Chapter 12

Science and Technology for Putting an End to Nuclear Explosions

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Dear Distinguished Ladies and Gentlemen,

Thank you for inviting me to be here with you for the XXI Eduardo Amaldi Conference in the beautiful facilities of the Accademia Nazionale Dei Lincei. The Comprehensive Nuclear-Test-Ban Treaty, the CTBT, was designed to establish a mechanism to monitor and verify the cessation of all nuclear explosions—to help humanity put an end to the grave consequences of nuclear explosions. As the Director of the International Data Center Division of the CTBT Organization (CTBTO), or the Provisional Technical Secretariat (PTS) as it is commonly referred to, I'm delighted and honoured to engage with this scientifically and politically elite group of experts to elaborate on a few of the CTBTO's most significant science and technology pursuits in the context of putting an end to nuclear explosions.

The nuclear test ban became comprehensive more than three decades after the adoption of the 1963 Partial Test Ban Treaty, which had banned nuclear weapons tests in the atmosphere, in outer space and underwater. In the 1990s, the global community sought to achieve the discontinuance of all test explosions in all environments, including underground for all time. The CTBT opened for signature and ratification 23 years ago. Annex II of the treaty specifies the signature and ratification by a mandated set of 44 nations who all possessed nuclear reactors in 1995. Eight nations remain of the 44 mandated who must either ratify or sign and ratify the treaty to enter into force. Currently the treaty has 184 signatories and 168 ratifications.

The CTBT is a treaty rooted in the recognition that the cessation of all nuclear explosions is a requisite to nuclear disarmament and non-proliferation. In the preparations for the 2020 NPT Review Conference the international community could chose to concentrate their efforts on issues of broad common agreement, such as the CTBT. As the statements of support towards the CTBT showed in the May 2019 NPT PrepCom in New York, there are shared beliefs and principles about a large set

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of security and humanitarian consequences of nuclear testing and about the necessity of preventing their use.

The CTBT is an instrument supported by a technology-led verification regime. Scientific technologies are essential for verification of nuclear non-proliferation and disarmament. The CTBT Verification Regime Elements established in Article IV of the treaty are as follows:

- *The International Monitoring System (IMS)* of 321 stations that include seismic, hydroacoustic, infrasound, radionuclide components, the International Data Centre (IDC), and the Global Communications Infrastructure.
- *Consultation and Clarification* to allow State Signatories the right to seek clarification on matters that indicate the possibility of non-compliance with the Treaty following entry-into-force.
- *On-Site Inspection* to provide for the ability to conduct on-site verification activities if a nuclear detonation is suspected by States Signatories. The on-site inspection regime is designed to confirm on the ground whether a nuclear explosion has taken place. The PTS can build the capacity to perform these on-site inspections and test our preparedness, but no on-site inspection will take place until the treaty has entered into force.
- And finally, *Confidence Building Measures* intended to strengthen CTBTO capabilities, prevent misinterpretations and allow for better calibration of the stations of the IMS.

The IMS will ultimately be made up of 337 facilities, 321 of which are monitoring facilities and 16 radionuclide laboratories. These facilities are located around our earth and they collect and transmit data to the IDC for processing and analysis. The IMS is more than 91% complete at this time with 44 of 50 primary seismic stations, 108 of 120 auxiliary seismic stations, 11 of 11 hydro-acoustic stations, 51 of 60 infrasound stations and 71 of 80 particulate radionuclide stations certified. Forty of the radionuclide stations will have noble gas detection capabilities once the IMS is fully constructed. Since 2012, 25 noble gas systems have come online, been certified and are sending data to the IDC. Thirteen of sixteen radionuclide labs are currently operational and certified.

In summary, today the IMS is comprised of 297 certified facilities, including radionuclide laboratories. There are nine installed facilities that are not yet certified for operations, six facilities under construction, and 25 planned facilities for the total of 337 IMS facilities. The precise location of each facility was envisioned by the treaty negotiators between 1993 and 1996. The locations were selected based on optimal global coverage. Scientific communities from around the world were heavily involved in site selection optimization. Figure 12.1 is a current map of the IMS.

The charge of the PTS in the context of the data generated from the monitoring facilities is to receive, collect, process, analyse, report on and archive the data from the IMS, and to provide States Parties with open, equal, timely and convenient access to all IMS data, raw or processed, and all IDC products. The PTS also provides technical assistance to individual States Parties whenever this assistance is requested.

Fig. 12.1 Map of the International Monitoring System (IMS)

To accomplish the above, the PTS established the Global Communications Infrastructure (GCI) to provide a massive communications system, which utilizes nine geostationary satellites to bring data from the IMS facilities to the PTS in Vienna, Austria. The communications network also transmits data to the National Data Centres (NDCs) operated by the States Signatories. This allows the States Signatories to draw an independent conclusion on the nature of events picked up by the system and ultimately determine whether it was a nuclear explosion. Approximately 14 terabytes of data per year is transmitted through GCI making the CTBT second to none when it comes to monitoring and understanding our planet. This communications infrastructure is key to the operation and security of data from the IMS. The current GCI satellite coverage is summarized in Fig. 12.2. The GCI is in its third 10-year contract (GCI III). GCI III is operated by Hughes Network Services.

I just mentioned the four technologies that allow the CTBT to detect nuclear explosions—seismic, hydroacoustic, infrasound, and radiation detection. Tens of thousands of naturally occurring events affect our planet each day. To date the PTS has characterized nearly 600,000 events. Figure 12.3 provides a summary of all PTS relevant nuclear detonations between 2000 and 2018.

With that as an overview to establish some practical and political background of common interests, let me narrow in on the operations of the IMS led by the IDC Division of the PTS. I would like to share two specific examples of CTBT global contributions that illuminate our science-based technology capabilities. After that, I will summarize one example of science and technology needs required to continue to advance our progress in nuclear event detection.

I have the honour to lead the IDC in Vienna as Director where about 100 analysts, scientists, engineers, specialists, technicians, administrators and leaders navigate the IMS data to monitor for nuclear explosions and report on all relevant energetic events

Fig. 12.2 GCI III global satellite coverage

Fig. 12.3 Events totalling 577,573 located by the IDC between 2000 and 2018

to our States Signatories. The IDC staff also steward capacity building programs designed to strengthen national and regional capacity to promote understanding of these unique data and apply them for verification purposes, disaster management capabilities and sustainable development.

The first global contribution highlight I offer is the PTS leadership provided following the Japan earthquake of 11 March 2011, which resulted in a massive tsunami that led to the Fukushima Daiichi Nuclear Power Plant accident. The earthquake was a magnitude 9 event and generated 9800 aftershocks. Figure 12.4 shows the event (represented by the black star) and the 9800 aftershocks. Infrasound signals generated in Japan were seen at station I44RU in Kamchatka. Figure 12.5 illustrates

Fig. 12.4 Japan Earthquake 11 March 2011; magnitude 9 earthquake and 9800 aftershocks

the infrasound signatures. Importantly, radioactivity released from the Fukushima Daiichi Nuclear Power Plant was detected worldwide by the IMS and then characterized by IDC analysts. Figures 12.6 and 12.7 show the atmospheric dispersion of a standard radioactivity release from the accident and the specific radionuclide detections at the closest IMS station, respectively.

The PTS cooperation in the global response to the Fukushima accident was notable. We were the only organization in the world to possess the ability to measure radionuclides continuously at the global scale. Our results were used by States Signatories as well as UN organizations to prioritize response activities and understand potential public health consequences.

Fig. 12.5 Infrasound signals generated in Japan on 11 March 2011 by earthquakes and tsunami as seen at I44RU (Kamchatka)

Fig. 12.6 An illustration of atmospheric transport modelling that portrays release of radiation from the Fukushima Daiichi Nuclear Power Plant accident

Fig. 12.7 Nuclide detections measured over time following the Fukushima accident measured from radionuclide station RN38 located in Japan

Fig. 12.8 DPRK test 1 conducted on 9 October, 2006 as detected by 22 IMS stations globally

Fig. 12.9 Historical seismicity in the region of DPRK test site

The second highlight that illustrates the significance of PTS capabilities is the significant analysis of the Nuclear Testing Program carried out by the Democratic People's Republic of Korea (DPRK), which has announced a total of six nuclear tests. The first test was conducted on 9 October 2006. Twenty-two IMS stations detected the test as illustrated in Fig. 12.8. History had provided a glimpse into the seismicity of the region near the test site. On 16 April 2002 an earthquake was characterized in the region. This earthquake provided strong comparison waveform data to evaluate against the test of 9 October 2006. Figure 12.9 summarizes the proximity of the earthquake location and the test event location.

Following the event, IDC analysts began examining the data from IMS monitoring stations. Figure 12.10 provides a tutorial of the distinction between an explosion, which generates a spherically symmetric propagation of shock waves (P waves),

Fig. 12.10 Data characteristics for explosion versus earthquake

Fig. 12.11 Comparison of data characteristics between an explosion and an earthquake in the region of the DPRK test site

and an earthquake, which generates both P- and shear waves owing to a substantially more complex double-couple mechanism. The resultant distinction between the seismograms is illustrated in the right half of Fig. 12.10. The seismogram for the earthquake is illustrated in blue and shows propagation of large surface waves as well as emergent arrivals. The seismogram for the explosion is illustrated in red and shows a sudden, impulsive onset, but lacks the later surface wave characteristics. Figure 12.11 illustrates the seismogram results for the 9 October 2006 nuclear test in comparison to the 16 April 2002 presumed earthquake.

IDC software automatically processes metadata that arrives from monitoring stations. The primary purpose of the software is to help eliminate events that are clearly of natural origin. Key screening criteria are applied. One important criterion is a comparison between surface wave magnitude (M_s), waves that travel along the surface of the earth, and body wave magnitude (m_b), waves that travels down into the earth's core. M_s and m_b are both measures of the amount of energy released and are recorded as amplitude of wavelength, in other words, the amplitude of the waveform signal.

Ms:mb criterion
to distinguish
between
explosions and
earthquakes

Fig. 12.12 Analysis characteristic criteria to distinguish between explosions and earthquakes

Fig. 12.13 Summary overview of all DPRK seismic events

As a result of the difference between M_s and m_b , explosion signals show an m_b/M_s ratio larger than that for earthquakes. Figure 12.12 illustrates a large data set from 2016 comparing four different sets of data categories stemming from the data characteristics.

To conclude the highlights of significant global PTS contributions, please see Fig. 12.13, which represents a summary of the six DPRK tests. Note that two of the tests generated radionuclide (specifically radioxenon) detections—the first DPRK test in 2006 and the 2013 third DPRK test. I'll speak more about these radioxenon detections as I begin discussing our science and technology needs example.

Before I transition to this example however, I would like to emphasize the CTBTO's readiness to make available our assets and expertise to contribute to DPRK denuclearization should the opportunity present itself. The three main areas the PTS could contribute to are:

- test site closure verification support activities,
- verification of a nuclear test moratorium

- and signature and ratification of the CTBT by the DPRK, which is one of the remaining 8 States required to adhere to the treaty.

Through any of these three areas, the CTBTO and its verification regime have the clear potential to contribute to the denuclearization of the DPRK. Other massive responsibilities such as removal of fissionable material and dismantlement of an actual nuclear arsenal fall well outside the mandate of the CTBT and the expertise of PTS staff capabilities.

The area of science and technology need that I would like to highlight for you today is associated with the noble gas technology. Radiation-based technologies provide rich research and development collaboration opportunities with scientists around the world. The two CTBTO radiation technologies, radioactive particle and noble gas detection, are the means by which we confirm that an event is verifiably a nuclear one. We are constantly looking for the presence of one or more of 87 anthropogenic radionuclides. Exposed to prevailing winds, radiation is dispersed in the atmosphere and may, after a certain period of time, be detected thousands of kilometers away from an explosion site. The objective of the CTBTO's radionuclide monitoring network is to detect residual radiation even if only in minuscule amounts. Our network of laboratories supports the radionuclides stations around the world.

Following the first DPRK test, PTS researchers carefully reviewed xenon data, specifically ^{133}Xe , according to meteorological predictions that forecasted where the air mass originating from the test site would be moving around the earth. The researchers narrowed in on the Yellowknife, Canada (CAX16) noble gas equipped radionuclide station. This station was impacted by noble gas background concentrations generated from the Chalk River Laboratories (CRL) in Canada. In October of 2006 a xenon emission became obvious that was not related to CRL. Background xenon was at a low point during this time period and atmospheric transport modelling, assuming an emission of 1PBq of ^{133}Xe from the 9 October 2006 nuclear test corresponded well with the detection observation. The first IMS radioxenon detection from a nuclear detonation was verifiably identified by the IDC analysis.

The only other strong evidence of IMS radioxenon detection of a nuclear test came following the 12 February 2013 DPRK third nuclear test. Stations RN38 (Takasaki, Japan) and RN58 (Ussuriysk, Russia) showed spikes in radioxenon concentrations more than 50 days after 12 February 2013. The nuclear test became evident as the source of these detections by a combination of estimating the origin time of the fission event based on the observed $^{131\text{m}}\text{Xe}/^{133}\text{Xe}$ activity ratios and atmospheric transport modelling scenarios which suggest strongly that delayed radioxenon emissions originating from the DPRK test site were captured by the noble gas systems at two IMS stations.

In both the 2006 and 2013 xenon detection evidence, background concentrations of radioxenon emissions at the three IMS stations were at abnormal concentrations but still less than many other observed spikes of radioxenon. The global inventories of xenon emissions around the world is unfortunately resulting in many detections every day including one or two at abnormal concentrations every day. This causes a background noise that doesn't always make it possible or easy to characterize

Fig. 12.14 Average background of Xe-133 Image provided by G. Le Petit, CEA, France

Fig. 12.15. “Hit rate” above detection limit Image provided by H. Miley and P. Eslinger, Pacific Northwest National Laboratory, USA

radioxenon origins. Essentially, the radioxenon that could be released from a nuclear test may be masked by the abundance of radioxenon present in the background. With sufficient knowledge and sophisticated methods nuclear test signatures may be unmasked and its source identified. Figures 12.14 and 12.15 provide a summary of the geographically varying abundance of radioxenon in the environment as a consequence of primarily isotope production and nuclear power plant operations.

The next big science and technology improvements for the PTS require methods to extract possible nuclear detonation signatures as unique against the interfering

Fig. 12.16 SnT19 goals

radioxenon background so that they are visible for verification activities. Characterizing sources to understand source-receptor relationships, conducting source receptor experiments, comparing isotopic ratios (i.e., comparing $^{135}\text{Xe}/^{133}\text{Xe}$ to $^{133\text{m}}/^{131\text{m}}\text{Xe}$), and confirming when multiple samples catch the same plume will allow the science to advance to a point where radioxenon signals possibly indicating a nuclear explosion could be distinguishable in a high radioxenon background environment. As you will see in my summary of the CTBTO Science and Technology 2019 Conference below, scientists are already making progress towards this goal.

I believe the CTBTO continue to exist as we walk towards entry-into-force. As we continue on our journey, we must become more efficient, effective, and sustainable. One way we look to the future is every two years we host a CTBTO Science and Technology (SnT) Conference. In fact, just this past June, SnT19 was hosted in Vienna. This extraordinary full week experience features the scientific and technical magnitude of the CTBT verification regime and welcomes collaboration to envision improving our science and technology base through experts working in test ban treaty monitoring. SnT events foster partnerships and discussions with the scientific communities in support of the CTBT and related national needs. SnT19 accomplish this while highlighting the accomplishments and accepting input from young scientists and enhancing geographic and gender representation. 1200 scientists, experts, practitioners, and youth from 100 countries attended the 2019 conference. Figure 12.16 provides an overview of the SnT19 goals.

I want to share just a few highlights from the SnT conference hosted this past June in Vienna at the Hofburg Palace.

- Numerous independent analysis of the DPRK announced nuclear test on 3 September 2017 demonstrated common understanding and raised confidence in IMS monitoring capabilities.
- Scientific experts are still considering data to search for radioxenon signals in background noise to associate radioxenon emissions with all announced nuclear tests of the DPRK.

- Progress is being made towards preserving and making available for research digitized data of historic nuclear explosions.
- Measurement campaigns at historic test sites confirmed the correlation of Ar37 and Ar39.
- The application of gamma spatial imaging is relevant in the context of an on-site inspection.
- Advancement in hydro-acoustic signal analysis and interpretation is now allowing researchers to identify direct and several reflected paths on various bathymetric structures and perform event location.
- Synergy between atmospheric observation and modelling with infrasound data demonstrates the strong link between improvement in middle atmosphere weather models and accurate infrasound analysis with signal interpretation.
- NET-VISA was successfully implemented in CTBTO operations for seismic network processing associated with event building.
- Earthquake detections by IMS stations supported advances in earth sciences on a global, regional and local scale with a key benefit resulting in better location accuracy for CTBT monitoring.
- Machine learning is quickly becoming a useful tool for significant improvements in the fast travel time calculation in various 3D earth models.
- New methods of event location based on waveform cross correlation (WCC) are able to improve the accuracy of absolute location by two orders of magnitude.
- Waveform correlation processing methods were demonstrated on aftershock sequences to be effective for operational monitoring systems with a sparse global network.

It was highlighted in multiple sessions and panels that artificial intelligence and machine learning is needed for cybersecurity advances and the management and subsequent use of our IMS data. Cyber security threats are coming faster and are becoming increasingly too complex for humans to respond to. By the time a threat has been noted, response is too late. The continuous increase in computational power and more sophisticated modeling is generating tremendous amounts of data. This in turn is beginning to lead to the accelerated development of artificial intelligence to deal with this data. There is already a large amount of data available to the CTBTO for more enhanced atmospheric and oceanic transport modeling.

Several SnT19 presentations highlighted the challenge of sustaining operational success of the IMS as focus shifts from network growth to sustainment, where the budget can no longer buy the same performance improvements. As the IMS reaches completion of the network, we need predictive maintenance approaches with fast issue identification to help support more effective resource allocation.

SnT19 hosted two language panels, one in French and one in Spanish, which highlighted the link between multilingualism and multi-lateralism, particularly in the context of a highly technical treaty and an international organization with state signatory stakeholders. The relevance of science and diplomacy approaches was undeniable and cooperation outcomes were substantially beyond what we could have accomplished in English alone.

Fig. 12.17 Civil and scientific applications of IMS data

The necessity of inclusion and development of expertise through capacity-building programs and scientific and civil applications is a continuous recommendation from the global community. Let me stay with this theme of a SnT19 highlights in the context of the importance of civil and scientific applications. In order to strengthen the support for the CTBT around the world, it is important to emphasize potential civil uses and benefits of the IMS data. As a scientist, I must draw your attention to the enormous potential of this data in terms of better understanding our planet.

Civil applications include tsunamis, volcanoes and earthquakes. Disaster risk mitigation, climate change, and the study of marine life are some of the scientific applications of these technologies. We collaborate with scientists who follow the migration of marine mammals with our hydro-acoustic technology, for example. At SnT 19, scientists suggested use of our data for monitoring of air pollution and research related to biodiversity changes. Figure 12.17 summarizes some of the applications and/or potential applications of IMS data to civil applications.

If you or anyone in your institution is interested in our IMS data for your own research purposes, please submit a proposal through our voluntary data exploitation center or vDEC. The process is fully described in our homepage at ctbto.org and the data you are approved to use for research purposes will be delivered to you months after our States signatories receive it. Historical data can be delivered following approval of your proposal.

I would like to close with two areas of best practice that I've seen demonstrated at CTBTO that I think are practical for all of us in our modern workplace. Global policy successes and science and technology advances are yearning for the benefits derived from increased participation by women and youth in STEM disciplines. This is nothing new. We have been talking about this for ages. We must find innovative and attractive ways to make these advances a reality. UN organizations are emphasizing

gender parity striving for a 50/50 women men staff ratio by 2030. The CTBTO senior leadership team has achieved gender balance with three women directors alongside three men directors. We are working diligently to advance gender balance in our technical areas as well.

CTBTO has sought to engage the views of young women and men determined to promote the CTBT and its verification regime. Created in 2016, the CTBTO Youth Group, the CYG, now has over 700 members from more than 100 countries. With generous financial support from the European Union, CYG members have participated in and contributed to major global and regional gatherings, including the CTBTO youth conferences held in Moscow and Astana in 2017 and 2018 respectively. The growing role of the CYG in advancing the ratification of the treaty shows how youth can act to change minds in countries that have not yet ratified. We increasingly find that young experts can reach countries and regions through their networks where other methods of advocacy have been ineffective. I invite the younger experts in the audience to join the CYG and discover fascinating technologies behind the CTBT verification.

With such considerations in mind, I truly appreciate the opportunity to address you as an expert group. I hope that together we will explore avenues towards increased exchanges or collaboration wherever possible. For my part, I thank you for inviting me to be here with you.

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