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The Comprehensive Nuclear-Test-Ban Treaty (CTBT): seismic monitoring

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Abstract. The Comprehensive Nuclear-Test-Ban Treaty (CTBT) is briefly characterized as a global arms control and disarmament initiative, which complements the goal of the Non-Proliferation Treaty (NPT). The verification regime of the CTBT is designed to monitor countries' compliance with the CTBT by detecting any nuclear explosion conducted on Earth - underground, underwater or in the atmosphere. This paper briefly goes through the International Monitoring System (IMS) of CTBT's verification regime that uses four different technologies - seismic, hydroacoustic, infrasound and radionuclide - to monitor the planet for nuclear explosions. It pays particular attention to the seismology monitoring techniques of CTBT IMS, including the practical steps in discriminating underground explosions and earthquakes using data mainly from the IMS seismic network. It also highlights the seismic analyses performed by the Malaysian CTBT National Data Centre (MY-NDC) that in principle, applies the practical steps of CTBT nuclear explosion seismology monitoring. In summary underground explosions produced seismic waves with unique characteristics which allowed the discrimination between explosions and earthquakes.

1. Introduction

After a half century nuclear weapons were developed, tested, and used, the Comprehensive Nuclear Test Ban Treaty (CTBT) banned all nuclear weapon test explosion or any other nuclear explosion, has been negotiated and opened for signature in September 1996. The underlying goal of the CTBT is to inhibit the further development of more sophisticated nuclear weapons, thus complementing the goal of the Non-Proliferation Treaty (NPT) that inhibits the spread of nuclear weapons (horizontal proliferation) [1]. As of November 2018, the CTBT has been signed by 183 nations and ratified by 166. The Treaty, however, cannot enter into force until it is fully ratified by 44 specific nations listed in the Annex II of the Treaty. Eight of which have yet to do so – China, Egypt, India, Iran, Israel North Korea, Pakistan and the United States.

Article IV of the Treaty elaborates on the global verification regime to monitor compliance with Treaty provisions. The Treaty establishes an extensive verification regime that is designed to monitor phenomena worldwide so as to detect the occurrence of nuclear explosions anywhere – be it underground, underwater or in the atmosphere, and to facilitate the resolution of ambiguous events. The breadth of its coverage is intended to create a significant deterrent against possible efforts to evade the ban on testing [2]. This verification regime consists of the following six elements:

- International Monitoring System (IMS)
- International Data Centre (IDC), iii)
- Global Communications Infrastructure (GCI)
- Consultation and clarification
- On-Site Inspection (OSI), and
- Confidence-building measures.

Article IV also provides that the verification regime shall be capable of meeting the requirements of the Treaty when it enters into force. This requires a substantial program of preparation in advance of the Treaty's entry into force. To make such necessary preparations, the Preparatory Commission for the CTBT Organization (CTBTO) was established in 1997, made up of CTBT States Signatories and supported by a Provisional Technical Secretariat (PTS). The key tasks of the CTBTO include the establishment of IMS, IDC in Vienna, GCI, as well as complete procedures for the operation of those facilities and for the conduct of OSI where concerns are raised about a possible nuclear explosion [3].

2. International Monitoring System (IMS)

The IMS uses four complementary verification methods, utilizing the modern technology available – seismic, hydroacoustics, infrasound and radionuclide technologies. Seismic, hydroacoustic and infrasound stations monitor the underground, the large oceans and the atmosphere respectively. Radionuclide stations detect radioactive debris from atmospheric explosions or vented by underground or underwater nuclear explosions. In addition, radionuclide laboratories assist radionuclide stations in identifying these radioactive substances [4].

The IMS is designed to be non-discriminatory and does not single out any country or region for enhanced monitoring [5]. There more than 300 IMS stations built worldwide to monitor the planet for any sign of a nuclear explosion. Data from these stations are transmitted to the IDC in Vienna through the GCI, a global private data network, which is largely based on satellite links. As stated in the Treaty, States Parties will have equal and direct access to all IMS data, raw or processed, for verification as well as civilian uses. However, also as stated in the Treaty, the responsibility for determining Treaty compliance and judgements about the nature of events detected by the IMS network rest with the States Parties, not with the CTBTO. Thus, States Parties can utilise IMS data, along with any additional sources of objective information available to them, to monitor the Treaty compliance [6].

The IMS network provides generally uniform coverage across the globe, and when completed, it will consist of:

- 50 primary and 120 auxiliary seismic monitoring stations to monitor shockwaves in the earth that could be caused by a nuclear test
- 11 hydro-acoustic stations listening for sound waves traveling through the oceans that could be caused by a nuclear test explosion
- 60 infra-sound stations on the earth's surface will be able to detect ultra-low frequency sound waves caused by large explosions – these sound waves are inaudible to the human ear.
- 80 radionuclide stations using air samplers to detect radioactive particles released from atmospheric explosions and/or vented from underground or under-water explosions
- 16 radionuclide laboratories for analysis of samples from the radionuclide stations

3. CTBT seismic monitoring

A seismic event, either from a natural earthquake or manmade explosion, generates body waves or compressional waves (P-waves) and surface waves or shear waves (S-waves) that are potentially detectable by wave sensors of infrasound, hydroacoustics, and seismic. Both P-waves and S-waves signals are crucial for the analysis of a suspicious Treaty-violation event. They provide essential information on the location, strength and nature of an event. P-waves are primary waves that alternately compress and expand the ground in the direction of the wave's propagation. They are the fastest travelling wave and can move through any material. S-waves are secondary waves in the ground that move perpendicular to the direction of the wave's propagation. They travel along the surface of the Earth are slower than P-waves waves and can only move through solids as this kind of movement is impossible in liquid or gaseous materials [7].

The direction from which the waves were emitted can be identified through the measurement of the azimuths of P-waves and S-waves. Since both waves travel at different speeds, it is also possible to determine the distance to the source by measuring different arrival times of the waves. During analysis, surface wave measurements help to identify the depth and magnitude of an event.

The Treaty calls for two global seismic monitoring networks – a primary seismic network with 50 stations and an auxiliary one with 120 stations. The stations of the primary seismic network transmit continuous authenticated data within 5 minutes of being recorded to the IDC in Vienna which is used in automatic processing. The auxiliary seismic network takes advantage of existing seismic stations which are being upgraded to meet the IMS technical standards, and do not send data in real time but upon request only.

4. The practical steps of CTBT nuclear explosion seismology monitoring

Practically, the CTBT nuclear explosion seismology monitoring can be organized in six practical steps as described in Table 1.

Detection of seismic resulting from either natural or man-made event is typically done with arrays of sensors (or seismometers) deployed as a group and spread out over an area, which can be on the order of tens or hundreds of square kilometres. Data recorded by the arrays can be interpreted to estimate the direction from which signals arrive.

Association is the process to identify sets of signals recorded from different stations, which originate from the same event. In such cases, data collected by arrays will provide directional information that is helpful in resolving which signals correspond to which event.

Table 1. The six practical steps of CTBT nuclear explosion seismology monitoring.

	Steps	Objective
1	Detection	Detects signals recorded by each sensor of a particular network
2	Association	Associate into a single group the various signal recorded by different sensors that originate from a common source/event
3	Location estimation	Estimate the location and time of that event and the uncertainty of the location estimate
4	Identification	Identify the nature of the event—whether suspicious or not in the context of CTBT monitoring
5	Yield estimation	Estimate how big was the event
6	Attribution	Determine what country carried it out if it was a nuclear test

Location estimation is needed for all the events for which a set of detections can be associated, since an interpretation of the location (including the event depth) is commonly used to reach preliminary conclusions on whether an event could possibly be an explosion [8]. Location estimation of the event is performed by measuring the arrival times of various seismic signals from the recorded waveforms. The identified arrival times are then used to estimate the latitude, longitude, depth, and origin time of each detected event. For any type of seismic wave that the station might observe, it is important to know the travel time from any assumed source-location to any particular seismographic station. The source-station distance and azimuth can be roughly estimated from data at a single station. The accuracy of a location estimate is best characterized with a confidence interval. Typically, detections at three or more stations are needed for confidence intervals to be calculated.

As mentioned earlier, the primary seismic stations send continuous near-real-time data to the IDC in Vienna. The IDC will search for signals of potential Treaty violation from these continuous waveform data of primary seismic, where lists of detections are formed. These detections are then associated with events, and the event location, depth, and origin time, including other associated parameters, such as magnitude, are estimated. The IDC will distribute those seismic data and derived products to States that are party to the Treaty [9]. The IDC is also required by the Treaty to routinely screen-out events considered to be consistent with natural phenomena or non-nuclear, man-made phenomena.

Identification is performed once the detections from a seismic event have been associated and an accurate location estimate has been obtained. The identification of the nature of a seismic event on the basis of its seismic signals is a process of making a determination from seismograms as to whether it could be a nuclear explosion, or a natural earthquake, or a manmade event. This process involves a large subject in view of the many possibilities as seismic event generate many different types of seismic waves, in various different frequency bands. Discriminating between earthquakes and explosions are performed based on interpretation of the event location, including its depth, on the relative excitation of a variety of P-waves and S-waves; and on properties of the signal spectrum associated with each of these two different types of source. With regard to these three broad categories, many different methods have been tried, with various degrees of success. No single method of event identification based on seismological data is fool proof, but in combination these methods have proven highly reliable [1].

In addition 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) to monitor effectively for large explosions, there has been growing recognition of the merits of regional seismic waves (i.e. those propagating at shallower levels) for monitoring down to lower magnitudes explosions, often well below magnitude three (3). 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. The method has been applied by many authors to seismic signals recorded from the three nuclear explosions conducted in the 21st century by North Korea. Figure 1 shows an example of comparing regional signals of a very small earthquake and a small explosion [10].

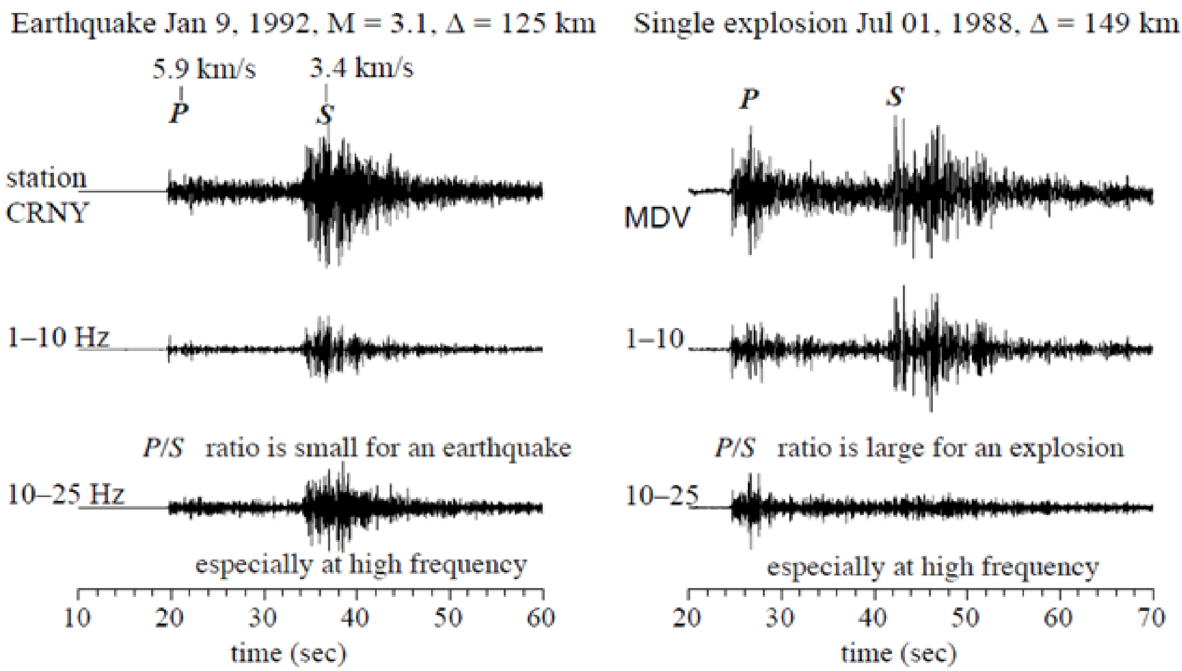

Figure 1. Typical vertical-component records from an earthquake and an explosion. Traces plotted are: (top) unfiltered; (middle) low-frequency bandpass filtered; and (bottom) high-frequency bandpass filtered. Arrivals of P and S waves are shown on the unfiltered traces [10].

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Since the CTBT bans nuclear explosive testing at all levels of yield, thus, all tests are violations. The capability to estimate yield, however, does not directly arise in the limited context of deciding whether or not a detected test would be a treaty violation. The interest in yield estimation is generally because of the need to interpret a characterization of seismic monitoring capability expressed in terms of seismic magnitude, to a monitoring capability expressed in terms of explosive yield. Estimating the size of a detected event in terms of nuclear yield could be derived from seismic magnitude [11]. A single relationship between magnitude and yield does not exist as explosions of a given yield generate different amplitudes and magnitudes of seismic waves depending upon:

- the efficiency of seismic wave propagation from source to recording station,
- the rock type at the source,
- depth of the explosion, and
- whether the explosion is well coupled or decoupled.

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

$$mb = A + B\, log(Y) \tag{1}$$

where Y is in kilotons, and A and B are constants that depend on features 1) to 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 [12].

Attribution denotes the ability of States Parties to identify the nation or organization responsible for a nuclear explosion, if it has been identified. In the CTBT context, attribution can occur in three generic ways either alone or in combination:

- National Technical Means (NTM) or intelligence assets identify the nation or organization associated with the explosion;
- the identified explosion occurs at a location that can be demonstrated to be under the control of a particular nation or organization; and/or
- analysis of the debris from an identified event reveals characteristics that can be associated with a specific nation or organization.

In principle, each of these steps or any combination of them for the attribution process is possible. It requires the development of analytical processes and data bases.

The responsibility of identification, yield estimation and attribution, within the context of the CTBT, are left to each State Party. This is because of the serious consequences of concluding that a nuclear test has taken place; and that it occurred on the territory of a particular nation [13]. There are likely to be strong technical components associated with making such calls. In this regard, the IDC assists States Parties by carrying out standard analytical procedures (screening) to screen out those events that could not be nuclear explosions. The CTBT Protocol indicates that the IDC may apply "standard event screening criteria" based on "standard event characterization parameters". If the IDC can screen out most events, the State Parties then can give more attention on the remainder. 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 eliminates events confidently estimated as deeper than 10 km.

For verification purpose, using seismic data alone, however, cannot be the only basis for verifying that a nuclear explosion has taken place. Only the measurement of relevant radionuclides from radionuclide monitoring technology can provide the 'smoking gun' that provides positive confirmation of nuclear explosion [14]. For example, 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.

5. Application of practical steps for CTBT nuclear explosion seismology monitoring by MY-NDC

MY-NDC, which was established in December 2005, is tasked to perform the CTBT data management and provide relevant information on CTBT related events to the Malaysian Nuclear Agency (Nuklear Malaysia), the CTBT National Authority [15]. In carrying out CTBT seismic monitoring and analysis, MY-NDC in principle applying most of the practical steps discussed above.

Taking MY-NDC participation in the National Data Centre Preparedness Exercise 2015 (NPE2015) as an example, MY-NDC has applied those practical steps to monitor seismic events occurring in the region of fictitious State of ENPEDOR from 1st October until 30th November 2015. The seismicity in the fictitious State of ENPEDOR was investigated in detail to identify the nature of the events, either as natural or induced within the specified time interval.

As for location estimation, Figure 2 illustrates the location of seismic event in ENPEDOR on 15th October 2015 at 08:05:44.3 UTC using data from three IMS seismic stations, namely FINES, AKASG and GERES. Subsequently, as for the identification step, Figure 3 shows the comparison of spectral characteristics of recorded seismic signal on 15th October 2015 (08:05:44.3 UTC) with the past earthquake recorded in the same location on 16th August 2015 and the seismic signal generated from underground explosion detected at seismic station of GERES. It shows low signal of P-waves that often recorded by an earthquake event, instead of high signal of P-waves of underground explosion event. However, since the event is also recorded a low magnitude, verifying the nature of the event whether it is an earthquake or explosion is even more complicated. On that basis, the association of seismic event with underground explosion could not be completely ruled out [16].

To estimate the yield of explosion, MY-NDC use the following formula proposed by L.R. Syres et.al which draw the relationship between seismic magnitude and yield of nuclear explosion [17].

$$mb = 4.262 + 0.973\, log(Y) \quad (2)$$

where, *mb*: Richter seismic scale, and *Y*: yield of nuclear explosion (kt).

The International Seismic Centre has recorded a reading of 3.1 on the Richter scale for that seismic event. A reading of 3.1 would correspond to an explosive yield of between 0.06 and 0.07kt of Trinitrotoluene (TNT) - equivalent, according to the above equation. TNT is a chemical compound, also known as trinitrotoluene, and is commonly used as an explosive for military and industrial applications. The explosive yield of TNT is considered the standard measure of strength of bombs and other explosives.

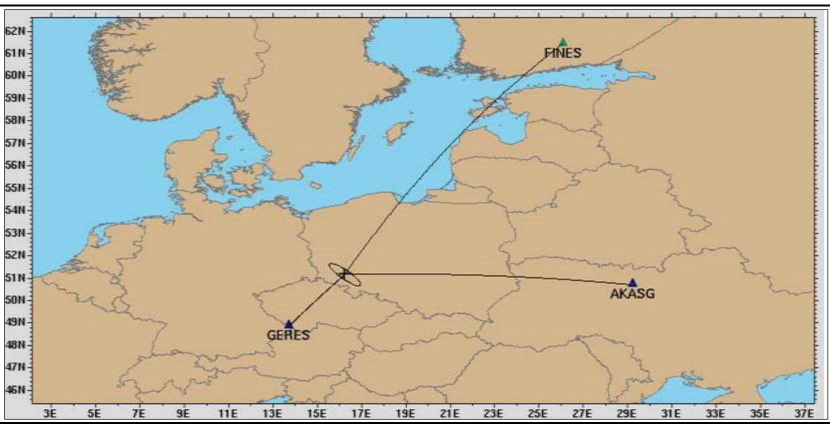

Figure 2. Location of seismic event in ENPEDOR on 15th October 2015 at 08:05:44.3 UTC using data from three IMS seismic stations.

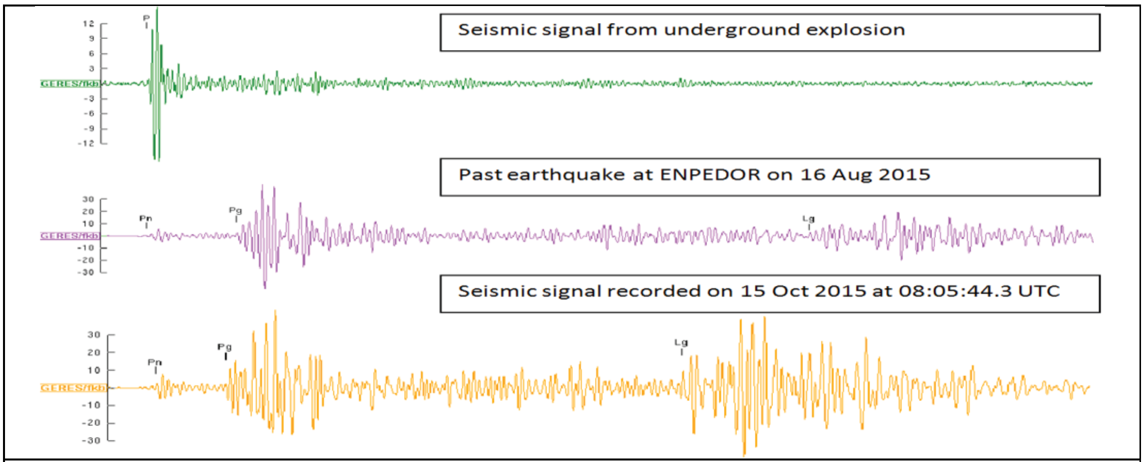

Figure 3. Comparison of seismic signals from explosion event (top), past earthquake at ENPEDOR (middle), and event recorded on 15th October at 08:05:44.3 UTC (bottom) detected at seismic station GERES.

Site forensic was carried out the get an insight of the seismic location. From site forensic, MY-NDC found that the seismic location is within fault zone and has a history of numerous seismic activities. In addition, there are also huge active mining activities within that area, which could involve man-made explosion activity. Several geological researches are being conducted at that area to study mining-induced seismic event.

MY-NDC preliminary concluded that the results of NPE2015 revealed that the seismic event recorded on 15th October 2015 at 08:05:44.3 UTC is most likely the origin of reported radionuclide release. Due to low magnitude event, MY-NDC could not rule out the association of seismic event with underground explosion. The detection of numerous relevant radionuclides and radioxenon isotopes suggest that the event is indeed a nuclear explosion, and not related to release from nuclear reactor event [16].

6. Summary

In summary, underground explosions produce seismic waves with unique characteristics which allow the discrimination between explosions and earthquakes. The CTBT nuclear explosion seismology monitoring can be organized into six practical steps. The monitoring and discrimination 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.

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