

chapter in Nuclear Weapon Issues in the 21st Century, edited by P. Corden, D. Hafemeister and P. Zimmerman, American Institute of Physics Conference Proceedings, Melville, New York, 2014

Comprehensive Nuclear-Test-Ban Treaty Seismic Monitoring: 2012 USNAS Report and Recent Explosions, Earthquakes, and Other Seismic Sources

Paul G. Richards

*Lamont-Doherty Earth Observatory of Columbia University
61 Route 9W
Palisades, NY 10964*

Abstract. A comprehensive ban on nuclear explosive testing is briefly characterized as an arms control initiative related to the Non-Proliferation Treaty. The work of monitoring for nuclear explosions uses several technologies of which the most important is seismology—a physics discipline that draws upon extensive and ever-growing assets to monitor for earthquakes and other ground-motion phenomena as well as for explosions. This paper outlines the basic methods of seismic monitoring within that wider context, and lists web-based and other resources for learning details. It also summarizes the main conclusions, concerning capability to monitor for test-ban treaty compliance, contained in a major study published in March 2012 by the US National Academy of Sciences.

INTRODUCTION

The Comprehensive Nuclear-Test-Ban Treaty (CTBT) was formalized in September 1996 after a checkered history that goes back to 1958, when negotiations began between the UK, the USA, and the USSR. The final text has more than twelve thousand words including eighteen Articles, and Annexes relating to governance procedures and giving a list of forty-four countries that must all sign and ratify this treaty before it can go into effect. Then there are more than ten thousand words in a Protocol specifying: an International Monitoring System (IMS) and an International Data Centre (IDC); the conduct of On-Site Inspections; and Confidence Building Measures such as procedures for reporting on very large chemical explosions. The formal treaty package ends with Annexes specifying more than three hundred stations in the five different global monitoring networks of the IMS, and a list of ways in which the IDC can analyze the resulting data (for preliminary purposes of characterizing the nature of signals which the IMS will acquire).

The basic obligations underlying this treaty are relatively simple, and are given in Article I 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 underlying goal of the CTBT is to inhibit the development of more sophisticated nuclear weapons, thus complementing the goal of the Non-Proliferation Treaty (NPT), a treaty which went into effect in 1970 for a period of twenty-five years and which in 1995 was converted to a treaty of indefinite extent on the basis of expectations that a CTBT (then still being negotiated) would shortly be realized. Whereas the NPT inhibits the spread of nuclear weapons (horizontal proliferation), the CTBT inhibits their further development (vertical proliferation; see [1] in which Donald Kerr, a former Director of the Los Alamos National Laboratory, wrote that “Nuclear weapon testing is ... a process intimately intertwined with the design of nuclear weapons systems”).

The United States from 1958 to 1996 played a leadership role in CTBT negotiations and in the design of associated monitoring systems, and became the first signatory state. But the advice and consent of the US Senate to ratification of this treaty was denied in 1999 and to date has not been reconsidered. Figure 1 gives details on signatures and ratifications for the CTBT, which, once it enters into force, establishes the CTBT Organization (CTBTO) based in Vienna, Austria, to ensure implementation of this treaty's provisions including international verification of compliance¹. Such work of building the monitoring system, currently in the hands of the Provisional Technical Secretariat, is part of overall efforts to inhibit nuclear weapons development.

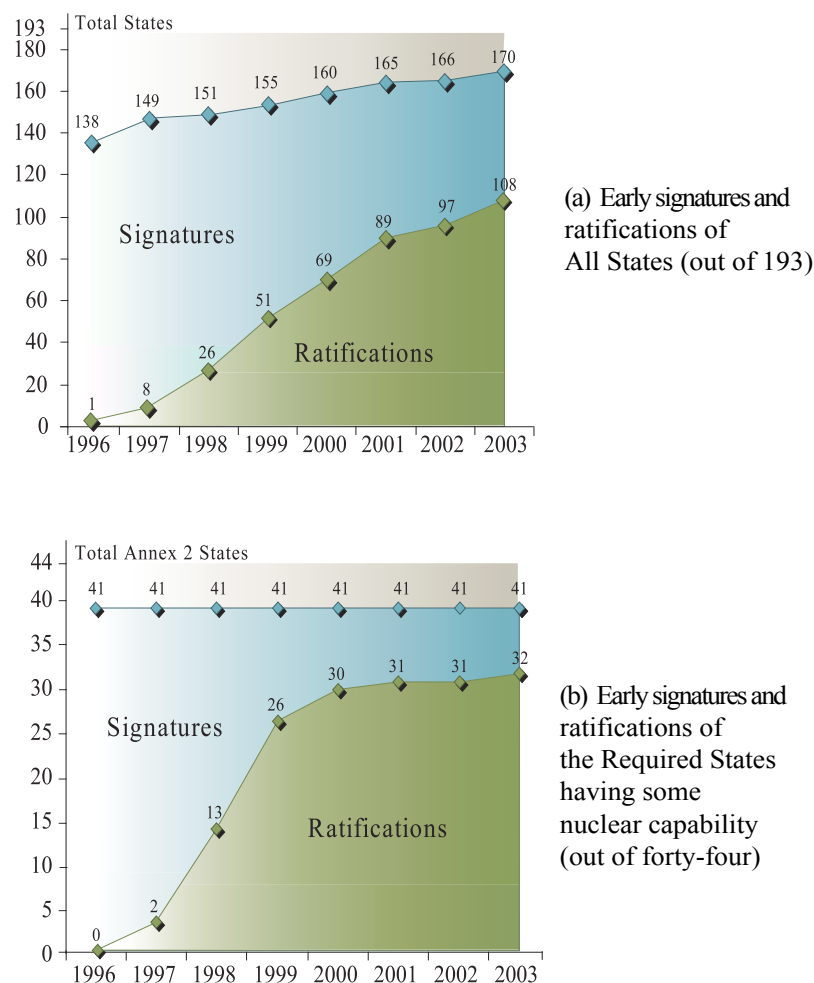


FIGURE 1. Signatures and ratifications of the CTBT States for several years after this treaty was finalized in 1996. (a) Shows the steadily growing record for all States. As of January 2014 there are 183 signatories with 161 ratifications (the latest, by Iraq in September 2013). (b) Shows the early rise and then a slow-down in the ratification rate, for those forty-four States listed in Annex 2 whose signatures and ratifications are required to achieve entry-into-force. Forty-one signed promptly in 1996; India, Pakistan, and the Democratic People's Republic of Korea have not signed as of January 2014. Indonesia, Colombia, the Democratic People's Republic of Congo, and Vietnam, have ratified since the thirty-two shown here for 2003. China, Egypt, Iran, Israel, and the United States have signed but not ratified as of January 2014.

¹ Until entry into force, the work of building the international monitoring system is formally managed by the Preparatory Commission for the CTBTO, staffed in Vienna by the Provisional Technical Secretariat.

The first five years of CTBT negotiations led, in 1963, to the so-called atmospheric test ban, more formally called the Limited Test Ban Treaty (LTBT), now signed and ratified—or acceded to—by more than a hundred nations. It banned testing in outer space, in the oceans and the atmosphere, but placed no constraint on underground testing. In part this early failure to achieve a CTBT was due to lack of confidence, in the early 1960s, in the capability to monitor for nuclear explosions in the underground environment. When CTBT negotiations began, there had been only one underground nuclear test (in 1957) in which radioactive by-products were contained underground. Seismology in the 1950s was a small-scale endeavor, conducted at very few institutions, and was largely restricted to the study of earthquake signals.

While the LTBT was successful in bringing the era of atmospheric testing to an end², and the associated radioactive fallout, it had little effect on nuclear weapons development by the recognized nuclear weapon states, since they conducted about 1500 underground explosive nuclear tests from 1963 to 1996. The LTBT is not associated with any international commitment to build a monitoring system.

Seismology was developed vigorously from the late 1950s to the 1990s, driven not only by the need to provide support for an eventual CTBT, but by the need—recognized by individual countries—to gain some appreciation of the programs of nuclear weapons development being conducted in this period by potential adversaries, as expressed by their nuclear testing programs. It is the full experience, developed by several different countries with their different perspectives, of having monitored those 1500 underground nuclear explosions³, which is available today to support the work of monitoring for compliance with the CTBT in future years. This experience entailed the use of several different technologies applied to explosion monitoring in different environments, as listed in Figure 2.

Seismology is generally recognized as the most important monitoring technology since it is the most effective for monitoring against the underground environment—which is the one most suited to attempts at clandestine treaty evasion, as well as being the one in which most weapons development experience has been acquired by countries with sophisticated nuclear arsenals.

Key Technologies \ Environment of test	Underground	Underwater	Atmosphere	Near Space
Seismic*	major	major	secondary	none
Radionuclide*	major	major	major	none
Hydroacoustic*	secondary	major	secondary	none
Infrasound*	secondary	secondary	major	none
Electromagnetic	secondary	secondary	major	major
Satellite Imagery	major	major	secondary	secondary

*technologies used by the International Monitoring System (Vienna)

FIGURE 2. Contributions of different technologies to CTBT monitoring for explosive tests conducted in different environments (adapted from [2]). The fifth technology (electromagnetic) uses sensors of many types, including ground-based or space-based detectors of the characteristic flash of a nuclear explosion in the atmosphere or in space. The sixth technology can be used for remote examination of activity at and effects on sites on land and in the ocean.

² France and China continued testing in the atmosphere for several years after 1963 but did eventually cease, with the last atmospheric test conducted by China in 1980.

³ Plus about 500 atmospheric tests, including a few at altitudes of hundreds of km; and several tests conducted underwater by the US and the USSR.

ELEMENTS OF SEISMIC MONITORING

Seismic monitoring for underground nuclear explosions must be done in the context of hundreds of earthquakes, chemical explosions, and other non-nuclear phenomena, generating seismic signals daily that will be recorded at multiple stations by any effective CTBT monitoring network. But although this multiplicity of signals complicates the work of explosion monitoring, it is associated with an extensive infrastructure of national and international agencies, having little to do with treaty-monitoring, that now sorts out and identifies the many signals from earthquakes, chemical explosions, plus the occasional underground nuclear explosion⁴.

Modern methods of nuclear explosion monitoring are vastly more capable than they were when such monitoring began in the late 1950s, in part because improvements in explosion monitoring in the period from about 1960 to 1980 led to improvements in monitoring for earthquakes and other phenomena, which then led to a general growth in monitoring assets that in turn can be applied back to explosion monitoring.

The Different Steps in Explosion Monitoring

The practical work of nuclear explosion monitoring can be organized in six steps, beginning with *detection* of signals and *association* (gathering all the different signals, recorded by different stations, that originate from the same 'event'). The next steps entail making a *location* estimate and an *identification* (did signals have the characteristics of an earthquake, a mining blast, a nuclear weapon test?). Finally there are the steps of *yield estimation* (how big was it?) and *attribution* (if it was a nuclear test, what country carried it out?). Each of these steps is further described as follows:

Concerning *detection*, nuclear explosion monitoring is often done with arrays of sensors, deployed as a group spread out over an area that can be on the order of tens or hundreds of square kilometers. Arrays facilitate methods to enhance signal-to-noise ratios. This is done typically by stacking signals from independent sensors, with appropriate delays, to increase signal strength and to reduce noise. In special cases where detection is sought for a signal that is expected to be the same as one previously recorded, cross-correlation can provide detection down to amplitudes ten or more times smaller than conventional detection methods [3]. And, array data can be interpreted to estimate the direction from which signals arrive.

Association is the effort to identify those sets of signals, from different stations, which originate from the same event. A high-quality seismographic station may record tens of small events per day—typically, small earthquakes or mine blasts, as well as the occasional large and typically more distant events. Association is one of the hardest steps in practice, especially when multiple seismic sources around the world are active at the same time, resulting in signals from different events that are interlaced in the waveforms recorded by each station. In such cases, array data providing directional information can be helpful in resolving which signals correspond to which event.

To obtain a *location* estimate, typically the arrival times of various seismic waves are measured from the recorded waveforms. Such times are used to estimate four parameters—the latitude, longitude, depth, and origin time—for each detected event. In this work, it is necessary to know the travel time from any hypothesized source location to any particular seismographic station, for any type of seismic wave that the station might observe. In practice, locating seismic events accurately on a global basis (say, to within about 10 km of their true location) using sparse networks (stations several hundred km apart) requires extensive efforts in station calibration. Thus, it is important to include path-specific travel-time corrections to standard travel-time models, to account for lateral variations of Earth structure [4]. Many authors have shown that greatly improved precision of location estimates can be achieved for a given region if seismic events are jointly located in large numbers—preferably thousands of them or more, all at the same time—rather than one-at-a-time [5], and this approach is becoming more widely applied. In practice, monitoring capability can be characterized via maps of the *magnitude threshold*, above which some percentage of the occurring seismic events can be detected at three or more stations (the least number of stations for routine location). Such maps (discussed further, below) build upon the component steps of detection, association, and location.

The *identification* of the nature of a seismic event on the basis of its seismic signals—that is, making a determination from seismograms as to whether it could be a nuclear explosion, or a natural earthquake, or a

⁴ As of January 2014, only North Korea has conducted nuclear explosions in the present century.

mine blast, or a landslide⁵, or something more exotic such as a bolide (meteorite)⁶ impacting our planet and exploding in the atmosphere—is a large subject in view of the many possibilities. Seismic events generate many different types of seismic waves, in various different frequency bands⁷; and different types of seismic source generate a different mix of seismic waves. We can make an analogy here with sound waves, and the capability of the human ear and brain to analyze them. A deep bass voice, a gun shot, a whistle, and rolling thunder, and a cello, constitute a set of sound sources that are easily distinguished from each other on the basis of their different frequencies, their emergent or impulsive nature, and their duration. It is the mix of information in both the time domain and the frequency domain that provides effective identification. Seismic methods for discriminating between earthquakes and explosions are based on interpretation of the event location (including its depth); on the relative excitation of a variety of body waves and surface waves; and on properties of the signal spectrum associated with each of these two different types of source. Within these three broad categories, many different methods have been tried, with various degrees of success. As the capabilities of each method are probed, the question of interest is often: “Down to what size of seismic event does this method of discrimination work?” In some cases discrimination is unambiguous even at very small event size. (For example: however small an event, it may be presumed to be an earthquake if it is confidently located at a depth greater than 15 km below the Earth's surface. Even a small event will attract attention, if it occurs in an area that is geologically stable, and that for decades has had no seismic activity.) In practice no single method of event identification based on seismological data is foolproof (for example, depth estimates are often uncertain) but in combination these methods have proven highly reliable.

The identification methods described so far, pertain to the use of teleseismic signals (i.e. those propagating to distances of 1500 km and more, via paths that can reach down substantially more than 100 km into the Earth's interior), which can be used to monitor effectively for large explosions, and on down to somewhere in the seismic magnitude range from 4.0 to 4.5 (which corresponds roughly to one kiloton for a well-coupled nuclear explosion). Since the early 1990s, there has been growing recognition of the merits of regional seismic waves (i.e. those propagating at shallower levels), to enable monitoring down to lower magnitudes, often well below magnitude 3 (and thus to explosions of a few tens of tons of chemical-explosion equivalent).

Regional methods are typically based upon the general observation that explosion signals, when compared to earthquakes, have much stronger *P*-waves at high frequency, whereas those from earthquakes have stronger *S*-waves (and surface waves). This modern method is being studied with frequencies in the range 0.5 – 20 Hz, and sometimes even higher. An example (from [8]) is shown in Figure 3 comparing regional signals of a very small earthquake and a small explosion. The method has been applied by many authors to seismic signals recorded from the three nuclear explosions conducted to date in the 21st century (all, by North Korea: see [9] for examples of the spectral ratio of regional *P*- and *S*-waves from the smallest, and first, of these three explosions). Though the method tends to improve with use of higher frequencies, there is a tradeoff since these may not be available (due to attenuation). The method is still often effective using frequencies around 4 to 6 Hz [10]. In application to discrimination between earthquakes and explosions occurring in separate locations over a wide region (say, over areas of hundreds of km sq, or more), it is appropriate to make a correction to the observed spectral ratio of *P*- and *S*-waves due to the differential attenuation imposed on these signals by their propagation, as discussed in [11]⁸.

⁵ On April 10, 2013 a massive landslide occurred at the Bingham Canyon copper mine near Salt Lake City Utah. In two episodes each lasting about 90s but separated by about 1.5 hours, about 65 million cubic meters of rock slid downwards, generating long-period seismic signals detected thousands of km away. See <http://www.geosociety.org/gsatoday/archive/24/1/pdf/i1052-5173-24-1-4.pdf>

⁶ On February 15, 2013 seventeen of the CTBTO's infrasound stations detected signals from an object that entered Earth's atmosphere from space and disintegrated with an energy of hundreds of kilotons above Chelyabinsk, Russia. See <https://www.sciencemag.org/content/342/6162/1069> for discussion of this, the largest natural airburst since the 1908 Tunguska event.

⁷ See for example the cover, or Figure 12. 1, of [6]; and discussion in [7].

⁸ The fact that *P*-waves attenuate with distance at a lesser rate than *S*-waves, can result in an observed spectral ratio (*P*/*S*) from an earthquake that looks explosion-like, unless a correction is made for the differential attenuation. Such a correction requires extensive efforts to characterize the regional variability in propagation characteristics of different types of regional seismic waves, as discussed in [11].

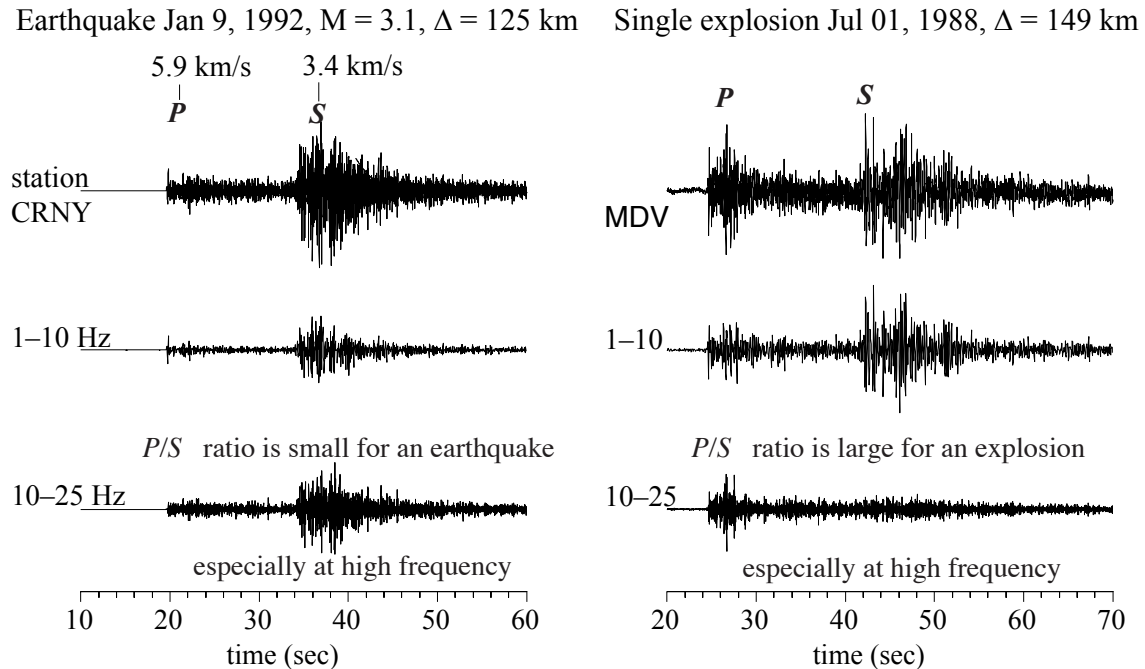


FIGURE 3. Typical vertical-component records from an earthquake and an explosion. Traces plotted are: (top) unfiltered; (middle) low-frequency bandpass filtered; and (bottom) high-frequency bandpass filtered. Arrivals of P and S waves are shown on the unfiltered traces. From [8].

In practice, there is often very little difference between the magnitude thresholds for detection (at enough stations to enable a useful location estimate), and identification, since so many regions of the Earth are now monitored to low magnitude for earthquakes as part of investigations into seismic hazard. It may take only one regional seismogram to enable discrimination to be carried out with high confidence (provided the recording is of adequate quality, and is for a station that has an archive of signals from previous known earthquakes and explosions). Obviously, methods of discrimination based upon comparison of P - and S -waves will fail for regions in which attenuation is so high (or the method is applied to events that are so small), that seismic signals are too small (in comparison to background noise) to make a spectral measurement.

In general for underground tests, seismic data alone cannot be the basis for distinguishing between nuclear explosions, and chemical explosions in which all the material making up the explosive was fired within less than about a tenth of a second. But such chemical explosions, if large, are very rare [12]. In the case of the North Korea tests in 2006, 2009, and 2013, all of which were announced by the DPRK as nuclear, objective evidence for the nuclear nature of the 2006 and 2013 explosions came from detections of radionuclides that are diagnostic of a nuclear explosion. Such radionuclides were not detected from the 2009 explosion, which, however, was so large as to be implausible as a chemical explosion, since it would have had to consist of literally thousands of tons of chemical explosives.

Concerning *yield estimation*, of the size of an underground nuclear explosion based upon its seismic signals, extensive practical experience was acquired in the 1970s and 1980s in the context of monitoring for compliance

with the bilateral Threshold Test Ban Treaty between the US and the USSR⁹. Since the CTBT bans nuclear explosive testing at all levels of yield, the capability to estimate yield does not directly arise in the limited context of deciding whether or not a detected test would be a treaty violation. All tests are violations. Nevertheless, there is interest in yield estimation on two grounds. First, because of the traditional (pre-CTBT) need to assess the size of any nuclear test in the context of its significance for the weapons program in which it was conducted¹⁰. Second, because of the need to translate a characterization of seismic monitoring capability expressed in terms of seismic magnitude, to a monitoring capability expressed in terms of explosive yield.

Quoting at this point from [13], a 2012 USNAS report discussed below in more detail:

To assess the size of a detected event in terms of nuclear yield, yield typically must be derived from seismic magnitude. A single relationship between magnitude and yield does not exist. This is because explosions of a given yield generate different amplitudes of seismic waves (and hence different magnitudes) depending upon 1) the efficiency of seismic wave propagation from source to recording station, 2) the rock type at the source, 3) depth of the explosion, and 4) whether the explosion is well coupled or decoupled...

Formulas relating the body-wave magnitude, m_b , to the yield, Y , based on data from past underground nuclear explosions are of the form

$$m_b = A + B \log(Y)$$

where A and B are constants that depend on features 1–4.

Most past tests of yield greater than about 1 kiloton were detonated at greater depths as yield was increased so as to ensure containment. Their data are well fit by $B = 0.75$ (Murphy, 1996 [14]). Nuclear explosions at eastern Kazakhstan, Lop Nor China and northern India are characterized by efficient propagation of P -waves such that

$$m_b = 4.45 + 0.75 B \log(Y),$$

where Y is in kilotons. Explosions in Nevada are characterized by poorer propagation of P -waves such that the constant A is smaller...

Hence for a given m_b the yields calculated for explosions at Lop Nor are smaller than those at the Nevada Test Site...

For explosions of varying yield *at the same depth* $B = 1.0$. For explosions with very small magnitudes, i.e. those less than $m_b = 4$, we calculate yields using $B = 1.0$ because such small nuclear tests are not likely to be conducted at the depths that $B = 0.75$ would imply...

Finally in the list of six steps entailed in nuclear explosion monitoring, there is the issue of *attribution*. To attribute an identified nuclear test to a particular nation, a quotation from [2] is relevant:

...procedures would differ somewhat depending on the environment in which the test was conducted. For the underground environment, there is the potential for long-lasting indications of the testing location (for example, a shaft or tunnel leading to a chamber with radioactive indicators of the explosion), whose coordinates may be estimated from seismic data followed up by identification of the site from satellite photos and other data, perhaps acquired as part of an on-site inspection. Attribution is likely to be more problematic for an underwater or atmospheric test, since a nation with a nuclear explosive could detonate it on a ship or a plane and the effects on the surrounding media would be more ephemeral. Though such a test would likely be detected and located, it might be attributed only with difficulty to the nation responsible.

It is noteworthy that responsibility for the steps of both event identification and attribution, within the context of the CTBT, are left to each State Party. This is because of the serious consequences of concluding

⁹ Negotiated in 1974 and intended to go into effect at the end of March 1976, this treaty banned underground nuclear explosions with yield greater than 150 kt. No other countries participated in this treaty, which was finally ratified by both sides, and went into effect, in 1990.

¹⁰ This perspective applies, for example, to the DPRK tests of 2006, 2009, and 2013.

that a nuclear test has taken place; and that it occurred on the territory of a particular nation¹¹. The CTBT establishes a forum in which allegations made by individual States, against another State, can be assessed. Objective evidence derived not only from data and analysis of the IMS and the IDC, can be introduced. It is therefore appropriate at this point to consider what methods of monitoring are important in addition to those associated with the IMS and the IDC.

Assets Available in Monitoring for CTBT Compliance

It is understood that the CTBT is in practice to be monitored by the international CTBT Organization in Vienna, Austria, as indicated throughout much of the above discussion¹². But in this section two additional types of asset are briefly described, that in their different ways provide alternative ways to monitor for nuclear explosions. From some perspectives these alternative approaches to monitoring are much stronger than the international treaty-based approach.

The first alternative, is monitoring by National Technical Means (NTM)—which for the US includes the Atomic Energy Detection System (AEDS) operated by the Air Force Technical Applications Center¹³ [15]. As noted in [13], global monitoring capabilities available to the US are generally better than those of the CTBT Organization because they can enhance data available from the IMS with data from other systems such as those based on satellites. Some of the additional data streams are classified, though many are not. Unlike the work done by the CTBT Organization through the IMS and the IDC, which must treat all countries equally, US NTM can focus on monitoring countries of concern to the US¹⁴. As also noted in [13], though US NTM provide monitoring capability that is superior to that of the CTBTO¹⁵, the use of US NTM for diplomatic purposes (such as making an allegation against a specific country, in the forum offered by the CTBT) may be constrained due to its largely classified nature. As noted in [2], the CTBT, LTBT, and NPT do not incorporate monitoring of space explosions as part of an international monitoring system. Thus monitoring of space explosions depends on national technical means. Sensors involved in observing explosions in space serve the dual role of treaty monitoring, and detecting and locating nuclear explosions should such explosions be used in actual combat. Deployment of monitoring equipment today continues to depend on the priorities given to the treaty monitoring missions relative to other possible space payloads.

The second alternative, is a type of monitoring based upon the loosely organized efforts of numerous institutions, that acquire and process data originally recorded for purposes other than treaty monitoring, e.g. from regional and national networks of seismometers, and from radionuclide sensors. Hundreds of institutions continuously operate thousands of seismometers; and seismically active regions of North America, Europe, Asia, North and South Africa, and the Middle East are now routinely monitored down to low magnitudes (below magnitude 3) in order to evaluate earthquake hazards. Many of these stations provide high-quality data on a continuous basis that is made openly and freely available to any user via the Internet.

¹¹ There are likely to be strong technical components associated with making such calls. The IDC assists States Parties by carrying out standard analytical procedures, collectively referred to as screening. The general intent is to screen out those events that could not be nuclear explosions.

¹² The CTBT specifies details of five global monitoring networks as part of the IMS. These are: a primary seismographic network of 50 stations that operates continuously and that is analyzed by the IDC to provide for example the times of arrival of seismic signals detected at each IMS station; an auxiliary seismographic network of 120 stations which acquires data continuously, segments of which can be requested and acquired by the IDC to assist in the characterization of the source of signals detected by the primary network; an infrasound network of 60 stations intended to provide signals from any atmospheric nuclear explosions and that has also detected explosions in the atmosphere from incoming meteorites and the occasional comet; a radionuclide network of 80 stations; and a hydroacoustic network of 11 stations to monitor for nuclear explosions in the ocean. Note that the CTBTO does not exist prior to entry into force. By CTBTO in the main text here, we are using a shorthand reference to the work of the Preparatory Commission as per footnote 1.

¹³ General Eisenhower in one of his last decisions as a military officer, in August 1948, prior to the existence of the US Air Force, gave to the then Army Air Force the responsibility for monitoring for foreign nuclear tests. His choice was based on the practical consideration at that time that such tests would be in the atmosphere, and thus suited to the possibility of using aircraft to gather radionuclide evidence. The Air Force did indeed acquire such evidence of the first non-US nuclear test, namely that conducted in Kazakhstan in the atmosphere by the USSR in August 1949. The US AEDS today still includes capability for aircraft-based air sampling, to seek evidence of radionuclides generated by nuclear tests (such evidence can be vented from an underground test). It also includes high-quality arrays of seismometers that are not part of the IMS.

¹⁴ For example, earthquakes and mine-blasting activity in Canada and Australia are not of concern to the US in the context of nuclear explosion monitoring; but such activity must be, and is, routinely documented by the IMS and IDC.

¹⁵ This is most obviously true, because NTM includes the data available through the CTBT Organization and adds significant other data streams

In one sense, this second alternative approach is not serious because no lead agency is tasked to provide an overall analysis of the multiple data streams it generates. Therefore, it does not reliably contribute to detection capability. Furthermore, the resource here is uncontrollable, from the perspective of an agency tasked with nuclear explosion monitoring¹⁶; and there are issues associated with how such open stations are calibrated, and whether their data streams could be corrupted. But in another sense the stations associated with this second alternative approach are obviously important, because in practice, in recent years, they have provided high-quality data that contributed very effectively to prompt characterization of specific seismically-detected phenomena, enabling in some cases a good understanding of events that were superficially explosion-like but that turned out to be benign (for example, a mine collapse [16]). As another example: open station data recorded from the first nuclear test conducted by North Korea in 2006 was of very high quality; and there is now a widely-appreciated understanding that the whole territory of that country can be monitored by openly available resources (as well as the resources available from the CTBTO and from US NTM) down to just a few tons of well-coupled explosive yield ([3], [9]).

Concerning this second alternative approach: although its contributions are hard to quantify, there is practical experience to show that it can be effective, and therefore it must presumably be taken into account by any country contemplating the execution of a nuclear test in violation of the CTBT. As such, this second approach is part of the overall deterrent, included in the totality of monitoring assets, which could influence a country contemplating a clandestine nuclear test program, persuading it not to go ahead in view of the likelihood that signals from even a small nuclear test could be detected by open stations in addition to the possibility of detection by CTBTO and NTM assets.

Tutorial Assets, and Other Materials, Available for Learning Further Details of Seismic Monitoring of Nuclear Explosions

It is widely recognized that the US, Russia, the UK, France, and China, have a substantial infrastructure for building, maintaining, and in general managing their nuclear weapons. These are the five nuclear weapons states recognized by the NPT¹⁷, and substantial resources must also be involved to maintain the nuclear weapons programs of India, Pakistan, Israel, and North Korea.

Less well known, is the existence of infrastructure associated with nuclear explosion monitoring—though each of the three monitoring approaches listed in a previous section of this paper¹⁸ is operating today at the level of hundreds of millions of dollars annually, using assets acquired via investments at or above the billion dollar level; and monitoring has a history going back to the 1940s. So, nuclear explosion monitoring is itself a substantial subject, for which there are decades of operational experience, driven in part by the desire for information on the nuclear weapons program of one nuclear weapons state, as needed by another nuclear weapons state.

Research programs to achieve better monitoring capability have poured funds into scientific fields such as seismology and the understanding and interpretation of radionuclide abundances, and have changed these fields, though it is no longer the case that such research is well funded¹⁹. There is a huge body of grey literature, of variable quality, that in some cases contains the key results which have re-directed practical and effective monitoring efforts.

Fortunately, much of the information on monitoring assets and on successful methods of analysis, that have emerged from the decades of monitoring experience, has been distilled in the last ten years and published in books [17] or in surveys in scientific journals [18] or in proceedings of international and national professional meetings of experts engaged in the work of explosion monitoring [19]. A substantial number of web-based presentations are also now available [20], including both general surveys of monitoring capability, and specialized examination of instrumentation and analytical procedures.

¹⁶ If an open station, capable of recording seismic events down to low magnitude in, say, parts of the Middle East, loses functionality, then from a monitoring perspective that station is useless until its operation, by happenstance, is restored.

¹⁷ They are also the five permanent members of the UN Security Council.

¹⁸ The international CTBTO program, NTM, and the approach based upon open stations.

¹⁹ The reduction in funding for R & D in monitoring is presumably due to a perceived lower priority of support for nuclear arms control initiatives, as compared to support for efforts to detect and interpret the signals from active nuclear weapons test programs in the era from about 1950 to 1990 when such tests were being routinely conducted at the rate of roughly one per week.

Detection Probabilities at Lower Magnitudes

To characterize the detection capability of a particular seismographic monitoring network, it is useful to show a map with shading and/or contours, indicating the magnitude down to which signals would be expected at three or more stations, from, say, 90% of the events at the contoured magnitude, or larger. An example is shown in Figure 4, for 38 stations of the IMS primary network (the number operating at the time in 2007 when this map was made). Such maps are based on signals being at some standard level (often taken, as in Fig. 4, at 10 dB, or equivalently a factor of 3.2 in amplitude) above background noise. Therefore, capability maps vary from hour to hour—even, from minute to minute—as noise conditions change. Levels of detection are often better in regions at nighttime rather than in daylight hours because noise levels are usually lower at night. And, the occurrence of a large earthquake can briefly make detection capabilities somewhat worse as discussed further, below.

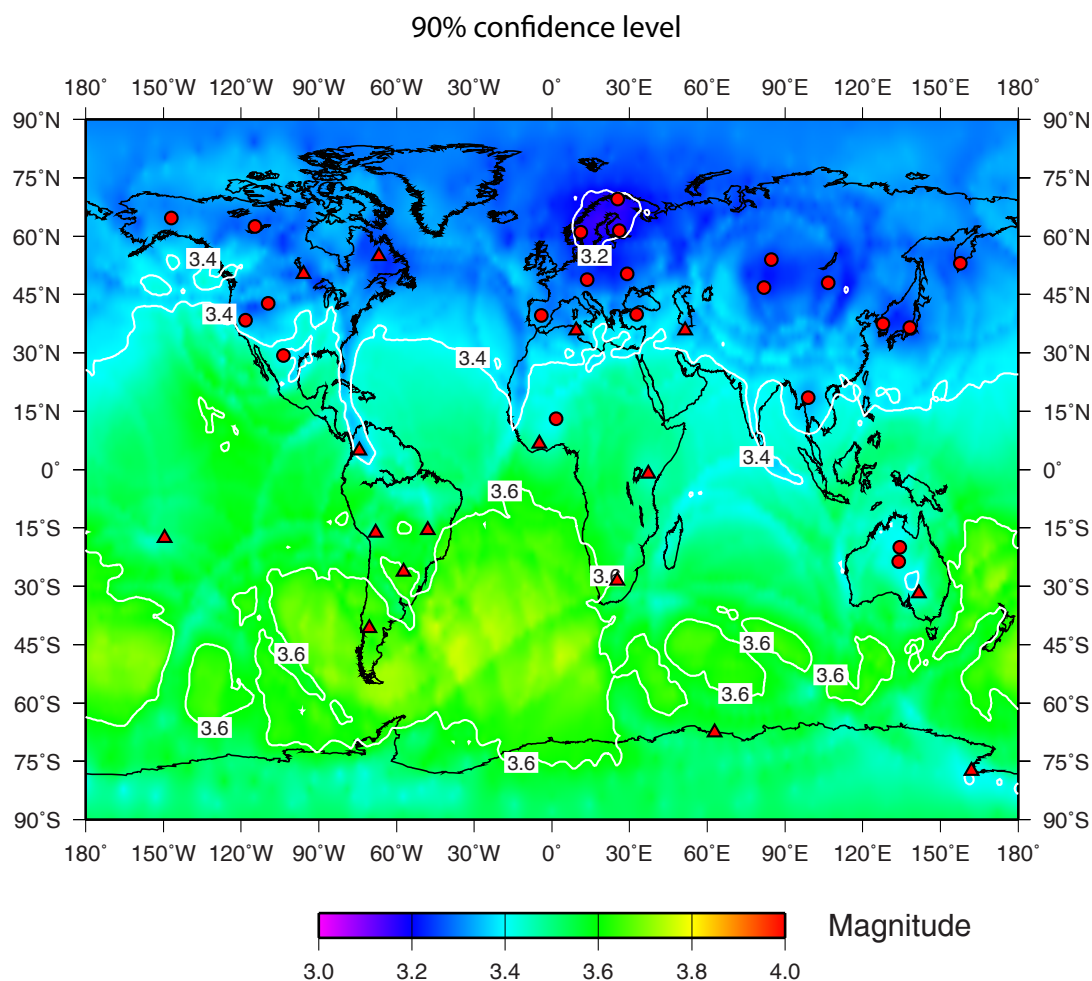


FIGURE 4. Detection Capability of the IMS Primary Seismic Network in late 2007 with 38 primary stations. For the detection of 90% of seismic events above the contoured magnitude for the entire world, the monitoring threshold level can be summarized as $m_b = 3.8$, which corresponds to about 0.2 kt well-coupled in hard rock with better propagation; and to about 0.6 kt for a region of poorer propagation to detecting stations. For detection of 90% of the seismic events in Asia, Europe and N. Africa, the levels are about 0.1 kt and 0.2 kt (2012 USNAS CTBT study [13], pg. 50.)

A different characterization of the same monitoring network results, if the percentage of detected events is set to a different level. This result is brought out in the 2012 USNAS report [13], which maps both the 90% detection probabilities as shown in Fig. 4 and the 10% detection probabilities as shown here in Figure 5. Specifically, Fig. 5 contours the magnitude above which 10% of the events are detected at three or more stations

(again: this is at enough stations to provide an approximate location). While it is appropriate to use a high percentage (such as 90%) in the context of characterizing the threshold above which a monitoring network performs well, it can be appropriate to use a low percentage (such as 10%) to characterize the situation faced by country contemplating an evasive test, and wanting to have a high level of assurance of avoiding detection. Such a country would need to restrict explosion-generated signals to magnitude levels more like those shown in Fig. 5, which are significantly below those shown in Fig. 4.

Note too that the probability of a test program evading detection drops with an increased number of tests. If there is 90% confidence for avoiding detection of one test, confidence drops to 73% when testing three times if we assume the probability of detection for each test is the same, but independent for each test²⁰.

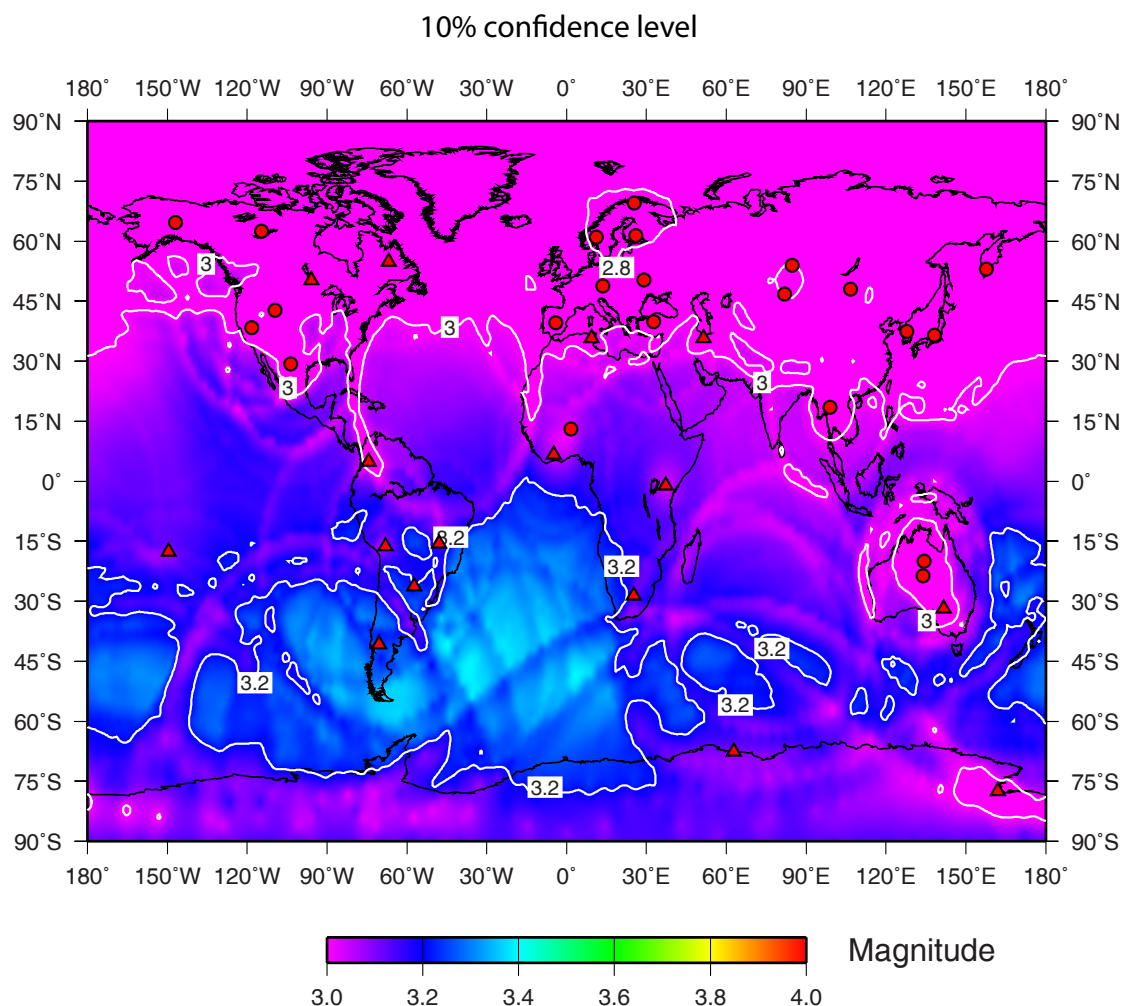


FIGURE 5. Detection Capability of the IMS Primary Seismic Network in late 2007 with 38 primary stations. Similar to Fig. 4, but now the magnitude threshold is such that 10% of the events larger than the contoured value would be detected. The image here is an alternative way to characterize the monitoring capability of exactly the same network—and with the same noise conditions—as shown in Fig. 4. In the present case (10% detection) it can be seen that the threshold level is lowered to magnitude about 3.4 globally, and better in Eurasia and North Africa. For reference, magnitudes of 2.8, 3.0 and 3.2, correspond to 0.022 kt, 0.035 kt and 0.056 kt respectively for well-coupled underground tests in hard rock. (2012 USNAS CTBT study [13], pg. 106.)

²⁰ $0.9 * 0.9 * 0.9 = 0.729$

SUMMARY OF A 2012 US NATIONAL ACADEMY OF SCIENCES REPORT

With US ratification of the CTBT denied in October 1999 by the US Senate advice and consent process, President Clinton appointed General John Shalikashvili, recently retired from chairing the Joint Chiefs of Staff, to make inquiries of as many Senators as he could, in order to determine the reasons for so many voting negatively and to receive suggestions for any additional steps that could be taken to build bipartisan support for ratification. He reported to the President in January 2001 just a few days before President G. W. Bush assumed office, noting [21] with respect to CTBT monitoring that “The Test Ban Treaty does not add new monitoring requirements. Instead, it adds new sources of information and creates greater political clout for uncovering and addressing suspected violations.” In 2000 General Shalikashvili commissioned several reports including one from the US National Academy of Sciences (USNAS) that would address technical concerns expressed to him by US Senators as their reasons for a negative opinion on US ratification. The concerns he found most prominent were

- Whether the CTBT had genuine non-proliferation value;
- Whether cheating could threaten US security;
- Whether the safety and reliability of the US nuclear deterrent could be maintained without nuclear explosive testing; and
- Whether it was wise to endorse a CTBT of indefinite duration.

A USNAS panel issued a report [2] in 2002 on technical aspects of these concerns. This report still has merit for tutorial purposes, but at the time it could not go very thoroughly into issues of stockpile stewardship and monitoring capability without having to make conjectures about how well new programs would turn out in practice²¹. During the Bush Administration from 2001 to 2009, though CTBT entry-into-force was not an objective, CTBT monitoring capability steadily improved as the IMS expanded and the IDC acquired more experience. US National Technical Means also improved with new stations added to the US AEDS network. Open networks of stations, acquiring data with some relevance to CTBT monitoring but operated for other purposes (e.g. earthquake monitoring, research into Earth structure, seismic hazard, and earthquake physics), grew rapidly²².

President Obama declared his support for the CTBT soon after assuming office in 2009, and his Administration requested an update of the 2002 USNAS CTBT study. After more than two years of work, with extensive input from agencies and institutions responsible for operational efforts in stockpile stewardship and nuclear explosion monitoring, the updated report was released in March 2012 [13]. The sections on stockpile stewardship and on-site inspections have been discussed in other presentations at the November 2013 APS Workshop. Conclusions of the 2012 USNAS report on monitoring capability are summarized in Figure 6, and an overview on seismic monitoring capability is in Figure 7.

²¹ In 2002 stockpile stewardship was still a new program in the National Nuclear Security Administration, and assessments of monitoring capability and capability to cheat entailed an evaluation of the nascent International Monitoring System and the International Data Centre, so assessment of capabilities in [2] was necessarily hypothetical (i.e. based upon a characterization of what could be done if systems were built and operation as planned). Ten years later, when the second US NAS report was published [13], the IMS was substantially complete for most regions around the world, and global transmission of high bandwidth data streams from hundreds of field stations to Vienna had become far cheaper and more reliable. The IDC had been able to acquire nearly full-scale operational experience at the data volumes originally contemplated.

²² For example, as of May 24, 2013, the US Geological Survey’s data center for global earthquake analysis was receiving more than 1500 channels of broadband high-quality digital seismographic data continuously in real time (personal communication from Gavin Hughes). Open stations continue to grow in number, driven in part by the occurrence of several very large and damaging earthquakes in recent years (M 9.1, Indonesia in December 2004; M 9.0, Japan in March 2011; four in the range M 8.6 to M 8.8 in the years 2005, 2007, 2010, 2012; and the M 7.9 earthquake in May 2008 in Sichuan, China, which killed more than 87,000 people). See <http://earthquake.usgs.gov/earthquakes/eqarchives/year/byyear.php> for basic information on the largest and deadliest earthquakes in recent decades.

Overview: Monitoring

The United States has technical capabilities to monitor nuclear explosions in four environments:

- * **Underground**
- * **Atmosphere**
- * **Underwater**
- * **Space**

Conclusion

Technical capabilities have improved significantly in the past decade, although some operational capabilities are at risk. Seismology now provides much more sensitive detection, identification, and location of explosions.

90 percent confidence levels for IMS seismic detection are well below 1 (kt) worldwide for fully coupled explosions.

Factoring in regional monitoring and improved understanding of the backgrounds, an evasive tester in Asia, Europe, North Africa, or North America would need to restrict device yield to levels below 1 kt (even if the explosion were fully decoupled) to ensure no more than a 10 percent probability of detection by the IMS.

3/29/2012

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES 8

FIGURE 6. Principal conclusions of the 2012 USNAS CTBT report [13] on capability to monitor nuclear explosions.

Seismic Monitoring

- Seismology is the most effective technology for monitoring underground nuclear-explosion testing. Seismic monitoring for nuclear explosions is complicated by the great variety of geologic media and the variety and number of earthquakes, chemical explosions, and other non-nuclear phenomena generating seismic signals every day.
- **Technical capabilities for seismic monitoring have improved substantially in the past decade, allowing much more sensitive detection, identification, and location of nuclear events. More work is needed to better quantify regional monitoring identification thresholds, particularly in regions where seismic waves are strongly attenuated.**

3/29/2012

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES 9

FIGURE 7. Principal conclusions of the 2012 USNAS CTBT report [13] on seismic monitoring capability.

In making assessments of whether monitoring capability is in some sense good enough to support a policy objective such as the CTBT, it is recognized that there can be the technical possibility of a nuclear explosive release so small as to be undetectable in practice by the usual monitoring assets—for example, there could be a nuclear firecracker (in a sealed chamber) with energy release at the level of just a few grams of TNT; and such an activity would be a CTBT violation if conducted by a State Party²³. But what matters from the perspective of wanting to achieve a successful arms control initiative, namely a ban on nuclear testing at yield levels thought to have significance in the context of weapons development, is that the banned activity would likely be detected if it occurred at yield levels deemed to have military significance. In this regard, it was important that the membership of the panels that produced both USNAS reports, in 2002 and 2012, included weapons designers with extensive nuclear testing experience, administrators who have been deeply involved in the development of the US nuclear arsenal, and military personnel who have had the responsibility of planning for the use of that arsenal. Most notably this experience influenced the evaluation of a variety of scenarios that have been proposed, by which, at least conceptually, the usual signals from a nuclear explosion could be concealed.

As an example of an evasion scenario, consider the possibility of preparing an underground nuclear test explosion, but not setting it off until a large earthquake took place, suitably near the test site; and then setting off the test explosion with some level of expectation that the large seismic signals from the earthquake would swamp those generated by the explosion, so that the explosion would not be detected seismically. This is the “hide-in-earthquake” scenario. On the one hand, one could evaluate such a scenario with access to available knowledge on the notoriously uncertain probability of occurrence of future earthquakes, and on the ability to detect the occurrence of a large earthquake within seconds and to estimate its location and size with high confidence (i.e., the fact that it was indeed large and sufficiently near the test site). But in practice, it is not easy to come up with a prompt estimate of the size of an earthquake that is underway²⁴. And then, in practice, it has been demonstrated that the high frequencies from an explosion can still be detected against the background of larger low-frequency earthquake-generated ground motions²⁵. Also, from a monitoring perspective, the likelihood of a release of radioactivity would not be diminished by the earthquake, and observations of such a release would lead to significant efforts to find a corresponding seismic explosion signal superposed on the earthquake signal. But also important in the overall evaluation of such an evasion scenario, are perspectives based on experience with the conduct of a nuclear test, and, furthermore, a test not just to see if a treaty could be clandestinely violated, but a test in which the objective was to acquire presumably new information on the tested device (which, if it were of new design, might have an explosive yield that prior to the test would be uncertain, with concomitant uncertainty on the strength of its seismic signals).

From the perspective of an agency charged with developing new nuclear weapons, and wanting not to be detected and labeled as a treaty violator if it attempted a clandestine test, the hide-in-earthquake scenario (with its commitment to hold a test, possibly for years, until an earthquake deemed suitable were to occur) is not attractive.

Though we have reached this point by discussion of a series of hypothetical situations, the overall conclusion with respect to this particular scenario is that CTBT monitoring capability would be a deterrent.

Of all the proposed evasion scenarios, the two deemed most serious and potentially most practical, according to the USNAS reports of 2002 [2] and 2012 [13], are those called “mine masking” and “cavity decoupling.” Thus the blasting activity associated with large-scale mining adds up to several megatons of chemical blasting agents annually, and some blasts can even get up to the 10 kiloton level. Could not a somewhat-smaller nuclear explosion be conducted nearby and at about the same time, generating seismic signals that would be obscured by those from the chemical blasting agents? This question has prompted several studies, revealing, most importantly, that the commercial goal of blasting activity is almost always to fracture rock, which is best achieved by ripple-firing practices that do not efficiently generate seismic signals [12]. Therefore, typical mine blasting simply does not provide the mask necessary to hide the signals from a significant nuclear explosion. In more detail, one must address what is meant here by significant, and attempts to do this underlie the summary

²³ Even in such cases, for a treaty violation thought likely to be undetectable by the IMS technologies, the probability of detection is never zero since intercepted communications and perhaps satellite observations can provide opportunities for discovery.

²⁴ The assessment would need to be done while signals from the earthquake were still being received, and possibly even while they were still being emitted at the source (via rupture of a large fault).

²⁵ In the period from 1957 to the 1990s, so many underground nuclear tests took place that some of them did indeed by chance occur at times when significant natural earthquake activity was underway. Such explosions were more of a challenge to detect, but they were detected.

statements made in Figure 8 by the 2012 USNAS report, concerning the capability to monitor against the possibility of evasive testing.

Evasive Nuclear-Explosion Testing I

- **An evader determined to avoid detection would test at levels the evader believes would have a low probability of detection.**
- **Mine masking is a less credible evasion scenario than it was at the time of the *2002 Report* because of improvements in monitoring capabilities.**
- **With the inclusion of regional monitoring, improved understanding of backgrounds, and proper calibration of stations, an evasive tester in Asia, Europe, North Africa, or North America would need to restrict device yield to levels below 1 kiloton (even if the explosion were fully decoupled) to ensure no more than a 10 percent probability of detection for IMS and open monitoring networks.**

3/29/2012

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES 13

FIGURE 8. Principal conclusions, part I, of the 2012 USNAS CTBT report [13], on capability to monitor evasive testing.

Of all the proposed evasion scenarios, the most widely discussed is that associated with “cavity decoupling.” If an explosion is set off in a previously-constructed underground cavity that is suitably deep and large enough for the walls to respond elastically rather than suffering non-elastic damage, then the test is said to be “fully decoupled” and almost all the explosive energy goes into pumping up the gas pressure within the original cavity. This contrasts with a tamped explosion, for which most of the energy goes into non-elastic processes such as melting and crushing rock, thus creating a new cavity which in turn leads to the generation of strong seismic signals. The seismic signals resulting from a decoupled test can be reduced significantly—by a factor usually taken as about 70—compared to their size from an underground test in which the explosive device was “well-tamped”, i.e. in solid contact with the surrounding rock²⁶. But there are layers of difficulty in executing a nuclear test explosion satisfactorily in an underground cavity sufficiently large to achieve full decoupling²⁷, and for the USNAS reports of 2001 and 2012 the panel members with practical experience in the conduct of nuclear testing contributed greatly to the overall conclusions on monitoring capability against the possibility of evasive testing, as summarized here in Figure 9, which provides the bottom line summary of monitoring capability as best it has been given today in the US as a significant effort at reaching a set of consensus statements.

²⁶ Early theoretical estimates gave values larger than 70. The limited experience with field experiments tends to give smaller values.

²⁷ A fully-decoupled test is defined as one that does not take the cavity walls beyond their elastic limit. To achieve full decoupling in hard rock the radius of a spherical cavity would need to be on the order of 25 meters per cube root of the yield in kilotons (thus a cavity of 50 meters radius in order to fully-decouple eight kt).

Evasive Nuclear-Explosion Testing II

- **For IMS and open monitoring networks, methods of evasion based on decoupling and mine masking are credible only for device yields below a few kilotons worldwide and at most a few hundred tons at well-monitored locations.**
- **The States most capable of carrying out evasive nuclear-explosion testing successfully are Russia and China. Countries with less nuclear-explosion testing experience would face serious costs, practical difficulties in implementation, and uncertainties in how effectively a test could be concealed. In any case, such testing is unlikely to require the United States to return to nuclear-explosion testing.**

3/29/2012

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES 14

FIGURE 9. Principal conclusions, part II, of the 2012 USNAS CTBT report [13] on capability to monitoring evasive testing.

I conclude by noting that monitoring capability continues to improve, due to the growth in numbers of stations acquiring relevant data streams, and due to the development of better analysis of available data. Unfortunately, history shows that the prospect of such future improvements has sometimes been the basis for putting off decisions on whether to go ahead with specific steps towards a declared arms control objective, rather than providing part of a rationale for actually taking those steps.

Indeed, the perfect can be the enemy of the good.

ACKNOWLEDGMENTS

I thank many colleagues who have helped my understanding of seismic monitoring over the last forty years, most especially Lynn Sykes, Won-Young Kim, David Schaff, and Felix Waldhauser, all of them colleagues at Lamont; and John Filson of the US Geological Survey. Thanks also to David Hafemeister and Pierce Corden for advice on this paper. This is Lamont-Doherty Earth Observatory contribution number 7755.

REFERENCES

1. D. M. Kerr, writing in *Nuclear Weapons Tests: Prohibition or Limitation?*, edited by Jozef Goldblat and David Cox, Oxford University Press, SIPRI monograph, 1988.
2. Committee on Technical Issues Related to Ratification of the Comprehensive Nuclear-Test-Ban Treaty, *Technical Issues related to the Comprehensive Nuclear-Test-Ban Treaty*, National Academy Press, available via http://www.nap.edu/catalog.php?record_id=10471, 2002.
3. D. P. Schaff, W.-Y. Kim, and P. G. Richards, Seismological Constraints on Proposed Low-Yield Nuclear Testing in Particular Regions and Time Periods in the Past, with Comments on “Radionuclide Evidence for Low-Yield Nuclear Testing in North Korea in April/May 2010” by Lars-Erik De Geer, *Science & Global Security*, v. 20, pp155–171, 2012.
4. S. C. Myers, M. L. Begnaud, S. Ballard, M. E. Pasyanos, W. S. Phillips, A. L. Ramirez, M. S. Antolik, K. D. Hutchenson, J. J. Dwyer, C. A. Rowe, and G. S. Wagner, A Crust and Upper-Mantle Model of Eurasia and North Africa

- for Pn Travel-Time Calculation, *Bulletin of the Seismological Society of America*, v. 100, pp 640–656, 2010, doi:10.1785/0120090198
5. P. G. Richards, F. Waldhauser, D. P. Schaff, and W.-Y. Kim, The Applicability of Modern Methods of Earthquake Location, *Pure and Applied Geophysics*, v. 163, pp351–372, 2006, and F. Waldhauser and D. P. Schaff, Large-scale Relocation of Two Decades of Northern California Seismicity using Cross-Correlation and Double-Difference Methods, *Journal of Geophysical Research*, v. 113, doi:10.1029/2007JB005479.
 6. See the cover, or Figure 12.1, of K. Aki and P. G. Richards, *Quantitative Seismology*, University Science Books, 2002 or 2009.
 7. P. G. Richards and Z. Wu, Seismic Monitoring of Nuclear Explosions, in *Encyclopedia of Solid Earth Geophysics*, ed. Harsh Gupta, Encyclopedia of Earth Sciences Series, pp 1144–1156, Springer: Dordrecht, The Netherlands, 2011.
 8. W.-Y. Kim, D. W. Simpson, and P. G. Richards, Discrimination of Earthquakes and Explosions in the Eastern United States using Regional High-Frequency Data, *Geophysical Research Letters*, v. 20, pp 1507–1510, 1993.
 9. P. G. Richards and W.-Y. Kim, Commentary: Seismic Signature, *Nature Physics*, **3**, 4–6, January 2007, and W.-Y. Kim and P. G. Richards, North Korean Nuclear Test: Seismic Discrimination at Low Yield, feature article in *EOS, Transactions of the American Geophysical Union*, **88**, no. 14, pages 157 and 161, 3 April 2007.
 10. M. E. Pasyanos, S. R. Ford, and W. R. Walter, Testing Event Discrimination over Broad Regions Using the Historical Borovoye Observatory Explosion Dataset, *Pure and Applied Geophysics*, pp 1–13, also <http://dx.doi.org/10.1007/s00024-012-0591-4>, September 2012.
 11. M. E. Pasyanos and W. R. Walter, Improvements to Regional Explosion Identification Using Attenuation Models of the Lithosphere, *Geophysical Research Letters*, v 36, 5 p, doi:10.1029/2009GL038505, 2009.
 12. V. I. Khalturin, T. G. Rautian, and P. G. Richards, The seismic signal strength of chemical explosions, *Bulletin of the Seismological Society of America*, v 88, pp1511–1524, 1998, and A. T. Smith, Discrimination of explosions from simultaneous mining blasts, *Bulletin of the Seismological Society of America*, v 83, pp 160–179, 1993.
 13. US National Academy of Sciences, *The Comprehensive Nuclear Test Ban Treaty: Technical Issues for the United States*, the National Academies Press, released March 2012 and available via http://www.nap.edu/catalog.php?record_id=12849, 2012.
 14. F. Ringdal, P. D. Marshall, and R. W. Alewine, Seismic Yield Determination of Soviet Underground Nuclear Explosions at the Shagan River Test Site, *Geophysical Journal International*, v 109, pp 65–77, 1992, and J. R. Murphy, Types of Seismic Events and their Source Descriptions, in *Monitoring a Comprehensive Nuclear Test Ban Treaty*, NATO ASI Series, eds. E. S. Husebye and A. M. Dainty, pp 225–245, Kluwer Academic Publishers, 1996.
 15. See <http://www2.gwu.edu/~nsarchiv/NSAEBB/NSAEBB7/nsaebb7.htm> for documents on US AEDS, and a detailed history of the early years of AEDS operations given by C. A. Ziegler and D. Jacobson, *Spying Without Spies; Origin of America's Secret Nuclear Intelligence System*, Praeger, 1995.
 16. D. Bowers and W. R. Walter, Discriminating between Large Mine Collapses and Explosions Using Teleseismic P waves, *Pure and Applied Geophysics*, v 37, pp 209–236, 2009.
 17. O. Dahlman, S. Mykkeltveit and H. Haak, *Nuclear Test Ban: Converting Political Visions to Reality*, Springer, 2009, O. Dahlman, J. Mackby, S. Mykkeltveit and H. Haak, *Detect and Deter; Can Countries Verify the Nuclear Test Ban?*, Springer, 2011, and A. Douglas, *Forensic Seismology and Nuclear Test Bans*, Cambridge University Press, 2013.
 18. D. Bowers and N.D. Selby, Forensic Seismology and the Comprehensive Nuclear-Test-Ban Treaty, *Annual Reviews of Earth and Planetary Sciences*, v. 37, pp 209–236, 2009, P. G. Richards and W.-Y. Kim, Monitoring for Nuclear Explosions, *Scientific American*, **300**, 70–77, March 2009, and [7].
 19. Two of my own presentations are on-line at <http://www.youtube.com/watch?v=byOgfBfnZVQ> (2009) and at http://www.youtube.com/watch?v=lhQCNF3_vaA (2013). An excellent short movie by Isao Hashimoto illustrating the global and temporal range of nuclear explosive testing in the 20th century is at <http://www.youtube.com/watch?v=cjAqR1zICA0>. The CTBTO maintains excellent resources including many lectures accessible via iTunes—as described at <http://www.ctbto.org/specials/ctbt-educational-resources/>
 20. For papers give at the US Monitoring Research Review of 2011, see <http://www.osti.gov/scitech/biblio/1027453>; and for 2010, see <http://www.osti.gov/scitech/biblio/1027452>. For papers given at recent Science and Technology conferences organized by the CTBTO in Vienna, see <http://www.ctbto.org/the-organization/science-and-technology-the-conference-series/>
 21. http://www.state.gov/www/global/arms/ctbtpage/ctbt_report.html