Seismological Methods of Monitoring Compliance with the Comprehensive Nuclear-Test-Ban Treaty

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1 Abstract

Seismology provides the key technology for monitoring the occurrence of underground nuclear explosions. A new International Monitoring System (IMS) which is being established under the provisions of the Comprehensive Nuclear-Test-Ban Treaty has begun its work in conjunction with a new International Data Centre in Vienna, and this work is likely to continue to develop even though prospects for entry-into-force of the treaty are unclear.

The technical work of treaty monitoring can be broken down into the separate steps of signal detection, signal association, event location, and discrimination. The new international treaty-monitoring network is likely to be reliable for detecting seismic events down to about magnitude 3.5 (corresponding to about 0.1 kiloton for most regions of the globe, for underground nuclear explosions conducted in the fashion typical of nuclear testing in the past), and significant IMS capability exists down to lower magnitudes. For the former nuclear test sites in China, Russia, and the U.S., monitoring capability is better by a factor of ten or more in terms of yield.

The effort to translate capability in terms of magnitude into statements about capability to monitor at different yield levels, is complicated by perceptions as to the plausibility of hypothesized evasion scenarios, in which seismic signals from an underground nuclear test would be diminished or masked by signals from other seismic activity. The most important proposed methods of treaty evasion have sometimes played a role in political debate, without being subjected to overall technical review.

Significant capabilities additional to the IMS are provided by numerous national and regional seismographic networks established for earthquakes studies. Such networks are becoming more widespread, routinely providing monitoring capability down to magnitude 3 for broad areas.

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2 Background

In September 1996, after almost forty years of negotiations marked by numerous setbacks, the text of the Comprehensive Nuclear-Test-Ban Treaty (CTBT) was at last agreed to and opened for signature at the United Nations. It was signed promptly by all five of the then declared nuclear weapons states — the U.S., the Russian Federation, China, the United Kingdom and France — and at the signing ceremony, President Clinton called this treaty "the longest sought, hardest fought, prize in nuclear arms control."

The basic obligations of the CTBT are stated in Article I of the treaty text as follows:

> 1. Each State Party undertakes not to carry out any nuclear weapon test explosion or any other nuclear explosion, and to prohibit and prevent any such nuclear explosion at any place under its jurisdiction or control.
>
> 2. Each State Party undertakes, furthermore, to refrain from causing, encouraging, or in any way participating in the carrying out of any nuclear weapon test explosion or any other nuclear explosion.

The CTBT is intended to prevent non-nuclear weapons states from proliferating nuclear weapons, and restrains nuclear weapons states from building weapons more sophisticated than those they now deploy. Though the term "nuclear explosion" is undefined, the CTBT is intended to be a zero yield treaty. As such, it presents the difficulty that any practical monitoring system based upon detection and identification of nuclear explosion signals can be expected to fail at some low level of yield. The question of whether the treaty is adequately verifiable or not, is therefore a political-military judgement in which the merits of banning *all* nuclear testing — which can be confidently monitored above some yield level — have to be weighed against the possibility that small unidentified tests might occur. The verification system must be designed so that tests at yields large enough to have military significance will be identified with high confidence. In this context, we know that crude fission devices of the types used as bombs on Hiroshima and Nagasaki in 1945, with yields around 15-20 kilotons, would be easily detected and identified today. Good verification capability can act as a deterrent to potential treaty violators, to the extent it becomes clear that violations would be detected and identified.

This arms control prize is not yet in hand, however, because although 160 nations have signed the CTBT as of November 2000, the treaty can enter into force only after being signed and ratified by 44 listed countries which operate nuclear power reactors. As of November 2000, 30 of the 44 listed countries had ratified and 41 had signed (the three exceptions being India, Pakistan, and North Korea). India and Pakistan declared their nuclear capability by a series of nuclear tests in May 1998. In October 1999, the U.S. Senate voted not to give its advice and consent to ratification. President Clinton and Presidential candidate Al Gore have stated strong support of the CTBT and expectation of its eventual ratification by the U.S. — which would require a new and favorable Senate vote. Presidential candidate George W. Bush has stated opposition to the CTBT, but support for a continued moratorium on US testing.

This record indicates that many political issues surrounding the CTBT are unresolved as of late-2000. Plans are nevertheless going ahead to establish the verification regime, in which seismology plays a key role. Global monitoring for nuclear explosions is still needed, whether or not the CTBT has entered into force.

This paper gives general background on test ban monitoring, describes relevant specialized aspects of seismology, and reviews the procedures being developed by the International Monitoring System (IMS) established by the treaty.

The most important technical issues in monitoring a CTBT all became apparent between 1958, when the so-called "Conference of Experts" was convened in Geneva to see if agreement could be reached on a verification system, and 1963, when the Limited Test Ban Treaty (LTBT, which banned testing in the atmosphere, the oceans, and outer space) was quickly negotiated, signed, and entered into force. In 1963 there was a perception, influential in some forums, that seismological methods for monitoring underground nuclear explosions were inadequate — a view that helped to prevent the conclusion of a CTBT in this early period (Richards and Zavales, 1996). The text of the CTBT approved by the United Nations in 1996 is about fifty times longer than the text of the LTBT of 1963, in large part because of the extensive provisions (in the 1996 CTBT) for verification. And the formal treatment of verification issues in the CTBT will continue to be developed and documented in extensive detail over the next few years. Much of this work will be specified in six different Operational Manuals, mentioned in the CTBT and its Protocol, that will spell out the technical and operational requirements for:

- Seismological Monitoring and the International Exchange of Seismological Data;
- Radionuclide Monitoring and the International Exchange of Radionuclide Data;
- Hydroacoustic Monitoring and the International Exchange of Hydroacoustic Data;
- Infrasound Monitoring and the International Exchange of Infrasound Data;
- the International Data Centre; and for
- On-Site Inspections.

The IMS seismographic stations send their data to an associated International Data Centre (IDC) for analysis and also, on request, for circulation to National Data Centres/Centers. The U.S. National Data Center is the U.S. Air Force Technical Applications Center.

The IMS can be expected to provide data adequate to monitor for underground explosions down to about magnitude 3.5. For explosions executed in the usual way in shield regions without making special efforts at concealment, this corresponds to a yield of around 0.1 kiloton. However, it is clear from the negotiating record that some countries desired a better monitoring capability. For example, the Geneva working paper CD/NTB/WP.53 of 18 May 1994 stated the U.S. position that: "The international monitoring system should be able to . . . 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." A few kilotons, evasively tested, could correspond in some cases to seismic signals of about magnitude 3. Assessments as to whether a given monitoring system is adequate for treaty verification, or not, will therefore in practice be driven by perceptions as to the plausibility of efforts at treaty evasion.

Up to 1963 when the LTBT was negotiated rather than a CTBT, very few underground nuclear tests had been carried out. Seismographic data then consisted of paper analog recordings from a few hundred stations around the world — data derived almost entirely from earthquakes and chemical explosions — and communications then relied upon standard postal services. But much practical experience in monitoring was acquired following the LTBT, because nuclear explosions were carried out underground at the rate of about one a week for almost thirty years. Yang *et al* (2001) list parameters of more than 2000 nuclear explosions conducted in different environments (atmosphere, space, underwater, underground) during the period 1945 – 1998. A small number (less than five) of these explosions were designed to evaluate certain evasion scenarios. At the beginning of a new millennium, seismology is improved in ways hardly imagined in the early 1960s. Thus, seismology today is based upon the operation of tens of thousands of stations, roughly half of them acquiring data that are recorded digitally so that the signals can easily be subjected to sophisticated processing. Such data in many countries are gathered electronically into nationally- and internationally-organized data centers, for purposes of scientific research and for the study of earthquake hazard and hazard mitigation, as well as for nuclear explosion monitoring. A growing trend since the mid-1980s has been the use of stations equipped with sensors that respond to a broad band of frequencies, with recording systems of high dynamic range so that both weak and strong signals are faithfully documented. Digital seismograms from such systems are now sent to centers from which data segments may be freely accessed by a wide range of users.

The seismic waves of principal interest in CTBT monitoring are the regional phases Pg, Pn, Sn, Lg, and Rg; the teleseismic phases P, pP, pS, S, sS, and sP (and sometimes PKP and $pPKP$); and Love and Rayleigh surface waves. The basic reason for the effectiveness of seismology as a monitoring technology is simply that the different types of seismic sources — earthquakes, explosions (both chemical and nuclear), volcanic eruptions, mine collapses — generate these seismic waves in distinctively different ways. It has therefore been possible to develop objective procedures to identify the nature of the seismic source. The fact that there are so many different types of seismic waves, each with its distinctive characteristics, is on the one hand a burden in explaining the details of monitoring to the many people interested in the subject for policy reasons but not having an interest in seismology *per se*, and on the other hand the essential key to the effectiveness of seismology as a monitoring tool. Having so many different types of seismic wave, each of which can vary strongly over the distance ranges for which it is observable, means that a great deal of information about the seismic source is potentially available.

An understanding of the terms "regional" and "teleseismic" is essential for an appreciation of the practical problems of CTBT monitoring — and of solutions to these problems. The underlying reason for such a grouping of seismic waves is a property of the Earth associated with a zone of lower velocities and/or lower velocity gradient in the upper mantle, beneath which is a region of higher velocity and/or higher gradients at greater depths. The net effect is that the simplest and most important seismic wave — the first-arriving compressional wave (P) traveling downward from the source into the mantle and then back upward — is defocussed and thus has low amplitudes at distances within the range about 1000 to 2000 km from a seismic source. Figure **??** shows schematically the way in which the amplitude of seismic P-waves at first decreases and then increases as waves propagate to greater distances. Waves beyond about 2000 km are teleseismic, and P-waves throughout most of this range are simple, having very little change in amplitude with distance out to more than 9000 km.

The compressional waves known as Pg and Pn, traveling within the crust or just beneath it, are regional in the sense that they do not propagate to teleseismic distances. But the word "regional" here carries the additional implication that such waves are dependent on local properties of the Earth's crust and uppermost mantle — which can vary quite strongly from one region to another. Regional waves can have large amplitudes (and can thus be easily detected if a seismometer is operated at a regional distance from a source of interest), but they are complex and thus harder to interpret than teleseismic waves. Shear-wave energy can propagate even more efficiently than compressional energy to regional distances. In particular, the largest wave on a seismogram at distances up to 2000 km from a shallow source is usually the Lg wave, which consists of shear waves traveling so slowly that they are trapped by total internal reflections within the low-speed crustal wave guide — similar to the physics by which light can travel to great distances within a low-speed optical fiber. An extensive dataset of seismic signals from a given region must first be acquired and understood before the regional waves from a new event can be interpreted with confidence. (Sometimes, however, the data from a second, more easily accessed region, can be used to aid in the interpretation, if the two regions are known to be geologically similar.)

The key methods of event identification, all discovered too late to have any impact in the early period of CTBT negotiations (1958 – 1963), entail comparison of the amplitude of different seismic waves. For example, slow-traveling surface waves (Rayleigh, Love), with wavelength several tens of km long, are generated much more efficiently by shallow earthquakes than by explosions. This result was obtained in academic research in the 1960s (e.g., Brune *et al* , 1963; Liebermann *et al* , 1996), became thoroughly documented over the subsequent years (e.g., Lambert and Alexander, 1971), and proved during the era of underground nuclear testing to be a reliable method for discrimination using teleseismic signals for sources down to magnitudes in the range 4 to 4.5 (Sykes *et al* , 1983). Over the last 15 years there has been growing recognition that regional P-waves (such as Pg and Pn) are often generated much more efficiently by explosions than by earthquakes, in comparison to the excitation of regional S-waves (such as Sn and Lg). If signals can be recorded with high enough quality, then the comparison between regional P and Lg often enables discrimination between earthquakes and explosions to be done at low magnitudes — even lower than magnitude 3 (Hartse *et al* , 1997; Kim *et al* , 1997).

3 General aspects of CTBT monitoring

This section presents two general points, (1) and (2), and then in (3) describes treaty language on verification and the practical steps such work entails.

(1) An underlying difficulty in treaty monitoring is making the trade-off between simple methods of analysis that are robust, objective, unchanging, and easily explained to people who lack technical training; and those more sophisticated methods which, to a highly-trained audience, are demonstrably more effective but that require a greater degree of expert judge-

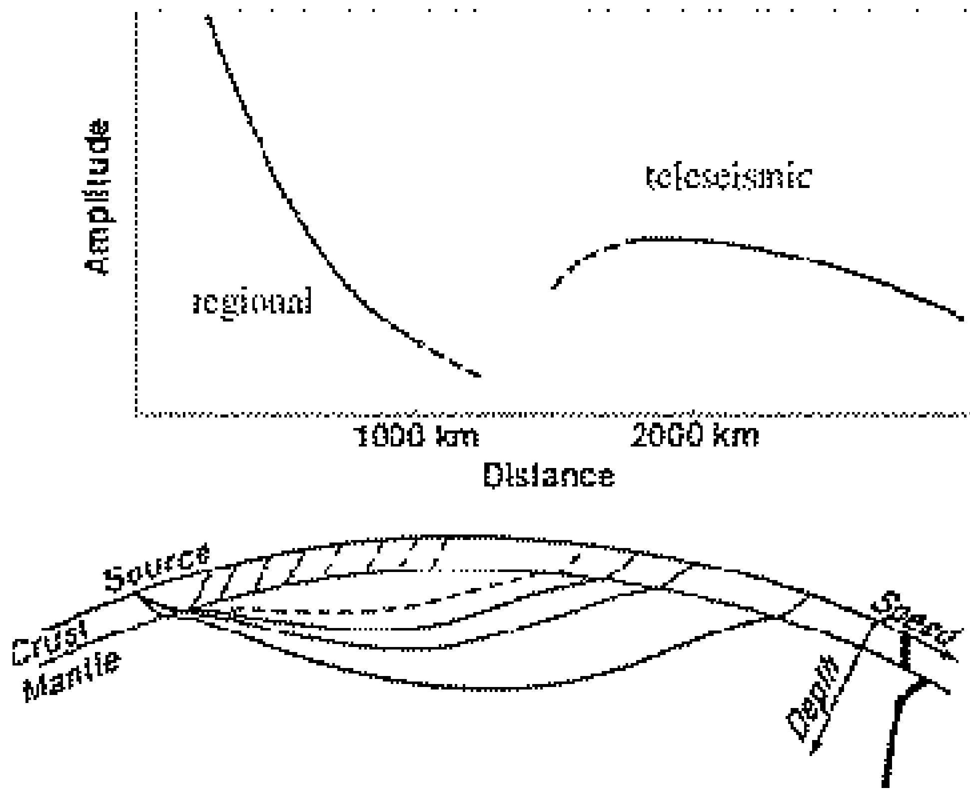


Figure 1: This is a generic illustration of the main differences between regional and teleseismic waves. Seismic wave amplitudes at regional distances are strong near the source, for waves such as *Pg* (propagating within the crust) and *Pn* (propagating mostly just below the crust/mantle interface), but they decrease and can disappear at about 1000 km. Amplitudes increase at around 1700–1800 km, due to the arrival at these distances of the teleseismic *P*-wave, which has traveled deeply into the mantle and is less affected by shallow structure. The teleseismic *P*-wave varies very little in amplitude out to much greater distances. The reason for the different behaviors of regional and teleseismic waves is the variation in seismic wave speed with depth in the Earth (heavy line, bottom right). The *P*-wave speed in average Earth models typically increases from about 5.8 km/s at the top of the crust to about 6.5 km/s at the bottom, jumping up to a little more than 8 km/s at the top of the mantle, beneath which there is often a layer of lower velocities and then at greater depths an increase in velocity with depth. The layer of lower velocities in the upper mantle causes *P*-wave amplitudes to be low in a range of distances around 1200–1300 km. The lower section of the Figure shows ray paths in the crust and upper mantle. For decades following the LTBT of 1963, when nuclear testing was carried out underground and in-country monitoring was not permitted, monitoring was conducted by National Technical Means (NTM) using teleseismic signals. With the CTBT and the permitted use of in-country stations, attention returns to the study of regional waves since they provide the strongest signals. Regional waves may be the *only* detectable seismic signals, from small magnitude sources. [Figure adapted from Romney, 1960.]

ment and which will surely change from year to year as methodologies improve. The very existence of so much practical and specialized experience (coming from the decades of monitoring nuclear weapons tests), and of so many seismological resources generating potentially useful data, fundamentally enhances CTBT monitoring capability.

(2) The CTBT will, in practice, be the subject of three types of monitoring, namely:

- that carried out directly by the IDC using data contributed by the IMS;
- that carried out by National Technical Means (NTM), i.e. the procedures established unilaterally by various countries using any available information, and all having rights (per CTBT Article IV, ¶34 & ¶37) to use objective information from NTM as a basis for requesting an on-site inspection; and
- that carried out by numerous private or national organizations, each acquiring and/or analyzing data of some relevance to CTBT monitoring.

The third of these types of monitoring, associated with what the CTBT (Article IV, ¶27 & ¶28) calls supplementary data, is more nebulous than the other two types, but can nevertheless be important, for example in confidence-building measures and as a source of much basic information and many skills needed by the IMS and IDC. Vast regions of North America, Europe, the Western Pacific, and parts of Central Asia, Northern and Southern Africa and the Middle East are now being monitored closely for earthquake activity down to magnitude 3 or lower, by organizations whose data and methods of analysis are freely available. It is from this type of earthquake monitoring, and from field programs to study the structure of the crust and uppermost mantle, that the broad seismological community has acquired its knowledge of regional wave propagation; and familiarity too with the differences between seismic signals from earthquakes and from blasting associated with the mining, quarrying, and construction industries. Seismology is still a growing science, likely to be driven indefinitely by the need to understand and mitigate earthquake hazards. Individual earthquakes can still kill many thousands of people, and they are one of the few catastrophic phenomena capable of matching the trillion dollar levels of damage a single nuclear weapon can inflict. It can hardly be emphasized too much, that explosion monitoring for the CTBT will be greatly improved in the long term by cross-fertilization between the earthquake monitoring and explosion monitoring communities.

(3) The main part of the CTBT dealing with verification is Article IV, of which ¶1, in its entirety, reads as follows:

> In order to verify compliance with this Treaty, a verification regime shall be established consisting of the following elements:
> (a) An International Monitoring System;
> (b) Consultation and clarification;
> (c) On-site inspections; and
> (d) Confidence-building measures.
> At entry into force of this Treaty, the verification regime shall be capable of meeting the verification requirements of this Treaty.

Then follow 67 more paragraphs with details on verification. The treaty Protocol further spells out details of the IMS and IDC functions, procedures for on-site inspections, and in an Annex lists the location of 321 IMS stations that are to acquire seismic, radionuclide, hydroacoustic and infrasound data in support of the treaty.

The work of monitoring for underground nuclear explosions using seismological methods entails the separate steps of:

- detecting seismic signal;
- associating into a single group the various seismic signals that are generated from a common seismic source;
- estimating the location of that source, and the uncertainty in the location; and
- identifying the seismic source (whether earthquake or explosion), together with estimating the source size. The role of the IMS, vis-à-vis identification, is that of "Assisting individual States Parties . . . with expert technical advice . . . in order to help the State Party concerned to identify the source of specific events." (CTBT Protocol, Part I, ¶20(c).) The responsibility of identification is left to each State Party, but the IDC assists by carrying out a process called event screening, described further, below.
- Seismology also plays a role in on-site inspections and in confidence-building measures.

It follows that much work of the IMS and IDC focusses on the development of routine procedures for data acquisition and data analysis of all detected events. But historically it is known that monitoring for nuclear explosions results in the need, in practice, to pay special attention to what are called "problem events," which by definition are events that are detected but that cannot be unambiguously identified routinely as not being nuclear explosions. Such problem events can become targeted for special efforts in the acquisition of additional data, and for the execution of additional data analysis. Care will be needed in spelling out appropriate procedures for addressing problem events, since, by their very nature, singling out a detected event as a problem (requiring more than merely routine analysis) entails a preliminary effort to identify the event — which is not an IMS function. Instead, the IMS can carry out event screening, entailing the use of standard procedures to measure agreed-upon parameters that are helpful for characterizing whether an event is a nuclear explosion, or a chemical explosion or an earthquake. Different countries will likely reach different conclusions on how to treat a problem event, given the territory on which the event appears to be located, and given the possible predisposition of one or more State Parties to believe that serious efforts might somewhere, someday, be taken to conceal a small nuclear explosion. For example, much has been written on the possibility (or impossibility) of masking a nuclear explosion with a large chemical explosion, and/or reducing its seismic signals by carrying out the nuclear explosion secretly in a large underground cavity that has been sealed to prevent the escape of radionuclides. We may note Article II ¶51 of the CTBT, which states (with reference to the Technical Secretariat) that "The Director-General may, as appropriate, after consultation with the Executive Council, establish temporary working groups of scientific experts to provide recommendations on specific issues." However, if problem events arise with great frequency, an advisory group convened to deal with them could be overwhelmed. Only time will tell how much of the work of attempting to identify problem events will be done by the IMS and the IDC, and how much will be done by States Parties, which can receive IMS data at their National Data Centres (NDCs) as well as having access to their own National Technical Means.

With the above items (1) – (3) as background, let us now turn to brief reviews of the specific steps that must be taken in CTBT monitoring by seismological methods.

4 Technical issues arising in routine monitoring

4.1 Detection of seismic signals

The CTBT Protocol lists 50 sites around the world at which either a three-component seismographic station or an array of seismometers is to be operated, sending uninterrupted data to the International Data Centre (IDC). It is generally understood that this is a digital datastream, available at the IDC in near real time. These 50 stations constitute the primary network, deployed at sites indicated in Figure **??**. Much experience is now available from a network of similar size, operated since 1995 January 1, initially as part of the Group of Scientific Experts Technical Test #3 (GSETT-3, carried out under the auspices of the Geneva-based Conference on Disarmament which negotiated the text of the CTBT), and later under the Comprehensive Test Ban Treaty Organization, headquartered in Vienna. The GSETT-3 IDC, based near Washington, DC, became the Prototype IDC (PIDC) shortly after the CTBT was opened for signature in 1996, and served for five years as the testbed for many procedures that were taken up by the Vienna-based IDC in February 2000.

For seismic sources whose signals are detected by the primary network, and for which the location estimate and other attributes of the source are likely to be better quantified if additional signals are acquired, the CTBT Protocol lists an additional 120 sites around the world at which either a three-component seismographic station or an array is to be operated. These stations, constituting the auxiliary network with locations shown in Figure **??**, are to operate continuously; but their data is to be sent to the IDC only for time segments that are requested by a message from the IDC. Much experience with such an auxiliary network, of somewhat smaller size, has now been acquired during GSETT-3 and later by the PIDC.

More than half of the 50 primary stations, and some of the 120 auxiliary stations, are listed in the CTBT as operating an array. A seismographic array consists of a number of separate sensors, typically between about 10 and 30 with short-period response, spaced over a few square km or in some cases over tens of square km, and operated locally with a central recording system (see the previous article in this Handbook by Alan Douglas). Array data can be processed by introducing a system of signal delays at each sensor and then signal summation, to improve the strength of coherent signals and to reduce the incoherent noise. The resulting improvement in signal-to-noise ratio enables a single array to detect teleseismic signals approximately down to m_b 4 to 4.5 (Jost *et al* , 1996), and significantly lower in the case of some well sited arrays. From the detection of slight differences in the arrival time of a particular seismic wave at the different sensors, it is possible to infer both the azimuth

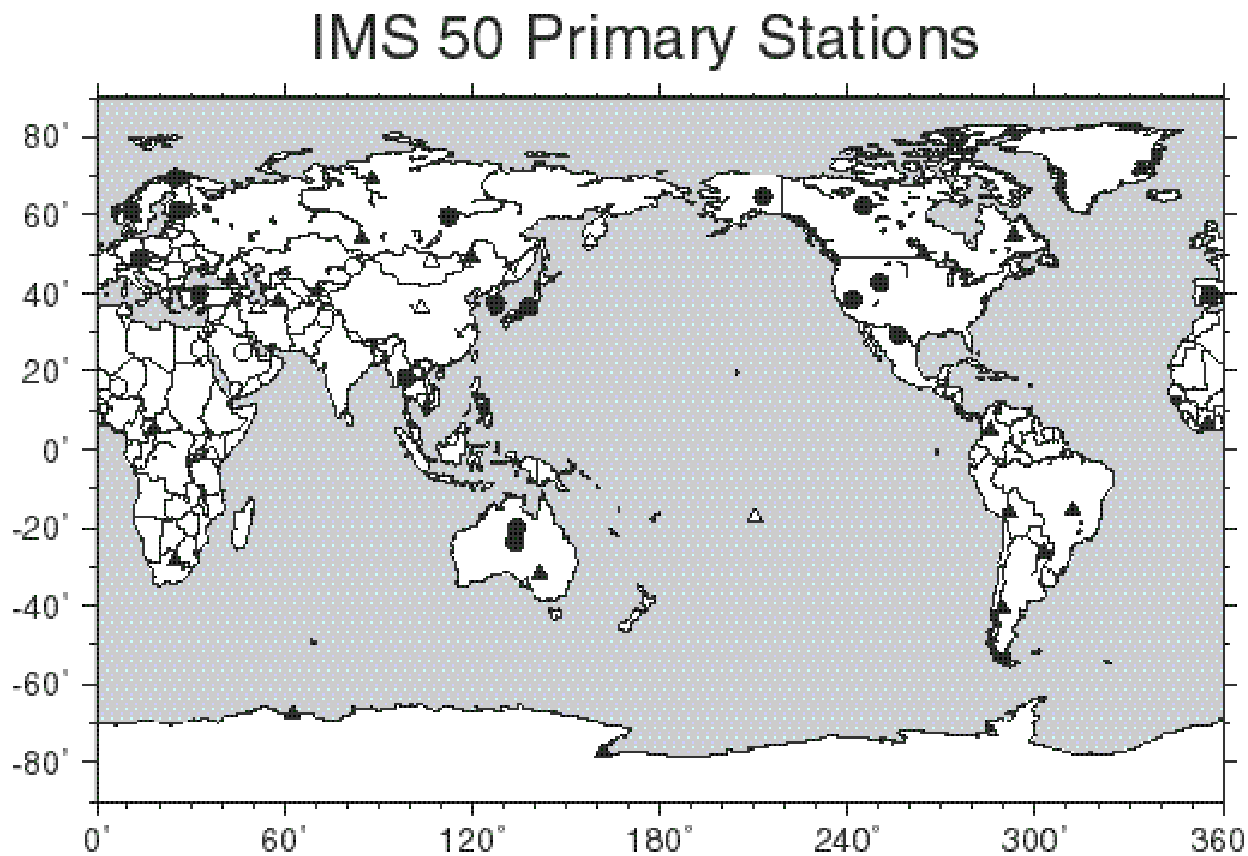


Figure 2: Map showing the location of IMS primary seismographic stations (circles and triangles). All these stations are to include at least one three-component broadband instrument. Filled symbols, are for stations contributing data in near real time as of July 2000; open symbols, are for proposed stations. Triangles, indicate stations that operate only a three-component sensor; circles, indicate stations that also operate arrays of short-period vertical sensors. 49 primary stations are shown; the location of one more station is to be decided.

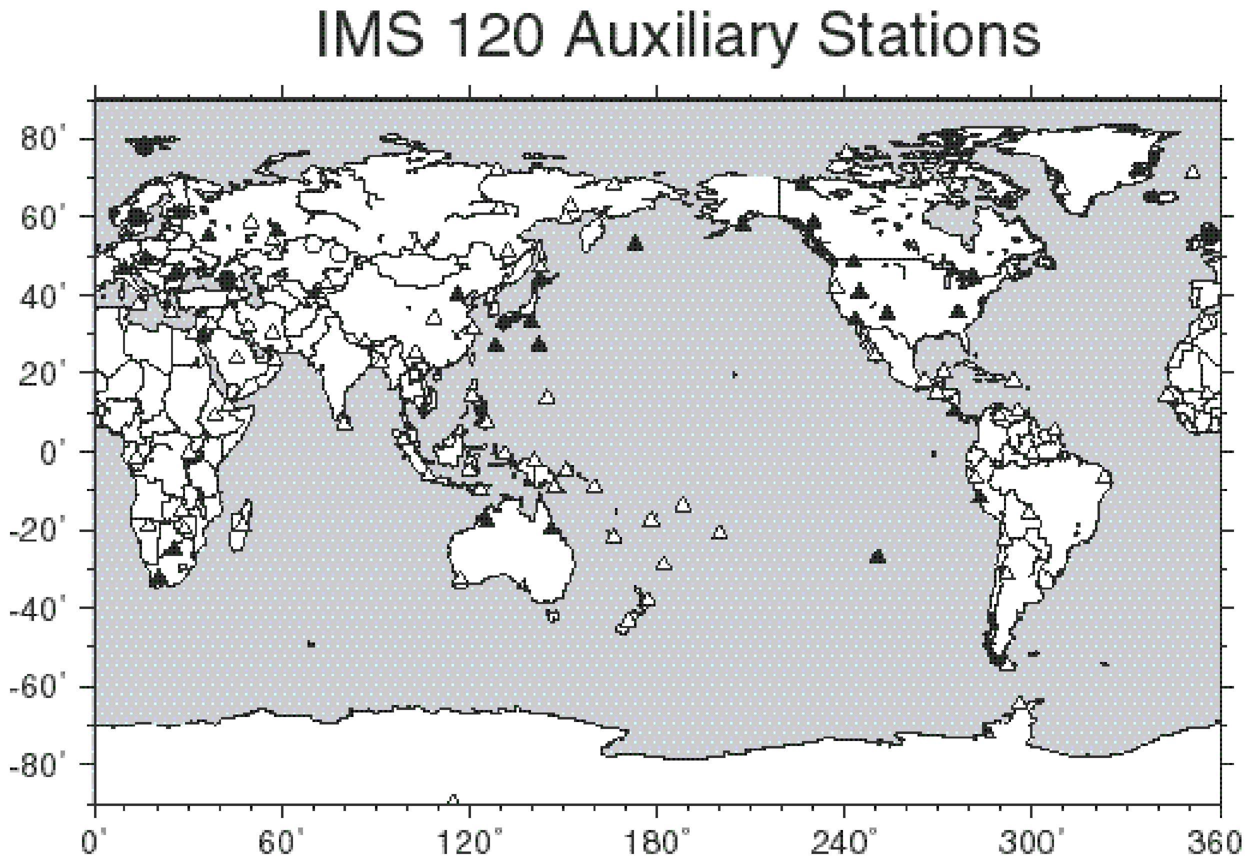


Figure 3: Map showing the location of 119 IMS auxiliary seismographic stations, which contribute their data on request to the International Data Centre; the location of one more station is to be decided. Symbols, are as in Figure 2.

and the horizontal slowness of the arriving signal. IMS array stations also have at least one three-component broadband sensor.

What then is the expected detection threshold of the CTBT primary seismographic network? (Note, the auxiliary network does not contribute to the IMS detection capability.)

For detection of enough signals to provide some type of location estimate, GSETT-3 was planned (CD/1254) to have a threshold detection capability in the magnitude range below 3 for large parts of Eurasia and North America. (It was above magnitude 3.4 in some continental areas of the southern hemisphere, and above magnitude 3.8 in parts of the southern oceans.) The design capability of the CTBT primary network has not been specified. In practice, however, the CTBT 50-station primary network appears capable of providing detection at 3 or more stations for at least 90% of events with $m_b \geq 3.5$, for almost all of Eurasia, North America, and North Africa. In certain areas, which include the former test sites in Nevada for the U.S. and in Novaya Zemlya for the Russian Federation, the IMS seismographic network is essentially complete, and detection capability is typically below magnitude 2.5. The IMS station nearest to the Chinese former test site at Lop Nor is an array at Makanchi, Kazakhstan, which began operations in mid-2000 and which can be expected to provide detections down to low magnitudes for Western China.

From January 1995 to February 2000 when operations transferred to Vienna, the stations operating under the auspices of the CTBTO grew from about one-half up to two-thirds of the intended 50-station IMS primary network, and reached about one-half of the intended 120-station IMS auxiliary network. During this five-year time period, the PIDC made available (at http://www.pidc.org) a number of reports of global seismicity derived from the primary and auxiliary networks. The most important report is the daily Reviewed Event Bulletin (REB), typically published three to five days in arrears, listing the events that have occurred that day, including location estimates, magnitudes, a map of the reporting stations for each event, and arrival times of detected phases at these stations. About fifty events have been reported each day on average, with some wide variations, for a total of about 100,000 events included in the REB over its first five years. The production of reviewed bulletins has to be done for all four monitoring technologies used by the IMS (seismology, hydroacoustics, infrasound, radio nuclide monitoring), but for the foreseeable future the most highly developed and most important of these technologies is seismology, and almost all of the events reported each day by the IDC are earthquakes and mining blasts.

The transfer of IDC operations to Vienna in February 2000 has been associated with a significant change in practice, namely that the daily Reviewed Event Bulletin and the seismographic and other data upon which it is based, are no longer, as of mid-2000, being made openly available to the research community — as had been the case during operations under GSETT-3 and by the PIDC. The IDC makes the REB and all IMS data available to National Data Centres, but data can then be subject to Article II, ¶7: "Each State Party shall treat as confidential and afford special handling to information and data that it receives in confidence from the Organization in connection with the implementation of this Treaty." Many voices have been raised in support of a return to open availability of IMS data and IDC data products such as the REB, for example on grounds that the CTBT itself states in Article IV, ¶10, that "The provisions of this Treaty shall not be interpreted as restricting the international exchange of data for scientific purposes." The quality of IDC operations and products will be greatly enhanced in the long term by having a diverse community of data users. Such users find problems with station calibration, occasional mistakes in the REB and other data products, and continually provide suggestions for improvement — in this way promoting a higher level of monitoring operations at the IDC. Many States Parties, including the U.S., have indicated their position that all IMS data should be made openly available without delay.

In subsections that follow, further detail is given on the work of seismic signal association, on making seismic location estimates, and on seismic event screening, as carried out by the International Data Centre.

4.2 Association of signals

Each year, somewhat more than 7000 earthquakes occur with magnitude $m_b \geq 4$; and about 60,000 earthquakes occur with $m_b \geq 3$. While chemical explosions with $m_b \geq 4$ are rare (a few per year, if any), there are probably on the order of a few hundred worldwide at the $m_b \geq 3$ level, and many thousands per year at smaller magnitudes that are detectable at stations close enough. The problem then arises, of sorting through the tens of thousands of signals each day that will be detected at a large data center from analysis of array data and three-component station data; and collecting together all the signals that are associated with the same seismic source. This has been a major computational problem of the GSETT-3 IDC, since seismic sources with $m_b > 4$ typically generate more than one detection at many IMS stations (for example, detection of P, pP, PKP, S, SS, Love and Rayleigh waves), and the detections from different events can overlap in time at each station. Effective methods of sorting through the interspersed detections have been found, but in practice 40% or more of the detections recorded on a given day remain unassociated. In the work of assembling sets of detections common to the same event, array stations in principle have the advantage, over three-component stations, of permitting determination of the direction of the source from a station at which there is a detection. An array can even indicate two or more different source directions from which signals arrive at the array at about the same time. However, in practice, automated determinations of the azimuth of signal arrival can often be inaccurate. While the azimuth estimate may be useful for association purposes, it is typically not used in event location.

4.3 Location of seismic sources

The CTBT Protocol, Part II, ¶3, states that

> The area of an on-site inspection shall be continuous and its size shall not exceed 1000 square kilometers. There shall be no linear dimension greater than 50 kilometers in any direction.

This condition presents a challenge for those at the IDC, who may have to estimate the location of an event that could become the basis of an on-site inspection request. The challenge is especially difficult for small events, when the estimate may have to be based upon regional seismic waves alone.

Note that accurate location estimates are needed not only for events destined to be considered for on-site inspection. They are needed for essentially *all* the events for which a set of detections can be associated, since in practice an interpretation of the location (including the event depth) is commonly used for screening at the IDC, and perhaps for rapid identification by NDCs. It can be crucial to know if an event is beneath the ocean, or possibly on land; if it is more than 10 km deep, or possibly near the surface; if it is in one country, or another. One of the first statements of failure to meet these technical challenges was given by North (1996), reporting on GSETT-3 after about twenty months of REB publication:

> “many of the events listed in the (REB) are poorly located. The 90% confidence ellipses exceed 1000 sq. km for 70%, and 10000 sq. km for 30%, of all REB events. Furthermore, comparison by various countries of the locations produced by their own denser national networks with those in the REBs show that the REB 90% confidence ellipses contain the national network location less than half of the time .... One feature ... that is particularly troublesome is that

> many events will be recorded only at teleseismic distances, and that few will be recorded only to regional (< 2000 km) distances. Thus an appropriate means of implementing path-dependent teleseismic travel times, and of transitioning from these to regional travel time curves, will need to be developed."

After more than five years of REB publication, the same problems were still to be found: purported 90% error ellipses were often much larger than 1000 sq. km, they did not include true locations 90% of the time, and depth uncertainties did not adequately represent errors in depth.

It is important to understand why REB location estimates using conventional methods have been so poor, since the error in measuring the arrival time of seismic waves is usually less than one second (and is usually less than 0.1 second when signal-to-noise ratios are good); and the speed of seismic waves is less than 10 km/s in the Earth's outer layers where the events of interest occur and where the measurements are made. It would therefore appear that seismic sources can routinely be located to within a few km, and an areal uncertainty much less than 100 km^2. In principle this conclusion is valid, nevertheless it does not apply using conventional methods of event location, because these are not based upon a sufficiently good model of the Earth's velocity structure. It is the model errors, not the pick errors, which as of this date (mid-2000) dominate the resulting location errors, at least for events larger than about m_b 4. (For smaller events, the pick errors can be comparable to model errors.) The overall goal of improving locations for events larger than m_b 4 based on seismic arrival times can be achieved only by reducing the effect of model errors.

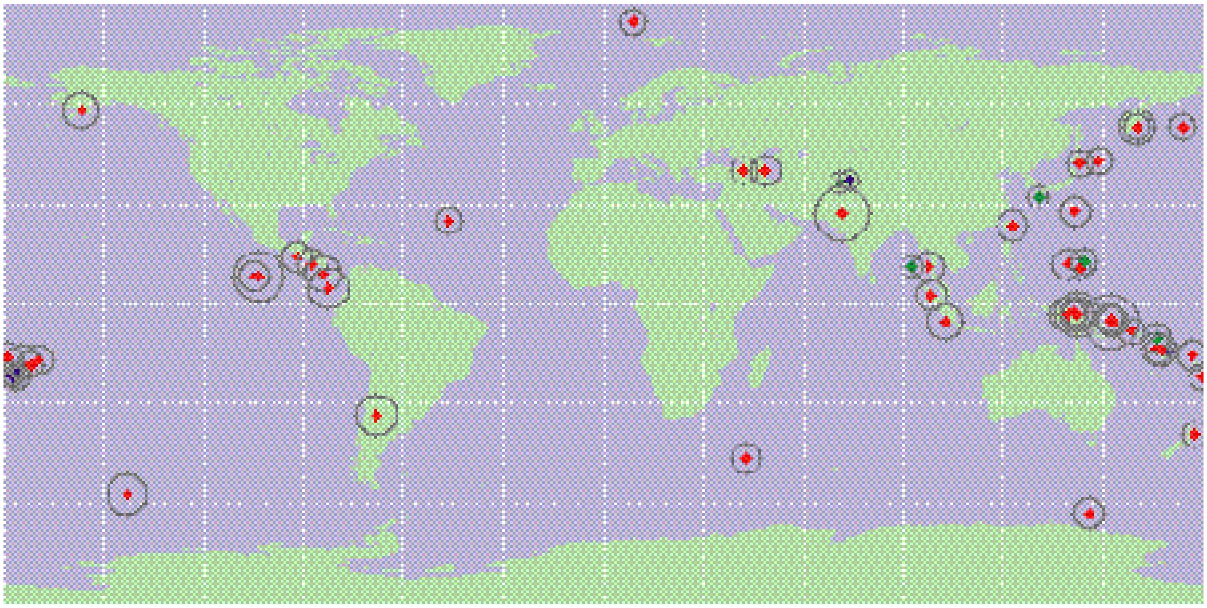
At depths greater than about 200 km, the Earth's velocity structure is known quite accurately (i.e. to well within 1% at most depths, the biggest exceptions being in regions of subducting lithospheric plates, and at certain places just above the core-mantle boundary). The main difficulty is at shallower depths, i.e. within the crust and uppermost mantle, where the actual speed of seismic waves may differ in unknown ways, sometimes by as much as 10%, from the velocity that we often assume (such as that given by *iasp*91 or some other standard Earth model). The actual Earth also has non-horizontal interfaces, which are not allowed for in simple Earth models, and which can affect the azimuth of an arriving signal. In summary, the measured arrival times and directions of teleseismic waves are influenced in unpredictable ways by unknown Earth structure. But the arrival times and directions of regional waves, which depend much more strongly on shallow structure, can be even more variable than teleseismic waves. For example if a seismic event is actually 1000 km from an IMS station and generates a regional wave that is detected at the station, and if the arrival is interpreted with a speed that is wrong by 5%, then the event will be estimated from that observation alone as having originated at a distance that is incorrect by about 50 km.

When estimating event locations and their uncertainty, there are essentially only three ways to get around the practical problem of ignorance of Earth structure (i.e., model error):
(a) by using numerous stations at different azimuths around the source and thus averaging out the effects of the difference between the Earth's actual velocity structure and that of the model (which traditionally has been taken as a 1D distribution in which velocity depends on depth alone);
(b) by building up information about the Earth's velocity structure and thus finding a more

sophisticated and significantly more accurate 3D model with which to interpret arrival times; and
(c) by "calibrating" the station (or array), so that in effect the source of interest is located with reference to another event, whose location is known accurately, and which preferably is not far from the source of interest. In this latter approach, the data for the unknown event is the difference in arrival times for the two events, as recorded at each station. From such data, we can often estimate accurately the difference in location between the known and unknown locations, and hence estimate the unknown location. Equivalently for enough calibration events, and using appropriate methods of smoothing, one can use empirically determined travel times for each seismic wave from each potential location to each station. The monitoring community now refers to seismic events whose location is known to within, say, 5 km, as "GT5" events (GT standing for "ground truth," the accurate location information coming for example from a local seismographic network, or from field observations of ground rupture in the case of a shallow earthquake, or from special efforts to record the location and origin time of mineblasts).

The USGS and the International Seismological Centre (ISC) rely upon (a) for routine processing, for then the effect of using an incorrect Earth model is reduced. The research community uses one or more of (a), (b), (c) but only in studying special sets of events, restricted to very limited regions. The IDC cannot use (a) except for large events since the REB is based on IMS stations alone, and for events below m_b 4 only a small subset of IMS stations provide detections. The IDC is therefore beginning to use methods (b) and (c). But even with great efforts based on hundreds of special studies, we will not know the Earth's 3D shallow structure adequately on a global scale for decades, ruling out reliance on (b) alone in the short term, though this method can be used successfully for some regions. This leaves (c), based upon ground truth events in the region for which accurate location capability is required, as the most important short term method. The IDC is likely to be the first organization to publish location estimates, on a global scale, using travel-time curves tailored individually for each station in the network from which the bulletin is prepared. The method will succeed, to the extent that GT events of sufficient quality and quantity can be found to calibrate IMS stations. Ideally, one would like to have numerous GT0 events for calibration purposes all over the world. In practice, GT5 events or in some regions GT10 events may be the best that are available.

To conclude this section with a practical example of a day with a typical number of seismic events, Figure **??** shows the location of 58 events reported in the REB for 1998 May 11. One of these events was the nuclear test carried out by India, and announced as consisting of 3 near-simultaneous nuclear explosions. This test of course attracted headlines, though from the monitoring point of view the initial work of association and event location was done by the PIDC in just the same way as for 57 other events that day. In 1998, event location was based upon interpretation of arrival times using the *iasp*91 model of the Earth. For the Indian event, 62 stations provided detection of 86 different arrivals, and this event was well-located because of the numerous stations which contributed data — see (a) above.



Date	Time	Lat	Lon	Nph	Depth	Mag	Region
1998/05/11	00:16:12.1	11.84S	170.43E	6	604.8	mb 3.1	VANUATU ISLANDS REGION
1998/05/11	00:25:48.8	39.04N	42.11E	11	55.4	mb 3.6	TURKEY
1998/05/11	00:58:11.0	31.94N	130.71E	9	76.4	mb 3.5	KYUSHU, JAPAN
1998/05/11	01:12:16.8	46.61S	42.63E	8		mb 4.0	PRINCE EDWARD ISLANDS REGION
1998/05/11	01:17:47.9	11.20N	93.11E	4		mb 3.9	ANDAMAN ISLANDS, INDIA
1998/05/11	01:24:33.8	8.40N	103.86W	20		mb 4.7	OFF COAST OF MEXICO
1998/05/11	01:27:42.0	8.64N	104.01W	7		mb 3.8	OFF COAST OF MEXICO
1998/05/11	01:54:42.4	23.32N	122.78E	5		mb 3.8	TAIWAN REGION
1998/05/11	02:24:27.9	42.58N	140.46E	16	51.1	mb 3.5	OFF COAST OF HOKKAIDO, JAPAN
1998/05/11	02:48:56.5	33.15S	68.19W	7		mb 4.4	MENDOZA PROVINCE, ARGENTINA
1998/05/11	04:00:26.0	17.40S	174.53W	6		mb 4.1	TONGA ISLANDS
1998/05/11	04:01:17.6	3.07S	142.11E	16		mb 4.7	NEAR N COAST OF NEW GUINEA, PNG.
1998/05/11	04:06:17.7	27.58N	141.12E	11	40.7	mb 3.9	BONIN ISLANDS REGION
1998/05/11	04:41:36.5	2.75S	141.22E	1		mb 3.5	NEAR N COAST OF NEW GUINEA, PNG.
1998/05/11	05:07:24.4	40.28N	48.91E	8		mb 4.0	EASTERN CAUCASUS
1998/05/11	06:02:54.7	2.88S	142.10E	5		mb 3.8	NEAR N COAST OF NEW GUINEA, PNG.
1998/05/11	06:06:06.6	11.44S	166.10E	7	45.6	mb 3.9	VANUATU ISLANDS
1998/05/11	06:18:54.1	16.29S	178.68W	6		mb 3.9	FIJI ISLANDS REGION
1998/05/11	07:11:26.6	16.17S	171.65W	1		mb 3.5	TONGA ISLANDS REGION
1998/05/11	07:12:08.2	22.28S	175.78W	1		mb 3.5	TONGA ISLANDS REGION
1998/05/11	07:16:18.6	39.26S	177.14E	1		mb 3.6	OFF E. COAST OF N. ISLAND, N.Z.
1998/05/11	08:47:31.6	13.77N	91.94W	7		mb 3.8	NEAR COAST OF GUATEMALA
1998/05/11	09:07:56.7	12.08N	87.74W	4		mb 3.8	NEAR COAST OF NICARAGUA
1998/05/11	09:11:16.1	8.24S	159.61E	1		mb 3.6	SOLOMON ISLANDS
1998/05/11	09:19:16.4	36.28N	70.82E	9	221.8	mb 3.4	HINDU KUSH REGION, AFGHANISTAN
1998/05/11	09:48:58.7	61.15S	146.90E	5		mb 3.8	SOUTH OF AUSTRALIA
1998/05/11	10:13:44.2	27.07N	71.76E	72		mb 5.0	INDIA-PAKISTAN BORDER REG.
1998/05/11	10:26:08.4	84.80N	8.72E	10		mb 3.6	NORTH OF SVALBARD
1998/05/11	10:50:46.9	37.07N	73.51E	6	110.5	mb 3.1	TAJIKISTAN
1998/05/11	11:10:23.9	2.13N	98.17E	4		mb 3.8	NORTHERN SUMATERA, INDONESIA
1998/05/11	11:14:30.1	11.57N	139.07E	6		mb 3.7	WESTERN CAROLINE ISLANDS
1998/05/11	11:42:16.9	10.43N	143.18E	1		mb 3.4	SOUTH OF MARIANA ISLANDS
1998/05/11	11:42:41.6	15.67S	176.82E	6		mb 3.7	FIJI ISLANDS REGION
1998/05/11	12:00:26.0	52.73N	160.11E	9		mb 3.7	OFF EAST COAST OF KAMCHATKA
1998/05/11	12:00:45.4	21.04S	177.46W	1		mb 3.7	FIJI ISLANDS REGION
1998/05/11	12:14:48.9	53.13N	160.09E	17		mb 4.1	NEAR EAST COAST OF KAMCHATKA
1998/05/11	12:40:16.4	5.08S	152.50E	19	10.7	mb 4.9	NEW BRITAIN REGION, P.N.G.
1998/05/11	12:49:06.5	4.89S	152.46E	15	50.6	mb 3.8	NEW BRITAIN REGION, P.N.G.
1998/05/11	13:22:14.5	2.69S	139.55E	10		mb 4.2	NEAR NORTH COAST OF IRIAN JAYA
1998/05/11	13:22:27.1	57.09S	142.87W	7		mb 4.4	PACIFIC-ANTARCTIC RIDGE
1998/05/11	13:50:55.6	17.07S	169.71W	4		mb 4.0	TONGA ISLANDS REGION
1998/05/11	14:24:10.1	24.61N	46.16W	6		mb 3.7	NORTHERN MID-ATLANTIC RIDGE
1998/05/11	14:29:40.5	21.06S	177.48W	6	486.9	mb 3.1	FIJI ISLANDS REGION
1998/05/11	14:36:18.6	2.97S	142.41E	16		mb 4.2	NEAR N COAST OF NEW GUINEA, PNG.
1998/05/11	15:12:46.1	9.89N	83.53W	24	21.7	mb 4.1	COSTA RICA
1998/05/11	16:22:03.9	4.41S	151.90E	1		mb 3.5	NEW BRITAIN REGION, P.N.G.
1998/05/11	16:42:26.4	10.67S	165.90E	6	100.2	mb 3.8	SANTA CRUZ ISLANDS
1998/05/11	17:29:50.8	21.65S	178.74E	4		mb 3.6	SOUTH OF FIJI ISLANDS
1998/05/11	18:46:12.9	42.12N	143.14E	11	55.1	mb 3.6	HOKKAIDO, JAPAN REGION
1998/05/11	19:11:06.5	58.12N	156.54W	22	16.6	mb 4.1	ALASKA PENINSULA
1998/05/11	20:01:07.1	11.18N	92.72E	7	167.8	mb 3.4	ANDAMAN ISLANDS, INDIA
1998/05/11	20:25:46.2	12.29N	144.08E	7	71.1	mb 3.7	SOUTH OF MARIANA ISLANDS
1998/05/11	20:29:54.5	5.14S	153.15E	11	41.7	mb 3.9	NEW IRELAND REGION, P.N.G.
1998/05/11	20:48:17.1	20.83S	175.80W	4	700.0	mb 2.7	TONGA ISLANDS
1998/05/11	21:34:30.4	51.28N	173.72E	5		mb 3.7	NEAR ISLANDS, ALEUTIAN ISLANDS
1998/05/11	22:08:42.5	4.72N	82.12W	18		mb 4.5	SOUTH OF PANAMA
1998/05/11	23:29:31.9	5.21S	102.74E	7		mb 4.2	SOUTHERN SUMATERA, INDONESIA
1998/05/11	23:48:13.1	14.21S	167.68E	6		mb 3.9	VANUATU ISLANDS

Figure 4: The Reviewed Event Bulletin for 1998 May 11 contained 58 seismic events, of which the 27th was an Indian nuclear test. Shown here is a map and list of these event locations. Larger circles on the map indicate larger magnitudes. (Obtained from http://www.pidc.org)

4.4 Identification of seismic sources

Once the detections from a seismic event have been associated and an accurate location estimate has been obtained, the next step in monitoring is that of event identification. A review of the best technical methods for carrying out this step is given, for example, by a report of the Office of Technology Assessment of the U.S. Congress (1988). But the actual identification of an event as possibly being a nuclear explosion and hence a treaty violation, perhaps warranting a request for an on-site inspection, entails judgements that bring in political as well as technical assessments. Therefore, as noted above, the IDC's role in event identification is limited to providing assistance to states party to the treaty, rather than actually making an identification. Further detail is given in Annex 2 to the CTBT Protocol, which indicates that the IDC may apply "standard event screening criteria" based on "standard event characterization parameters." To screen out an event, means that the event appears *not* to have features associated with a nuclear explosion. The underlying idea is that if the IDC can screen out most events, then states party to the treaty can focus their attention on the remaining events. For example, an event may have its depth estimated with high confidence as 50 km. Such an event would be screened out, by a criterion that "events confidently estimated as deeper than 10 km are not of concern."

For events detected by the IMS seismographic stations, Annex 2 lists the following parameters which may be used, among others, for event screening:

- location of the event;
- depth of the event;
- ratio of the magnitude of surface waves to body waves;
- signal frequency content;
- spectral ratios of phases;
- spectral scalloping;
- first motion of the P-wave;
- focal mechanism;
- relative excitation of seismic phases;
- comparative measures to other events and groups of events; and
- regional discriminants where applicable.

There is an extensive literature on how each of these characteristics can help to achieve event identification, but it will take a number of years to develop detailed objective criteria in the context of IMS event screening. For the present paper, a few examples must suffice to demonstrate how methods of identification may become the basis of standard screening by the IDC. Thus, one of the most successful discriminants is based on comparison of the magnitude m_b, measured from the amplitude of short-period P-waves, and the magnitude M_s, measured from the amplitude of long-wavelength surface waves. As mentioned above in Section 2, this discriminant was discovered in the 1960s. It exploits the fact that shallow earthquakes are far more efficient than nuclear explosions in exciting surface waves, for events with comparable P-waves. As a preliminary result from studies at the PIDC, Figure 5 shows that a large percentage of shallow events (but no nuclear explosions, in this example) may be successfully screened out if they have $M_s \geq 1.25m_b - 2.45$.

Another screen, conceptually even simpler, is one based upon depth estimates, recognizing that depths greater than 10 km are in practice inaccessible to human activity including nuclear testing. Events can thus be screened out if (a) their depth estimate is greater than 10 km $+2\sigma_D$ where σ_D is the variance of the depth estimate; and (b) certain criteria are met, to ensure that elementary mistakes have been avoided in making the depth estimate. In work at the PIDC, a conservative approach has been taken to ensure that events which appear to be deep, in terms of interpreting their P- and S-arrivals, have additional depth indicators (such as surface reflections pP and sP, and significant changes in the time interval between P and pP with increasing distance). The preliminary result is that about 20% of events with magnitude ≥ 3.5 are screened out by a combination of (a) and (b) (D. Jepsen, paper presented at a DTRA-sponsored workshop, Kansas City, June 2000). It is to be hoped that this percentage will rise significantly if more precise estimate of depth can be made with confidence. Note too that discriminants often work well in combination, so that by making better depth estimates, one can expect to reduce the number of deep events (say, in the range $\geq$ 50 km) that have to be subjected to the $M_s : m_b$ screen. Such a reduction would help the latter discriminant perform better (i.e., increase the separation between earthquake and explosion populations), since deep earthquakes are less efficient in exciting surface waves and tend to look more explosionlike in an $M_s : m_b$ diagram.

Depth estimates, and measurements of m_b and M_s, can be based upon teleseismic waves. In practice it is important also to develop discriminants, and their specific application as screens, for events too small to be well-characterized teleseismically. One example is the use of high-frequency spectral ratios of P and S regional waves (such as Pn/Lg ratios). Hartse *et al* (1997) and Kim *et al* (1997) have shown in practice that such ratios are abnormally high for small underground explosions as compared to shallow small earthquakes, and this discriminant can be applied successfully down to magnitude 3 and possibly even smaller. The preliminary result is that more than 60% of events with magnitude ≥ 3.5 are screened out on the basis of their P/S spectral ratios (D. Jepsen, paper presented at a DTRA-sponsored workshop, Kansas City, June 2000). In practice, objective screening based upon such a discriminant may be developed over a period of time and routinely applied at the IDC in ways that may have to be fine-tuned slightly differently for different regions.

Below magnitude 4, mine-blasting can result in seismic events detected and located by the IDC, which appear similar to small nuclear explosions using criteria such as depth estimates, weak surface waves, and high P/S spectral ratios. Hedlin *et al* (1989), Kim *et al* (1994) and others have found characteristic spectral interference patterns for such events, based presumably on the fact that commercial blasts routinely consist of numerous small explosions which are fired in a sequence of delays. The resulting seismic source is therefore somewhat spread out in space and time. Another potential discriminant of mine-blasting

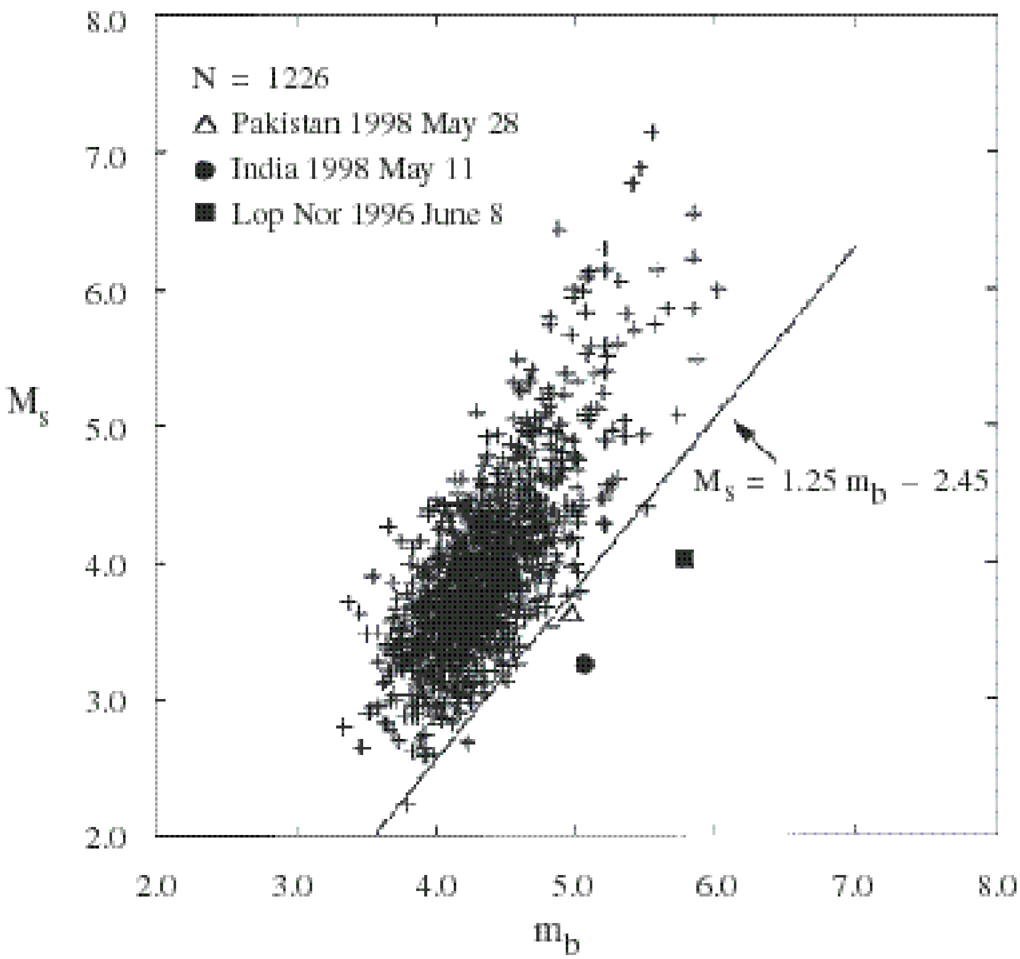


Figure 5: The $M_s : m_b$ discriminant, in practical application, depends upon the particular details of how seismic magnitudes are defined. Here are shown magnitudes for 1226 shallow events in the REB, presumed to be earthquakes, in which m_b has been assigned after making corrections for station magnitude bias with respect to network-average m_b values. Three nuclear explosions are included, and a screen that removes events for which $M_s \geq 1.25m_b - 2.45$ is very effective in removing a large fraction of the shallow earthquakes and none of the nuclear explosions. (Adapted from work of David Jepsen and Jack Murphy.)

is the infrasound signal which can be generated by such sources (Hagerty *et al* , 2000), and which would not be expected from a small underground nuclear explosion unless it vented significantly — which, in turn, would likely result in a characteristic radionuclide signal. New discriminants for particular types of small seismic events continue to be developed, both in field projects with specially deployed monitoring equipment, and in subsequent adaptation for candidate screening methods to be applied at the IDC to IMS data.

In addition to widely applied screens based upon m_b and M_s and upon depth, more specialized screening desired by a particular State Party may be carried out by the IDC as described in the Protocol, Part I, ¶21:

> The International Data Centre shall, if requested by a State Party, apply to any of its standard products, on a regular and automatic basis, national event screening criteria established by that State Party, and provide the results of such analysis to that State Party. This service shall be undertaken at no cost to the requesting State Party.

5 Evasion scenarios

If a nuclear explosion is conducted deep underground (depth around 1 km) at the center of a large spherical cavity in hard rock, with radius greater than or equal to about 25 meters times the cube root of the yield in kilotons, then the seismic signals can be reduced by a so-called decoupling factor that may reach up to about 70, i.e. by almost two magnitude units. It is easier to build cavities of the same volume that are elongated rather than spherical, and apparently such aspherical cavities can also achieve high decoupling factors, but they also increase the concentration of stress on the cavity and make it much more likely that radionuclides will be released into the atmosphere and detected by the radionuclide monitoring network of the IMS. An overall evaluation of the cavity decoupling scenario therefore raises a number of different technical issues:

- Does a country considering an evasive test have access to a suitably remote and controllable region with appropriate geology for cavity construction?
- Can the site be chosen to avoid seismic detection and identification (recognizing that seismic events are routinely reported down to about magnitude 3 by earthquake monitoring agencies for many areas in industrialized countries, and many countries routinely monitor neighboring territory)?
- Can cavities of suitable size and shape and depth and strength be constructed clandestinely in the chosen region, with disposal of the material that has to be removed from below ground?
- Can nuclear explosions of suitable yield be carried out secretly in sufficient number to support the development of a deployable weapon? (This question covers numerous technical issues, including the ability to ensure the yield will not be larger than planned; and to keep all yields of a test series large enough to learn from, yet small enough to escape identification.)

- Can radionuclides be fully contained from a decoupled explosion?

Each of these questions has been the subject of extensive technical analyses.

My own opinion is that it is technically possible to address a few of these issues in a clandestine program in isolation from the others, but mastery of all these issues combined could not be achieved except possibly by a full-blown multi-billion dollar effort by a nation that already had practical experience with underground nuclear testing. Such a nation would have little to learn technically, much to lose politically, and the treaty evasion program would still be at great risk of discovery since multi-billion dollar efforts intrinsically attract attention in the modern world.

Another evasion scenario is the use of mining operations and large chemical explosions to mask or disguise an underground nuclear explosion. There is a limit on the yield of any nuclear explosion that could be hidden in this way. Chemical explosions are almost always delay-fired at shallow depths, so they are inefficient in generating seismic signals, relative to nuclear explosions that are tamped (Khalturin *et al* , 1998). It therefore appears that only mines with the largest blasting operations are conceivably candidates for hiding militarily significant efforts at CTBT evasion.

There are two types of technical effort that can be carried out to help monitor mining regions for compliance with a CTBT. The first of these is installation of nearby seismographic stations that record digitally at high sample rates. The purpose would be to provide high quality data that can distinguish between single-fired explosions and the multiple-fired explosions typical of mining operations. The second is provision of technical advice to mine operators so that they execute their blasting activities using modern methods of delay-firing — which have economic advantages, as well as enabling the blasting of rock in ways that do not make the large ground vibrations (and strong seismic signals) typical of old-fashioned methods of blasting.

Addressing the reality of how the IMS and State Parties will handle large blasting operations — or the occasional single-fired chemical explosion (whose seismic signals may indeed look just the same as those of a small nuclear explosion), the CTBT Article IV, ¶68, states that

> In order to . . . [c]ontribute to the timely resolution of any compliance concerns arising from possible misinterpretation of verification data relating to chemical explosions . . . each State Party undertakes to cooperate with the Organization and with other State Parties in implementing relevant measures . . . .

These measures are spelled out in the Protocol, Part III. They provide, on a voluntary basis, information on single-fired chemical explosions using 300 tons or more of TNT-equivalent blasting material; and information on mine blasting (such as mine locations) for all other chemical explosions greater than 300 tons TNT-equivalent.

To the extent that mine blasting remains a serious concern, problems can be addressed with nearby installation of infrasound and radionuclide monitoring equipment, and with site visits. These activities would be voluntary under the CTBT — but they could also be made the subject of bilateral agreements.

For a suspected nuclear test, the CTBT contains extensive provisions for on-site inspection — at the request of a State Party and with at least 30 affirmative votes of the 51-member Executive Council of the CTBT Organization.

Some remarkable assessments of evasion scenarios were presented in the U.S. Senate debate of October, 1999, leading up to the negative vote on CTBT ratification. Thus, the Senate majority leader stated in executive session that

> "a 70-kiloton test can be made to look like a 1-kiloton test, which the CTBT monitoring system will not be able to detect."

He was referring to the decoupling scenario. Treaty opponents gave speeches which included exactly the same sentence:

> "While the exact thresholds are classified, it is commonly understood that the United States cannot detect nuclear explosions below a few kilotons of yield."

It was also stated that

> "Advances in mining technologies have enabled nations to smother nuclear tests, allowing them to conduct tests with little chance of being detected."

Let us address each of these three statements in turn.

70 kilotons would be an enormous explosion, about twice the energy of the combined Hiroshima and Nagasaki bombs, and would indeed be of military significance. The cavity that conceptually might reduce signals from a test of this size to something comparable to 1 kiloton would have to be deep underground (on the order of 1 km deep), with volume equal to that of a sphere 200 m in diameter. Such a spherical cavity could not be built in practice, not even in the open, let alone in secret. Just supposing it could be built, almost all the 70-kiloton energy released by the test would go into pumping up gas in the cavity to about 150 times normal atmospheric pressure. These gases would be radioactive, and the high pressure means they would leak through cracks that inevitably would exist in the 125,000 m^2 or more of cavity wall even if the cavity did not collapse. Distant radionuclide sensors of the IMS would detect the test if only 0.1% of the radioactivity escaped. The small fraction of energy released as seismic signals, if comparable to those from a typical (well-coupled) 1 kiloton test, would travel far beyond the rock surrounding this hypothetical (impossible-to-construct) cavity, and would be large enough for detection at numerous seismometers all over the world, including those of the CTBT monitoring system.

As for the United States not being able to "detect nuclear explosions below a few kilotons of yield", this might have been an accurate representation of the state of affairs in about 1958 when CTBT negotiations began. But it is more than 40 years later. Unclassified arrays of seismic instruments continuously and routinely monitor vast areas of the globe for earthquakes and explosions down to low seismic magnitudes, reaching down to about magnitude 2 at Russia's former nuclear test site on Novaya Zemlya. This capability translates into the ability to detect down to about 0.01 kilotons of well-coupled yield.

As for mining technologies, the overall trend of modern methods of mine blasting has resulted in general in smaller seismic magnitudes than prevalent a few decades ago. There are only a limited number of mining regions where signals from a small ($\sim$ 0.1 kiloton) nuclear test could be masked by a simultaneous mineblast without taking the additional steps of putting the nuclear test in a cavity — which would be associated with the complications listed above.

To summarize this section: if concern over evasion scenarios is sufficient that problems are targeted for resolution, then the goal of "... monitoring ... nuclear explosions down to a few kilotons yield or less, even when evasively conducted" (the U.S. position quoted in CD/NTB/WP.53 of 18 May 1994) is achievable.

6 Concluding remarks

The work of monitoring the CTBT by seismological methods will be demanding, because of the technical difficulty and the scale of organizational effort that is necessary, and because of the need to interact with political and bureaucratic decision-making. Evaluations of CTBT monitoring capability may be carried out as part of the domestic ratification process in each of the different signatory States. Such evaluation during the U.S. Senate debate of October 8, 12–13, 1999 relied upon a series of unsupported assertions. Evaluations are carried out from time to time, together with budgetary review, by government agencies, not all of which are eager to put resources into a major initiative in nuclear arms control. A review of nuclear explosion monitoring has not been carried out in the U.S. political arena since the 1980s (U.S. Congress, 1988).

It may be noted that there is an ongoing need to monitor all environments for nuclear explosions, regardless of whether the CTBT ever enters into force. The IMS and IDC therefore have an important role in global and national security, independent of the treaty's status.

The work of treaty monitoring is enhanced by the existence of major seismological resources other than the IMS primary and auxiliary networks and the IDC. This point is acknowledged in the CTBT and its Protocol, which make several references to the need to take national monitoring networks into account. In this regard, it is relevant to note that national seismographic networks are not operated by military organizations, but rather by civilian agencies such as the China Seismological Bureau; and, in the United States, the U.S. Geological Survey. National networks are increasing in number and quality. They are associated with the production of detailed bulletins of regional seismicity that typically are intended to meet objectives in the study of earthquake hazard. Such bulletins, and easy access to the underlying digital seismogram data, can be very helpful in CTBT monitoring, for the study of problem events and for improving the IDC's routine seismicity bulletins. In years to come, it is likely that the background of earthquakes will provide a means of calibration and new methods of data acquisition and data analysis, providing useful information that will improve the work of the IMS, and assisting in the attainment of national and international monitoring goals for a CTBT.

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