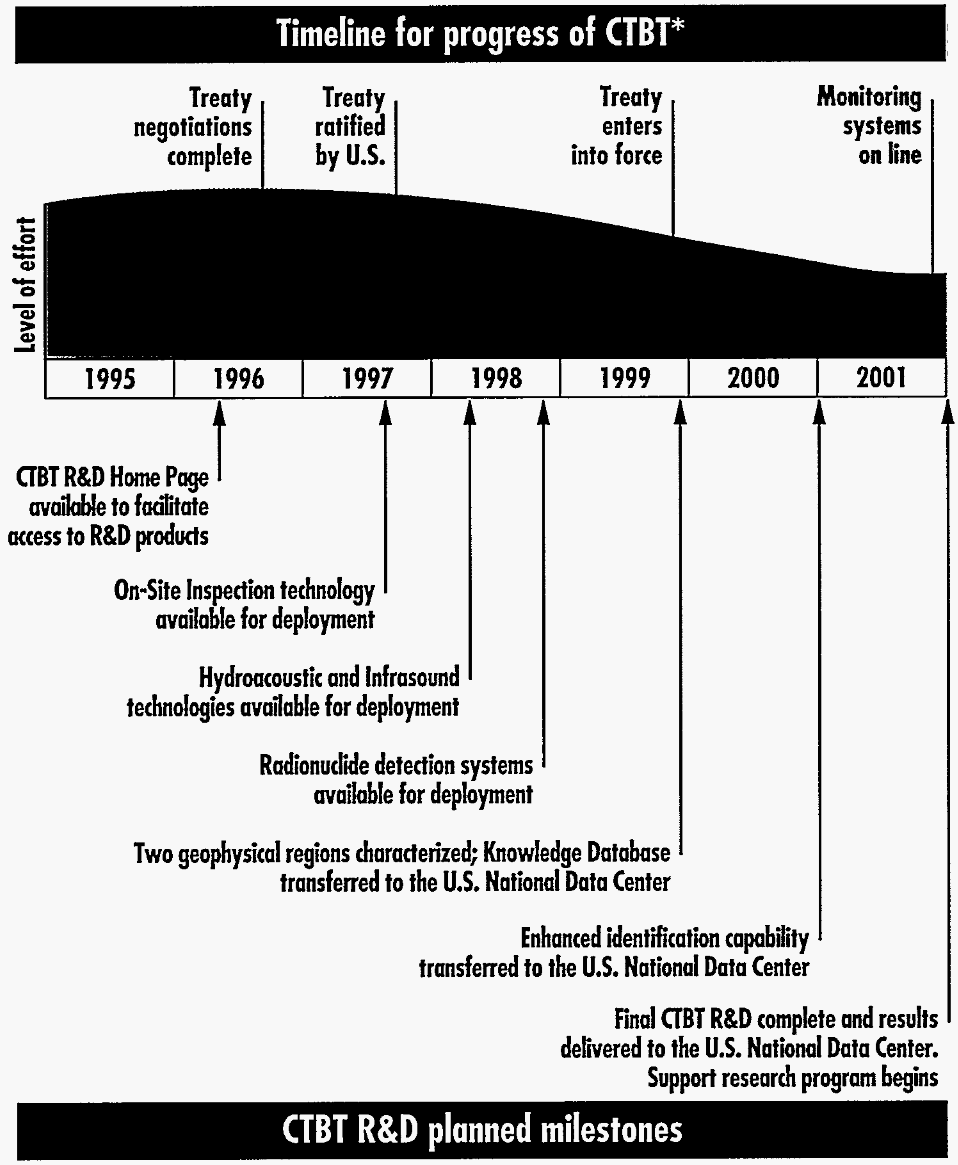
To learn more, click on a research area in our logo above, or on any underlined words.

General Information

Information about the CTBT R&D Program, including an on-line bibliography, is provided on our World Wide Web home page (http://www.ctbt.rnd.doe.gov/).

Program timeline

Red items show, for R&D planning purposes, an assumed timeline for the progress of the treaty. Blue items show CTBT R&D major planned milestones. The Program is structured to deliver products to the U.S. National Data Center that are necessary for monitoring of the treaty.



*assumed for planning purposes

http://www.ctbt.rnd.doe.gov/