GLOBAL MONITORING OF THE EARTH, OCEAN AND ATMOSPHERE FOR THE CTBT

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Abstract

The Comprehensive Nuclear-Test-Ban Treaty (CTBT) provides for monitoring of the whole globe by a network of stations, using various technologies, in order to verify the absence of nuclear explosion tests. For this purpose, vibrational energy is monitored in earth, ocean and atmosphere, with nearly uniform global coverage. Of the 321 stations that comprise the full network of the CTBT, 241 stations monitor vibrations. The sensors used are seismometers (in the ground), hydrophones (in the water) and microbarometers (in the atmosphere) detecting seismic, hydroacoustic and infrasound energy respectively. This International Monitoring System (IMS) has been under construction since 1997 and currently is over 50% complete. This first ever fully global vibration monitoring system includes stations in very remote locations (such as Robinson Crusoe Island and the South Pole). Waveform data from these stations are transmitted continuously in real-time to the CTBT's International Data Centre in Vienna, Austria. There the data are analyzed to detect and locate impulsive events occurring anywhere in the world at any time. These events have many different causes in addition to nuclear explosions, such as earthquakes, volcanoes, meteors, whale vocalizations, mining explosions. The impulsive events detected by this global observatory are analyzed to ensure that a clandestine nuclear explosion does not go undetected.

Introduction

The Comprehensive Nuclear-Test-Ban Treaty (CTBT) was opened for signature in 1996 at the United Nations. The negotiations on a treaty banning nuclear testing had lasted almost four decades. The CTBT has a technical requirement to ensure verification that no nuclear explosion can take place without being detected.

In order to achieve this verification task, a number of capabilities are required. Firstly, data are collected from around the globe using technologies that have the potential to reveal the existence and/or location of a nuclear test. The system to collect this data is called the International Monitoring System (IMS) and is the focus of this paper. The collected data are sent to the International Data Centre (IDC), located in Vienna Austria, where scanning is performed to identify events that need to be more closely examined. Finally, there is a capability for performing an on-site inspection of a location at which a suspicious event has been identified.

The IMS uses four technologies for monitoring, three based on vibrations in the ground, water and atmosphere, while the fourth seeks to identify radioactive products from a nuclear explosion.

This paper addresses the three vibration based components of the IMS, providing a description of the monitoring system and giving status on its construction. The system described here is the first fully global network for monitoring vibrations.

CTBT

Early formal negotiations on a test ban treaty took place in 1958. Negotiations, with a major emphasis on technical issues associated with verification [1], lasted for decades. Finally, after conclusion of several limited test ban treaties, a fully comprehensive treaty, the CTBT [2], was opened for signature at the United Nations in New York in 1996. A Preparatory Commission was then established to facilitate entry into force of the Treaty. This Commission established [3] a Provisional Technical Secretariat to carry out the task of implementing the technical requirements of the Treaty. This Secretariat is based in Vienna, Austria.

The Treaty is open for signature and ratification by all States. As of 01 June 2004, the CTBT has been signed by 171 States and ratified by 113. To enter into force, the Treaty must be signed and ratified by 44 particular States, listed in the Treaty. So far, 32 of these states have ratified the Treaty. Updated status on signatures and ratifications can be found on the web site of the Preparatory Commission: www.ctbto.org.

In parallel with obtaining signatures and ratifications, establishment of the International Monitoring System is proceeding. The substantial completion of the IMS is a requirement for entry into force. The Treaty specifies the technologies to be used as well as the number and location of each type of monitoring station.

International Monitoring System

The International Monitoring System is based on four technologies: seismic, hydroacoustic, infrasonic and radionuclide. In simplest terms, the seismic technology uses seismometers to measure vibrations in the ground, the hydroacoustic technology uses hydrophones to measure vibrations in the ocean, the infrasonic technologies uses microbarometers to measure vibrations in the atmosphere, while the radionuclide technology uses gamma spectrometric analysis of collected particulate and noble-gas samples.

In an analogy, the vibration sensors detect, locate and characterize the sound of a gun, while the radionuclide sensors sniff the air for the smoke of the gun.

This unique global observatory is being constructed at a cost of many millions of dollars. Construction began in 1997 and is expected to be essentially complete by the end of 2007. Because establishment of this monitoring system was a new enterprise, given to a new organization, initially some time was spent establishing organizational and technical procedures, surveying the sites for station construction, gaining permission from the hosting State to build the station, etc. This, combined with the fact that there is a lengthy process to fully build a station, resulted in it taking a few years to achieve a high rate of station completion. The organization is now mature in station building and this work is proceeding smoothly and steadily.

For a station to fully contribute to CTBT verification it must be certified that it meets all of the technical specifications and operational requirement set by the Preparatory Commission. Thus station certification is an important milestone in the life of a station.

The monitoring process continues 24 hours a day, for every day of the year. Data are transmitted continuously to the IDC in Vienna, predominantly using satellite links directly from the station.

In order to have confidence in the data, it is necessary to be sure that the data have not been altered. To achieve this, authentication codes are applied to the data. A digital signature is applied that can confirm that there have been no changes to the data. Note that there is no encryption of the data, it is merely authenticated.

Seismic Monitoring

Introduction to Seismic Monitoring

Seismic monitoring [4] is primarily aimed at detecting underground nuclear explosions. This is the technology that was most debated since 1958 regarding the ability to achieve the required task. Technological developments over the intervening decades have been extensive, especially in respect of improved seismometers, digital processing techniques and the establishment of affordable high bandwidth communications.

Seismic stations use seismometers as sensors. A seismometer is a sensor which transforms transient ground motion into an electrical voltage as a function of time. Seismometers are typically based on a mechanical system where a mass is suspended stationary in space with the surrounding frame moving with the motion of the ground. The response is amplified and shaped by electronics within the seismometer.

Time series data from seismic stations can be used to locate and characterize the nature of a seismic source. This is the classical work of a seismologist. Experience has shown that these techniques can be applied directly to the determination of time, location and characterization of an event that may be a clandestine nuclear explosion.

Each type of natural event has its own characteristics. An earthquake can be described as a shear process, best modeled using dipoles. In contrast, an explosion has a point source origin and is best modeled using a monopole. These differences in source mechanism give rise to differences in the detected signals, which can be used to distinguish between the different sources.

On average, there are roughly 20 earthquakes per day of greater than magnitude 4, which is the size of earthquake that corresponds approximately to the seismic magnitude produced by an underground explosion of 1 kiloton in hard rock. It is empirically observed that for each reduction of 1 magnitude unit, there are roughly 10 times more earthquake events. Thus, if an underground nuclear explosion occurs, it will have to be identified from a quite large number of other events of similar size.

Types of Seismic Wave

There are several of types of seismic wave that can be detected from a single causative event.

There are two types of wave that propagate through the body of the earth: compressional waves have particle motion in the direction of propagation, while shear waves have particle motion perpendicular to the direction of propagation. These waves are referred to as P and S, respectively, by seismologists. The designation P and S comes from Primary and Secondary, referring to the order of arrived at a sensor (the P waves have a higher speed of travel).

Another type of commonly observed seismic wave is called a surface wave; it is characterized by propagation mainly along the Earth's free surface. Shallow (crustal) earthquakes generate larger surface waves, often resulting in surface waves dominating the seismic recording from such an event.

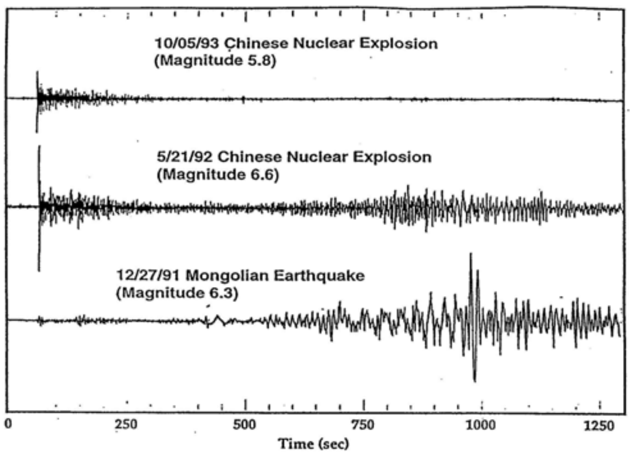


Figure 1. Seismic records from two nuclear explosions and an earthquake.

Figure 1 shows two examples of underground nuclear explosions and an earthquake that occurred in a nearby region, all recorded at a broad-band seismic station at

Obninsk, near Moscow in the Russian Federation. The magnitude of the body wave, m_b, is determined from the signals at the left of the figure and the magnitude of the surface wave, M_s from the signals at the right. The ratio of the body wave magnitude to the surface wave magnitude is one of the discriminants used to distinguish underground explosions from earthquakes.

Seismic Component of the IMS

The CTBT requires establishment and operation of two global seismic monitoring networks, distinguished by the mode of use, funding and specifications.

The primary seismic network will consist of 50 stations and forms the backbone of the seismic monitoring network. Many of the primary seismic stations have been used previously in other monitoring programs. These stations are being modified and upgraded to meet the CTBT standards. Data from the primary stations are sent continuously in real time to the IDC. These data are used for detection of seismic events, to form the initial parameters of the seismic event (location and origin time), and for event characterization.

The auxiliary seismic network consists of 120 stations. With a few exceptions, these are existing seismic stations belonging to national or international networks. The minimum requirements for auxiliary stations differ little from those for primary stations, except regarding data transmission and data availability. Auxiliary stations are not required to send data in real time, but instead data are retrieved on a query basis as deemed necessary by the IDC to supplement data from the primary network in order to refine the event location and characterization.

The seismic stations of the IMS have one of two basic configurations. One type has a single location of measurement, but uses seismometers to measure in all three Cartesian coordinates. This type of station is referred to as a 3-component station.

The other type uses a horizontal array of individual sensors (seismometers) in a geometric pattern with an aperture ranging from a few kilometers to several tens of kilometers. The number of array elements varies, but with a minimum number of nine. In these array stations, the arrival time differences of signals at the various elements can be used to reduce the signal to noise ratio and to calculate a direction to the source as well as an apparent wave speed across the array of sensors. This apparent wave speed helps in characterizing the nature of the signal being investigated.

The primary network of the IMS has 60% array stations, with the remainder being 3-component stations. In contrast, over 90% of the auxiliary network consists of 3-component stations.

Regardless of type of station or number of sensors, the frequency band covered by an IMS seismic station is from 0.02 to 16 Hz.

The geographical layout of both seismic networks is shown in Figures 2 and 3, also indicating the distribution between array and 3-component stations. Event location is determined by an inversion technique using the data from a minimum of three stations. Accuracy of location is important because the area of an on-site inspection is limited by the CTBT text to no larger than 1,000 km^2, equivalent to a circle with radius a little under 18 km.

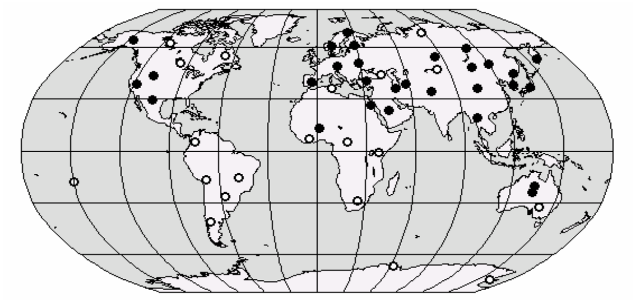
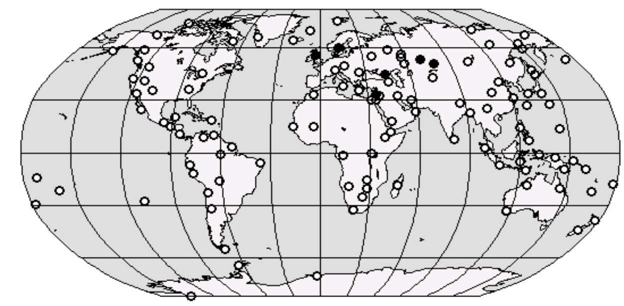


Figure 2. Primary seismic network of the IMS.
Filled dots are array stations.



Open dots are 3-component stations.

Figure 3. Auxiliary seismic network of the IMS.
Filled dots are array stations.
Open dots are 3-component stations.

Hydroacoustic Monitoring

Introduction to Hydroacoustic Monitoring

Hydroacoustic monitoring [5] is primarily aimed at detecting underwater nuclear explosions. During the treaty negotiations in the late 1950s it was assumed that monitoring the world's oceans would not be a problem because of the excellent acoustic propagation in the ocean (compared to the land situation).

Traditionally hydroacoustic stations use hydrophones as sensors. A hydrophone is a sensor which transforms pressure fluctuations in water into an electrical voltage as a function of time. Hydrophones typically use a piezoelectric ceramic, sized and shaped to provide the required frequency response. Frequently the hydrophone will have a preamplifier packaged with it.

Just as for the other wave technology stations of the IMS, time series data from hydroacoustic stations can be used to locate and characterize the nature of a source of hydroacoustic energy.

Types of Hydroacoustic Events

Each type of natural event has its own characteristics. It turns out there are many different sources of hydroacoustic energy that are picked up by the IMS hydroacoustic monitoring network. Sources of transient events includes: earthquakes, whale vocalizations, geophysical oil exploration and undersea volcanoes.

The generation of hydroacoustic signals by earthquakes is a somewhat complex process. First the earthquake generates seismic energy which propagates to the water mass of the ocean. On reaching the oceanic boundary (whether from the side or underneath) some energy is converted to horizontally propagating hydroacoustic energy. This energy is then transmitted with the usual hydroacoustic characteristics, including very low losses. T waves (or T-Phase) is the designation given by seismologists to these waves that (predominantly) travel through the ocean.

Hydroacoustic Propagation Effects

The ocean has a predominantly stratified structure, with only gradually changing sound speed in the horizontal direction. The combination of the depth variations of temperature and pressure gives rise to a waveguide effect. A minimum in the sound speed, at a depth of approximately 1 km, gives rise to a phenomenon known as the SOFAR channel which guides the acoustic energy away from the sea surface and the sea floor. The rate of physical absorption in the ocean is also very small. These two effects combine to provide very efficient propagation of hydroacoustic energy.

Hydroacoustic Component of the IMS

The hydroacoustic network will consist of 11 stations located to provide coverage of the broad ocean areas. The relatively low number of stations is made possible because of the extremely good propagation characteristics of hydroacoustic energy. Data from the hydroacoustic stations are sent continuously in real time to the IDC.

The hydroacoustic stations of the IMS are of two distinctly different types.

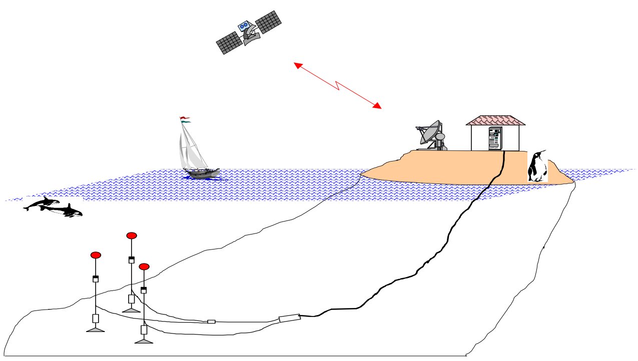


Figure 4. Cartoon of a hydrophone station showing one triplet of hydrophones, the shore facility and the satellite antenna.

The hydrophone based stations, of which there are six, use undersea trunk cables with three hydrophones at the end of each cable (see Figure 4.).

Cables and sensors are deployed on opposite sides of small islands in order to avoid bathymetric blockage by the island. The signals from the hydrophones are returned to the shore facility in digital form by the optical fibre cables.

The hydrophone sensors are placed at or near the axis of the SOFAR channel, supported by a float above and kept in place by an anchor below. The hydrophones are horizontally arranged in a triangular pattern, with separation of approximately 2 km. The frequency band of an IMS hydrophone station is from 1 to 100 Hz.

The other type of hydrophone station is known as a T-Phase station. There are 5 of these in the IMS hydroacoustic network. This type of station uses seismometers to detect seismic waves generated by the coupling of waterborne energy at the flanks of the island. The frequency band of an IMS T-Phase station is from 1 to 40 Hz.

The hydrophone based stations are very capable but also very expensive. In contrast, the T-Phase stations are less capable, but also are considerably cheaper to build and install.

The hydrophone network is capable of detecting very small explosions (down to just a few kilograms) right across the broad oceans. Also the hydroacoustic stations have great ability to distinguish explosions from other transient phenomena detected. This is facilitated by the extra information contained in the wider frequency band (compared to the other two waveform technologies). Further, explosions within the ocean cause a very characteristic bubble pulse, which enables not only identification as an explosion but also provides information on the size and depth of the explosion.

The IMS hydroacoustic network is described in more detail in a separate paper at this conference [6].

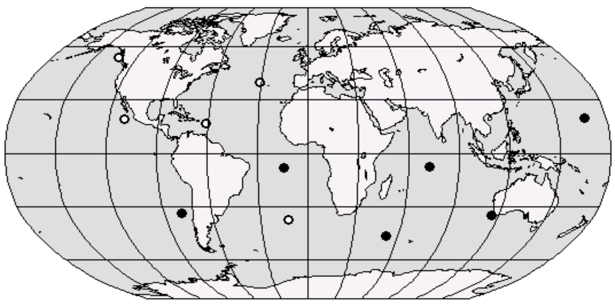


Figure 5. Hydroacoustic network of the IMS.
Filled dots are hydrophone stations.
Open dots are T-Phase stations.

Explosion Scenarios - Hydroacoustics

The IMS hydroacoustic network will very easily monitor explosions in the ocean. However, this network will also monitor explosions on small islands, as well as in the lower atmosphere over the oceans and even underground explosions provided they occur within a few hundred kilometres of the ocean boundary.

Infrasound Monitoring

Infrasound monitoring [7] is primarily aimed at detecting atmospheric nuclear explosions. This technology was widely used during the era of atmospheric nuclear testing almost 50 years ago. It fell into somewhat of a decline until it was revived by the introduction of the CTBT, which included infrasound monitoring as one of the means of verification. The modern infrasound stations now being built are, unsurprisingly, considerably more technologically advanced that the previous generation of stations.

A significant amount of effort has gone into refining the design of infrasound stations to meet the needs of the CTBT and to make maximum use of modern technology. The old infrasound networks were designed to detect large explosions at constrained locations, while the new network has to detect smaller explosions at any location.

Almost half of the energy released in a low altitude nuclear explosion is carried away in the shock wave. The longer period components of this wave evolve, with propagation distance, into infrasound. Infrasonic energy has a very small absorption rate, enabling nuclear explosions to be detected at ranges up to some thousands of kilometers.

Infrasound stations use microbarometers as sensors. A microbarometer is a sensor which transforms transient air pressure fluctuations into an electrical voltage as a function of time. The microbarometers are connected to a wind-noise-reducing pipe array, in order to achieve sufficiently good signal to noise ratio for the desired signals. These pipe arrays have multiple inlets for the air pressure fluctuations, which are summed by the mechanical design of the system at a single microbarometer. The long wavelength infrasound signals from distant events will be coherent over the pipe array, while the noise fluctuations will be incoherent. Hence there is improvement in signal to noise ratio.

Just as for the other wave technology stations of the IMS, time series data from infrasound stations can be used to locate and characterize the nature of an infrasonic source. Because of the lack of a large body of earlier work on this topic, and the large variety of different sources of infrasound, the use of infrasound signals to characterize event type is a field of work being actively pursued.

Types of Infrasound Events

Each type of natural infrasonic event has its own characteristics. It turns out there are many different sources of infrasound that are picked up by the IMS infrasound monitoring network. A list of sources of infrasound includes: volcanoes, space shuttle launches, elephants calling, mining explosions, icebergs calving, meteors, earthquakes, severe storms (especially over oceans), air flow over mountains, space debris re-entry and supersonic aircraft.

Without looking in detail at all of these sources, it is noted that ReVelle [8] estimates that around 12 bolides (meteors) with explosive energy of 1 kiloton or more enter the atmosphere each year.

Infrasound Propagation Effects

The atmosphere is a spatially inhomogeneous dynamic medium with properties that are constantly changing on a variety of time scales ranging from a few minutes to a few months. The accurate modelling of infrasound propagation is thus a difficult and challenging problem.

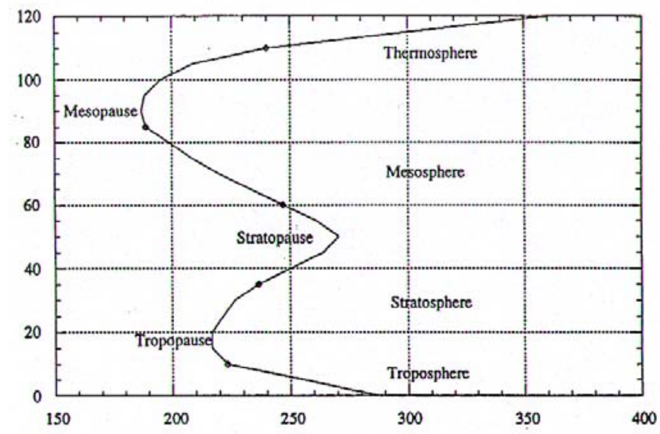


Figure 6. Sound Speed (abscissa in km/hr) versus height above sea level (ordinate in km)

Figure 6 shows a standard version of the sound speed profile. The profile given in the figure will in practice be complicated by the superimposed wind speeds, which are not negligible in comparison with the sound speed values. This gives rise to such effects as the propagation being very different into the wind, as compared to propagation with the wind direction.

Infrasound Component of the IMS

The infrasound network will consist of 60 stations located as uniformly as possible across the surface of the globe. All of these stations needed to be built from scratch, since there were no preexisting stations of the required capability. Data from the infrasound stations are sent continuously in real time to the IDC.

The infrasound stations of the IMS are all based on horizontal arrays of microbarometers, each of which has its own noise-reducing-pipe system. The frequency band of an IMS infrasound station is from 0.02 to 4 Hz.

The aperture of the sensor array is typically a couple of kilometers, using a minimum of 4 elements. Up to 8 elements are used to deal with noisy sites, with both number and spacing depending on the characteristics of the installation location.

As for arrays in the other technologies, the arrival time differences of signals at the various elements can be used to reduce the signal to noise ratio and to calculate a direction to the source as well as an apparent wave speed across the array of sensors. This apparent wave speed helps in characterizing the nature of the signal being investigated.

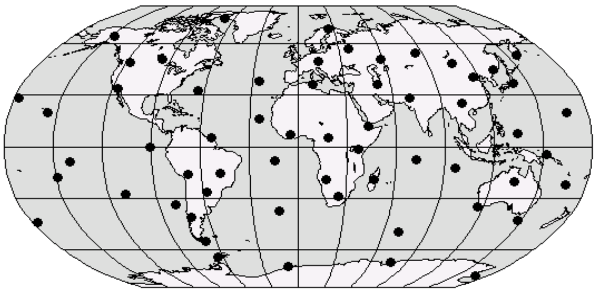


Figure 7. Geographical layout of the infrasound network of the IMS

Three Technologies Together

There is synergistic coverage of the globe by these three waveform monitoring technologies. Given that a major rationale for monitoring the CTBT is the deterrence effect on a would-be tester, the fact that each technology covers more than just its own environment makes clandestine cheating even more difficult.

The seismic network can be expected to detect nuclear explosions not just underground, but also in the ocean and in the lower atmosphere over the land masses.

The hydroacoustic network can be expected to detect nuclear explosions not just in the ocean, but also in underground locations within several hundred kilometres of the coastline, as well as in the lower atmosphere over the oceans.

The infrasound network can be expected to detect nuclear explosions not just in the atmosphere, but will also have some capability for underground explosions and underwater explosions.

In each case, the prime technology for an environment will work the best, but there is back up capability from the other technologies. It is not unusual for some natural events to be detected by all three technologies.

The timing of data arrival from an event depends on a combination of distance to a station and on wave speed. The wave speed through the interior of the earth is typically 8 km/s, through the ocean it is 1.5 km/s and through the atmosphere it is 0.3 km/s. Thus, in general the seismic data arrives first, followed by the hydroacoustic and then by the infrasound data. In fact, the automatic processing of data in the IDC first examines the combined seismic and hydroacoustic data and only at a later stage includes the infrasound data.

Remote Stations

IMS station locations were selected in order to achieve as uniform global coverage as possible. Considering the geography of the globe, with large oceans, deserts, and such like, it is a natural result that many stations are sited at remote locations. Obviously, these remote locations lead to many logistical difficulties in building and operating stations.

Some examples of locations of remote stations serve to illustrate this aspect of the network. The island of Tristan da Cunha (in the South Atlantic) hosts stations of three technologies. Tristan da Cunha has no airport and only one scheduled ship visit per year. The South Pole hosts an auxiliary seismic station. Robinson Crusoe Island, in the Juan Fernandez archipelago hosts two stations. This is the island on which a Scottish sailor was marooned in 1704, leading to the famous fictionalized account by Daniel Defoe.

Station Operation

The IMS network is gradually progressing from a stage of construction of the network to one of operation of the network.

This transition has to be accompanied by consideration of the logistical difficulties of maintaining and operating a network of 321 stations scattered around the globe. The challenges are increased by the mandated very high data availability requirements. A system of configuration management also needs to be developed to a mature stage, to enable these stringent demands to be met.

Interestingly, the Treaty has explicit text setting out that States own and operate those IMS stations located on their territory. However, the Treaty also give the Commission the role of funding the construction and operation of the stations, and with providing the overall supervising and coordinating role for station operation.

The large number of legacy stations in the seismic network means that there is quite a variety of different types of equipment in use in the network. This lack of uniformity also makes network management harder than it otherwise would be.

Yet another challenging issue for station operation is the far flung nature of the IMS network. Many stations are in very remote locations, the station operators speak a variety of native languages, and customs problems can also be very difficult to resolve in a timely manner.

Status

Roughly, the IMS network is about half complete.

In order to provide a more revealing statement about the current status, the establishment of each station may be broken into several components. Following a site survey, major activity commences consisting of site preparation, equipment manufacture and installation. The percentage of stations, in each technology, for which this work has been commenced is set out in Table 1. This Table also shows the percentage of stations that are complete to a stage where data streams are flowing to the CTBT Organization headquarters in Vienna. The final process in establishing a new station is the certification that the station meets the requirements of the CTBT (also provided in the Table). Table 1 percentages are given for the status at the beginning of 2004.

Table 1. Status of Waveform IMS Network

Technology	Started Work	Sending Data	Certified
Primary Seismic	78%	62%	50%
Hydroacoustic	91%	56%	44%
Infrasound	78%	38%	28%
Auxiliary Seismic	83%	48%	09%

With the progress achieved to date and expected funding over the next few years, it is likely that this network will be substantially complete by the end of 2007. Inevitably there will be some stations incomplete. We do not yet have the permission of the host State to build some of the stations specified in the Treaty. It is unlikely that the issues with all of these stations will be resolved quickly. Wisely, the IMS network was designed with a degree of redundancy built in. Thus there can be several stations not operating and the network will still perform its required function.

Performance

The data availability requirement for primary seismic, hydroacoustic and infrasound stations is 98% of total possible data received in Vienna. The timely data availability requirement, which refers to data received in Vienna within 5 minutes of arriving at the sensor, is 97% of total possible data received. Taking into account that the Treaty has not yet entered into force, in order to save costs there is dispensation to currently operate at somewhat lower levels.

The International Data Centre operational system processes data from well-behaved, stable stations. During 2003, there was on average 68 events per day listed by the IDC in the Reviewed Event Bulletin issued to State Parties.

Civil and Scientific Uses of IMS Data

The raw data sets from the IMS stations have the potential to be used in quite a number of civil and scientific applications. There have been a number of workshops devoted to the topic in the last several years.

Civil uses discussed include earthquake monitoring and response, earthquake hazard assessments, tsunami warning systems, volcanic ash warnings for aircraft, information collection after nuclear accidents (for example, tracking of dispersal of radioactive materials).

Scientific uses include basic research on the structure of the earth, earthquake processes, better delineation of the active tectonic features of a region, improved understanding of ocean processes (currents and temperature), monitoring of whale population and movement, ocean noise studies, infrasonic monitoring of many phenomena such as storm systems and city hum, better understanding of background radionuclide levels (especially at remote locations). Some of these scientific applications would also have civil implications in the future.

As always when a new instrument is first used, it is possibly the unexpected results that will be the most significant. It is noteworthy that the seismic stations that were installed for monitoring of partial test ban treaties played a large role in the development of the current understanding of plate tectonics.

However, at the present time there is not yet a unanimous view of the States Parties regarding the release of CTBT data.

Conclusion

The International Monitoring System for verifying compliance with the CTBT is a unique global observatory. The fully global geographical coverage provided for these three waveform technologies is far beyond anything previously available. As well, the data are collected continuously with a much higher data availability than normally available. These continuous data sets will be collected for years and will be stored indefinitely.

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