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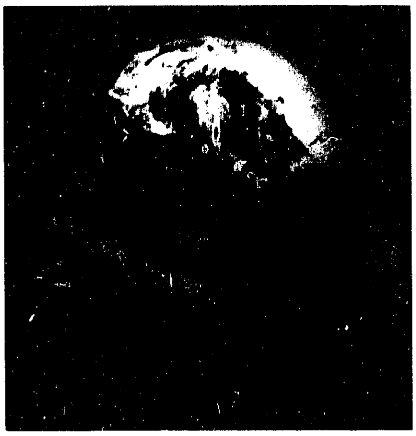
Arms Control and Nonproliferation Technologies

Second Quarter 1994

Technology options and associated measures for monitoring a Comprehensive Test Ban



The cover

Verification of a CTBT requires global environmental monitoring. The technologies described in this issue could collectively provide monitoring coverage underground, underwater, in the atmosphere and in space.

The purpose of *Arms Control and Nonproliferation Technologies* is to enhance communication between the technologists who develop means to verify compliance with agreements and the policy makers who negotiate agreements.

Monitoring a Comprehensive Test Ban

This newsletter contains reprinted papers discussing technology options and associated measures for monitoring a Comprehensive Test Ban Treaty (CTBT). These papers were presented to the Conference on Disarmament (CD) in May and June 1994. An interagency Verification Monitoring Task Force developed the papers. The task force included participants from the Arms Control and Disarmament Agency, the Department of Defense, the Department of Energy, the Intelligence Community, the Department of Interior, and the Department of State.

The purpose of this edition of *Arms Control and Nonproliferation Technologies* is to share these papers with the broad base of stakeholders in a CTBT and to facilitate future technology discussions.

The papers in the first group discuss possible technology options for monitoring a CTBT in all environments (underground, underwater, atmosphere, and space). These technologies, along with on-site inspections, would facilitate CTBT monitoring by treaty participants. The papers in the second group present possible associated measures, e.g., information exchanges and transparency measures, that would build confidence among states participating in a CTBT.

For increased readability we have made minor editorial changes. No changes in meaning or content are intended. If you have comments or questions regarding this newsletter, please call Leslie Casey, DOE/NN-20, phone 202-586-2151.

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U.S. Department of Energy, Office of Nonproliferation and National Security
John G. Keliher, Director

DOE/ACNT Project Manager
Michael F. O'Connell

Scientific Editor
George Staehle

General Editors
Sue Stull
Jim Bruner
Tim Peck
Cynthia Talaber

Scientific Editorial Consultant
Peter Moulthrop

Art/Design
Ken Ball

Printing and Production
Lawrence Livermore National Laboratory

Correspondence
George Staehle or
Sue Stull
Arms Control and Nonproliferation Technologies
Lawrence Livermore National Laboratory
P. O. Box 808, L-205
Livermore, CA 94551

Phone
(510) 422-7365

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Background of technology options and associated measures for monitoring a CTBT

In July 1945, the U.S. conducted the first nuclear test explosion. Indian Prime Minister Jawaharlal Nehru in 1954 first called for a treaty banning such tests. Since then, conclusion of a CTBT has been elusive. In 1958, President Eisenhower proposed convening a Conference of Experts to examine the verification of a CTBT. In 1959, the U.S. released data from reports on specific underground nuclear explosions, which some took as proof that verification of a CTBT was more difficult than commonly thought. Disagreement about the significance of these results and a variety of other political factors ended the discussions. During the following years, individuals and nations introduced a variety of CTBT proposals, but none came to fruition. U.S.–U.S.S.R. negotiations to place less than comprehensive limits on testing did succeed, however. These include the Limited Test Ban Treaty (signed in Moscow, 1963), the Threshold Test Ban Treaty (signed in Moscow, 1974), and the Peaceful Nuclear Explosion Treaty (signed in Washington and Moscow, 1976). Trilateral discussions of a CTBT began in 1977 among the Soviet Union, the United Kingdom, and the U.S., but adjourned unsuccessfully in 1980.

Several factors stimulated recent interest in the U.S. and the international community to reopen negotiations for a CTBT. Included were the breakup of the Soviet Union and President Clinton's declaration of a U.S. moratorium on nuclear testing. Congressional legislation directing the negotiation of a ban by 1996, and the upcoming extension conference for the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) provided additional impetus. The current negotiations began in January 1994 in the Conference on Disarmament in Geneva. Most negotiators agree that various types of monitoring stations (i.e., seismic, radionuclide) and some level of on-site inspections are required for an effective international monitoring regime. While many policy issues remain, the negotiations thus far have focused on the technical details and the costs of acceptable monitoring systems. U.S. ratification of such a treaty will depend, in part, on the existence of a combined national and international monitoring system sufficient to meet its requirements for effective verification.

The first group of papers reprinted in this newsletter discusses possible technology options for monitoring a CTBT in all environments (underground, underwater, atmosphere, and space). These technologies, along with on-site inspections, would facilitate CTBT monitoring by treaty participants. The second group of papers presents possible associated measures, e.g., information exchanges and transparency measures, which would build confidence among states participating in a CTBT.

Overview of the U.S. approach to monitoring a CTBT

The purpose of this paper is to further elaborate on the U.S. approach for an international regime to monitor and verify compliance with a Comprehensive Test Ban Treaty (CTBT). During the intersessional period that just ended, the U.S. has carefully reviewed its thinking on a CTBT monitoring system, taking into account the views presented by other participants over the course of the first round. In particular, this paper will lay out U.S views on the following major aspects of the monitoring system we envisage:

- The contributions of various technologies to an international CTBT monitoring system, including estimates of the costs of these technologies and the role the U.S. is prepared to play in the development and fielding of international capabilities in these areas.
- The role of on-site inspections, exchanges of information, and associated "transparency" measures in a CTBT monitoring system.
- The role of the International Data Center (IDC) within a CTBT monitoring system.

Verification objectives

At the outset, it should be noted that, in Geneva during the first round of the 1994 CD session, Ambassador Ledogar on several occasions summarized our overall approach to and objectives for an international CTBT monitoring system. A few main points warrant re-emphasizing:

It is the U.S. view that the primary verification objectives of a CTBT international monitoring system should be to confirm the absence of nuclear explosions in all environments, and to facilitate the resolution of ambiguous events detected by the system. While acknowledging that technological progress over time should permit improvements in the quality of CTBT monitoring, the U.S. also believes that we should set high standards from the outset in order to create a more significant deterrent against those who may be tempted to try to evade detection. The U.S. continues to believe that event identification, using any or all of the data which would be reported to the IDC, is the responsibility of the individual States Parties. The international monitoring system should be able to do the following:

- Facilitate detection and identification of nuclear explosions down to a few kilotons yield or less, even when evasively conducted, and attribution of those explosions on a timely basis.
- Provide credible evidence to the States Parties to aid in resolving ambiguities and to serve as the basis for collective or individual action.
- Help confirm any declarations and notifications made by States Parties under the provisions of a CTBT.

During the last round, Ambassador Ledogar also noted that a variety of resources will be needed to meet these requirements. The U.S. believes that a mix of technical resources will be necessary to monitor the testing environments. While we seek a CTBT that is effectively verifiable, it should not create unnecessary burdens on participants. We should certainly employ existing resources efficiently. But we also need to significantly enhance current capabilities, both collectively and as States Parties.

Elements of an international monitoring system

Against this backdrop, the U.S. recommends the following for consideration as the components of an effective international monitoring system. Overall, we see six technologies that, when combined with on-site inspections and exchanges of information and notifications, could contribute to the monitoring regime. The technologies include the use of seismic, radionuclide, hydroacoustic, infrasonic, optical, and electromagnetic pulse (EMP) sensor systems.

A global system of seismic stations reporting data to an IDC

This system could be based, for the most part, on the concept to be tested in the GSETT-3 experiment. The U.S. is prepared to provide data from at least the three primary and nine auxiliary stations on its territory that it will contribute to GSETT-3. The seismic system would report high-quality data either continuously or on-demand, and the IDC would provide both raw waveform data and seismic parameters used in event identification, which could be tailored by each country to meet its own needs. The U.S. believes that the international seismic system should consist of about 50 to 60 primary stations and more than 100 auxiliary stations. The costs of primary stations could range between $250,000 and $10 million, and each auxiliary station will cost between $200,000 and $2 million. The Conference on Disarmament has been presented with some idea of the GSETT-3 costs by the Group of Scientific Experts, with the cost of completing the technical development of the seismic components of the IDC estimated to be about $8 million. It is difficult at this point to estimate the cost of including the other disciplines in the IDC and the total cost of building and operating a Center.

A global system of radionuclide sampling stations providing data to the same IDC that collects the seismic data

The U.S. believes that this element is important because, in some circumstances, it can provide unambiguous evidence of a nuclear explosion. Though a rigorous meteorological study must be completed to define the required size of the sampler networks, preliminary studies indicate that the system should include between 100 and 150 stations collecting xenon gas and 100 to 150 stations collecting particulates. These stations, which may or may not be collocated, would perform continuous, in situ analysis and report the results of this analysis to the national facilities and/or the IDC on a near real-time basis. The U.S. is prepared to provide data from a number of these stations that will be installed on its territory. For a system of this scope, which we believe should be a high priority of a CTBT verification system, each installation would cost about $100,000, with annual operating costs of about $10,000. Further, this system should include access to certified laboratories to perform a more detailed analysis on the samples, if needed. If certified laboratories were not available, each would cost about $2 million to build and equip, and another $2 million per year to operate. The U.S. is prepared to participate actively in the development of this network. We can provide the technology for the sampling stations, and develop partnerships with other nations in the construction of this network. We can make available the services of U.S. certified laboratories that could help in the post-event analysis. But contributions by other CTBT participants would be necessary to create a worldwide capability.

A global system of hydroacoustic stations providing data to the IDC

The U.S. believes that a global hydroacoustic network would be complementary to the seismic system for detecting oceanic earthquakes and be the primary means for identifying explosions in the oceans. The U.S. is prepared to provide continuous waveform data from two hydrophone arrays used by the U.S. Missile Impact Locating System (MILS) and operated in the Atlantic and Pacific oceans. It is also prepared to make available the technology necessary to build permanent arrays, or moored and/or drifting hydroacoustic sensors, for incorporation in the network by individual participating States. A single stationary array could cost up to $20 million for equipment and installation, but its lifetime would be over 15 to 20 years. Individual moored and/or drifting hydroacoustic sensors could cost between $40,000 and $150,000, depending on the equipment, and last for a year or two. Successful construction, installation, and operation of such a global network of hydrophones of up to 20 installations, depending on the type, will require contributions by other CTBT participants.

A global system of infrasound detection stations providing data to the IDC

The U.S. believes that a global system of about 50 such stations would be necessary to detect and provide a general location of the source of the atmospheric shock wave produced by the air blast from an atmospheric nuclear explosion. This system would work in concert with the radionuclide debris collection system, indicating the geographical location of those stations which would most likely pick up debris from an atmospheric explosion. The U.S. is prepared to integrate its existing infrasound stations located in Nevada into a global CTBT network. We are also prepared to make available the technology that would be included in this type of station. Each station would cost about $80,000 and have a lifetime of 15 to 20 years with minimal maintenance. Contributions by other States would be needed to develop a global network.

A global system of stations capable of detecting an optical signal from an atmospheric nuclear explosion and an explosion conducted in the upper atmosphere and near space

These stations would also provide data to the IDC. They would facilitate event identification, and they can provide the unique optical signatures of a nuclear explosion in these environments. An atmospheric explosion can be detected and identified by the characteristic time history of the light emitted by the fireball. An explosion in space can also be detected and identified by the high-altitude air fluorescence caused by the x rays from a nuclear explosion in space interacting with the nitrogen and oxygen within the upper atmosphere. The U.S. is prepared to make available the technologies for these stations and would consider deploying stations on its territory. System capabilities will depend on the details of the final system configuration, which depends on the number of CTBT States that participate in the system. For global landmass coverage, at least 150 to about 300 stations will be needed. Each station would probably cost between $50,000 and $100,000, with infrequent maintenance.

A global system of EMP stations

A global network of 20 to 40 stations capable of detecting the EMP from a nuclear explosion would significantly aid in rapidly providing a location for the explosion. Although such a station would pick up a number of naturally occurring events (e.g., lightning), it would complement the infrasonic and debris-collection networks in detecting and identifying atmospheric nuclear explosions. The U.S. is prepared to make available the technology for these stations. We estimate that each station would cost between $150,000 and $200,000. Global coverage would again depend on the number of CTBT States that participate in the network construction.

An on-site inspection system to resolve ambiguities and reduce uncertainty

While a multifaceted OSI regime with robust capabilities will not always resolve the nature of either suspicious or ambiguous events, the Treaty right to conduct inspections coupled with a demonstrated ability to employ the full inspection regime as required will serve as a strong deterrent. The U.S. estimates that the initial cost of equipment required to conduct a challenge OSI would be about $8 million, and each challenge inspection would cost about $5 million.

Exchanges of information about and notifications of certain activities that might create uncertainties about Treaty compliance

In particular, we have in mind exchanges of information on such things as locations of mines where explosions above a certain threshold occur. For example, these exchanges could include pre-event notifications of scheduled large chemical explosions along with post-event notification of large, accidental industrial explosions, rock bursts in mines, earthquakes, or any other phenomena above a certain threshold that would be detected seismically by national and international seismic detection systems.

Monitoring the four testing environments

In order to portray the interactive and mutually supporting nature of the several technologies in a CTBT monitoring system, it is useful now to describe how the technologies would contribute, across the four testing environments, to detecting and identifying nuclear explosions. A chart is attached to assist in understanding these relationships.

Underground

The primary tool for promptly detecting explosions in the underground environment would be the global seismic network. If the explosion vented, the global radionuclide network could provide crucial data to aid in event identification where the seismic data does not provide enough information. The hydroacoustic system would be of considerable importance in providing data for identification of events that are detected and located in the broad ocean areas by the seismic system. The infrasound system could also aid in the detection of underground explosions in some circumstances.

Underwater

The global hydroacoustic system would provide important data that would aid in the identification of underwater explosions. It could also detect explosions detonated in the atmosphere near the water surface. The seismic system would also be of substantial use in detecting and identifying underwater events. In limited circumstances, the infrasound systems could also contribute to event identification. The global radionuclide network could again provide crucial event identification data.

Atmosphere

A combination of the global infrasound network, the radionuclide debris collection network, and the optical and EMP sensors would all aid in detection and identification of atmospheric explosions. The seismic and hydroacoustic networks could also aid in event identification if the explosion was conducted close to the Earth's surface.

High altitude and near space

The optical sensor that detects the reaction of the atmosphere with the energy from a near-space explosion—the air fluorescence—will provide the basic detection and identification of nuclear explosions conducted in near space.

As this survey of the testing environments illustrates, the U.S. sees the various monitoring technologies combining in a synergistic fashion to significantly increase deterrence against any state that might contemplate conducting a covert nuclear test. While the U.S. recognizes that no international monitoring system can be expected to be foolproof, the technologies just described, working in conjunction with on-site inspections, information exchanges, and notifications certainly should raise the cost and complexity of a covert test to levels where any benefits may well be outweighed by the considerable risk of being detected.

The role of national monitoring means

However robust, the international monitoring system will not be operating alone in the global CTBT verification effort. Each participant will have the right to use its national monitoring means, both technical and non-technical, to help verify compliance with the Treaty. As is now the case in support of IAEA and certain other United Nations activities, the U.S. will employ the full range of its national monitoring means to supplement the international system. Moreover, the U.S., on a case-by-case basis, will consider sharing information acquired through its national monitoring means with other States Parties or the international CTBT organization, if it appears that such information would be useful in addressing a compliance question. We would expect other States Parties to do likewise. The U.S. takes this approach in recognition that nuclear testing cannot be viewed as an activity that occurs in isolation from the broader process in which a state would have to engage to acquire or advance nuclear weapons capabilities.

The exact shape of the final international verification regime will, of course, be the outcome of negotiations of all the Parties. It will depend in large measure on consensus in the CD, not only on the necessary elements of that regime, but also on the degree of technical and resource contributions by all the Parties, as well as a workable and equitable cost-sharing basis for the international organization.

The U.S. hopes that this overview of the U.S. approach to CTBT monitoring has provided food for thought as we enter a new round of negotiations in Geneva. Over the course of the next several weeks, we expect to present detailed papers on the technologies touched upon, on our approaches to on-site inspections, information exchanges, and notifications, and on the structure and role of the international organization.

Contributions of key technologies to international monitoring of a CTBT (ground-based systems)

	Underground	Underwater	Atmosphere	Near Space
Seismic	P	P	S	N
Radionuclide	P	P	P	N
Hydroacoustic	S	P	S	N
Infrasound	S	S	P	N
Air fluorescence/Optical	N	N	P	P
EMP	N	N	S	N

P = Primary, S = Secondary, N = None

Seismic monitoring system

The issue is to define an International Seismic Monitoring System (ISMS) that will provide a stable, capable, and cost-effective means of supporting the monitoring requirements of States Parties to a Comprehensive Test Ban Treaty (CTBT), and that will draw on and avoid adverse impact on existing and other planned seismological resources. The role of this seismic system would be to provide the primary technique used in monitoring for underground nuclear explosions and to serve a complementary role in monitoring for explosions underwater and at low altitudes.

Background

Seismic monitoring includes the collection, processing, archiving, and provision of the seismological data needed to detect and locate seismic events, so as to allow States Parties to identify those events as earthquakes or explosions. Seismology is the primary technique for this task when the events are in the subsurface environment. The seismic technique can also trigger and supplement other techniques for monitoring explosions underwater and at low altitudes in the atmosphere. The detection of an underground nuclear explosion must be carried out against a background of natural and other manmade seismic activity (e.g., earthquakes and chemical explosions). The seismic monitoring technique involves (a) the collection of ground motion data generated by seismic events and recorded remotely by a network of seismic stations, and (b) the interpretation of those data using models and/or empirical experience that characterize the nature of seismic events, the propagation of seismic waves from seismic events to seismic stations, and the station site characteristics (e.g., seismic noise level, geologic structure and instrumentation).

The seismic monitoring regime defined in this paper is based on the Conference on Disarmament (CD) Group of Scientific Experts (GSE) concept for an International Seismic Monitoring System (ISMS), supplemented by additional "open source" seismological information. Many of the components of the ISMS are being tested on a large scale now, with full-scale testing to begin in January 1995. Details on the GSE concept have been submitted to the CD, including CD/I211 (August I993), CD/1245 (February I994), and CD/1254 (March I994). Comprehensive briefings on the GSE concept were provided to the CD in March 1994. This monitoring regime, drawing upon the best available and planned global resources and on the operational experience gained by the GSE and others, would provide a capable and cost-effective means of supporting the verification requirements of States Parties to the CTBT.

The International Seismic Monitoring System

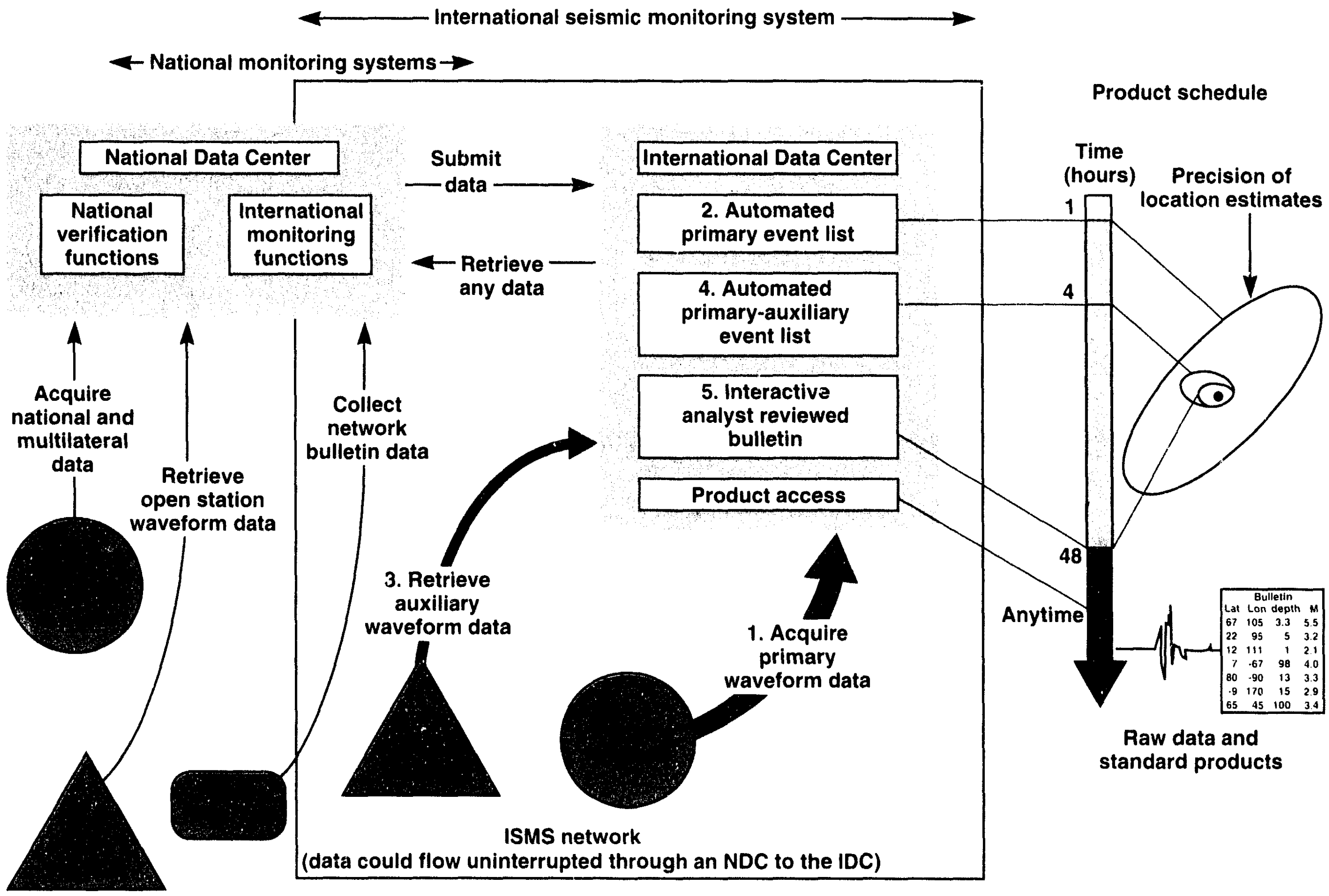
The principal components of the system (Figure 1) are (1) the ISMS Network of "certified" seismic stations, based on the concept proposed by the GSE; (2) other seismological resources, comprising seismic data from other seismic stations, and from catalogs and bulletins of seismicity; (3) a single International Data Center (IDC); and (4) National Data Centers (NDCs) established by States Parties. The following discussion focuses on the overall structure of the ISMS.

ISMS Network

The ISMS Network would consist of two categories of stations: Primary and Auxiliary. The Primary network would consist of very high quality seismic stations, mostly arrays, located at carefully selected sites throughout the globe, with equipment for continuous and reliable communications. Waveform data from these stations would be telemetered continuously to the IDC, either directly or uninterrupted through an NDC. These data would provide the primary means of detection of seismic events on a global basis. The Primary stations would be "certified" to meet or exceed high technical standards (e.g., CD/1254), and would be operated according to well-established procedures.

The Auxiliary stations would support rapid, on-demand, automatic retrieval of data for use in improving the location of events detected by the Primary network. These stations would be principally three-component stations, with some arrays. The Auxiliary stations would also be "certified" to meet or exceed technical standards (e.g., CD/1254).

The ISMS Network stations would be selected based on geographic location, technical characteristics of the stations and station sites, operational experience, computer simulations and practical matters (host countries' recommendations, station availability, communications, etc.). Most of these stations would be drawn from existing stations meeting the ISMS technical standards, with additional stations added or



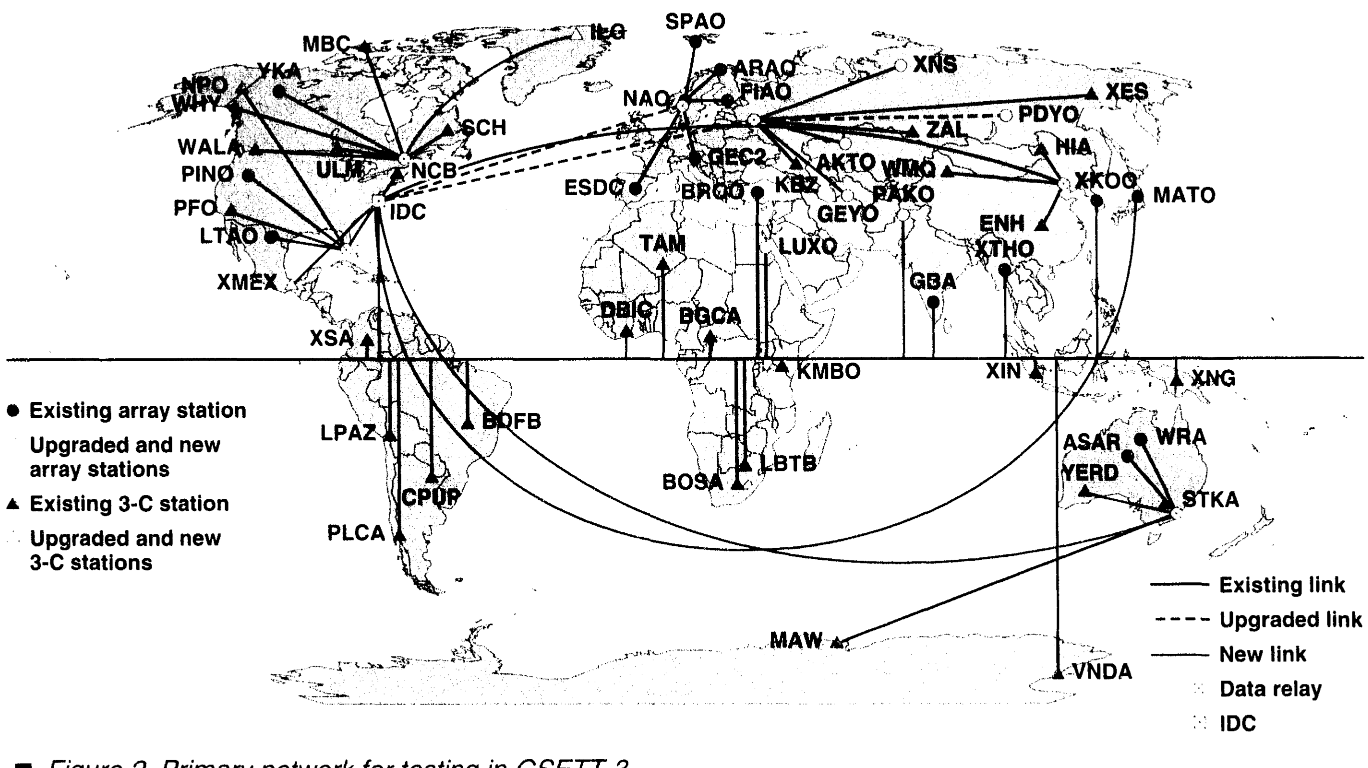
■ *Figure 1. General flow of data and information between the ISMS Network stations, IDC, and NDCs within the International Seismic Monitoring System, and within national components (left) that are external to the international system. The information on the right shows the relative schedule of products from the IDC and the improvement of the product quality, represented by the decreasing area of location confidence ellipses, as processing proceeds. Automated products from the IDC are available relatively rapidly, with human-reviewed products, in which more confidence can be placed, available at a later time.*

upgraded to meet the standards. The GSE has used the above criteria to design a Primary network for testing in GSETT-3 (Figure 2). The initial ISMS Primary network could be based upon the high-quality stations in this GSE network. The number and location of the initial set of ISMS Auxiliary stations could be based upon the experience of GSETT-3 as well. The monitoring regime would provide for the addition, deletion, improvement, or change of status (e.g., from Auxiliary to Primary) of ISMS stations.

Each State Party would own and be responsible for ISMS Network stations and communications on its territory, and would undertake arrangements with the International CTBT Organization to operate and maintain these resources according to ISMS standards established by the International CTBT Organization. This process allows for the establishment and expansion of the ISMS network, while ensuring the ISMS Network is maintained to rigorous technical standards. The International CTBT Organization would undertake responsibility for all international communications between ISMS stations and the IDC. This provides the most cost-effective communications architecture, and permits international pressure to be brought to bear to lower or drop taxes and tariffs, which are a significant part of the estimated cost.

Other seismological resources

Other open scientific resources in the field of seismology would be available for use in treaty monitoring applications such as the calibration of ISMS stations and products, verification research, and resolution of difficult seismic events. Such open data could be important to Treaty monitoring. These resources include the products of international, national, and regional data centers and waveform data from open stations. They include seismic data collection and processing activities that are currently part of national and international data exchanges for earthquake monitoring and basic seismologi-



■ *Figure 2. Primary network for testing in GSETT-3.*

cal research. The Treaty would recognize the existence of these resources, recognize their value for supplementary monitoring and support their accessibility both for the reasons for which they were established and for Treaty-related purposes.

Open stations

There are many seismic stations including those of local, national, regional. and global seismic networks, e.g., those operated by members of the Federation of Digital Seismographic Networks, that meet high technical standards and have "dial-up" communication capability for waveform data. Such data could be accessed directly, as needed, to supplement treaty monitoring. The international exchange of open station data should be encouraged, and States with such high-quality stations should be encouraged to "certify" them for inclusion in the ISMS Network.

Network bulletin data

At least one international and many national and regional data centers routinely process seismic data from national and international sources, and publish event bulletins and other data on various time schedules. These data are termed Gamma data by the GSE. Under the ISMS concept, States could voluntarily transmit bulletin data in an agreed format to the IDC where they would be organized in an archive and made available for open and rapid access by any State Party. All States should be encouraged to participate actively to make these data available.

International Data Center

The International CTBT Organization would own, fund and operate an IDC, which would provide raw data and standard products and services for the benefit of all States Parties. The IDC would receive all of the seismic data transmitted from the ISMS Network stations. It would process these data to produce global seismic bulletins and other products (cf., CD/1211, CD/1254). The bulletins would provide the location, time of occurrence, depth, and size (magnitude) of seismic events, along with other standard seismological parameters that describe signal detections and events. An initial, automatically computed event bulletin could be available in about one hour after the event's occurrence, with a final analyst-reviewed bulletin available in about two days. The analysis procedures at the IDC would be scientifically validated, automated to an appropriate degree, and documented in the Operational Manual for the International Data Center. This manual would specify that IDC procedures could evolve to meet changing requirements and to improve operational quality and efficiency.

The IDC would monitor the calibration of the ISMS Network stations and ensure overall quality control of the data generated by the ISMS. The IDC would also monitor the status of stations and communications and provide feedback to the station operators. Data from the ISMS Network stations would be checked for quality and placed in a long-term archive. In addition, this archive could include other data received or produced by the IDC. All seismic data and data products are immediately and openly available to the States Parties. Subsets of the standard data and product sets could be provided to meet the needs of each State Party.

National Data Centers

NDCs established by States Parties would serve as the interface between the States and the other components of the ISMS. The NDC, inter alia, coordinates the operation and maintenance of, and submission of data from, the ISMS Network stations on its territory. The NDC may receive any or all of the data collected and produced by the IDC.

Resources

The ISMS will draw heavily from the best existing seismological resources. Estimates for new investment to build one seismic array range from $1–5 million and to build one three-component station from $200,000– $2,000,000. The ranges in the estimates for annual operation costs are $50,000–$500,000 for arrays and $20,000–$450,000 for three-component stations.

A prototype IDC is being developed in the U.S. as a contribution to GSETT-3 and tested, with international participation, during GSETT-3. The IDC equipment and software will be available to the CTBT organization to install at a site to be determined under the CTBT. The current estimate for the operational cost for seismic monitoring within the GSETT-3 IDC is approximately $7 million per year. This estimate is for a staff of 45, including approximately 25 scientific professionals, 15 computer science technicians, and 5 administrative staff. The GSETT-3 IDC budget estimate also includes funds for the facility, computer hardware and software, as well as other standard expenses.

The implementation of a CTBT ISMS would involve a number of factors whose overall costs cannot be estimated at present. Some of the factors to be taken into consideration include:

- Location of the International Data Center;
- Administrative overhead;
- Level of product and service quality;
- Data and facility security;
- Maintaining reliable operations in the event of a loss of capabilities (e.g., emergency IDC and communications); and
- Maintaining and upgrading equipment over time.

Synergy

The ISMS Network would provide a near-real-time monitoring capability for events around the globe, including events underground, underwater, and at low altitudes in the atmosphere. Also, the detection of an event by the ISMS Network could trigger a retrieval of or search through data collected from other techniques. For example, a seismic detection and location could be used to retrieve or search time series segments from hydrophones, or spectra and filter samples from radionuclide particulate sensors. It is possible that raw data from multiple techniques could be combined to locate events that cannot be located using one technique alone (i.e., to improve the effective detection and location capability). The ISMS data could also contribute to global earthquake monitoring and general seismic research.

Table 1. Preliminary estimate of GSETT-3 costs (in millions of dollars).

Element	Prior Investment	New Investment	Annual Operating Cost
Primary stations	97	14	7
Auxiliary stations	10	4	4
Communications	10	1	8-12
IDC	30	8	7
Total	**$147**	**$27**	**$26-30**

Radionuclide monitoring system

The information provided by many monitoring sensors/techniques is not always adequate to positively identify an event as nuclear. Underground, underwater, and atmospheric nuclear tests create several particulate and gaseous fission products that if emitted into the atmosphere may be collected at large distances from the source. Collection and subsequent measurement of this radionuclide debris provides unambiguous physical evidence of an event's nuclear nature. This paper outlines the main elements and concepts recommended for an effective radionuclide monitoring system.

Background

On March 9, 1994, the U.S. introduced a working paper (CD/NTB/WG.1/5) that provided a description of an operational concept for a radionuclide monitoring system. The concepts presented here expand on the key elements of this paper. The U.S. monitoring concept involves sampling the atmosphere on a global basis to detect particulate debris from a nuclear explosion in the atmosphere, or to detect xenon which might escape from an underground or underwater nuclear explosion.

System description

The radionuclide monitoring system is composed of three main components: global sampling networks, data centers, and certified laboratories.

Global sampler networks

The backbone of the radionuclide system will be global networks of continuous sampling stations specifically designed for collection (of xenon/particulate debris), on-site analysis, and data reporting. Because many of the radioisotopes that provide unambiguous evidence of a nuclear test have short half-lives, analysis at the sampling site is required to increase the probability of detection. The near-real-time detection and reporting also allows for more accurate debris cloud tracking and more prompt meteorological evaluations to determine probable source locations. The typical delay experienced between collection and analysis from off-site analysis reduces sensitivity and timeliness. These conditions and the lack of coordination between existing systems make them impractical as primary monitoring systems. For these reasons, the primary radionuclide monitoring systems must perform analysis at the sampling site. The samplers would be owned and operated by States Parties and deployed in locations to best provide global detection coverage.

Particulate debris samplers. The particulate sampling stations will collect debris in the atmosphere by passing large volumes of air through filters and measure the radionuclides captured on the filters using gamma spectroscopy. The sampler will typically operate on a 1–3 day cycle and transmit its data using a reliable communications circuit such as a telephone modem or satellite link. The data will be provided to the International Data Center (IDC) and the National Data Centers (NDCs). Several organizations worldwide operate particulate collection networks for various reasons and programs. However, we know of only one 10-station network that performs analysis at the sampling sites. All the other networks require laboratory sample analysis; therefore, the majority of existing particulate samplers could not be used as primary CTBT monitors. Technical requirements for the sampler are included in Appendix 1. The cost of a unit using the simplest detector (sodium iodide) with phone modem communications is approximately $60,000. A more sophisticated detector (a germanium detector) and satellite communications equipment each add approximately $25,000 to the cost of the system (i.e., $50,000 if both are added). We anticipate a deployment cost of $15,000 per sampler with a yearly operational/maintenance cost of $15,000 per sampler. U.S. prototypes will be available for testing later this year and production systems could be available in early 1996.

Xenon samplers. The xenon collector will concentrate xenon from air, measure the concentrations of the radioxenon isotopes (xenon-131m, half-life 11.9 days; xenon-133m, 2.19 days; xenon-133g, 5.25 days; and xenon-135g, 9.1 hours)[1] present, and store the sample (in case an additional laboratory analysis is required). At the end of each sampling cycle, typically one day, the stations will transmit their results to a data center. Xenon samplers are employed today that collect samples for laboratory analysis; however, no on-site xenon analysis samplers exist. The analysis delay caused by sample shipment would make these samplers impractical as primary CTBT monitors. Xenon systems capable of on-site analysis are under development in the U.S. and should yield a prototype system by late 1995. Field testing will occur through 1996 with production beginning in mid 1997. Appendix 2 lists the technical requirements for the xenon sampler. We estimate the purchase cost will be approximately $100,000 per sampler (assumes existing communications link or telephone modem) with deployment and yearly operations costs of $15,000 each.

Sea-based samplers. To provide true global coverage it may be necessary to develop sea-based xenon and particulate samplers. Whether or not sea-based systems are critical to radionuclide monitoring will depend on the coverage offered by land-based systems (including systems on islands). We estimate the purchase cost of sea-based systems will be at least twice that of land-based systems. Since we have not determined the operational concept for sea-based systems (i.e., whether it will involve continuous monitoring, deployed on requirement, etc.), we cannot estimate their operational costs. Further study of sea-based systems is required before intelligent cost trade-off estimates may be made. Until (and if) sea-based samplers are developed, sampling using airborne collectors may be used to provide the required coverage. The cost of operating and maintaining a contingency aerial sampling capability (at three missions a year) is at least $3,000,000 per year.

Sampler location. The sampling stations must be distributed based on wind patterns in order to provide an effective detection tool. In some circumstances, it may be appropriate (as determined by meteorology) to collocate sampling stations with stations of the international seismic monitoring network. The number and locations of the sampling networks would be determined by performing meteorological studies. Preliminary and very basic studies suggest networks of 100–150 samplers of each type (particle and xenon) may be required. The studies also indicate complete coverage of the world's ocean areas may not be possible using land-based samplers only. If these early indications hold true, either alternate sampling methods, such as airborne samplers, or sea-based samplers must be explored. The network size and location must be identified during treaty negotiations.

Data centers

Key to the flow and evaluation of data will be the international and national data centers. In the following paragraphs, we delineate the major responsibilities and services provided by the data centers.

National Data Centers. States Parties could manage and coordinate their radionuclide monitoring efforts through their NDCs. The degree and scope of evaluations performed by the individual NDCs will be left to the States Parties; however, as a minimum the States Parties will:

- Operate and maintain the certified samplers under their jurisdiction.
- Receive data from samplers under their jurisdiction within 24 hours of collection and forward it immediately to the IDC. They will also insure any sample identified for laboratory analysis is delivered to the specified location within 24 hours of notification.

International Data Center. The IDC will act as the primary data clearing house for radionuclide data. The IDC would review all radionuclide data, analyze it

[1]Note: Some isotopes decay to an excited energy state, a metastable state (designed by m), before they decay to their lowest energy state, the ground state (designated by g).

(as described in the next section, "Analysis"), assess its quality, and make the data (unprocessed and processed) available to all States Parties. Samples fulfilling one or more of the criteria may receive a laboratory analysis:

- Presence of short-lived fission products on filter samples.
- Presence of xenon signatures consistent with nuclear tests.
- Activity elevations after a suspected violation detected by another sensor or sampler.

Certified laboratories

In certain circumstances, it will be necessary to verify the results and/or provide more information on the samples collected by the field samplers. To meet this need, a minimum of four laboratories should be certified to receive samples and to perform standard analyses. A four-laboratory minimum was chosen to accommodate the following scenario. A suspect event occurs in State A with the primary data provided by State B. The certified laboratories in these states would be disqualified from analyzing samples associated with the suspect event. Because two independent laboratories are required to analyze filter samples as a cross check for contamination and errors, this scenario requires at least four laboratories to exist. The laboratories will be owned and operated by States Parties. The results of analyses performed by these laboratories will be provided immediately to the IDC. The laboratories would participate in an inter-laboratory calibration program to maintain certification. We estimate annual infrastructure costs of operating and maintaining a certified laboratory at approximately $1.5 to $2 million (including personnel). Laboratory requirements may most efficiently be met by utilizing the capabilities of existing laboratories. If analyses could be contracted out to laboratories as piece work, we estimate analysis costs of $400 per gamma spectroscopy analysis and $600 per xenon analysis. If radiochemistry analyses are also performed, the cost would depend on the extent of the analysis by an average cost of $1000 per filter sample is a reasonable estimate. We estimate the annual cost of the inter-laboratory calibration program at $1 million.

Analysis

Analysis performed

Particulate collector. In addition to an unprocessed gamma spectrum, the collector's analysis system will provide a routine gamma unfolding analysis to identify isotopes on the sample. The gamma spectrum along with the initial analysis will be provided to the NDCs and the IDC where additional evaluations will be conducted. The IDC evaluation will include the application of a more sophisticated computer program to quantify the radionuclides present on the filter as well as a review of the data by experienced analysts (personnel educated in nuclear science) who will validate and assess the quality of the data (i.e., perform a quality control function). The IDC will compare the data with prescribed criteria to determine if further analysis is warranted. Filter papers identified from sampler data as containing fresh fission products will be expedited to the IDC. These papers will be split at the IDC, and a portion of the papers will be forwarded to at least two certified laboratories for analysis (the remainder of the paper will be archived by the IDC). The certified laboratories will perform a high-resolution gamma spectroscopy analysis on the samples to identify and quantify the radioisotopes present on the filter samples. Results from the gamma spectroscopy analysis will be provided to the IDC for evaluation and dissemination. The laboratory may possess the capability and wish to perform supplementary analysis techniques, such as radiochemistry dissolution (a technique more sensitive than high-resolution gamma spectroscopy for individual particulate isotopes. Isotopes are separated and radioassayed individually). Typical radioassay methods employed include high-resolution gamma spectroscopy, beta counting, alpha counting, and alpha spectroscopy. Radiochemistry would be employed when analysis results from the gamma spectroscopy analysis warrant further investigation. Results from the supplemental analysis would be provided to the IDC.

Xenon collector. The initial products will be a stored xenon sample, a spectrum, and an analysis of that spectrum. The spectrum and analysis data will be provided to the IDC where experienced analysts will evaluate and check the quality of the data. Samples identified to contain xenon isotopes of interest will be expedited directly to an IDC-specified laboratory (associated collections from other samplers would be sent to other laboratories for analysis). We do not recommend splitting xenon samples because of the small volumes likely to be involved and the time criticality. The laboratory would perform a beta-gamma coincidence radioassay technique to identify and quantify the principal radio xenon isotopes, xenon-133g and xenon-135g (by the simultaneous measurement of the beta and gamma radiation emitted from the xenon isotopes) present in the sample. Supplemental analyses which may be performed include:

- High-resolution gamma spectroscopy is an alternate xenon radioassay technique to identify and quantify the principal radioxenon isotopes, xenon-133m, xenon-133g, and xenon-135g, by the measurement of the gamma radiation emitted from the xenon isotopes present in the sample. High-resolution gamma spectroscopy could be used for low to high activity samples.
- Liquid scintillation is an alternate xenon radioassay technique to identify and quantify the radioxenon isotopes (xenon-133g and xenon-131m) by the simultaneous measurement of the beta and conversion electron radiation emitted from the xenon isotopes present in the sample. Liquid scintillation would be ideal for very-low-activity samples, but no analysis information on xenon-135g would be possible.

Meteorological analyses. In addition to evaluations performed to determine the isotopes present in/on samples, meteorological evaluations will be required to determine the source of activity elevations. When samples meet one or more of the criteria for laboratory analysis, trained meteorologists will perform standardized meteorological analyses to determine the most probable source. The IDC could provide these meteorological evaluations as a service, through a contract to a meteorological organization, or through agreements with one or more States Parties. The required minimum system resources to perform meteorological analyses include:

- Access to WMO data.
- At least two validated atmospheric dispersion models (short range and long range).
- A computer with at least 15 gigabytes storage and multiple workstation capability (a workstation for each meteorologist).

We estimate the envisioned sampler network may require approximately four to six meteorologists and two technicians to maintain meteorological data. The system requirements translate into $200,000 for computer equipment and $350,000 for model purchases. Annual operational costs include $100,000 for world meteorology data services, $60,000 for software system maintenance, and $50,000 for computer hardware maintenance.

Analysis results

Samplers and laboratory. The results of the sampler and laboratory analyses will include a list of the isotopes detected, their activity concentrations, and the standard deviation of the measurement. The error associated with the measurement depends on the amount of material present, interfering radiation, and the measurement duration. We believe that in most instances concentration errors (1 sigma) of 30 percent or less will be routinely possible.

Meteorology. The meteorological analyses will yield the most likely trajectory of the air mass containing elevated radionuclide activities. The error in tracing back to a source is case dependent. Several factors affect one's ability to determine source location: the amount of debris released, the number and locations of samplers detecting debris, the number of interfering sources, and the isotopes collected (for timing). If samplers are hundreds of kilometers from the source, the debris is collected at several samplers, and isotopes that provide timing information are collected, then the source of the debris could probably be located within tens of kilometers (availability of accurate meteorological data and sampler data with 2-hour-time resolution assumed). The tracking error will increase if the conditions and assumptions listed above are not met; for example, if time resolution of the sampler data is 24 hours, the associated tracking error could be on the order of hundreds of kilometers.

Data evaluation. In most cases, the relative ratios of the isotopes detected will allow States Parties to discriminate between natural phenomena, civil nuclear activities, and nuclear testing. In other cases, the combination of the concentration data and meteorological analyses will provide the required discrimination.

Synergy

Relationship to other systems

The radionuclide debris collection and analysis techniques could provide unambiguous proof that a nuclear event occurred and emitted debris into the atmosphere. These systems are also a means of detecting a nuclear event that occurs above ground or at high altitude. A sufficiently robust system of ground-based and airborne samplers would detect a nuclear event underground which vented debris. The debris collection and analysis techniques are required for physical evidence and to support the other early detection techniques, such as seismic. The time between the event and the debris drifting over a sampling site may range between hours to weeks. In addition, the radionuclide debris system provides information on the location and time of the nuclear event (the accuracy of the estimates depends on the amount of the data, number of samplers, meteorological data, etc.).

Requirement for complementary system

The debris collection and analysis system is dependent on the debris being released into the atmosphere and drifting over the collection site. A real-time detection system is required to provide immediate verification of the time and location of a nuclear event.

Issues

Sea-based sampler

A definite requirement for sea-based samplers is not defined at this time. Preliminary meteorological studies indicate land-based systems alone may not provide global coverage. The extent to which or whether sea-based systems are the solution to gaining the coverage is not clear. A better picture of the need for sea-based samplers will be evident after the sampler placement studies are complete. In the meantime, we should study possible sea-based solutions and determine their cost benefit.

Sampler placement

A factor in the effectiveness of the international monitoring system will be the placement of samplers. Ideally, State Parties would form a multinational group to provide recommendations on sampler placement. The network size and location must be identified during treaty negotiations.

Countermeasures

The question of assuring data integrity should be explored to determine if a cost-effective method of maintaining data integrity can be added to a radionuclide sampler. While "spoofing" of radionuclide samplers is possible, we believe a sufficiently dense network is the best deterrent to tampering with samplers or their data. While a country with a large land mass might avoid detection by tampering with samplers in their country, they could not be certain they would go undetected by samplers in bordering states.

Appendix I
Particulate sampler technical requirements

Collection

- Continuous collection of particulate from the atmosphere on removable filter media.
- Minimum of 10,000 cubic meters of air per day.
- High efficiency for trapping particles with diameters from 0.1 to 5.0 micrometers.
- Capability for trapping particles with diameters below 0.1 micrometer.

Analysis

- Radionuclide measurement shall be performed on-site.
- Background and calibration spectra will be acquired and analyzed.
- Detection sensitivity: 7 becquerels of molybdenum-99 from 10,000 standard cubic meters of air.
- Spectrum range 50 keV to 2 MeV.
- Emphasis shall be placed on reducing/eliminating background interference.
- Emphasis shall be placed on reducing/eliminating radon daughter interference.
- Minimum collection/analysis cycle time: 24 hours.
- Maximum collection/analysis cycle time: 72 hours.

Data storage and communication module

- Unit shall record background, calibration, and sample spectral information separately for each exposure cycle.
- Unit shall be able to record start and stop collection/analysis times and correlate with filter media exposed.

Operation and logistics

- Maintenance requirements: Easy to repair configuration.
  Annual programmed maintenance.
  Self-diagnostics to detect operational degradation.
  State-of-health information to on- or off-site personnel.
  Components are off-the-shelf equipment, if possible.
- Normal reporting time: within 24-hours from collection.
- Unit shall be self-calibrating.
- Unit shall be able to allow shipment of filter media to the IDC on a selective basis.
- Mean-time-between-failure shall be a minimum of 12 months.

Appendix 2
Xenon sampler technical requirements

Collection

- Continuous collection of xenon from the atmcsphere.
- Minimum collection cycle time: 6 hours.
- Xenon gas yields: Minimum of 0.5 cc/minimum collection cycle (includes effects of radon removal process).

Analysis

- Isotopes of interest: Xe-135g, Xe-133m, Xe-133g, Xe-131m.
- Gas separation and measurement on-site.
- Sensitivity for detection (in minimum collection)
  - Xenon-131m – 217 milli-becquerels.
  - Xenon-133m – 50 milli-becquerels.
  - Xenon-133g – 17 milli-becquerels.
  - Xenon-135g – 6.7 milli-becquerels.
- Precision of measurement: Relative standard deviation of 10%.
- Radon must be removed to the level where there is no interference with xenon measurements.
- Counting system shall be shielded to reduce background levels.

Data storage and communication module

- Unit shall record background, calibration, and sample spectral information separately for each collection/analysis cycle.

Operation and logistics

- Maintenance requirements:
  - Modular design.
  - Easy-to-repair configuration.
  - Only annual programmed maintenance.
  - Self-diagnostics to detect operational degradation.
  - State-of-health information to on- or off-site personnel.
  - Components are off-the-shelf equipment, if possible.
- Normal reporting time: 24 hours from collection.
- Unit shall be self-calibrating.
- Unit shall be able to store collected xenon from seven collection periods for possible shipment to a certified laboratory on a selective basis.
- Mean-time-between-failure shall be a minimum of 12 months.

Hydroacoustic monitoring system

The oceans cover more than 70% of the Earth's surface, with much of the seismic activity from earthquakes and volcanic activity occurring along coastlines, in oceanic ridges, and in the Pacific Ocean trenches. The hydroacoustic system would have the primary role in identifying explosions in the oceans and would also complement the seismic system in discriminating the naturally occurring seismic activity.

Background

Types of oceanic events

The problem that the hydroacoustic monitoring system would address is monitoring the three important types of suspicious man-made oceanic events: fully contained underwater explosions, explosions that vent at the water's surface, and shallow atmospheric explosions over the water's surface. There is a unique feature of the world's oceans that significantly enhances the capabilities and usefulness of a hydroacoustic system to monitor these explosions. This feature is a deep sound channel bounded at its top and bottom by higher velocity layers; in this sound channel, hydroacoustic signals travel great distances on a global scale with little attenuation.

Fully contained underwater explosions. If underwater explosions are sufficiently deep relative to their yield, they produce a bubble that expands and contracts repeatedly while it rises to the surface. This expansion and contraction manifests itself as repeated bubble pulse signals that are typically clearly evident in hydroacoustic data even after propagating great distances through the sound channel. The presence of these bubble pulse signals provides high-confidence identification of an event as an explosion, and conversely their absence identifies an event as a submarine earthquake or a near water-air interface explosion that vents to the atmosphere before the first bubble collapses.

The global seismic system would detect and accurately locate most fully contained underwater explosions down to yields less than 1 kiloton since water is an excellent coupling medium that transmits hydroacoustic energy to seismic energy at the water-land interface. However, as currently envisioned, the seismic technique will not provide high-confidence identification of such oceanic events. The hydroacoustic technique could complement the seismic analysis by providing high-confidence identification of these explosions and submarine earthquakes. This identification capability would significantly reduce the degree of seismic analysis that is necessary for ve··ying as earthquakes the large number of submarine events that occur on a daily basis. It could also provide a trigger for deployment of sampling assets (for example, by a State Party) to distinguish between different explosion types (such as nuclear and chemical).

Vented and shallow atmospheric explosions. The hydroacoustic technique would also provide a detection and identification capability for the vented and shallow atmospheric explosions that are not resolvable by the seismic method. In these cases, the coupling at the air-water interface is most likely adequate for transmission of acoustic energy into the sound channel. Identification of these explosions is given by the sharp rise time of the associated transient hydroacoustic signal as compared to submarine earthquakes.

The capability of the hydroacoustic method for location on a real-time basis of these suspicious oceanic events that are not resolvable by the seismic method is marginal because of large location errors (on the order of hundreds of kilometers) associated with multipathing of the acoustic waves and poorly defined oceanic velocity models. However, the hydroacoustic method could provide an initial location for a suspicious oceanic event. Fast airborne deployment of a Small Underwater Sound (SUS) charge (again for example, by a State Party) into the area encompassed by the location error bounds could then be accomplished. The known time and location of this calibration explosion is used to significantly reduce the extent of the initial error. This refined location estimate technique has had excellent success in other applications and could provide a basis for deployment of sampling assets to the area where the suspicious event occurred.

Hydroacoustic monitoring systems with on-demand or continuous data

In most CTBT scenarios, hydroacoustic data are used to discriminate oceanic events that are initially detected by the seismic, optical, and/or infrasound systems. Using the location and origin time, the hydroacoustic stations are queried on-demand for a time window of data. The returned data are then processed to find the hydroacoustic signal and evaluate it for the presence of a bubble pulse and high-frequency energy and for the sharpness of onset time. This procedure is more than adequate for resolving a 1-kiloton explosion detonated below the ocean's surface.

For vented and shallow atmospheric sources, the seismic signal may be weak, an optical signal may be obscured by clouds, and the infrasonic signal may be missed because the explosion has too low a yield or due to extreme variation of winds. Continuous transmission of raw hydroacoustic data from many sites to a central location and then application of the most sophisticated automatic detectors and data processing would be required to resolve these events. The analyst uses the continuous stream of data to resolve weak detections or determine causes of missed detections, such as coda signals from previous events. This procedure could potentially resolve the vented and shallow events not detected by the other methods.

Discussion of hydroacoustic system

System description

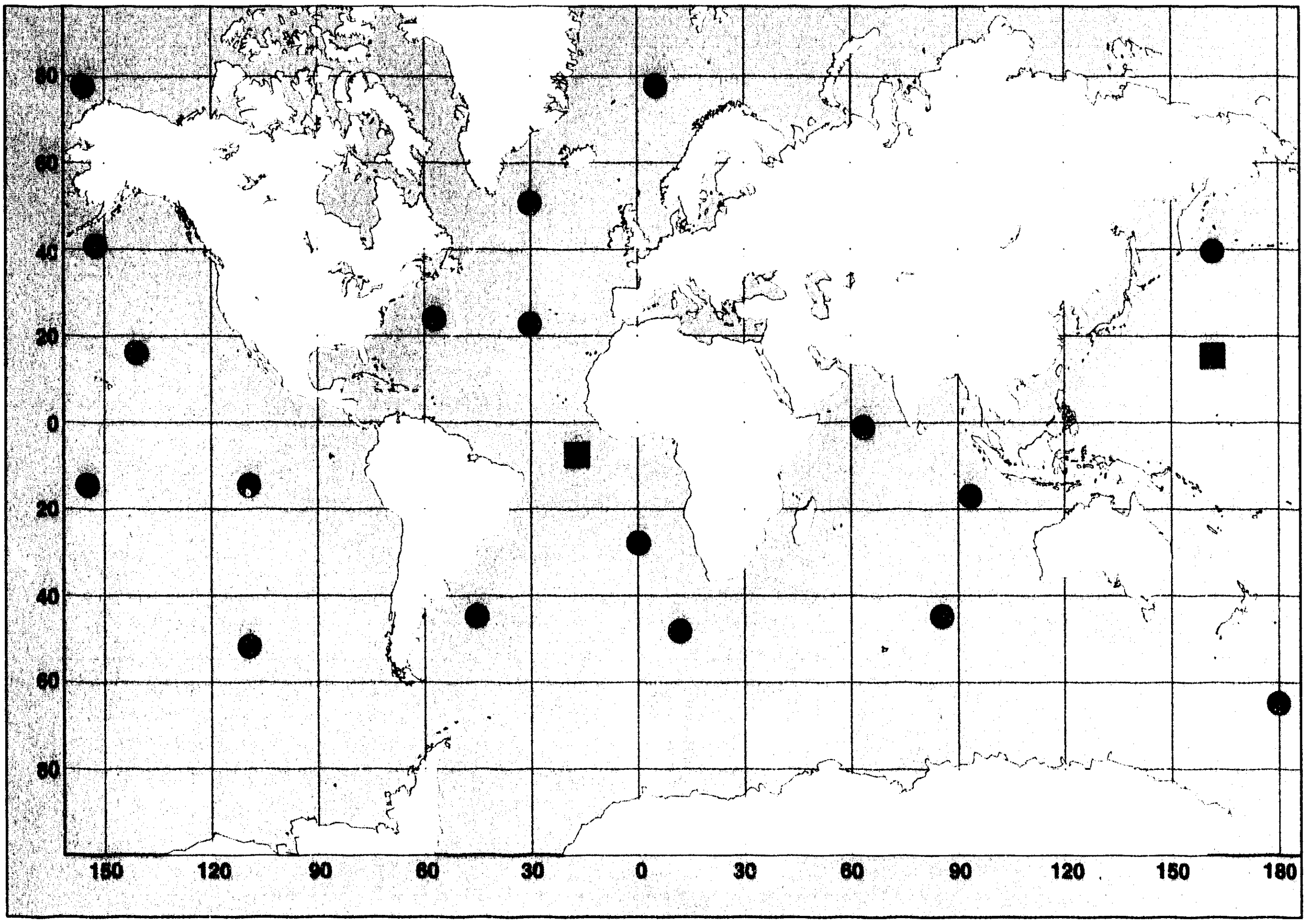
The hydroacoustic system is a network of hydrophones, carefully located at sites throughout the oceans, together with procedures for communication and data analysis. There are two system options: fixed arrays cabled to shore, and a hydrophone or hydrophone array suspended from a moored or freely drifting buoy. The fixed arrays cable data to a shore station, which can telemeter data to a satellite, and the buoy systems telemeter data directly from the buoy antenna.

The hydroacoustic system would contribute data to an International Data Center (IDC) by way of a National Data Center (NDC) for assets owned by States Parties. The hydroacoustic stations should meet the minimum defined technical criteria outlined here. However, hydrophone stations with critical features such as hydrophone location that do not meet certain of the technical criteria could still be included in the network.

Hydrophones. The most important component of the hydroacoustic system at a hydroacoustic station is the hydrophone itself. The hydrophone should have a dynamic range of 140 decibels (dB) in an unpowered state to record both the large pressures associated with fully contained nuclear explosions and the much quieter ambient deep ocean noise. Any preamplifiers installed at the hydrophone or at the hydrophone cable termination should not degrade the overall hydrophone dynamic range. The hydrophone should have sufficient sensitivity at frequencies less than 50 Hertz (Hz) to resolve explosion and related bubble pulse signals. A typical hydrophone sensitivity is –220 dB relative to one volt per micropascal. Calibration information in the form of sensitivity data as a function of frequency should be available for the hydrophone. The self-noise of the hydrophone should be at least 10 dB below the average ambient noise in the deep ocean sound channel.

Locations. Appropriate locations for the hydrophones are those positioned in the deep ocean sound channel to take advantage of its unique waveguide characteristics. The unique properties of the sound channel where the sound waves travel with little attenuation minimize the total number of hydrophones required to achieve coverage throughout the oceans and seas for a CTBT. The problem areas for coverage are where the sound channel pinches out due to topography (such as in the Indian and Arctic oceans and south of Australia). In these areas, the sound energy cannot leak out into the broad oceans. Hydrophones are required in this type of blocked area as well as in the broader oceans.

A network of approximately 20 stations with hydrophones suspended or floated into the sound channel of the broad oceans and blocked areas is shown in Figure 1; this network would provide sufficient coverage to identify fully contained underwater explosions to yields less than 1 kiloton on a worldwide basis. As illustrated in Figure 1, approximately six widely spaced hydrophones are located throughout the northern, central, and southern areas of the Atlantic and Pacific oceans, for a total of 12 hydrophones over both oceans. There are two hydrophones in the Indian Ocean, one in the Arctic Ocean, and five just north of Antarctica, for a total of eight additional units. Care must be taken to ensure that the hydrophones are not acoustically shadowed or otherwise obstructed by a land mass such as an island chain or shoreline, which would prevent adequate coverage of broad areas. For example, hydrophones to the north of the Hawaiian islands



■ *Figure 1. Proposed hydroacoustic monitoring network. Squares are existing assets and circles are proposed assets.*

have little to no capability for recording signals propagating from south of the island chain.

Data acquisition system. The data acquisition system for these hydrophones should record the hydroacoustic signals at a minimum of 100 samples per second to adequately resolve the bubble pulse and its associated harmonic signals. The digitizer system should not degrade the performance of the hydrophone. In this case, for hydrophones with a dynamic range of 140 dB, a 16-bit, gain-ranging, or 21- to 24-bit data acquisition system is required, with the least significant bit set approximately 20 dB below the average ambient noise for the deep ocean. The timing accuracy should be to at least 1 millisecond, with synchronization of the digitizer clock to the time signal of the Global Positioning System (GPS). Data authentication could be used at stations to ensure integrity of the signals. The authenticated hydroacoustic data stream would include hydroacoustic data, an alarm status, and a time stamp. State of Health (SOH) messages are required and must include (at a minimum) clock status, alarm status, and calibration mode.

Communications. Since the hydroacoustic network acts primarily as a complementary network, its raw data can reside at a hydroacoustic station or, after continuous data transmission from a station, at an NDC. The IDC could collect the appropriate hydroacoustic data directly from the stations or NDCs. For example, the seismic processing system at the IDC could predict arrival times of hydroacoustic signals based on the seismically determined event location. The appropriate hydroacoustic signals could then be sent to the IDC and analyzed as to the presence or absence of a bubble pulse. This first method is sufficient for detecting, locating, and identifying fully contained underwater explosions to low yields (less than 1 kiloton). Similarly, other nonseismic systems could provide a trigger for analysis of associated hydroacoustic signals. This could potentially resolve low-level hydroacoustic signals that are from shallow and vented or atmospheric explosions and are not resolvable by the seismic method.

Similar communication and data transmission criteria as for the Group of Scientific Experts (GSE) global seismic network are required for the hydroacoustic system. That is, the number of formats for data transmitted to the IDC should be limited. The data protocol is required to be Transport Control Protocol/ Internet Protocol (TCP/IP) for data transmitted to the IDC. Data compression with standard decompression algorithms is encouraged to minimize cost of communications to the IDC. The maximum acceptable transmission delay is 15 seconds for an NDC to transmit hydroacoustic data to the IDC upon request by the IDC. The data frame length is 1 second. Seven days of data (either waveform segments or continuous data) should be stored on-line in a disk buffer at the hydroacoustic station and/ or NDC.

Analysis

The analysis of hydroacoustic data could include automated signal detection to generate a detection list, frequency analysis to identify a bubble pulse and to determine the center frequency for the primary signal, characterization of the rise time of the primary signal, and a location algorithm. The detection algorithm should be based on signal amplitude relative to ambient noise and signal duration. The bubble pulse identification algorithm and associated frequency analyses should be automated to run after the detection algorithm detects signals of interest. The location algorithm should incorporate variable oceanic velocity models for different regions of the oceans.

The frequency analysis could include cepstral, correlation, and spectra analysis to characterize the hydroacoustic detections. The cepstral calculation is essentially a Fourier transform applied to the log of the original frequency spectrum; this gives a modulation frequency in the que-frequency domain that confirms the presence of a periodic, repeated bubble pulse in the data following the primary arrival. Similarly, the bubble pulse contains features common to the primary arrival, which are emphasized and occur as peaks in the correlation time domain after correlation of the data trace with itself. Also, the center frequency of a signal and the sharpness in its rise time provide a measure of the signal's transient nature; transient signals associated with explosions have higher center frequencies and rise times than do signals from submarine earthquakes.

It is anticipated that States Parties will do additional analysis at NDCs. The analyzed data from the IDC, available to the NDCs, could include a bulletin of hydroacoustic detections with their associated frequency and time-domain characteristics to indicate the presence or absence of a bubble pulse and to indicate the center frequency and rise time.

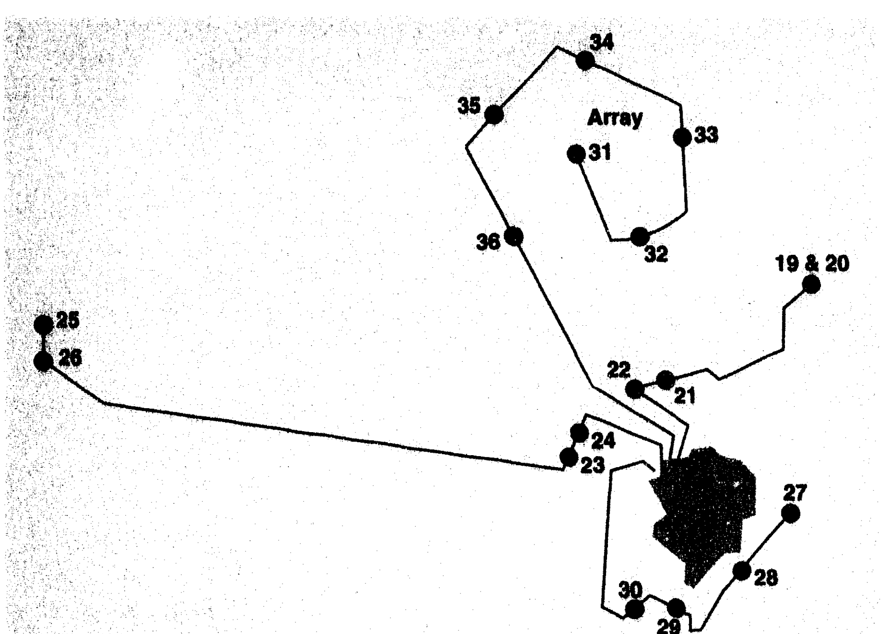
Resources

There are two contributing systems recommended for the hydroacoustic network; the first is fixed arrays, either new or existing—such as the former U.S. Missile Impact Location Systems (MILS)—which have hydrophones on the bottom and in the sound channel and are cabled to shore; the second is suspended acoustic receiver systems that are either freely drifting or moored. Figure 2 illustrates the configuration of a typical MILS site, Figure 3 a moored and floating version of a suspended acoustic receiver, and Figure 4 a schematic of a typical multi-element fixed array.

MILS systems. Two former MILS sites are available as part of the hydroacoustic network (see Figure 1). The first is off Wake Island in the Pacific and the second is off Ascension Island in the Atlantic. Each site has a bottom-mounted pentagonal array of hydrophones and hydrophones floated into the sound channel from a moored platform, as illustrated in Figure 2. The hydrophones are unpowered, with approximately 150 dB of dynamic range in the passband of interest for explosion monitoring. The data is transmitted to a hydroacoustic station on shore via a cable with signal amplification in an amplifier in the surf zone. The continuous data sampled at 100 samples per second could then be transmitted by commercial means over a 9600-kilobaud line through the NDC to the IDC.

The technical effort and cost associated with bringing the MILS data to the U.S. NDC is modest since all of the infrastructure is currently in place and the two sites are operational. The total cost, including communications cost and limited maintenance at the hydroacoustic station, would be approximately $50,000 per MILS station. This assumes no deep-water repair of the system is required, which would raise the cost on the order of $20,000 per incident. Additional communication arrangements are required to transmit the data forward to the IDC; cost for this is estimated at $30,000 per year for each site.

Suspended acoustic receiver systems. The suspended acoustic receiver unit is currently a development effort. The suspended acoustic receiver device could consist of two, low-noise, omnidirectional hydrophones (as illustrated in Figure 3) with a zero-dB preamplifier at the hydrophone for impedance matching to the cable. The continuous analog signal is transmitted to a digitizer unit mounted in a pressure-cased unit at the buoy. The digitizer unit includes analog signal conditioning, a 21- to 24 bit analog-to-digital converter, and two digital buffers. When a buffer is filled, a



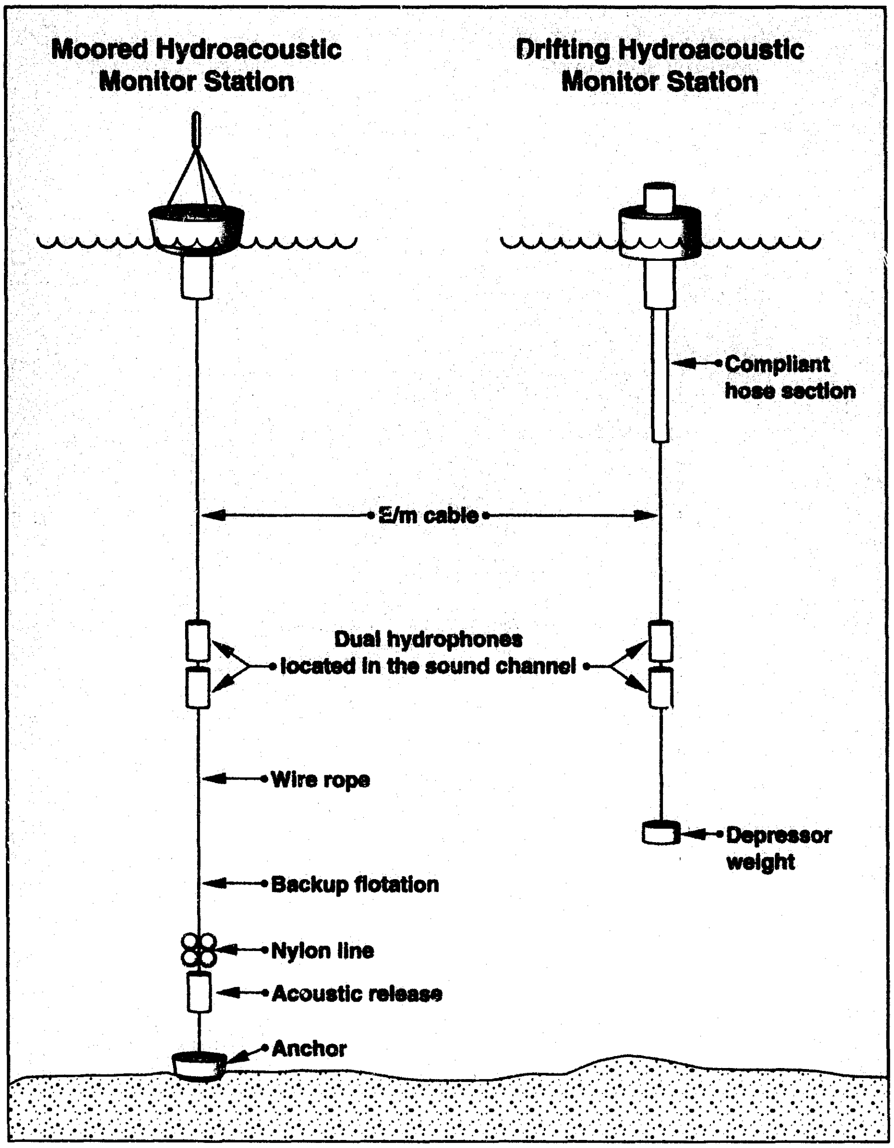
■ *Figure 2. Typical configuration for the existing assets of Figure 1.*

signal is generated that wakes the system controller. The controller is a microprocessor unit that handles time and position data from a commercial (off-the-shelf) GPS receiver and also data buffer storage and an on-board signal processor. The signal processor could run a detection algorithm over the raw data to generate time-tagged event blocks. These time- and position-tagged data or event blocks are placed in the satellite output queue for later transmission based upon prioritization from other active detection systems.

The main power for the suspended acoustic receiver stations should be provided by an array of solar panels on the buoy. The solar panels will charge secondary cells, which will power the system controller, digitizer unit, satellite transmitter, and other subsystems. The life of this solar-panel charging system is at least two years for this configuration. A large primary battery pack is also provided for backup in case of temporary failure of the solar-powered systems, such as during extended periods without sun.

A study of data telemetry options indicated that the Low Earth Orbit (LEO) satellite offers the best compromise between throughput, coverage, cost, and power. The Vitastat LEO system provides two-way global coverage with at least three passes per day at any location. Data rates up to 19.2 kilobaud (with 10-watt transmitter and omni-antenna) are supported, which allows 1 megabyte to be transferred during a 10-minute pass. Costs are expected to be on the order of $1 per kilobyte, with approximately 50 kilobytes transmitted per day (2 kilobytes per event) for each site. The system will be operational in late 1994. There are additional plans for other communication means using LEO satellites (for example, using the Iridium satellite).

The system development costs, which include analysis and design, hardware and software development, and field testing would be approximately $2 million over 18 months. Three prototype units would be ready for at-sea deployment and testing after 12 months. The estimated cost for fabrication and deployment of approximately 20 units to provide coverage, as illustrated in Figure 1,

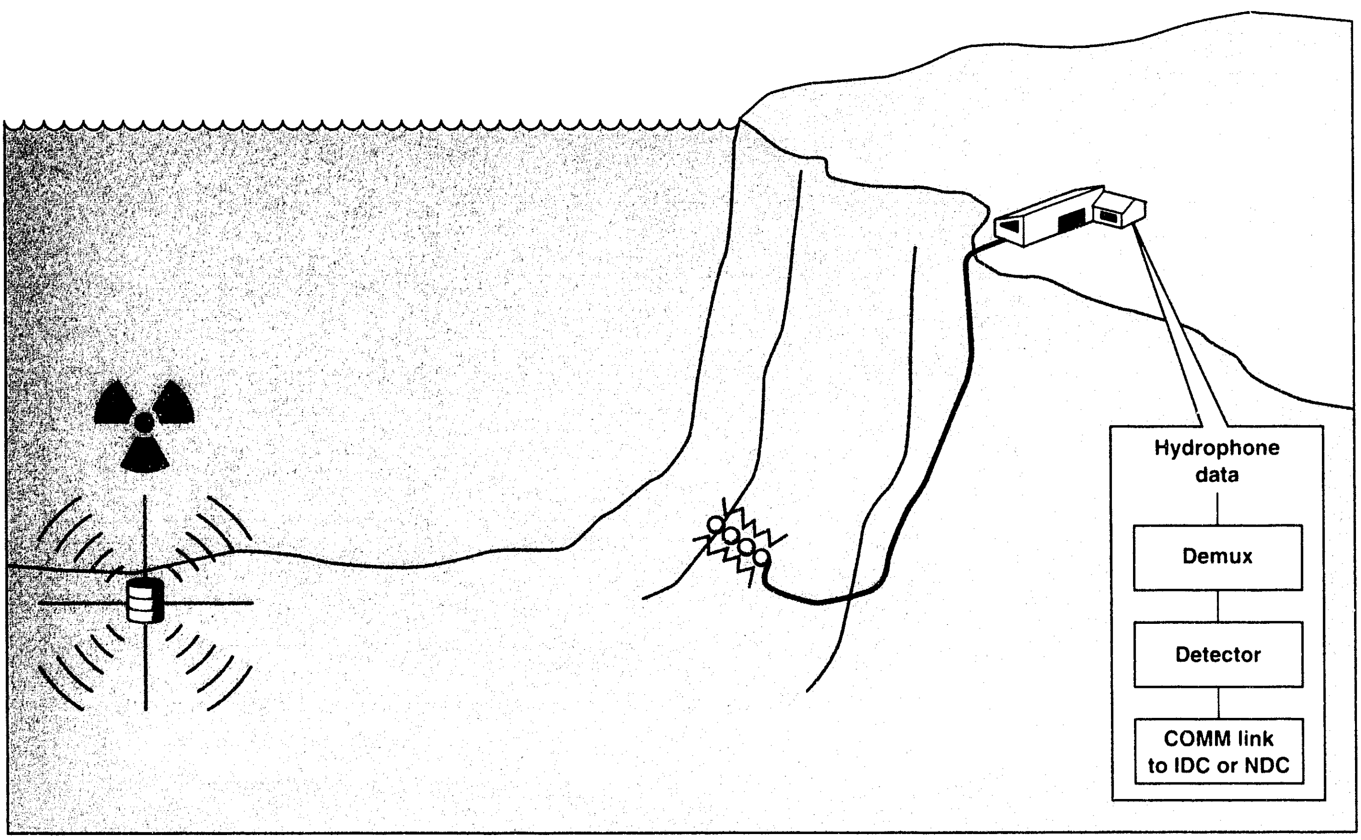


■ *Figure 3. Proposed moored and drifting hydroacoustic monitoring stations.*

is $6 million. It would require 18 to 24 months to complete this phase. Unit costs are $100,000 to $150,000 for the moored stations and $40,000 for the drifters. Annual operating costs are estimated at $2 million to $3 million, assuming annual replacement of drifting stations and 20% replacement of moored stations. This assumes annual visits to each moored station and telemetry transmission costs for on-demand data on the order of $20,000 per site yearly.

Fixed arrays. The fixed array system is currently a conceptual effort as illustrated in Figure 4. The array design includes a number of equally spaced (on the order of three to five) hydrophones with a preamplifier to record quiet acoustic sources. In addition, at least two unpowered hydrophones with the corresponding 150-dB dynamic range would be embedded into the array to record the larger acoustic sources without saturating the system. The data would be transmitted continuously to a shore facility via a cable mounted on the sea floor and from there forwarded to an NDC. The projected life of such systems is estimated at 40 years, with minimal preventive maintenance (typically for electronic equipment at the shore facility).

The nonrecurring cost for installation of a fixed array is estimated at up to $20 million with an average cost of $10 million, which includes design, procurement of materials, and construction. The total recurring costs—which include maintenance, equipment, and spare parts—and communication services are estimated at $500,000 per site. The at-sea survey and installation could begin approximately 18 months after funding is approved.



■ *Figure 4. Schematic of configuration for fixed arrays.*

Synergy

Although the hydroacoustic system would have both continuously transmitting and on-demand stations, it would operate primarily as a complementary network to the seismic system for resolving oceanic events, including submarine earthquakes and fully contained explosions. It will also operate as a complementary network to the other nonseismic systems for resolving vented and shallow atmospheric explosions.

Recommended system

The global hydroacoustic network would consist of both continuously transmitting stations and on-demand stations similar to the international seismic system. The two continuously transmitting MILS stations and perhaps other similar continuous flow data stations would contribute raw data from the NDCs to the IDC for timely processing at the IDC. Although some of the hydroacoustic stations will thus provide a continuous flow of data to the IDC from an NDC, it is anticipated that most of the hydroacoustic stations will operate as a complementary network (in an on-demand mode) triggered principally by seismic detections of oceanic events. For this type of complementary network, the seismic technique would predict the arrival times of the associated hydroacoustic signals based on the seismically determined event location. The IDC would then retrieve the appropriate data from the complementary network for analysis, calculate a refinement of the location, and extract agreed parameters. These raw and analyzed data would then be made available to all NDCs for their own analysis.

Initially, the U.S. could transmit continuous data from two MILS arrays, one in the Atlantic Ocean and one in the Pacific Ocean, through the NDC to the IDC. The suspended acoustic receiver units and/or other fixed arrays could complement the MILS arrays in a global hydroacoustic CTBT monitoring system to give coverage over broad and blocked ocean regions. The suspended acoustic receiver units are currently in the design and development stage and are modeled after prototype units deployed in support of a program to measure temperature changes in the ocean on a global scale. The new fixed arrays are in the concept stage only and are modeled after existing assets owned and operated by several countries.

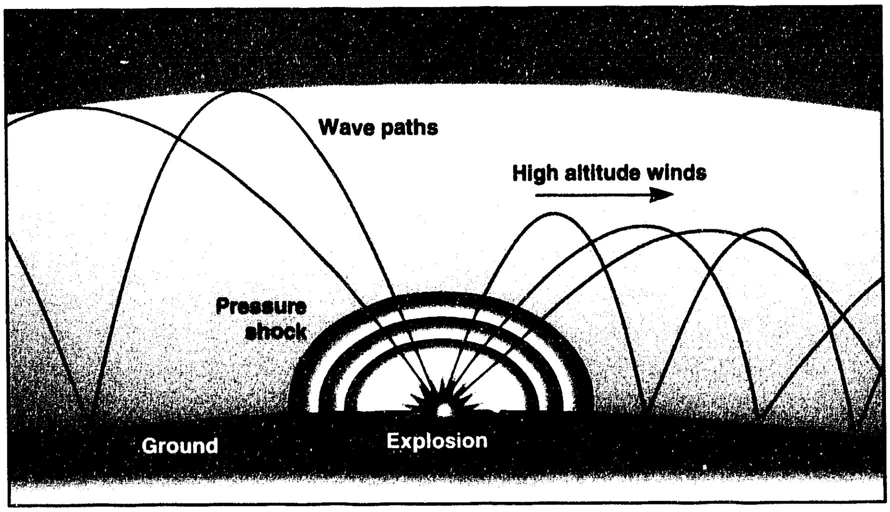
Near and far infrasound monitoring system

The near and far infrasound is a system capable of detecting an atmospheric air shock wave produced by the air blast from an explosion, i.e., the infrasound.

Background

The near and far infrasound system would consist of two different detectors which detect near and far infrasound produced by an explosion. Sensitive microphones are used to detect the near infrasound and are sensitive to a distance of 2000 kilometers. To detect the far infrasound, sensitive barometers called "microbarographs" are used and can detect beyond a distance of 2000 kilometers.

The near and far infrasound system can detect partially buried, partially contained, or atmospheric nuclear explosions, and can provide a secondary confirmation for either the seismic or hydroacoustic monitoring systems. Detecting the infrasound signal generated by a partially buried, partially contained, or an atmospheric nuclear explosion has the advantage that it is the most difficult signal to hide or obscure, so that its detection is a very dependable and resilient diagnostic.



■ *Figure 1. Propagation of infrasound waves.*

False events

Based upon the past operational system, the rate of false alarms is very small to nonexistent This is especially true for the low-frequency detection.

Status

This system was successfully deployed by the U.S. in the 1960s and 1970s. The technology is simple, and there is an extensive database to support the use of the concept as part of an international CTBT. Simple noise reduction techniques are used which reduce the local wind noise.

Description of the system

How the technology works

A large explosion which is not fully contained in the earth produces an intense pressure pulse in the atmosphere (Figure 1). Near the source of the explosion this is a destructive blast wave, but as it moves away from the point of explosion, it weakens into an ordinary sound wave. This wave travels away from the source in all directions. The frequency (pitch) of the sound wave decreases as it moves further away from the point of origin, becoming sub-audible at ranges of 10 to a few thousand kilometers (hence the name infrasound). The frequency at these distances is in the range of 0.1 to 10 hertz. At distances on the order of 2000 kilometers or greater, the frequency drops below 0.1 hertz. In general, frequencies this low are not considered sound, but rather air pressure, fluctuation. In both cases, the signals have characteristics which identify them as originating from an explosion. The signals are, in the case of the sound waves, detected by specialized microphones, or, in the case of the pressure fluctuations, by microbarographs.

Description of sensors

There are two different sensors used to detect near and far infrasound:

(1) Near Infrasound (0.1–10 Hz) utilizes ultrasensitive microphones. Detection range is 1–2000 kilometers.

(2) Far Infrasound (0–0.1 Hz) utilizes microbarographs. Detection range is several thousand kilometers.

Number of sensors required

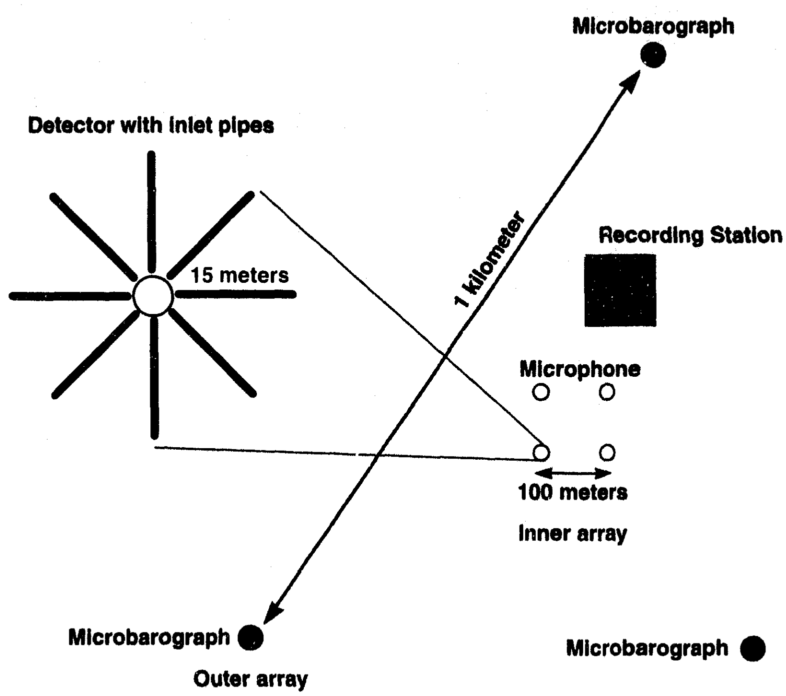
A total of 50 detection stations appropriately located around the world would provide global coverage. It is possible that further study may show that optimal placement can reduce this number. Each station (Figure 2) would consist of

- An internal array of four microphones on 100-meter spacing between each of the four.
- An external array of three microbarographs on 1-kilometer spacing.

The microphones are enclosed in a case which utilizes specially designed inlet pipes to shield from wind noise at frequencies above 10 hertz. Each microphone case with the appropriate noise-reducing pipes requires sufficient space to encompass a 15-meter-radius circle. A small signal recording station is connected to the near infrasound microphones by cables. The microbarographs utilize a 70-meter pipe in a similar manner to the microphone to shield the main unit from wind noise. The microbarographs must be more widely spaced on the array because the lower frequency sound is at longer wavelengths. As a result, it is less convenient to run cables to the central recording station. It is possible to use low power transmitters and receivers to send and receive the data for central recording. The recording station would require data storage and handling hardware which could be as simple as a personal computer with commercially available enhancements, which would include hardware for transferring data to the International Data Center (IDC), and might be as simple as a telephone modem connection. If deemed appropriate, a more sophisticated satellite-based communications system could be utilized.

Location of sensors

It would be efficient from a communications and maintenance perspective for the near and far infrasound detection stations to be co-located, when possible, with the seismic network stations. The two detection systems could utilize common space and an integrated data acquisition and data transmission system. When it is not possible to co-locate the two detection systems, there will clearly be additional costs for the otherwise common utilities. The require-



■ *Figure 2. Infrasound array set-up.*

ments for isolation from cultural activities is less severe for the near and far infrasound than for seismometers, but there are, nonetheless, noise reduction considerations with the desirability of avoiding busy highways, airports, and large mechanical equipment which might produce interference in the frequency regimes of interest. Infrasound detection also improves in the presence of windbreaks such as those provided by a sparsely forested field. One would like to avoid vast open areas when possible.

Data collected by sensors/data transmission mode/communication system requirements

Data rates are on the order of 20 samples per second at 16 bits for a seven-channel array (four microphones and three microbarographs) for a total of 2.3 kilobits/sec. Data-handling requirements would therefore be similar to that for the seismic stations. This data could be continuously transmitted on a low-speed data link (i.e., a telephone line) or stored and transmitted periodically at a much higher data rate. If this technique is to be utilized as a primary monitoring method, it still might be reasonable to accumulate the data for an hour before transmitting it to the IDC.

Cables connect the near infrasound microphones to a recording area. The microbarographs could use low power transmitters and receivers to send the data to a central recording area. The recording station would consist of data storage and handling hardware such as a PC-based system and some method for transferring data to the IDC such as a telephone modem connection. If appropriate, satellite links could be shared with other systems.

Technical sensitivity of proposed system

The overall sensitivity of the near and far infrasound to detect and discriminate a signal from an explosion is quite good. Extrapolating from past performance data, we predict that such a system would be capable of routine detection of a two-kiloton equivalent atmospheric burst at distances in excess of 1500 kilometers with very good signal to noise. There is documented data of a test of this size being detected at a distance of 5300 kilometers.

Authentication

This system would produce digital data which can be authenticated by standard digital circuitry which would cost about an additional $1000 per station. These established procedures will protect the integrity of the data obtained from the near and far infrasound stations and maintain the original data until it is received at the National Data Center (NDC) and the IDC. The systems can also be constructed in tamper-resistant forms which will, at a minimum, indicate that tampering has occurred.

Data analysis

Analysis is required to understand the data, discriminate explosions from other events, and estimate the location of the event. Much of this analysis could be performed on-site with a moderately capable personal computer system, with only processed event data sent on to the data centers. The moderate data rates required for the full data sets mean that the raw data could be sent to the IDC or NDCs for processing. The signal-processing methods and algorithms are well developed and based upon commonly utilized techniques. This information could readily be made available for the international system.

Processing could be completed either at the IDC or the NDCs. This would also provide a forum for international discussion and calibration of the system in a manner similar to the GSETT-3 set of experiments. Appropriate man-made calibrates can be carried out.

Detection

The infrasound system will be able to detect the unique infrasound signature from a large explosion. Based upon previous experience, the number of false events is anticipated to be small.

There are scenarios for which the near and far infrasound system could be essential for the detection of tests carried out in an evasive manner. This method has particular utility for sea/air interface, land/air interface, land/sea/air interface, and air explosions. The method will be synergistic with hydroacoustic, seismic, and other atmospheric techniques depending upon the circumstances of the test.

Location

The infrasound system can provide a location accuracy of

50–100 km. The location accuracy is a function of the detector's location relative to the explosion and the number of stations detecting the signals. The system depends upon triangulation for good location accuracy and therefore requires several stations reporting data. This technology will be of particular utility for detecting partially decoupled explosions within the wide ocean areas.

Identification

A single point initiated explosion—either nuclear or conventional—will generate the same infrasound signal and will therefore be indistinguishable by this technique.

OSI

The data obtained from an infrasound system, when used in conjunction with other detection systems, can clearly be utilized as a technical indication of suspect activities to support the request for an OSI. This is a wide area monitoring technology and not of any particular utility during an OSI.

Transparency

The data obtained from a near and far infrasound system is transparent for both event identification and calibration.

Resources

Equipment: existing and required

There are three near-infrasound stations operational in the continental U.S. which may be made available to an international network. There are systems extant in other countries, but we are unaware of any discussions about their current status and the possibilities of their availability for an international system.

Unit cost

One station (seven channels) is estimated to cost about $75,000, which includes recording and analysis capabilities, but does not include communications services. In general, the site preparation is minimal and maintenance costs are low.

The station costs would be dependent upon the level of quality assurance and intrusion protection required by the national and international organizations responsible for the systems. The installation costs will be dependent upon whether or not the near and far infrasound station can be co-located with other CTBT monitoring networks such as the seismic stations. All the obvious cost sharing benefits will accrue from collocation.

System cost

Total system cost for 50 stations is $4 million for hardware costs. The estimated lifetime per station is 15–20 years (with replacement of noise reduction hoses and minimal maintenance). Operating cost per year is dependent upon the overall costs of data acquisition, site maintenance, and event classification. Overall, we believe the costs would be relatively low in comparison to either the seismic or the hydroacoustic systems.

Data handling, transmission, and communication costs

Costs for the data handling, transmission, and communication have not been determined. The data rate would be on the order of 2.3 kilobits/second per station.

Development and availability status

The near and far infrasound technology has been well developed and tested. There is an extensive data base of nuclear signature data from the 1960s and 1970s that can be used. The theoretical understanding of the generation and propagation of low-frequency acoustic signals from explosions is well characterized and has been widely published. The U.S. Government has operated similar acoustic systems for the detection of atmospheric explosions.

The near and far infrasound technology is inexpensive and well understood. The development of a standard integrated system is desirable for uniformity for the CTBT. The technology is readily available. The following steps would need to be taken for the development of a functional monitoring system.

- Identify instrument standards for microbarographs and microphones.
- Incorporate global stratospheric wind data into existing propagation codes.
- Further determine detection probability estimates as a function of number of stations, source size, and background noise levels for more complete specification of an international monitoring system.
- Determine amount of on-site data, signal, beam-forming, and event detection processing. This includes data collection, transmission, and storage.

- Assemble and deploy several stations and exercise against man-made signals.

Synergy

Relationship to other systems

The near and far infrasound system is generally not a stand-alone system for CTBT treaty verification. It is a supplementary means of explosion detection to the proposed seismic, radionuclide and hydroacoustic systems. In certain situations it will provide the most readily identifiable early signal which would then bring other detection means to bear on the problem.

Requirement for complementary system

The near and far infrasound detection and location capabilities make this an important component of a monitoring system, but its lack of discrimination means that it does need complementary information to resolve the nature of the explosion. Detection of a coincident EMP signal would provide strong evidence of a nuclear explosion, although there may not always be an EMP signal present. EMP, if detected, can also give a much more accurate location than infrasound alone.

This method is highly complementary to seismic and hydroacoustic methods because they cannot detect an above ground/water atmospheric burst in a stand-alone manner. There is particular synergism for partially contained explosions which may couple, albeit poorly, seismically and hydroacoustically. Thus, the presence of an infrasound signal might rule out natural causes for an ambiguous seismic or hydroacoustic event, but the absence of infrasound would not necessarily be conclusive. For events that are very poorly coupled into the water or ground, infrasound might be the only early time indication of a test.

Options

The complete system configuration would include the 30 to 50 stations worldwide located either with the proposed seismic stations or other safe locations. The equipment for each station is relatively inexpensive. Uniformity of the system configuration and data handling would be desirable. The data could be provided to the IDC and then to the NDCs for analysis and event identification. The resources required to analyze the data are not extensive and could be completed in conjunction with existing institutions throughout the world.

In the event of an above-ground, partially contained or atmospheric burst—either chemical or nuclear of a given yield—the near and far infrasound systems would detect the event. The information would be available, at the latest within a few hours, depending upon the location of the explosion versus the location of the infrasound system. Different infrasound locations would detect the propagating wave at varying times and places providing a triangulation to locate the event point.

The near and far infrasound is important because it provides detection in cases where seismic or hydroacoustic may not provide a clear signal, and it also provides a second confirmatory signal that an event took place. The near and far infrasound system has a long history of use with nuclear event data to support its deployment. And based upon the past history, it is predicted to have few false events which will require characterization.

Issues

The main areas which require further work are

- The identification of the location of the detectors throughout the world to achieve global coverage.
- The data collection system and transfer to the NDCs and IDC.
- The cataloging of explosive events.
- A uniform system for data analysis.
- Refinement of the cost estimate.

False events

Based upon the past operational system, the rate of false alarms is very small to nonexistent. This is especially true for the low-frequency detection.

Status

This system was successfully deployed by the U.S. in the 1960s and 1970s. The technology is simple, and there is an extensive data base to support the use of the concept as part of an international CTBT. Simple noise reduction techniques are used which reduce the local wind noise.

In general perspective, the amount of work required to complete a deployable, worldwide, near and far infrasound network is small.

Ground-based air fluorescence and optical detection system

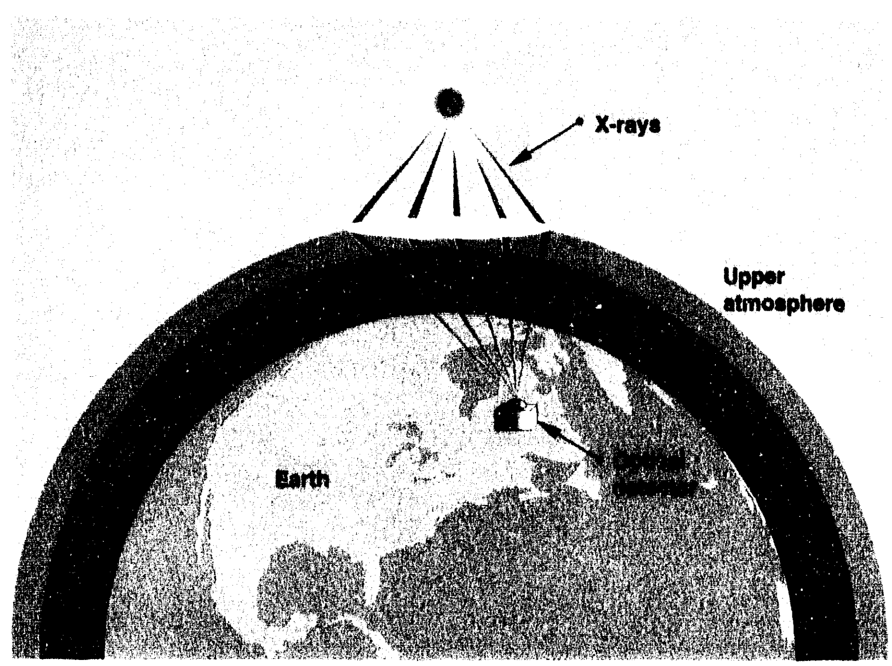
An optical detection system consisting of two different, co-located optical sensors is capable of detecting atmospheric and space nuclear explosions. A white light detector would be used to detect atmospheric explosions, and a narrow-band optical sensor would be used to detect air fluorescence from a space-based explosion.

Background

An optical detection system consisting of a visible light radiometer to detect atmospheric nuclear explosions and a narrow-band optical sensor to detect air fluorescence from a space-based nuclear explosion could cover two important monitoring regimes for the CTBT. An atmospheric explosion can be detected by the characteristic time history of the light emitted by the fireball. The detection range for an atmospheric explosion is extended over the horizon by Rayleigh scattering of the light (Figure 1). A space-based explosion can be detected by the high altitude air fluorescence caused by the weapons x-rays interacting with the nitrogen and oxygen within the upper atmosphere. Both signals have unique optical signatures which provide unique discrimination against false events.

The radiometer provides good sensitivity, low data rate, good event location, low false alarm triggering, and allows simple analysis. The narrow-band optical sensor has similar characteristics, which make it relatively easy to implement. The two technologies employed in conjunction with each other provide a complementary system which eliminates false triggers from lightning and other natural events.

A narrow-band optical detector provides a unique identification of a nuclear event since the observed phenomena are unique to a nuclear detonation within either the atmosphere or space. The technology is simple and easily obtained. Calibration of the system will depend upon past measurements and modeling of system performance, since only nuclear detonations can generate the phenomena of interest on a wide enough scale for a practical demonstration. Although the U.S. has not deployed this specific system in the past, sufficient optical data is extant to benchmark the system's performance. The



■ *Figure 1. Space explosion geometry.*

proposed optical detection system uses simple, inexpensive, and proven technology that can be readily obtained for a world-wide monitoring network.

False events

The number of postulated false events for the optical detection system is predicted to be quite low. The two optical sensors co-located will provide a means of detecting and eliminating false events.

Status

A ground-based optical detection system has not been deployed, although several prototypes have been built and similar technology has been used. The technology is simple and can be easily obtained, while a standard calibration procedure will have to be developed based on prior data and modeling. A world-wide network will require a large number of individual stations.

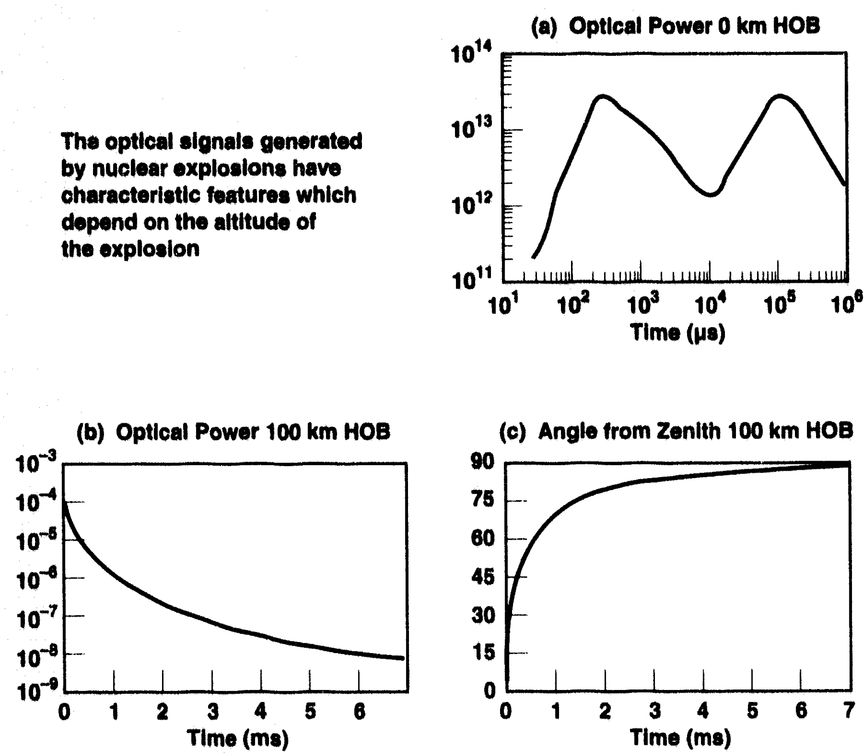
Description of the system

Atmospheric detection: whitelight photometer

The fireball resulting from a nuclear explosion within the atmosphere produces a distinct optical signal (Figure 2a). The shape of the time history of this signal is the same for all nuclear explosions. The duration in time and details of the time history of the optical emission will change with the size of the explosion. The specific time of certain features within the time history can be used to estimate the size of the explosion. This optical signal is extremely bright at the source, and radiates at all wavelengths in the optical spectrum. A small amount of the light will be scattered by the dust in and the molecules of the air. This very well-understood phenomenon is called "Rayleigh scattering." It is the Rayleigh scattering which transmits some of the light to locations over the horizon from the actual event point. The light is so bright and its time history so distinct that it is possible to detect this momentary flash even against the brightly lit daytime sky at distances from 500 to 1000 kilometers. The greater distance corresponds to larger explosions.

The light source covers the visible spectrum and is therefore best detected with a wide-band detector, such as unfiltered silicon. This type of whitelight photometer has been called a Bhangmeter. With such a detector, compensation (signal subtraction) is required for the background when looking against the sunlit sky. This compensation is well understood and can be readily accomplished. Sun glints from airplanes and other objects entering the field of view present discrimination problems requiring real-time data processing. The fast rise time of the optical signal and its unique shape allow efficient triggering and false event rejection, resulting in a low data rate from such a system. Event location is accomplished by triangulation using multiple stations.

The optical signals generated by nuclear explosions have characteristic features which depend on the altitude of the explosion



■ *Figure 2. Optical power time curves.*

Space-based detonation detection: narrow-band optical sensor

X rays from a nuclear explosion in space propagate outward from the detonation point in all directions. The x rays are not attenuated by their passage through space, but the intensity of the signal decreases with distance because the x-ray energy is being distributed over a spherical shell of increasing size. The x rays which impinge upon the earth's atmosphere begin to cause air fluorescence (light emission) at an altitude of approximately 80 kilometers. The light first appears at the point directly beneath the explosion, and then spreads out in a circle towards the horizon. The duration of the light pulse at a single point in the sky is about a microsecond (Figures 2b and c), and the pulse moves across the whole sky in a few hundred microseconds. A 1-kiloton explosion at an altitude of 100,000 kilometers results in a sufficiently bright signal to be detected from the ground against the day-lit sky.

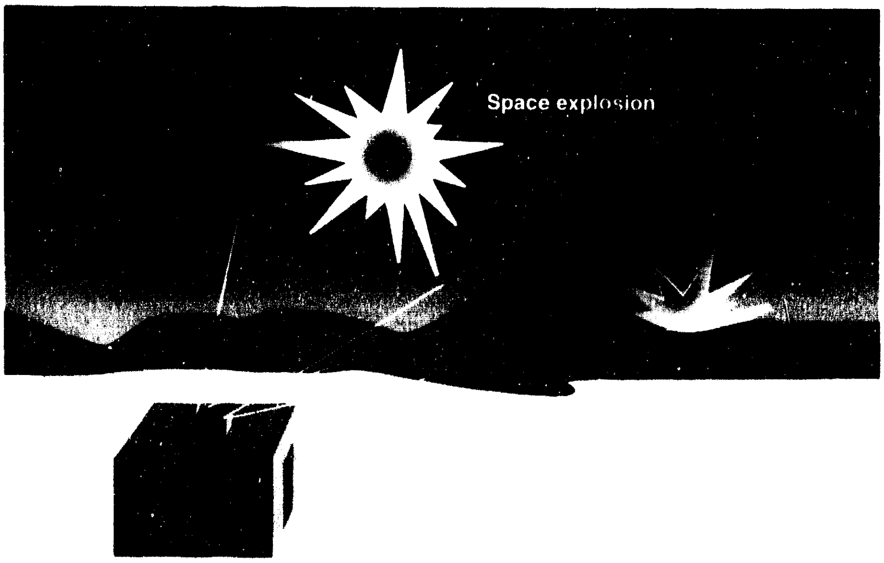
The light is produced by the interaction of the explosion-produced x rays with the oxygen and nitrogen atoms in the atmosphere and appears at specific wavelengths. The light is best detected using a narrow-band optical sensor which is tuned to one of these specific wavelengths. This allows the detector to record all of the fluorescence signal while rejecting most ordinary sunlight. Combining this filtering with a fast rise time trigger results in very efficient event detection with a low false alarm rate. Location is accomplished by triangulation.

Lightning can produce fast-rising signals and will generate both fluorescence and whitelight signals. Therefore, it will be detected by both the Bhangmeter and the narrow-band optical detector. The Bhangmeter can discriminate lightning signals by looking for the unique shape of the nuclear explosion-produced signal. The narrow-band optical system can also use the signal shape as a discriminant, and, in addition, it can distinguish lightning from space explosions by looking only for events which do not have simultaneous signals in the Bhangmeter. Thus the Bhangmeter acts as a detector for atmospheric explosions and an anti-coincidence filter for space explosions.

Description of sensors

An optical detection system would consist of an all-sky assembly with two silicon detectors. The Bhangmeter detector would be unfiltered and the narrow-band optical detector would have a narrow-band filter. In addition, on-site processing for triggering and background compensation logic, data recording, and transmission system are required (Figure 3).

The average sky background must be subtracted from the Bhangmeter detector in order to detect the low-level transient light signal against a sunlit sky. This can be accomplished easily and efficiently by a simple compensation circuit. A simple rise-time and



■ *Figure 3. Optical station.*

threshold trigger is used to detect transient events. Other features of the signals are then examined to distinguish from atmospheric events, including coincident signals from the narrow and wide-band detectors. Signal processing and background subtraction can be accomplished on-site. The data from the remaining events is then recorded and sent to the IDC, either in real time, intermittently, or on request.

Number of sensors required

A minimum of 150 optical detection stations located worldwide would be required. This number is based upon an assumed detection range of 1000 kilometers for atmospheric explosions with a minimum height of burst of 100 kilometers for space-based explosions. The actual spacing is dictated by the more limited range of the narrow-band detector. Further siting studies are required. Location capability would require four times as many stations: approximately 600. Accepting a higher minimum height of burst for space-based explosions and a resulting longer maximum detection range could reduce the number of stations by as much as a factor of 2 or 3.

Location of sensors

The sensor stations should be distributed around the globe in a uniform manner. They should be located in areas away from bright lights with an unobstructed view of the sky. Exact site locations may depend on local meteorology; for example, they should not be placed in areas with frequent fog where the optical signature could be obscured.

Stations could be co-located, when possible, with the other CTBT monitoring stations including the seismic, radionuclide, infrasound, or EMP stations. The monitoring systems could use common space, data acquisition, and maintenance. If it is not possible to co-locate the monitoring systems, then other existing, safe locations would be selected.

Data collected by receiver stations/data transmission mode/communication system requirements

The data collected by the sensors consists of measurements of optical power at specified time intervals. The data would be digitized for ease of handling. The time resolution of the system should be approximately 10–20 microseconds. The record length for a space event is approximately 10 milliseconds. An atmospheric event may last as long as one second. With uniform time sampling the space-based event would then require 500–1000 data points, while the atmospheric event would generate 50,000–100,000 data points. The nature of the atmospheric signal allows the system to use non-uniform time sampling, which reduces the data to approximately 1000 data points, matching the space-based event record length. A data record from either detector would consist of 1000 8-bit data points, plus time and location information.

The IDC could correlate data and perhaps calculate event location. Further signal analysis of the raw data could be done by States Parties.

Technical sensitivity of proposed system

The system capability and configuration is based upon analyses completed 25–30 years ago and should be updated to account for technological innovations in optical detectors. Conservative estimates of the sensitivity are detection of one kiloton at 500 kilometers distance for atmospheric explosions and one kiloton at 100,000 kilometers for space-based explosions. This will be degraded at times by local weather conditions for any given site, but site diversity should ameliorate this problem.

Authentication

This system will produce digital data that can be authenticated by standard digital circuitry which would cost about an additional $1000 per station. We believe it is possible to protect the integrity of the data obtained from the optical detection stations, and maintain the original data until it is received at the NDCs and the IDC. Cross-correlation of the data with other stations and with the other CTBT technologies could be used to authenticate the data. This is especially true for the systems based upon the optical detection since many stations at different locations will detect an event.

Data analysis

The analysis of the data from this system is fairly simple. A significant amount of false event rejection is done by the sensor control system on-site. Most of the remaining events can be immediately classified by a human operator, who could sit either at the IDC or at a national analysis center. Correlation of data from different sensors and determination of event location are probably best done at the IDC. It is generally not necessary to make corrections to the data for propagation effects.

What data analysis will provide

The data from this system will provide good detection and location capability, and very good identification of a nuclear event.

Detection. The optical detection system would be used to detect atmospheric and space-based nuclear explosions. Conservatively, the optical detection system should detect a one-kiloton burst at 500 kilometers for atmospheric events and 1 kiloton at 100,000 kilometers for space-based events. This may be degraded at times by local weather conditions for a particular site, but if one station is unable to detect a signal due to bad weather, then several of the other stations should detect the event. The number of false events is anticipated to be small.

Location. The location accuracy of the optical detection system will depend on the number of stations and the time resolution of the system. The optimal accuracy for a system with 20-microsecond resolution would be six kilometers. A more realistic number is probably 10–15 kilometers for atmospheric and low-altitude space-based explosions (100–150 km), with increasing error as the altitude of the explosion increases above 1000–2000 kilometers.

Identification. The unique shape of a nuclear explosion's optical signatures provides very good identification. These signals may be sufficient to unambiguously identify a nuclear explosion without other evidence. In the case of atmospheric explosions, the method also provides a determination of explosion yield.

OSI. The data obtained from an optical detection system may be enough to technically support the request for an OSI for an atmospheric event. As a stand-alone technology, it can discriminate between a nuclear and non-nuclear explosions. Such evidence would clearly strengthen the request for an OSI. This is a wide area monitoring technology and not of any particular utility during an OSI.

Transparency. The data obtained from an optical detection system is transparent for event identification. Calibration will be required.

Resources

Equipment: existing and required

There are no existing ground-based stations for an optical detection system. All components are standard commercial parts, however, and can be readily obtained. The technology is simple, and is well understood.

Unit cost

One station: $50,000

Communications: To be determined (TBD)

These are the costs for hardware, hardware assembly, and integration. In general, the site preparation and maintenance costs are low, but are not included. The station costs may increase, dependent upon the level of required quality assurance. The siting costs will be dependent upon the optical detection station being co-located with other CTBT monitoring systems. It is advantageous to co-locate the different CTBT detection systems to afford centralized data acquisition and transmission, maintenance, security and certification of operation.

System cost

Total system cost for 150 and 600 stations: $7.5 million and $30 million

Estimated lifetime per station: TBD

Operating cost per year: TBD

Site preparation is minimal and the system requires only infrequent maintenance, so operating costs are expected to be low. An on-site person may be needed in some situations such as to perform snow removal.

Data handling/transmission and communication costs

Data handling at the station is automatic, so there is no data handling cost at the recording site. The data does not require a high-speed line, so transmission costs are low. The data stream needs to be examined by an operator in the data center, but this would not be a full-time job. If the optical detection station were co-located with other CTBT monitoring systems, the data handling, etc., could be shared.

Development and availability status

A small amount of development is required to make a rugged, field deployable unit. No significant engineering development is required. A prototype system could be built and tested in six months to a year. It would be worthwhile to examine 25–30-year-old calculations of system performance, although we do not expect there to be significant changes in the results.

Synergy

Optical detection systems produce a very distinctive signature. The unique nature of the optical signal provides very good identification of a nuclear event. This signal would be solid evidence in and of itself. In the case of atmospheric events, if combined with another type of data (such as radionuclide air sampling), there would be evidence to request an OSI. Because it is possible to evade this detection scheme under certain circumstances one may wish to use complementary detection technologies as well.

Issues

Atmospheric transmission in the presence of clouds is complex and therefore requires continuing system response studies.

The optical detection system should be considered for a worldwide monitoring system for atmospheric and space-based nuclear explosions for an international regime.

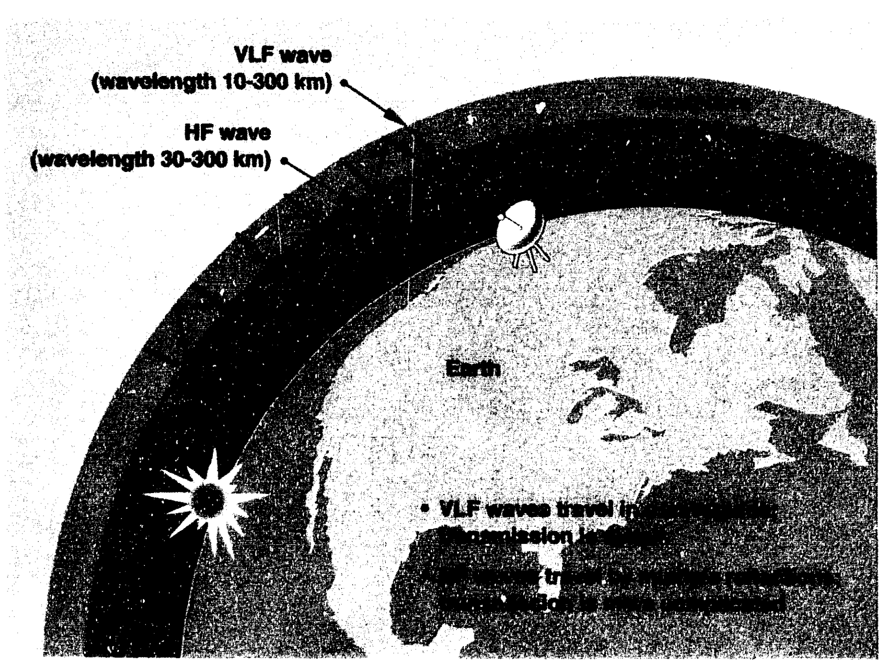
Ground-based electromagnetic (EMP) detection system

The ground-based electromagnetic pulse (EMP) system detects atmospheric events by the nuclear-explosion produced EMP.

Background

The first radiation to appear in the air after an atmospheric nuclear explosion is gamma-ray radiation. These gamma rays interact with the air to produce energetic electrons which swarm around the early explosion. As a result of the earth's magnetic field, these electrons behave as a large antenna which radiates a broadband radio wave signal (which propagates away from the explosion region in all directions). It is possible to detect the explosion by looking for this broad spectrum pulse of radio waves. In general, radio waves—like all electromagnetic waves—travel in straight lines. The interaction of these radio waves with the electrically charged ionosphere, however, extends the range of detection over the horizon, enabling detection at great range. The false alarm rate for this detection method is quite significant as a result of the signals' similarity to radio noise produced by lightning. This problem precludes the use of this method for a primary detection technology.

An EMP detection system will contribute in the location and corroboration of an atmospheric nuclear explosion. Conventional explosions produce only a very weak electromagnetic pulse and will therefore not be confused with a nuclear explosion. When compared with other atmospheric monitoring methods, EMP detection has the advantages of good sensitivity, good event location, and relatively straightforward analysis. It has the disadvantages of a high data rate and a correspondingly high false alarm rate. The EMP system detects signals and reports data promptly, although it may not recognize a nuclear event without other information.



■ *Figure 1. Electromagnetic pulse (EMP) propagation.*

False alarms

The number of postulated false alarms for the EMP detection system is high, though a potential discriminant has been identified. This discriminant has never been implemented in an operational system.

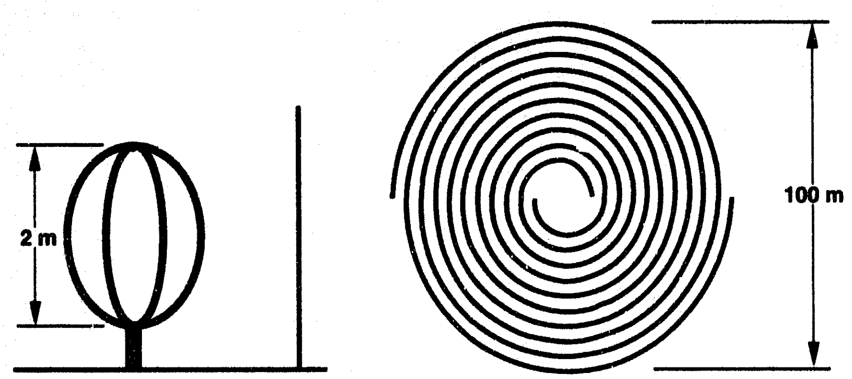
Status

The technology for a ground-based EMP system is available.

Description of the system

How the technology works

A nuclear explosion produces a brief, intense burst of gamma rays. If it is an atmospheric explosion, the gamma rays are rapidly absorbed by the surrounding air and produce a very strong electric current, which in turn produces a burst of radio-frequency waves, i.e., the electromagnetic pulse. Radio power is produced over a broad frequency range, from 1 hertz (Hz) to 150 megahertz (MHz). The lower frequencies have the highest energy. The signal is produced on a very short time scale at the burst point, which enables the location to be accurately determined from time-of-arrival measurements at distributed stations. Signals in the range from 1 to 100 kilohertz (kHz), called the very low frequency (VLF) band (Figure 1), propagate well in the earth-ionosphere wave guide and will travel to great distances, up to 10,000 kilometers. Signal distortion from propagation effects in this frequency range are small and fairly easily accounted for. Signals in the 1–20-MHz range, the high frequency (HF) band, will be reflected from the earth's ionosphere and the ground. Signals in this band-width can propagate to distances of thousands of kilometers by means of multiple reflections. In this frequency range, signal distortion from propagation effects are much more important and must be accounted for to properly interpret the signals. Large chemical explosions generally do not produce EMP because they do not produce ionizing radiation. There is a significant background of natural EMP signals, due primarily to lightning, which is difficult to distinguish from nuclear events. It is also possible to deliberately suppress the generation of EMP from a nuclear explosion.



■ *Figure 2. EMP monitoring station antennas.*

Description of sensors

We recommend an EMP detection station with both VLF and HF receivers (Figure 2). The VLF receiver would have two crossed loop antennas and a flat plate antenna to give omni-directional coverage and single station direction capability. The operating frequency would cover the range from 3–30 kHz or so. This configuration is similar to the standard configuration of the VLF lightning location systems operated by SUNY (the State University of New York) and the U.S. Bureau of Land Management (BLM). The signals from the antenna would go to a digital receiver with trigger logic to detect transient events.

The HF receiver would consist of eight to ten separate channels, each with 10-kHz band-width, which could be tuned over the range from 1–20 MHz. The system would need auto-tuning logic to dynamically move the channels to quiet places in the HF spectrum, which vary throughout the day. Because of the variability in the transmission paths with time of day, season, and solar activity, there will have to be models for determining what frequencies will provide coverage of a given area at a given time, and the receivers will have to be adjusted to ensure proper coverage. This is best accomplished by manual operator control, although the operator need not be physically located at the receiver site. As with the VLF, there would be logic to trigger on transient events. Near-simultaneous events in most of the channels (about seven out of ten) would help reduce problems with interference from man-made sources, but differences in propagation time for different frequencies should be allowed. The difficulty of making a reliable triggering scheme results in a large number of false alarms, probably 10,000–20,000 per day from each station.

Number of sensors required

The effective detection range for this method is 3000–5000 kilometers. The entire earth can be covered with 10–20 stations, properly situated. If location by triangulation is desired, the number of stations should be increased to 30 or 40 stations to ensure that there are three stations in view of all locations.

Location of sensors

The EMP sensors need to be situated in a relatively uniform manner around the world, although with their large detection range, the exact location is not crucial from a system performance standpoint. The important consideration is to locate sites which are electronically quiet.

Stations could be co-located, when possible, with the other CTBT monitoring stations including the seismic, infrasound, or optical stations. The monitoring systems could use common space, data acquisition, and maintenance. If it were not possible to co-locate with the other monitoring systems, then other existing, safe locations could be selected such as universities or similar existing facilities. If an EMP detector is co-located with other CTBT detectors, it may be necessary to design the other systems to be as electronically quiet as possible, particularly if they contain motors or other similar electrical systems.

Data collected by receiver stations/data transmission mode/communication system requirements

The data collected by the sensors consist of measurements of VLF/HF power at specified time intervals. The data should be digitized for ease of handling. The EMP detection system would have 9–11 channels of data, with an event record consisting of about 250 points per channel. Multiple propagation path effects in the HF may cause a single EMP event to appear as several events when the data reaches the receiver. In addition to the raw data, information about the time, location, and the configuration of the receiver is required. The data from a single event at the receiver will consist of approximately 3000 bytes. With the expected event rate of 10,000–20,000 events per day a total of 30–60 million bytes of data per day from each station might be expected unless a discriminant is implemented. This data could be retained at the station and discarded on a regular rotating schedule. This data would be of great interest to the global climate research community but could be disregarded for verification purposes after a short time, unless a primary detection system were to report an event of interest.

The IDC could correlate data and pass it along when appropriate. Further signal analysis of the raw data can be carried out by the States Parties.

Level of technical sensitivity of proposed system

An EMP detection system can detect below a 10-kiloton event at 5000 kilometers. The performance of the HF segment of the system may be degraded during periods of high geomagnetic activity.

Authentication

This system will produce digital data which can be authenticated by standard digital circuitry which would cost on the order of an additional $1000 per station. We believe it is possible to protect the integrity of the data obtained from the EMP detection stations, and maintain the original data until it is received at the NDCs and the IDC. Cross-correlation of the data with other stations and with the other CTBT technologies will be used to authenticate the data. The primary difficulty will be distinguishing events of interest from background events.

Data analysis

Analysis could be done or provided by the sensor, the data, IDC, national means. The analysis for the data from an EMP detection system is not trivial but is well understood. Almost no analysis of the data is performed at the EMP detection station itself, other than basic triggering to detect transient events. The data from a single VLF station will give a direction to the event, although it cannot give range directly. Time-of-arrival data from multiple stations can be used to determine a three-dimensional location. A reasonable location can be obtained from the VLF data without correction for propagation effects, and there are good models to account for propagation signal distortion if higher precision is required. Propagation effects are more pronounced in the HF spectrum, but such propagation signal distortion has been the subject of considerable study and there are good models to account for these effects as well. Application of these models is by no means automated, however, and requires a knowledgeable analyst for implementation. To make this information useful to all signatories, this propagation analysis could be carried out at the IDC. Some degree of event discrimination can be achieved by using signal arrival and spectral characteristics, but there remain a number of large events which cannot be discriminated on the basis of the VLF/HF data alone.

The EMP signal provides a prompt and unique discrimination between nuclear and non-nuclear explosions in addition to an accurate location. This provides synergism with systems such as infrasound, which cannot identify the explosion type, and radionuclides, which do not locate accurately or promptly. Unfortunately, the absence of EMP may not be definitive proof that an explosion was not nuclear. If EMP is detected and identified, it can provide location information, which would be useful for initiating an OSI.

Detection

A ground-based EMP system cannot be depended upon solely for detection due to the large number of false events. It can be used for confirmation if another CTBT detection technology were to provide a trigger.

Location

The location accuracy of the EMP detection system is high if recorded by three stations (within 1 kilometer).

Identification

The EMP detection system can provide confirmation of a nuclear event if correlated with other CTBT technologies.

OSI

The data obtained from an EMP detection system can be used to support an OSI.

Transparency

The data obtained from an EMP detection system is transparent for event identification. Calibration will be required.

Resources

Equipment: existing and required

There are no existing stations. All components are standard commercial parts, however, and can be readily obtained. The standard ground station used by the SUNY and BLM lightning location networks would be suitable for the VLF part of the system, although the detection logic would have to be changed to detect events beyond 100 kilometers, which are currently rejected.

Unit cost

One station: $150,000.

Communications: To be determined.

These are the costs for the ground stations. In general, the site preparation and maintenance costs are low, but are not included. The station costs may increase dependent upon the level of quality assurance required by the CTBT. The siting costs will be dependent upon whether or not the EMP detection station can be co-located with other CTBT monitoring networks such as the seismic, infrasound, or optical stations, and if so, how the costs will be shared between the systems for siting and data transmission. It is advantageous to co-locate the different CTBT detection capabilities to have a centralized location for data acquisition and transmission, maintenance, security, and certification of operation.

System cost

Total system cost for 20 and 40 stations: $3 million and $6 million.

Estimated lifetime per station: To be determined.

Operating cost per year: To be determined.

Site preparation is minimal. Experience has shown that such equipment needs periodic maintenance. The main expense of the system, however, would be in the operator(s) required to monitor the receivers and ensure that they are suitably tuned so as to provide the desired coverage, and to perform analysis on suspect events.

Data handling, transmission, and communication costs

Data handling costs would be dictated by the decision to either pass data only when queried (store data at the station) and therefore discard data on a regular rotation or institute an on-site discriminant. If only discriminated or queried data is sent to the IDC, the data rates would be low. A 9600-baud line could ship this data in a few minutes per day, assuming four or five events might occur in a time span of interest or had passed the discrimination criteria. This data rate would be compatible with other suggested detection techniques.

Development and availability status

A small amount of development is required to make a rugged, field deployable unit. No significant engineering development is required. A prototype system could be built and tested in six months to a year. Given the size of the data stream, ongoing work on event discrimination is required.

Synergy

Relationship to other systems

The EMP detection system is one of several methods that could be used to monitor the atmospheric environment. The number of stations is comparable to that required for the infrasound technique, and it might be possible to co-locate some of the EMP detectors with other CTBT monitoring stations. The data requirements are demanding for an EMP detection system, and could share a high-speed data line, or a low data rate system could share on the EMP data transfer line.

Requirement for complementary system

Because of the high false alarm rate, an EMP detection system would be operated as a confirmation system rather than a primary detection system. Its utility would be to provide additional evidence in the case of an ambiguous event seen by other CTBT monitoring stations and to provide accurate event location. The prompt nature of EMP means that this system must be continuously recording data.

Issues

Further system, cost, and siting studies need to be completed. Continued work is required on the control logic and discrimination of false alarms.

Challenge on-site inspection

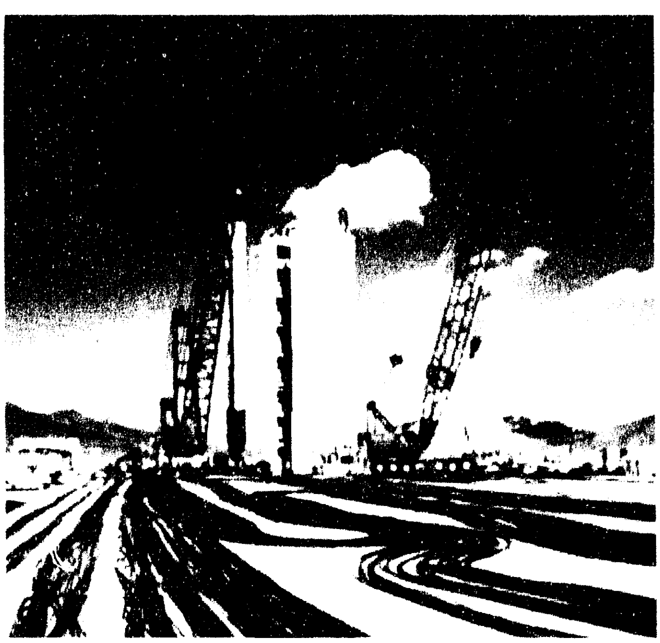
A *challenge* on-site inspection (OSI) involves an inspection team visit to a site to collect data and examine evidence in order to determine the source of an ambiguous event detected via remote monitoring systems or other measures. Its purpose is to collect the necessary collateral evidence necessary for States Parties to determine if the treaty has been violated. Challenge OSIs can also deter violations and build confidence.

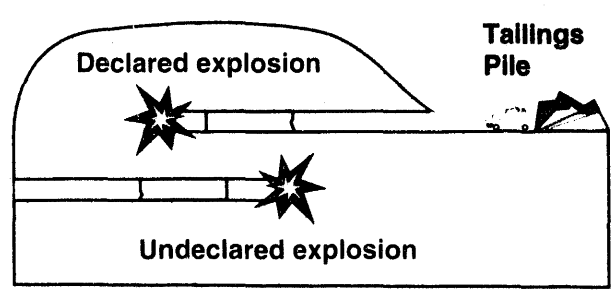
Traditionally, challenge OSIs in the CTB context are thought of as being carried out against underground events. However, an evader might also choose to carry out a test in the lower atmosphere or underwater.

Background

Nuclear explosions release large amounts of energy, some of which can travel great distances to create signals that are observed on remote monitoring systems. Remote monitoring systems record other natural and human-generated signals as well, such as those from lightning bolts, earthquakes, and quarry blasts. Under certain conditions, signals from non-nuclear events will have characteristics similar to those of the signals from nuclear detonations, and their source can be difficult to identify (Figure 1). The number of such explosion-like events could be greater than the number of OSIs that can be reasonably carried out.

The nuclear detonation creates residual effects that become the object of an OSI. In the case of an underground detonation, the most important of these effects are the creation of radioactive residues, the generation of aftershocks, and the formation of the cavity and rubble zone. An evader could attempt to mask





■ *Figure 1. Comparison of typical Nevada Test site test preparation and potential evasion scenario.*

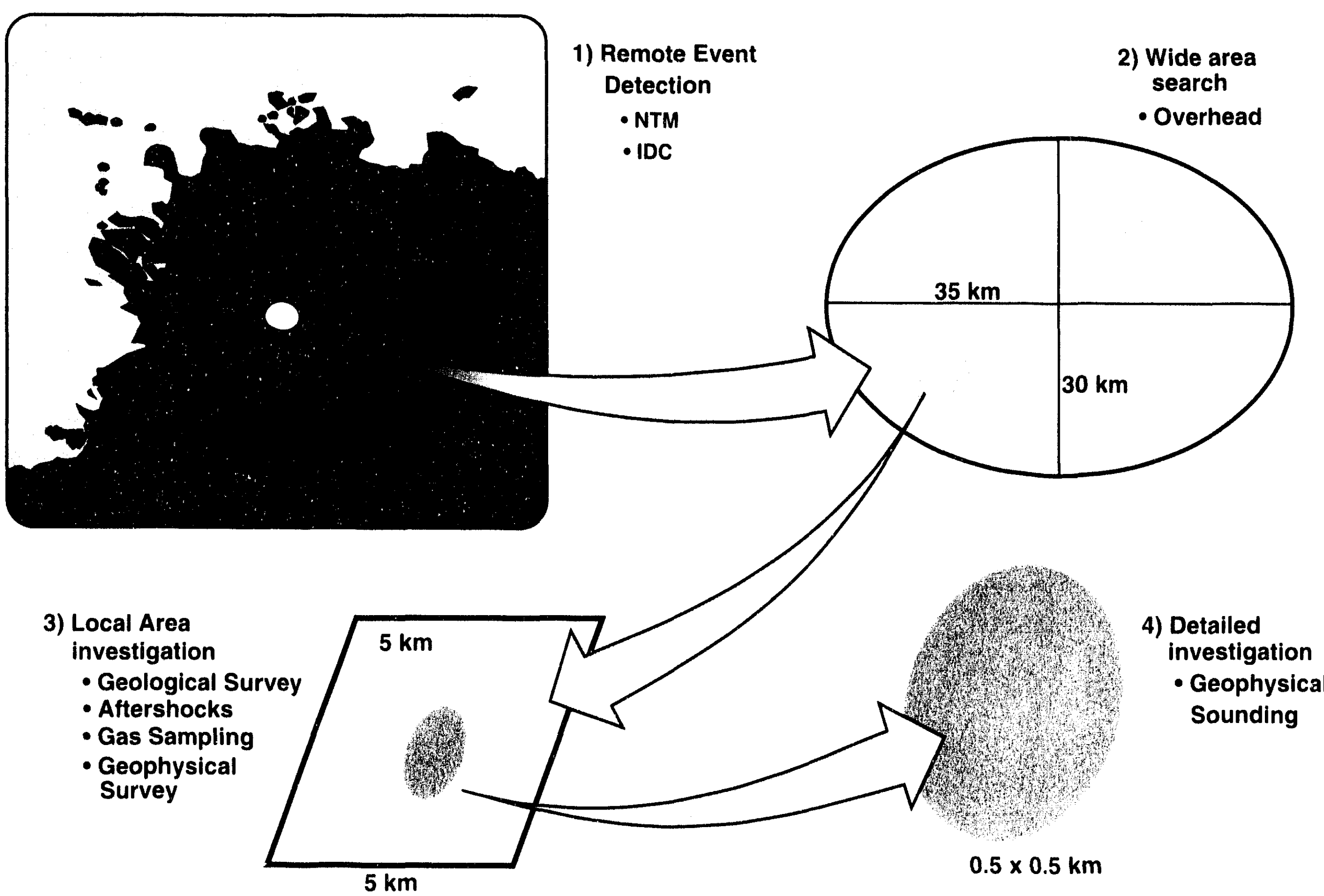
these effects by conducting the clandestine nuclear test in a deeply buried cavity near a mine. (The depth could prevent the formation of a crater and slow the escape of radioactive gases. The cavity could muffle the explosion's seismic signals. Legitimate operations of the mine could provide cover for the test preparations and a simultaneous, legitimate chemical explosion could mask the signals to the remote monitoring systems.) One could also imagine other evasion scenarios involving nuclear tests in oil fields (Figure 1).

Underwater explosions release radioactive debris into both the water and atmosphere. Near-surface atmospheric explosions release debris into the atmosphere, producing downwind fallout and could scorch the ground and cause it to become radioactive.

The system described in this paper is designed to have a high probability of identifying an evader. The purpose of this paper is to describe in detail the technical aspects of the proposed verification system and the tools that would be useful in specific situations.

Challenge OSI technologies

Challenge inspections could be conducted on land for underground and lower atmosphere events, and over and on water for lower atmosphere events and underwater events. Given the location accuracy of remote monitoring systems envisioned for the treaty, the initial inspection area could be as large as 1000 square kilometers over land. This area would be narrowed during the course of the OSI (Figure 2). The only conclusive evidence of a



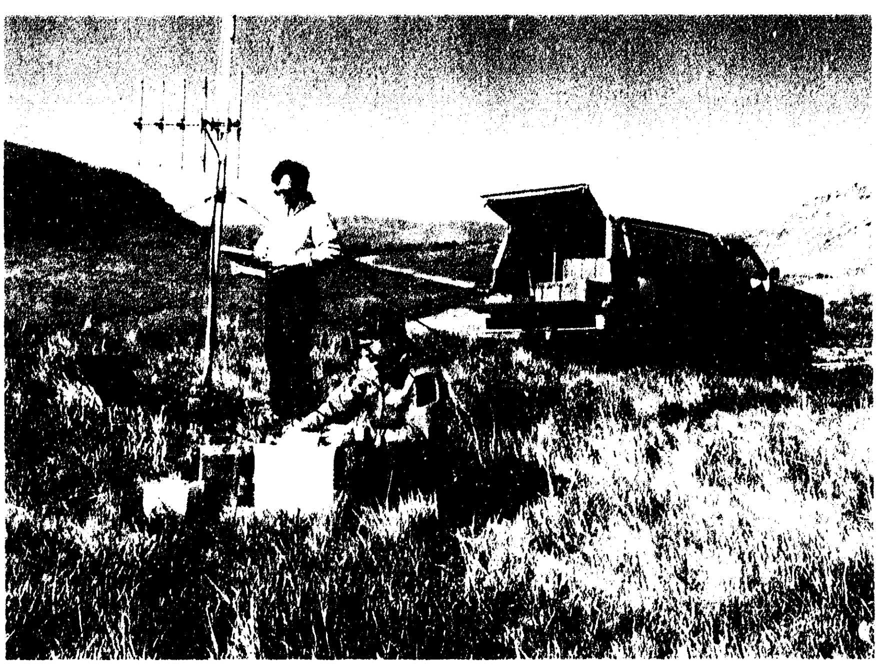
■ *Figure 2. Narrowing of search area during a challenge inspection on land.*

nuclear explosion is the retrieval of a radioactive sample containing certain characteristic isotopes. Other evidence collected in the course of an OSI may provide a plausible explanation for the source of the ambiguity, other than a nuclear explosion, to allay concerns and build confidence. The technologies fall into two basic categories: those that detect and quantify radioactive material and those that guide the search to it.

Many of the targets of an OSI are short-lived. It is very important that the OSI team arrive at the site as soon as possible. If the inspectors arrive at the site within seven days of the event, there is a good chance of observing the short-lived aftereffects of a nuclear explosion (Figure 3). The time-dependence of the various phenomena is discussed below.

Upon arriving at the inspection site, the inspectors will need to set up a field camp to control operations and carry out in-field data analysis. They may also require a base at the port of entry or other location to coordinate in-country operations. The equipment they use will need to be certified for use in OSIs. Inspection teams in the field need to be able to communicate with each other and with the permanent offices of the Technical Secretariat. They should be able to use their own equipment or that provided by the inspected party if it is acceptable and more convenient. Furthermore, they may deploy remote systems that need to communicate with the field camp or other locations. The inspectors should have the right to use authentication techniques on these data streams.

Data analysis in the field needs to be capable enough to enable the inspectors to vary the search parameters in real time. After the inspectors leave the field, their data and field reports are presented to the Technical Secretariat for standard processing, distribution to States Parties, and archiving.



■ *Figure 3. Example of aftershock detection equipment. Picture shows remote digitizer unit, antenna for telemetry, solar panel and battery, and seismic sensors.*

Underground events

Aftershock detection system

Phenomenology. Aftershocks following both earthquakes and underground explosions last for several months, but their rate of occurrence decreases rapidly with time. Typical aftershock production rates for nuclear tests in the range of 20–100 kilotons, after two weeks, are about two events per day in alluvium, and 20 events per day in harder rocks such as tuff. Smaller nuclear explosions and decoupled explosions will have smaller rates. Deeply buried high-explosive blasts could also have aftershocks. Explosion aftershocks have smaller seismic magnitudes than those of the original explosion and would probably be detected only by stations located within 1–2 kilometers of the explosion. Aftershocks from nuclear tests tend to be clustered around the detonation point. Aftershocks from earthquakes are generated along planes and tend to extend to much greater depths. However, some underground explosions can result in movement along local faults. This movement can cause the seismic source and the distribution of aftershocks to assume some of the characteristics of an earthquake. It is also possible, under certain circumstances, to discriminate between explosion and earthquake aftershocks on the basis of wave-form shape and depth of source.

System characteristics. Aftershock detection equipment would consist of portable, high-frequency (approximately 4–50-Hz) seismic stations that either record their data locally or telemeter the data to a central location. The system should be able to record continuous data since explosion aftershocks can have indistinct onsets. Stations need to have accurate relative timing and locations, both of which can currently be achieved with Global Positioning System (GPS) technology. Ten to twenty stations would be required for a deployment. A basic computer workstation at the central location would be required to record the data and provide preliminary field analysis so that the network configuration can be altered in real time to focus on regions of seismic activity. Final analysis of the data would be carried out by States Parties. The IDC could provide archive services.

Resources. Aftershock detection equipment is currently available off-the-shelf from several different manufacturers. Modifications are potentially necessary to include full GPS capability and incorporate tamper protection and authentication. Cost will run from $15,000–20,000 per remote station. Local telemetry would use line-of-sight radios and is included in the station cost. The central recording station would consist of radio receivers and computer equipment and would cost $100,000–200,000.

Visual and geological survey

Phenomenology. This effort would be an intensive ground-based examination of the area to look for artifacts of the testing activity, such as surface workings, ground fractures, and other geologic evidence that would further narrow the search area. This survey should be done at the beginning of the OSI in order to permit examination of the site before other OSI activities disturb the area. This survey would help locate the most appropriate sites for aftershock detection stations and to note areas where intensive searches, either geophysical or radiometric, should be undertaken. Any surface dislocations, and their pattern, would be noted. Mines would be explored to the extent possible. The survey would also attempt to characterize surface and subsurface geologic features that would be useful in the interpretation of the geophysical and seismic surveys.

Analysis/Resources. The survey techniques are well established and routinely used by geologists and experts in other domains. Data analysis can be carried out in the field using available maps or overhead imagery. Specialized equipment needed includes GPS receivers, geological mapping tools, and photographic and video equipment.

Gas sampling and radiation survey

Phenomenology. On-the-ground radiation monitoring would probably be a major activity of an OSI. Radioactivity characteristic of a nuclear explosion is the only unique post event indicator of a nuclear explosion. An underground test produces radionuclides that are trapped underground in the immediate vicinity of the explosion if the event is satisfactorily contained. These radionuclides will be transported away from the source region initially by pressure-driven flow through cracks and fissures and later by gaseous diffusion. Depending on the local geologic conditions and the effectiveness of event containment, the gases could reach the surface in a matter of hours or only after several months. Gases from a well-contained test that does not fracture the surface or produce a collapse crater may not reach the surface for months. The most likely radionuclides to diffuse out are the noble gases and tritium. The isotopes of xenon are indicative of a nuclear test, but they are short-lived and are probably not useful for OSI. Argon-37 is a reaction product of the device's radiation and the surrounding material. It has a half-life of 35 days and is a good indicator of a recent test. Krypton-85, with a half-life of 10.76 years is also produced from nuclear explosions, but there is also a worldwide background from reactor operations. It would be indicative of a test if detected well above local background levels.

System characteristics and analysis. Gas samples can be taken by spreading tarpaulins on the surface and drawing the gas collected under the tarps into sample bottles. If conditions permit, probes can be driven into the ground, and the gas can be sampled from a few feet underground. Any visible surface fracture would make a good collection point. Soil gas samples should be collected during atmospheric lows, and the noble gases should be separated by gas chromatography and analyzed. This would require an appropriate chemical laboratory on site so that, based on the results of the analysis, parameters can be changed in the field. Sensitivity of available field instruments is approximately 10 parts per billion, which is adequate to detect argon-37 from small nuclear explosions up to one year after detonation. Analysis using accelerator-based techniques at permanent labs can increase the sensitivity to detect argon-37 from the same explosion to about two years. Appropriate arrangements for removal of the samples from the territory of the inspected country would also be arranged for analysis at certified laboratories. Man-portable radiation detectors could also be used in case the clandestine test was not satisfactorily contained and there was a prompt venting of radionuclides.

Resources. Current technology is adequate for detecting radionuclides from nuclear tests. With some minor repackaging, noble-gas detection equipment could be made to fit into a vehicle the size of a passenger van. Gas bottles, pumps, tarps, and ground probes would need to be included in the system. The cost per system is approximately $250,000.

Aerial survey

Phenomenology. Visible-light images can show evidence of surface workings such as roads, mine tailings, cables, and shock-induced fractures. Multispectral images can be used to search for patches of ground that have been disturbed by spallation or violent shaking from the interaction of the shock wave with the surface. Areas where pre-test multispectral images are not available for comparison may still show sufficient plant stress or ground emissivity changes to assist in choosing targets for further investigation. Aerial electromagnetic and radiation survey equipment can be used to look for buried metal artifacts or radioactive debris respectively.

System characteristics. Satellites could provide the necessary imagery, but the availability of imagery on short notice may be limited due to cloud cover and targeting restrictions. In order to gather the electromagnetic and radiation data, as well as some of the imagery, it will be necessary to arrange a fly-over of the area to be inspected by an aircraft equipped with appropriate sensors.

Analysis. Visible-light images can be produced quickly and will be essential for choosing regions for detailed analysis within the initial large search area. Currently, the analysis of multispectral images is time-consuming because of the need to reduce large amounts of data. However, with GPS capability and modern portable computers, the analysis time could be greatly reduced.

Resources. Commercial satellite images cost up to several thousand dollars per image depending on the system. Flight costs for low-altitude imaging could range from $200,000 to $300,000, depending on how close the aircraft is to the survey site.

Geophysical sounding

Phenomenology. The rubble zone from the explosion and the void above it, as well as buried metallic cables, are the appropriate targets for geophysical sounding. In areas without complex geologic structure, it may be possible to locate the rubble zone using such techniques as direct-current resistivity, seismic reflection imaging, low-frequency electromagnetic sounding, as well as others. Ground penetrating radar would probably not reach deeply enough (limited to a few tens of meters) to be effective. Magnetometer surveys could be useful in searching for buried wires and emplacement pipes and cables. Gravity surveys might be useful in cases where a large cavity for decoupling may have been constructed.

Most active techniques (for example, seismic or electrical) map the distribution of energy that is returned to the surface after being introduced into the ground and perturbed by underlying geologic structures, including the rubble zone. Such surveys need to pass within a depth of burial to detect the target. Therefore, the inspection team should use these active techniques when the search has been narrowed to a small region by other means. The geophysical phenomena measured by these techniques are not short-lived and could be detected long after the explosion. Results from surveys to detect the phenomena could be used to determine a potential drilling target or to assist in determining appropriate locations for gas sampling. However, the results may be inconclusive because the rubble zone is a small target compared to the possible background geologic structures.

System characteristics. Geophysical sounding equipment would consist of low-frequency electromagnetic sounding, seismic reflection and refraction imaging, direct-current resistivity surveys, and other similar techniques. These systems are labor-intensive and can involve deployment of many sensors, together with their associated cables and power sources. Seismic sources are truck-mounted vibrators, impulsive sources, or explosives.

Analysis. Preliminary data analysis in the field is possible, but complete analysis usually needs to be carried out in a larger facility after the survey because of the enormous amount of data involved. Sophisticated processing techniques require use of supercomputing capabilities.

Resources. Since geophysical sounding is used extensively in the oil and mineral industries, equipment is available off the shelf, and surveys and data processing can be readily contracted. Most contractors are accustomed to operating in remote parts of the world. Typical costs per kilometer of seismic reflection survey range from $100,000–500,000, depending on the remoteness of the location, ruggedness of the topography, and processing requirements.

Extended monitoring stations

Phenomenology. Gases from underground nuclear explosions can be detected at late times when atmospheric lows draw them to the surface. Extended monitoring stations could be used to monitor for these gases at the OSI site for periods of several months. Inspectors would not be on site except for routine periodic maintenance. These stations would take gas samples and store them for retrieval by inspectors when they visit the sites. The samples would then be analyzed for argon-37 and krypton-85. Depending on the results of other OSI technologies, from two to ten stations would need to be deployed. In some cases, extended seismic monitoring might be considered, but seismic stations are unlikely to detect aftershocks from a test for more than a few weeks. Such stations would only be useful in verifying a natural explanation for the event; for example, aftershocks from an earthquake might occur over an extended period of time.

System characteristics and analysis. The system should be capable of taking a sample at times of low atmospheric pressure and either storing the sample or analyzing it locally and storing the result. The system should be capable of operating unattended for a month or two. During periodic maintenance, inspectors would retrieve the samples or results of analysis. Tamper protection and data authentication would be necessary.

Resources. Such systems would need to be developed. It is not known at this time what the development costs would be. After development, the cost per station could range from one to several hundred thousand dollars, depending on the security and on-site analysis that are desired.

Drilling

Phenomenology. If the results from gas sampling are negative and no other radioactive evidence is located, but there is some other compelling data, then drilling into the suspected region of the explosion to retrieve a radioactive sample may need to be considered. Drilling should be undertaken only if there is reason to believe that a specific location underground is the region of a clandestine explosion and that the location has been accurately determined. Such evidence could come from the results of geophysical sounding, for example. Based on U.S. experience at the Nevada Test Site, the drilling target, including the halo from pressure-driven gases, could be about 50 meters in diameter for a 1-kiloton explosion. The probability of drilling into a region of this size that is within 700 meters of the surface could be as high as 80%, if the precise location of the region is known. Highly experienced and trained drill crews might reduce the miss rate considerably. The inspection team would have to use directional drilling techniques and equipment to prevent blowout in case the anomaly was caused by an explosion and the cavity is still under pressure. Furthermore, the team would need facilities and training to handle intensely radioactive materials. Gas sampling, drill-hole logging, or core samples attained before reaching the actual explosion region may be sufficient to prove the presence of a nuclear explosion. Samples taken from the explosion region can be dated to establish the age of the test. Drilling more than one or two holes may be impractical due to cost and time on site limitations.

System characteristics and analysis. The drilling techniques and procedures used should ensure that the environment and the deployment personnel are protected against blowout hazards. Equipment for both vertical and horizontal drilling is needed. Directional drilling and blowout protection have been used for many years by the oil industry and at the Nevada Test Site. Preliminary on-site analysis of samples is possible using gamma-ray spectroscopy equipment.

Resources. The U.S. has made use of drilling equipment at the Nevada Test Site. Contractor services are also available. Table 1 summarizes representative drilling costs using available U.S. equipment.

Lower atmosphere events over land

Phenomenology. Local on-site effects from lower atmosphere nuclear explosions over land, such as thermal scarring of vegetation, thermoluminescence, air blast effects, fallout, and surface neutron activation can be minimized by raising the Height of Burst (HOB). The thermal, blast, and neutron-activation effects of a 1- to 10-kiloton explosion yield at a height of 3 kilometers or more would be extremely difficult to detect. Radiochemical analysis of the surface materials might detect small amounts of isotopes produced by neutron activation of the ground, such as cobalt-60 and isotopes of sulfur and europium. An evader could add material to the outside of the device case to reduce neutron and gamma emission, but this would greatly increase the weight of the device canister (by up to several tons). Radioactivity from local fallout generated by a 1–10-kiloton burst with an HOB greater than 300 meters will probably have decayed to below background levels within a week of the burst. However, certain distinctive fission isotopes, such as strontium-90 and cesium-137 (as well as uranium and plutonium) will remain for many years after the event.

Table 1. Drillback costs in thousands of dollars.

Type of hole	Equipment	Mobilization/ Demobilization	Support	Drill cost per hole	Preparation	Hole drill	Clean-up
Vertical	2100	2000*	800	200**	14	24	20
Horizontal	400	1500	800	70	13	12	11

*Assumes large drill rig. Small rig (up to 400 m) would require one less large transport aircraft and save $300,000.
**Assumes intermediate depth of 1200 m, and minimal difficulties. Worst case (1800 m) would be $400,000.
Notes:
Support equipment includes logging, cementing, directional survey, and sample containment equipment that would be needed for each deployment.
Costs reflected here include purchase of the equipment. Mobilization and demobilization costs would be charged for each deployment. As an example of using the above table, suppose an operation were fielded that drilled two vertical holes. The cost would be a one-time fixed cost of $2.9 million for the equipment, plus an operations (transport, setup, and cleanup) cost of $2 million plus the cost to drill two holes at $200,000 each, for a total of $2.9 million for equipment and $2.4 million for the exercise.

Rainout of device debris from the resulting radioactive cloud could still deposit local hot spots of radioactivity that might be detected by an on-site inspection. In addition, there is some incentive to test at a lower altitude since a greater HOB increases the likelihood of clouds (presumed to be present to hide the fireball from satellite observation) picking up the fission debris and depositing it in a locally concentrated form.

System characteristics. Portable x-ray, gamma-ray, and alpha-radiation detectors could be used to search for local hot spots of radioactivity and to measure radioactivity from surface samples. Aerial radiation surveys for hot spots are also now possible. Soil, rock, vegetation, and water samples could be collected for detailed radiochemical analysis at a certified laboratory to look for characteristic debris or neutron-activation isotopes.

Analysis. Radiation readings will be immediately available to the inspection team. Portable laboratory equipment for radiochemical analysis could identify isotopes if they are present in sufficiently large amounts. More detailed analysis of samples at a certified laboratory would be required, but may not be necessary to simply establish the presence of radioactive material.

Resources. Radiation-detection equipment is readily available from commercial vendors. Radiochemical laboratories are less common, and arrangements would need to be made to obtain access to such a laboratory.

Underwater events

Fission products and neutron activation

Phenomenology. Underwater nuclear explosions produce seismic signals and release radioactivity. Seismic events at sea are not as well located (areas with a 50-kilometer major-axis diameter) as events on land due to the reduced station coverage. The addition of hydroacoustic data will improve location accuracy. Shallow explosions also produce a radioactive cloud, similar to a lower-atmosphere event but rising to a much lower altitude, and a radioactive base surge containing fission products. Thermal effects are negligible. A deep underwater event does not produce an airborne radioactive cloud. It does generate a base surge, but the surge contains only a small amount of radioactive material. After a day, the residual radioactivity at the surface is significantly reduced. At this time, most radioactivity will be present in a disk-like *pool* within 100 meters of the surface. This pool will contain residual uranium and plutonium, fission products (such as strontium-89/90, zirconium-95, molybdenum-99, and barium- and lanthanum-140), tritiated water from explosion-produced tritium, and neutron-induced isotopes, such as sodium-24 and chlorine-36 (although the large chlorine background may prevent chlorine-36 measurement) produced by neutron capture on sea salts. The radioactive pool from a typical 20-kiloton event expands from a diameter of approximately 10 km at one day to 20 kilometers after one week. The dose rate decreases during that time to about 0.002 rads/hour, but it should be detectable for several weeks after the event.

Analysis and resources. Water samples would be collected and measured for radioactivity. Plankton collection could be useful due to the bio-concentrating properties of plankton. Radiation readings will be immediately available to the inspection team. Portable laboratory equipment for radiochemical analysis could identify isotopes if they are present in sufficiently large amounts. More detailed analysis of samples would be required at a certified laboratory. A mass spectrometer would be needed to look for characteristic isotopes with low radioactivity.

Sufficiently sensitive alpha, beta, and gamma counters could be obtained for $500,000–1,000,000 and could be used for all scenarios (underground, atmospheric, and underwater). A mobile radiochemical laboratory, including chemical separation and mass spectrometry capabilities, could be assembled for about $3 million. Instruments and a cryogenic sampler for measuring gas samples for krypton and xenon would cost about $250,000 (this is the same equipment that would be used for gas sampling for underground tests).

Options

Visual initial inspection

This option would start the inspection with a simple fly-over or drive-over of the inspection region. The advantage of this approach is that it could potentially resolve some events. The disadvantage is that it will not catch the determined evader who has left no surface expression of the testing. Meanwhile, time will be lost, and the chances of detecting short-lived phenomena will be diminished.

Ownership of OSI equipment

One arrangement would be for the Technical Secretariat to certify and maintain the OSI equipment. Much of it could be donated from the States Parties, possibly for some type of credit. Furthermore, there may be instances where a State's Party may contribute some equipment for a specific deployment. In this case, some sort of special certification will need to be worked out.

Inspectors

Two options could be considered. The inspection load might be a relevant factor. If inspections become a year-round activity, it might be more convenient for the inspectors to be permanently assigned to the Technical Secretariat. If there is a small number of OSIs, it may be more convenient for inspectors to be temporarily assigned to the Technical Secretariat for the duration of the OSI.

Issues

How OSIs are chosen is a primary issue needing resolution. The process by which requests by States Parties are handled, either initial requests for OSIs or subsequent requests for drillback or extended phases will need careful development. Given the transitory nature of nuclear-explosion-induced effects, a timely process is essential for the OSI regime to be effective.

Drillback for radioactive samples provides the possibility of supplying incontrovertible evidence of a clandestine underground nuclear test. However, the process is very expensive and can succeed only if the test's location in three dimensions is known with a high degree of accuracy and very careful drilling procedures are used. Hence, drillback should be deployed only for very special cases. The provision for a drillback phase for the OSI will need careful development. One issue is that an inspected State could insist on a drillback to *prove* a negative finding, thereby exonerating the State. If a test had actually occurred and the lack of detailed information about its location resulted in the failure of the drilling to discover it, the State might be falsely exonerated.

OSIs for ambiguous underwater events may provide evidence of a clandestine nuclear test, but attribution will be difficult. What techniques may be employed to resolve this situation will need careful study and analysis.

The boundary of the area within which an OSI is to be conducted will need to be specified carefully and unambiguously. In general, the movement of the inspection team within this boundary should be unrestricted, but the ability of the team to move outside of this area should be strictly limited. How to establish this boundary and protect the inspected Party's rights will need careful development.

It may be necessary for States Parties to protect certain sensitive facilities within the requested area from OSI intrusion. The circumstances under which such restrictions on the inspection team would be allowed will need careful development. Additional access restrictions due to health and safety concerns are likely. Concerns regarding protection of proprietary information belonging to private entities must be resolved prior to inspections.

It will also be necessary to develop procedures for certifying the equipment used in OSIs and the laboratories that analyze OSI samples.

Recommendation

The U.S. recommends that *challenge* OSIs be included as an element of the CTBT verification regime. Such challenge OSI should be conducted in three phases: (1) an Initial Phase, (2) an Optional Extended Phase, and (3) an Optional Drilling phase. Inspections for events in the atmosphere and over or under water will require only the Initial Phase. Inspections should be conducted as soon as possible after the OSI request, before radioactive products from the detonation disperse and/or the short-lived aftereffects decay below detection levels. After the Initial Phase, the data would be passed to the States Parties for final analysis.

For events on land, the Drilling and Extended Phases could then be requested if more evidence was deemed necessary. Since the targets of these phases are much longer lived, these phases can be carried out several months after the initial request and still find conclusive evidence.

Inspectors should be drawn from an international pool of inspectors that are on call. Data from inspections would be passed to the Technical Secretariat for reduction and then passed to the IDC for archiving.

Summary of costs for typical deployment

Cost estimates are derived from known and estimated equipment costs, manpower costs, experience gained from past experiments, and a Congressional Budget Office report, *U.S. Costs of Verification and Compliance Under Pending Arms Treaties*. Cost estimates are separated into nonrecurring costs, such as for equipment purchases, and recurring, per-deployment costs, such as manpower and transportation. Estimates were made for the number of personnel required to field each technology (e.g., 5 each for gas sampling, geological survey, seismic survey) and the length of time on-site (typically 1 month, with exceptions such as 5 days for the visual/geological survey). Estimates were also made for transportation ($300,000 per trip for each large airplane to $5000 to $10,000 for shipping of smaller equipment and personnel).

Costs do not include administrative costs of the Technical Secretariat, costs incurred by the requesting Party in determining the suspect area, or equipment storage and maintenance costs. They also do not include additional costs for aircraft that would be needed to access particularly remote locations, such as open ocean areas.

Table 2 shows costs, assuming a *typical* deployment, without a large number of complications. An approximate one-time cost of purchasing equipment is listed, along with the approximate cost that would be incurred for each separate deployment of the inspection team.

For example, an inspection of a potential underground event would probably deploy seismic stations, visual and geological survey, gas sampling, aerial multispectral survey, and geophysical sounding. This would require approximately $1.1 million in equipment and $1.4 million for deployment. Vertical drilling would add $2.9 million for equipment (if purchased new) and $2.4 million for deployment, and using radiation counters and a mobile radchem laboratory would add $4.0 million in equipment and $400,000 deployment, for a total cost using all technologies of approximately $8.0 million for equipment and $4.2 million for deployment.

Table 2. Costs of equipment and deployment in thousands of dollars.

Technology	Equipment	Deployment
Base camp and local vehicles	300	20
Seismic stations (20 stations)	500	200
Visual and geological survey	10	50
Gas sampling system	250	200
Aerial multispectral survey	0 (rent)	400
Geophysical sounding	0 (rent)	500
Drilling (2 vertical holes)	2900	2400
Drilling (2 horizontal holes)	1100	1640
Radiation counters	1000	300
Mobile radchem laboratory	3000	400

Associated measures

Recently, the U.S. presented its views on the contributions that six technologies could make to a robust CTBT monitoring regime. Here we present our concept of "challenge" on-site inspections (OSI) and will discuss other, associated measures and the role they could play in contributing to an effective CTBT monitoring and verification regime.

Associated measures

In the U.S. view, associated measures include measures that would supplement and reinforce the national and multinational technical means of verification. They include information exchanges and notifications and other measures to clarify or reduce uncertainty about events detected by remote sensor systems.

The national and multinational technical means of verification we have been discussing would be the backbone of the CTBT monitoring and verification regime. Nonetheless, it is widely understood that small clandestine nuclear tests could still be conducted in such a way as to mask many if not all of the effects detectable by remote sensor systems. For example, a nuclear explosion could be masked from remote technical sensor systems if it were conducted in an underground cavity or perhaps underground in a mine concurrently with a nearby chemical explosion. Remote sensors would also detect numerous naturally occurring and man-made events (e.g., lightning, earthquakes, and chemical explosions) whose signals could resemble those of a nuclear explosion or introduce an element of ambiguity as to the nature of the event. In other circumstances, national technical means might observe activity that, without additional information, might raise suspicions that a prohibited explosion could have occurred.

In cases of high concern that a nuclear explosion could have occurred, one or more States Parties would request an OSI to help confirm the nature of the event. While an OSI regime would not always resolve the nature of ambiguous events, the Treaty right to conduct inspections, coupled with a demonstrated resolve to employ the inspection regime as required, should serve as a strong deterrent. To achieve an OSI regime that is effective, it is important to minimize the number of ambiguous events that could prompt OSI, and to address promptly and effectively any OSI requests. In this context, the U.S. sees associated measures playing a significant role in clarifying potentially ambiguous information received by the technical networks.

Information exchanges

Information exchange would be designed to provide clarification of naturally occurring and certain man-made events detected by the technical networks. In our view, the Treaty should require information exchanges such as:

- Declarations, updated periodically, of locations where chemical explosions above a designated threshold are expected to be conducted routinely.
- Advance notification of each planned chemical explosion above a designated threshold, along with a characterization of the planned activity.
- Post-event clarification of unscheduled events such as accidental explosions, rock bursts, and collapses in mines, or of significant accidental discharges of radioactive material above a designated threshold.

The treaty could also provide for exchange of other information that might be helpful in avoiding potentially ambiguous situations and misunderstandings.

Other measures

The Treaty could provide for the following additional measures:

Calibration activities

These activities could include the use of chemical explosions to assist in calibrating regional or local seismic networks, and perhaps some hydroacoustic stations, thus improving their utility to help detect, locate, and identify seismic events. The calibration activities could be conducted by the international organization or on some other multilateral or bilateral basis.

Continuous presence monitoring

These measures could involve emplacement of sensor suites at mines and other locations where conventional explosions above a designated threshold occur routinely over a period of time. An evaluation team might set up sensor equipment, service it periodically, collect data in cases where remote transmission is not feasible, check for signs of tampering, and remove the equipment, when appropriate.

Notified event monitoring

These measures are conceptually similar to continuous presence measures, but would be keyed to one or more events above a designated threshold and falling within a relatively short period, such as a scheduled group of chemical explosions. The evaluation team might remain with its equipment at the site for the duration of the notified activity. Specialized sensors, such as gas sampling equipment, could be left on site for a longer period of time.

Conclusions

The U.S. believes that a well-designated package of associated measures should be included in the Treaty. It is important to consider the advantages of measures that could decrease false alarms and the number of ambiguous events for which an OSI would be required. At the same time, we would need to ensure that use of such measures would neither delay an on-site inspection, if a State Party believed one to be necessary, nor serve in lieu of an inspection in situations where one was warranted.

Calibration events

Well-characterized 50–200-ton chemical explosions detonated underground could improve our understanding of basic explosion phenomenology and calibrate the seismic monitoring system's capabilities to detect, locate, and identify events in specific regions. The increased understanding of the phenomenology would allow the States Parties to predict the system's capabilities in regions where extensive monitoring had not been previously carried out. The calibration efforts would improve the system's monitoring capabilities in the vicinity of the calibration explosions and, possibly, in broader areas of the tectonic regions where the explosions occurred. Dedicated calibration explosions could be conducted as a part of transparency measures or as part of an effort to reduce the number of ambiguous events. Explosions conducted for commercial or scientific purposes could be used as calibration events if they are well characterized.

The remainder of this paper describes some possible forms that calibration efforts could take and outlines some of the costs and benefits that might accrue from having calibration explosions as an associated measure in a Comprehensive Test Ban Treaty (CTBT). The discussion addresses the technical aspects of these explosions and does not address implementation modalities for Treaty purposes.

Background

The seismic monitoring system's capabilities depend on several factors. The type of source, its depth, the spatial and temporal distribution of its energy release, and the material surrounding it all determine the frequency content and amplitudes of the seismic waves leaving the source region. Attenuation, scattering, and the geographic structures along the path from the source to the seismic stations also affect the amplitudes of the waves that are recorded and their frequency content. These source and path effects, together with the spatial distribution of the monitoring stations, determine the data that will be recorded.

At present, the monitoring community is unable to predict, with high confidence, the system's location and identification capabilities for regions where there is little experience. As a result, it often relies upon empirically defined processes that are specific to given regions or specific source conditions. In order to make use of this empirical approach, data representative of the sources, paths, and locations of interest must be available. For many regions, however, appropriate sources have not been available or, if they have been, they have not been recorded at the sites where the monitoring stations will be located. Without such data, the empirical approach to monitoring cannot be applied in these regions.

Several factors compound the CTBT monitoring challenge. As the seismic detection level is lowered by CTBT monitoring requirements, the number of unidentified or ambiguous events is expected to increase significantly. Each year, more than 100,000 seismic events, both earthquakes and high-explosive blasts, occur worldwide and emit seismic signals that are roughly equal in magnitude to those expected from a 1-kiloton decoupled nuclear explosion. Even if only a small percentage of these 100,000 events is considered to be ambiguous, the number of ambiguous events could pose a serious challenge to CTBT verification. Finally, there are few definitive data available with which to evaluate the monitoring challenges posed by certain types of evasion schemes, such as the hiding of a decoupled nuclear test within a mine or quarry blast.

In order to meet most effectively their CTBT monitoring requirements, the States Parties will need to develop

- Methods to detect, locate, and identify small sources with high confidence in geographic regions where they have little monitoring experience.
- Procedures that use dedicated explosions or well-characterized explosions conducted for commercial or scientific purposes to develop an empirical understanding of the performance of the monitoring functions in specific geographic regions.

Without such developments, the States Parties would receive lower quality products from the International Data Center (IDC) and be less able to use them.

Calibration options

A systematic program to calibrate all areas of the world is neither required nor contemplated. It is recommended that calibration events be conducted in areas where the international community's limited experience may affect monitoring capabilities or at sites where ongoing commercial or scientific activities generate seismic signals that could be mistaken for signals from underground nuclear explosions. A potentially large number of sites (hundreds) could satisfy these conditions, but cost considerations will limit the number of explosions that can be conducted. The costs can be reduced by taking advantage of suitable explosions that are detonated for commercial purposes (e.g., regional studies for oil and mineral exploration) and by coordinating calibration efforts with scientific efforts designed to study the structure of the Earth's crust and upper mantle. Given the contribution of such explosions to improving monitoring and the potential for scientific and commercial benefits, the States Parties may be willing to volunteer such explosions.

The baseline—routinely recorded events with no on-site presence in the source region

Analysis of routine recordings made at stations of the International Seismic Monitoring System from large explosions conducted for commercial or scientific purposes (and some earthquakes) could provide a baseline for determining the properties of a region and the sources within it. No additional costs would be incurred other than the costs of analyzing the data.

Table 1 describes the elements of this baseline approach and its benefits to detection, location, and identification. Analysis of the signals from explosions that occur as part of ongoing commercial and scientific operations could provide relative locations that are accurate to within a few kilometers for other events in the vicinity of the explosions.

Table 1. Routinely recorded events.

Source option	Characteristics	Value to detection	Value to location	Value to identification
Large commercial detonation with no on-site presence	High explosive or blasting agent detonated with the following characteristics: –Signals sufficient to be recorded with good signal-to-noise ratios at regional monitoring stations –Location and time inferred from seismic signals/imagery	Minimal	–Helps determine velocities of various regional wave types used in locating events –Provides a reference event for determining relative locations in source area (e.g., a mining district)	In the absence of any information about the source, provides a poorly defined reference for comparison with other commercial explosions in the same region. Value similar to other commercial explosions in the same area.

However, the absolute locations could be off by 20 kilometers or more (depending on the numbers of stations, their locations relative to the event, and the availability of other information).

Drawbacks to the approach include the length of time required to develop a comprehensive data base, the increased uncertainty due to lack of definition of the properties of the sources, and the inability to characterize regions that lack sources. The data derived from these efforts is unlikely to provide definitive information about detection or identification capabilities because no independent information is available about the source. The lack of seismic recordings at locations other than the monitoring stations also limits the ability to extrapolate the results to other locations within the region or to other regions.

Option 1—basic source information acquired on-site for an explosion conducted for other purposes

In this option, the monitoring organization would make a few near-source ground-motion measurements using portable accelerometers on an explosion of opportunity conducted for commercial or scientific purposes. Global Positioning System (GPS) receivers would provide precise timing and location information. The monitoring organization would also make a high-speed video of the explosion if the event is a surface explosion. This video would record the sequence of detonations of any individual explosives making up the explosion. Cursory geologic characterization would provide a semiquantitative understanding of coupling phenomena. This basic information, together with any information about the explosion's design obtained from local personnel, would partially define the explosion's source function. The cost for this option might be as low as $50,000–100,000 per event (includes travel and daily living expenses), depending on the explosion's location, the number of measurements, and the number of people involved.

Table 2 describes the benefits derivable from adding these basic source region measurements. Two types of explosions are considered. One type is shallow and distributed in space and time. The other type is deep, spatially compact, and instantaneously detonated.

Near-source measurements could enhance the usefulness of both shallow and deep explosions to the location of other events near the site by determining the explosions' detonation times and their precise locations. This information would also help develop velocity models for the region. A deep source concentrated in space and time could aid the identification process because its seismic signals would resemble the signals expected from a nuclear explosion. A well-described explosion of this type could provide a major contribution to identification in a region where no nuclear explosions have been recorded on the monitoring stations. It would help calibrate discriminants between earthquakes and explosions and between deep explosions that are concentrated in space and time and shallow explosions that are distributed in space and time.

Neither type of explosion, in itself, is likely to provide significant insight into the basic phenomenology or identification of the factors that affect discrimination. If both types of explosions occur at the same site, comparison of the two could help determine the extent to which near-surface phenomena (e.g., spall) determine the effectiveness of some discriminants. This understanding would improve the States Parties' abilities to extrapolate the results to other sites.

Options 2 and 3—deep, concentrated, conventional explosions at locations of choice recorded by source region and regional instrumentation

Measurements carried out in addition to those described in Option 1 could improve the system's ability to detect, locate, and identify events. Table 3 describes three categories of additional measurements that could be made: near-source measurements, regional path measurements, and measurements at the monitoring stations.

The near-source measurements could be made on the surface and at depth. The surface measurements would use multiple accelerometers to provide information about the seismic source function. These measurements would identify features of the seismic waves that originated at the source and would help separate source region and propagation effects in the region where the explosion was detonated. Subsurface measurements could include cables and gages emplaced in the explosive to determine the extent to which the explosive detonated and a variety of measurements to measure the near-field seismic source

Table 2. Basic source region measurements.

Source option	Characteristics	Value to detection	Value to location	Value to identification
Shallow detonation distributed in space and time with on-site presence (supplemented by basic* measurements and information to determine time, location, geology, and yield)	High explosive or blasting agent detonated with the following characteristics: –Shallow –Distributed in space and time –Location and time accurately determined –Charge yields & total yield known –Signals sufficient to be recorded on regional monitoring stations with good S/N	–Provides a reference event for waveform arrivals and amplitudes from shallow events in the same area (e.g., a mining district)	–Determines amplitudes and velocities of various regional wave types used in locating events –Provides a reference event for determining precise relative locations in the source area (e.g., a mining district) and some improvements for absolute locations for nearby sites in same tectonic region	–Provides a well-characterized reference event with signatures similar to those expected from some conventional explosions at the specific location and, to a lesser extent, for nearby sites in same tectonic region
Deep detonation concentrated in space and time with on-site presence (supplemented by basic* measurements & information to determine time, location, geology, and yield)	High explosive or blasting agent detonated with the following characteristics: –Deep –Spatially compact –Instantaneously detonated –Location and time accurately determined –Geology and material properties determined –Total yield known –Signals sufficient to be recorded on regional monitoring stations with good S/N –Well-coupled	–Helps improve network detection model –Provides a reference event for waveform arrivals and amplitudes from deep events in the same area (e.g., a mining district)	–Determines velocities of various wave types used in locating events –Provides a reference event for determining precise relative locations in the source area (e.g., a mining district) and some improvement for absolute locations at nearby sites in same tectonic region	–Provides a well-characterized reference event with signatures similar to those expected from a nuclear explosion at the specific location and, to a lesser extent, for nearby sites in the same tectonic region

*Basic measurements could be made with a GPS receiver, an accelerometer deployed near the source (to determine detonation time), and a high-speed video camera. Geologic samples would be collected.

function from various angles. These measurements would provide additional information that could be used to separate source and path effects. In addition, they would help determine the phenomenology of seismic wave generation.

The regional measurements would be made at the stations of the monitoring network, at other seismic stations in the region, and at seismometers deployed along lines from the source to the monitoring stations and across geologic features known to affect seismic wave propagation. These measurements would determine the seismic-wave propagation characteristics throughout the region and would allow extrapolation of the results of the calibration events to other locations within the region.

Deployment of temporary, high-frequency seismic instruments and arrays (where appropriate) around the monitoring network's seismic stations would determine the extent to which the monitoring system's performance could be improved by modifying the instrumentation or the analysis. The array deployments would help determine the extent to which the station's recordings were being affected by geologic features near the recording site and help identify the regional waves being recorded at the station. These deployments could be done at any time, but if they are done at the time of the calibration event, they would complement the other measurements and help separate the source, path and receiver effects.

Option 2—Combine surface measurements in the source region of a dedicated, deep explosion with measurements along the path and at the receiver site to calibrate the region. The source for this option would be a deep explosion located at a site that is of interest either because of the seismic sources (conventional explosions, rockbursts, or earthquakes) that occur there, or because path effects (such as the blockage of the seismic waves used in identification) affect the monitoring capability along paths leading there. A minimal level of near-source instrumentation would be deployed, and 30–50 or more surface measurements would be made from near-source to regional distances using portable seismic systems. The site geology would be characterized to a moderate degree. This characterization could include drilling, logging, and geophysical surveys. The source could be an appropriate event of opportunity at an existing mine, or it could be a dedicated explosion. A dedicated explosion would be required in regions where no appropriate commercial blasting operations serve as targets of opportunity.

This option would provide information specific to the region where the explosion is detonated as well as at the site where it occurs. It would help determine detection thresholds and would provide data to improve models of the monitoring network's detection and location capability. It would also provide a basis for discrimination between explosions and earthquakes in the region where it occurred and would address masking scenarios in which a nuclear explosion is detonated at the same time as a shallow conventional explosion. Costs for this type of event range from $1–2 million (excluding travel and daily living expenses), depending on charge size and configuration, exact nature of instrumentation, geology, and type of explosive with its safety requirements. Additional costs could be incurred if the monitoring organization has to supply the equipment for emplacement. For example, one-time equipment costs for a drill rig to drill large-diameter holes could add an additional $2–3 million, and transportation costs for such a rig could add $500,000 to the deployment costs. Local alternatives would be less expensive.

Option 3—Option 2 plus additional near source instrumentation and site characterization to understand general source characteristics and calibrate the region. This option is essentially the same as Option 2 with the addition of extensive subsurface (free field) ground-motion measurements that would be made in the transition region from hydrodynamic phenomena to seismic wave propagation. These measurements would help to directly define the seismic source function. A detailed site investigation would be conducted, and material properties would be characterized, using drilling, logging, coring, laboratory measurements on rock samples,

Table 3. Enhanced measurement options.

Measurement option	Characteristics	Value* to detection	Value* to location	Value* to identification
Near the source	Measurements of signals made at distances from a few meters to tens of kilometers –Subsurface –Surface	–Improves confidence in network detection models –Identifies effects of source parameters on azimuthal variations in detectability –Identifies material and source geometry effects	–Minimal improvement	–Possibly significant improvement due to separation of source, source region, and path effects on seismic signal characteristics –Improves ability to extrapolate to other regions –Constrains evasion scenarios that combine nuclear explosions with calibration events
Within the region containing the source and the monitoring stations	–Measurements made at existing regional seismic stations –Measurements made along radial lines from the source at distances from 10s to 100s of km –Lines with 1–100 instruments along paths to monitoring sites or in transition regions	–Significantly improves network modeling capability in area bounded by monitoring stations	–Significant improvement throughout area bounded by the regional monitoring stations	–Possibly significant improvement due to separation of source and path effects on seismic signal characteristics
At the monitoring stations	Measurements made around the receiver site at distances from a few 100 m to a few km –Arrays around 3-component monitoring sites –High-frequency instruments at all sites	–May identify changes in stations that would significantly improve detection capability (e.g., different frequency bands)	–May identify changes in stations that would significantly improve location capability (e.g., sources of near receiver effects on the direction of approach of seismic waves)	–May identify changes in stations that would significantly improve identification capability (e.g., different frequency bands)

*Value determined relative to measurements made at regional monitoring stations from well-characterized sources as described in the previous table.

and geophysical surveys. These additional measurements would permit more definitive separation of source and path effects. If these near-source measurements were repeated on a variety of events, they could significantly improve the ability to predict the seismic signals that would be generated by underground explosions detonated under a variety of conditions. It is anticipated that costs of this event would range from $2–6 million (excluding travel and daily living expenses) after a basic phenomenology program that will identify a minimum set of required instrumentation has been completed. Additional costs could be incurred as described in Option 2.

Combining the results of Option 2 or Option 3 with the results of similar measurements made on a nearby large, shallow, conventional explosion that was distributed in space and time would provide a simulation of a potential underground evasion scenario-detonation of a (decoupled) nuclear explosion at depth near a shallow conventional explosion. The costs for Options 2 and 3 and for efforts using multiple shots would be greater than for the simpler calibration measures. However, when the costs are compared against the costs incurred in the course of OSIs that could have been avoided if the monitoring measures had been more effective, the calibration options become more attractive. Furthermore, the deterrence benefits of the increased monitoring capability should be considered.

Summary and conclusions

A systematic program to calibrate all areas of the world is neither required nor contemplated. It is recommended that calibration events be conducted in areas where the international community's limited experience may affect monitoring capabilities or at sites where ongoing commercial or scientific activities generate seismic signals that could be mistaken for signals from small underground nuclear explosions. Costs could be reduced by coordinating the calibration efforts with explosions planned for commercial operations or scientific experiments.

We have described a baseline case and three options for improving seismic monitoring in a region where the monitoring agency has had little experience. The baseline case makes use of existing explosions (and some earthquakes) and does not involve measurements beyond those routinely made at the monitoring stations. However, it does involve additional analysis of the data from these measurements in order to infer information about the source region and path.

Options 1 and 2 would improve the monitoring network's ability to locate seismic sources and identify their signatures when they are located at specific sites or within specific regions. The first option would refine the location capability and could provide an absolute reference for events located near the site of the calibration explosion. The second option would also improve the location capability. In addition, it would provide the means to extend the calibration results from the specific site to other sites within the region. As in the baseline case, these options would involve additional analysis of the data. The costs of the two options differ by roughly an order of magnitude.

Option 3 would provide all of the site- and region-specific calibration results of Option 2. In addition, its more extensive source region measurements would provide more information about the mechanisms by which seismic waves are generated. This information would help determine the seismic waves' dependence on the properties of the source and the source region. A program of explosions of this type and, to a lesser extent, those conducted under Option 2 could provide a basis for predicting the performance of the monitoring network in new regions where only the general characteristics of the sources and source media are known. The cost of this option would be 1 to 6 times the cost of Option 2.

The costs of the options should be compared against the costs associated with the alternatives. In particular, the more expensive options have the potential for significantly reducing the number of ambiguous events and thus the number of OSIs. The resulting cost savings could more than offset the increased costs of Options 2 and 3.

Calibration options offer the potential for significant improvements in the monitoring system's performance:

- Option 1 offers a low-cost procedure that would improve the location capability of the monitoring network. It would complement activities to monitor large explosions at specific mines.
- Provisions to carry out calibration activities of the level of Option 2 could provide significant improvements in the States Parties' abilities to detect, locate, and identify events in the regions where the activities are carried out.
- The activities of Option 3 would provide similar benefits and some additional understanding of the basic phenomenology controlling the generation of seismic waves. This understanding could provide a basis for predicting and optimizing the performance of the monitoring network in other regions where there is little monitoring experience. These activities could be the central element of a program of explosion studies carried out as a part of ongoing associated measures.

Mine monitoring

Some mines worldwide detonate conventional explosives that generate large seismic signals that could be used to mask the simultaneous detonation of a decoupled nuclear explosion. A seismic/radionuclide system might be deployed at such mines in order to give high assurance that such an evasion attempt would be unlikely to succeed.

Background

Some mines world-wide detonate conventional explosives that generate seismic signals comparable to those of a 1–10-kiloton (kt) decoupled nuclear explosion (m_b 2.5 to 3.5). These signals could mask a simultaneous decoupled explosion. In addition, some mines occasionally experience mine tremors or rockbursts of even larger magnitude (up to about m_b 5.0). Mining experts generally agree that it would be possible to control the size and time of occurrence of some of these events, particularly collapses.

Number of mines considered for monitoring

Based on a very rough estimate there are worldwide fewer than 50 mines emitting signals greater than m_b 3.5 (10 kt decoupled). Steps could be taken to refine these estimates before and during the Comprehensive Test Ban Treaty, and to identify which mines might be monitored. Those mines that produce the largest seismic signals could have monitoring systems installed.

Detection of masked event

In the current state of technology it is likely that in some mines such a masking scenario as that described above could not be distinguished from the chemical blast alone, using seismic data from only regional and teleseismic distances. It seems plausible that, in an evasion attempt, the cavity for decoupling the nuclear explosion would be located up to a few kilometers from the conventional blast in order to reduce the possibility of leakage of radionuclides. Detecting the relative location of two such sources detonated simultaneously is likely to be beyond the capability of regional or teleseismic systems.

A small, high-frequency seismic array could be located at, or on the perimeter of, the mine itself. Analysis could consist of examining the array data for multiple sources. There is extensive literature on the subject.

Many mines today have mine-monitoring seismic systems, and the individual instruments themselves might well be satisfactory for treaty monitoring purposes. However, the power supply, data structure, and security features required in a treaty-monitoring context might require systems built especially for this task.

Relation to the global seismic system

The mine seismic system would be queried, generally, only on the initiative of the global/regional seismic system, and it would complement that system. It would be useful if each monitored mine submitted a map plan and a record of past blasting activities. This map and alphanumeric data should be of substantial use to the analyst studying the mine with the seismic data. Proprietary data issues would have to be addressed.

The radionuclide system

The mine seismic system could be complemented by an on-site xenon system which, being so close to the source, should have a very low detection threshold. The radionuclide system would be similar to the inert gas stations described in the U.S. Radionuclide Monitoring Concept paper (see page 15). If installed within a few kilometers of the mine it should detect leakage from a test for any wind direction. Analysis of the mine inert gas data could proceed similarly as for the world-wide inert gas system.

While the mine seismic system would be of little use for monitoring events outside the mine, a mine inert gas system could serve as a supplement to the approximately 100-element world-wide xenon system, if it happened to be favorably located. For this reason there could be some cost sharing of the xenon system with the mine-monitoring system.

Options

The International Organization could consider the possibility of fostering information exchanges on the technologies of ripple firing and avoidance of rockbursts to reduce the number of mines emitting large signals. Those mines which world-wide emit the largest seismic signals might have mine monitoring systems installed.

Chemical explosions

Chemical explosions can generate seismic signals that are indistinguishable from nuclear explosions and may be falsely indicative of a CTBT violation. If a nuclear explosion were carried out underground in violation of a CTBT, it could potentially be masked by a chemical explosion or be explained away as a chemical explosion.

Background

Chemical explosions represent a problem in CTBT monitoring because

- They will be detected in large numbers by any good seismic network.
- They could potentially be used to obscure the seismic signal from a small nuclear explosion that was detonated simultaneously nearby.
- It does not appear possible, using seismic signals alone, to tell the difference between a contained underground nuclear explosion and a contained underground chemical explosion of comparable yield in which all the explosive is detonated as a single charge.

Four different uses of chemical explosions

Mining

The principal user of chemical explosives is the mining industry, which uses blasting agents of many types and in large quantities to break rock. Many thousands of mining explosions are now carried out each year around the world that may be expected to result in detectable seismic signals at low magnitude levels. In the U S. and other countries employing modern mining practices, most mining explosions greater than a few tons of TNT equivalent are detonated in surface mines as a series of smaller charges, in a practice known as ripple-firing.[1]

Also, explosions used in underground mining are typically much smaller than explosions used in surface mining, in order to avoid danger to people and damage to underground equipment and structures. In modern mining practice, it is rare for chemical explosions, of a size comparable to the yield of even a small underground nuclear explosion, to be detonated as a single charge.

U.S. blasting practice. The U.S. uses more than two megatons of chemical explosives per year. Of this total, about 70% is used in the mining of coal; 8% in mining for metal ores; 10% in quarrying and nonmetal mining; and 7% for construction. On a typical work day in the U.S., for example, there are thought to be about 30 explosions greater than 50 tons, including one greater than 200 tons. Explosions bigger than a kiloton may occur a few times a year in the U.S.

Most industrial explosions are ripple-fired and shallow; this results in their seismic magnitudes being considerably lower than what it would be if the charge were detonated all at once and fully tamped. As a rough rule, the magnitude is determined by the amount of charge set off in one component blast, which for a large explosion will be on the order of 1% of the total. Since magnitude scales are logarithmic, the magnitude reduction in this case would be about two full units.

[1]For the typical large chemical explosion now carried out for commercial purposes, tens or even hundreds of holes are drilled and separately filled with an individual charge, each having its own detonator system. The detonators are then fired in a sequence of preplanned delays, in order to fragment the rock in a controlled fashion. The total time over which separate charges are detonated may be on the order of a second, for explosions totaling a few hundred tons of TNT equivalent. The extent to which this technique is employed worldwide is unknown.

In the U.S., there are on the order of a few explosions a week reported as being above local magnitude 3.5; however it is not reported if these explosions have magnitude greater than 3.5 on a teleseismic magnitude scale (which is based on seismic waves that propagate through the solid earth for distances more than 2000 km, and is the relevant scale for characterizing the seismic signals from a nuclear explosion). The reason for the difference between magnitude values is that magnitude scales were designed for earthquakes and not for characterizing the strength of the very different type of signal put out by a shallow ripple-fired explosion.[2]

The largest signals from mining blasts in the U.S. are associated with surface coal mines in the Appalachian Mountains and open-pit metal mines in the western states and the northern midwest. There are perhaps hundreds of ripple-fired explosions in the U.S. each week above local magnitude 2.5.

Blasting practice outside the U.S. We do not yet know the scale of problems presented by chemical explosions in other countries, but there are data to suggest that blasting practice may be different from the U.S. in some countries. Of particular concern here is the extent to which large, single explosive charges are used in mining,[3] since such blasts could be mistaken as possible nuclear explosions on seismic records, or used to obscure recordings of an underground nuclear test. We do have preliminary indications that mining blasts of any type are rarely large enough to be recorded teleseismically (i.e., in the way that underground nuclear explosions have typically been detected). Therefore, the detection and analysis of mining blast signals must be done principally using regional or close-in seismic data.

Other industrial explosions

Occasionally, hundreds of tons or even kilotons of chemical explosive are detonated all at once (or in a small number of separate charges) for a special construction project, or as part of a military program. An effect of this firing practice can be the generation of seismic signals much larger than is the case for ripple-fired explosions. Such single-fired explosions are usually carried out on or close to the earth's surface and leave surface evidence such as a crater or other ground disturbance (but without radioactivity). Some of these explosions have had teleseismic magnitude greater than 4, and have therefore been detected at numerous seismic stations. An issue of concern here, for CTBT verification, is whether a country might carry out a small fully contained underground nuclear explosion and then claim it was a chemical explosion.

Accidents

Every few years in this century, a substantial accidental chemical explosion has occurred—usually at the earth's surface but occasionally underground. Several of these accidents have had teleseismic magnitude greater than 4. Again, there may be the need in such cases to be assured the event was indeed an accident and not a cover for a CTBT violation.

Geophysical exploration

Underground chemical explosions are used routinely for purposes of geophysical investigation, generating seismic signals

[2]Research has suggested several methods for analyzing seismograms to identify such explosions as indeed being ripple-fired, but no full-scale evaluation of these methods has been carried out.

[3]Coyote blasting. A few decades ago it was common industrial mining and quarrying practice in the U.S. to drive a tunnel into rock, to fill it with chemical explosive, and to fire the whole charge at once. This practice, known as "coyote blasting," was known to produce strong seismic signals since the explosion is mostly contained, but it is a notoriously dangerous practice because of the possibilities for miscalculation. Too much charge and the explosion will blow rock fragments far and wide; too little and the rock does not fragment as desired. As drilling technology has improved, the practice of coyote blasting has become obsolete in the U.S.—but is that the case in other countries? Note that, to the extent that coyote blasting is still carried out, there is the potential benefit of using such events as calibration explosions.

that are interpreted to learn details of internal earth structure. However, such explosions are quite small (usually not more than a few tons, and rarely a few tens of tons). Sometimes, such explosions are carried out in the ocean and can be detected teleseismically as well as by strong hydroacoustic signals in the water.

Discussion

For decades, research in seismic methods of CTBT monitoring has emphasized detection of earthquake and explosion signals, and procedures for discriminating between these two types of seismic source. In recent years, researchers have tackled—with some success—the harder problem of identifying differences between ripple-fired explosions and single-fired explosions. The companion paper on mine monitoring (see page 66) is principally concerned with solving this latter problem, even in the case that a single-fired explosion is carried out at the same time and same general location as a large ripple-fired explosion. That paper considers the use of high-quality local recordings of the seismic signals, which would be obtained and made available to the International Data Center. But the problem of identifying by seismic means alone the differences between a single-fired chemical charge and a nuclear explosion of equivalent yield is harder still, and there are good grounds for believing it to be intractable, at least with signals recorded at distances more than about a kilometer from the source.

It follows that additional information may be needed when signals apparently from a single-fired explosion are received by the International Data Center and are large enough to be of concern and there are no other data that would rule out the possibility that the explosion was not a nuclear explosion.

Additional information may also be needed when primary and auxiliary seismic networks detect some type of explosion, but available data are inadequate to determine whether the explosion was ripple-fired or single-fired, and the event magnitude is high enough to be of concern.

Issues

Given that additional information will be necessary for certain types of observed explosions, to have confidence that the event was not nuclear we then ask: what types of information may be used to resolve such problem events, and what criteria may be appropriate to trigger efforts to obtain the information? Examples of measures that may be used to address these issues are described further in companion U.S. papers, such as the paper on Associated Measures (see page 56).

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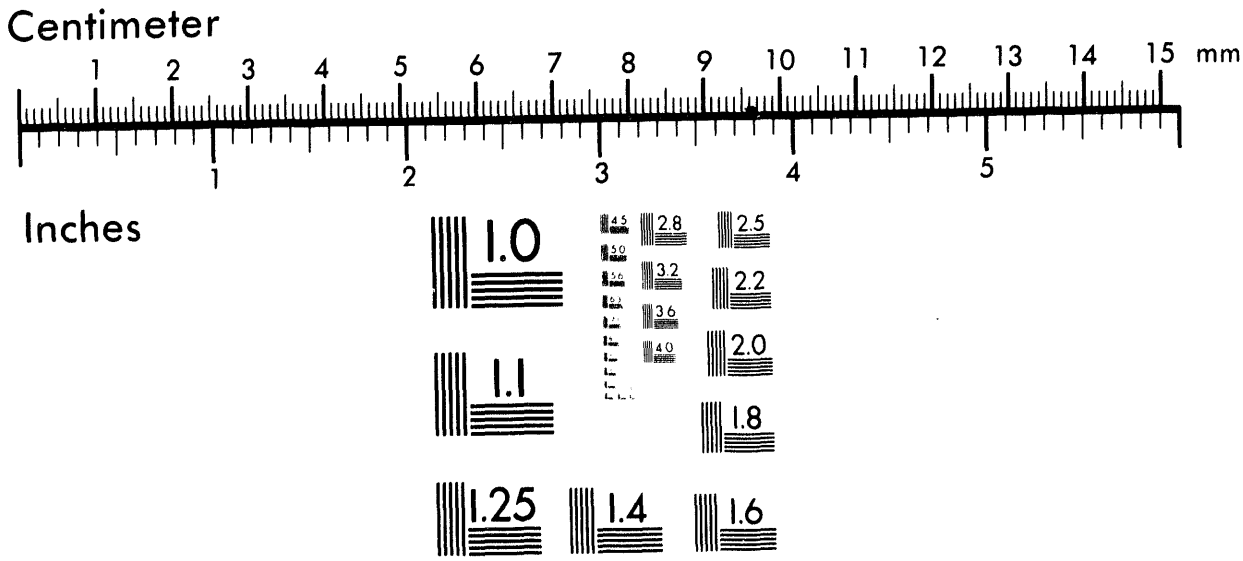

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