A new era of nuclear test verification

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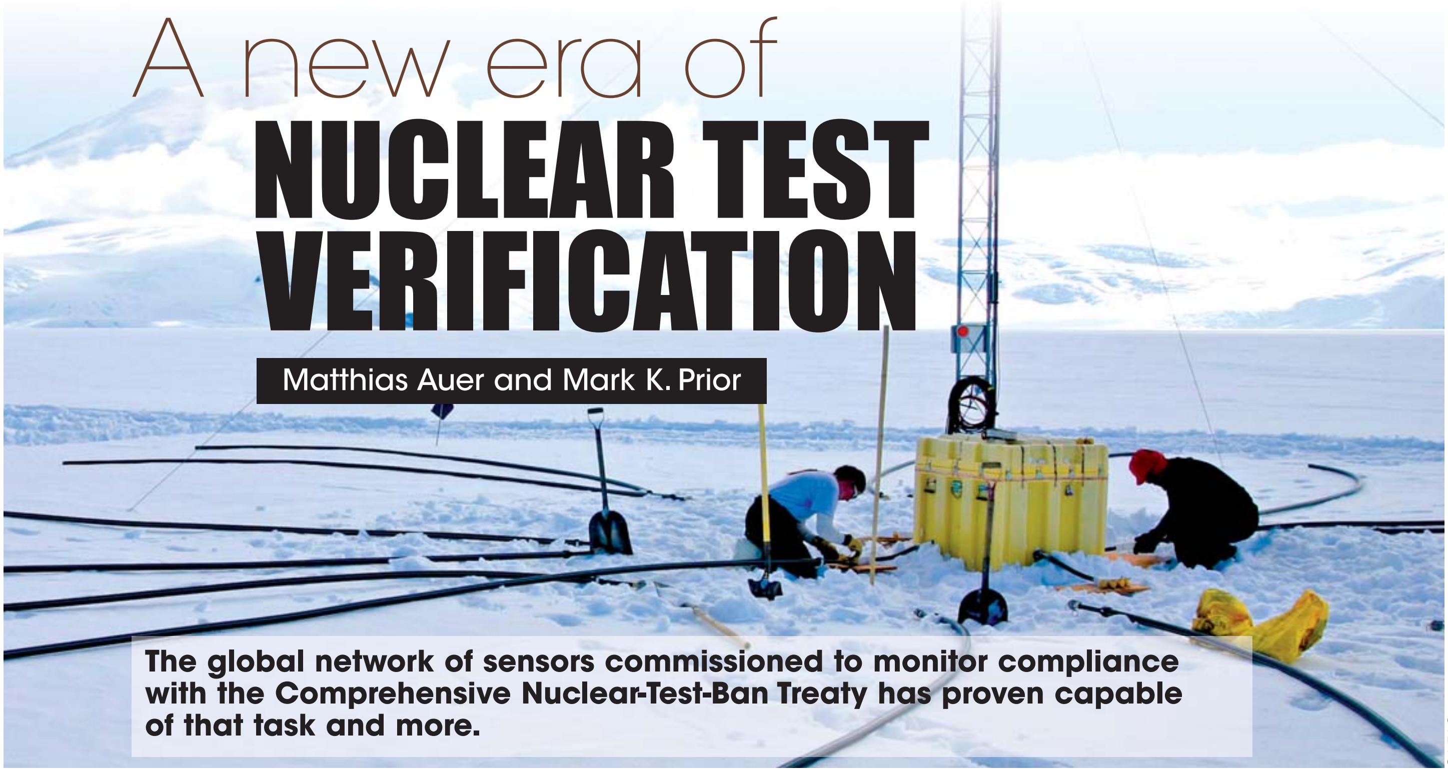

CTBTO

A new era of NUCLEAR TEST VERIFICATION

Matthias Auer and Mark K. Prior

The global network of sensors commissioned to monitor compliance with the Comprehensive Nuclear-Test-Ban Treaty has proven capable of that task and more.

In recent months considerable speculation has appeared in the international media about the prospects of a fourth nuclear test by North Korea. Although we hope, of course, that no such test comes to fruition, the hype is remarkable in itself: It shows how rare nuclear testing has become nowadays.

The credit for the slowdown in nuclear testing goes largely to the de facto moratorium that has been in place since the Comprehensive Nuclear-Test-Ban Treaty (CTBT) opened for signature in September 1996. (See PHYSICS TODAY articles by Jeremiah Sullivan, March 1998, page 24; Kai-Henrik Barth, March 1998, page 34; and Pierce Corden and David Hafemeister, April 2014, page 41.) The CTBT bans nuclear explosions by everyone everywhere and in all environments—underground, underwater, and in the atmosphere. Its no-test norm, freezing the global status quo in nuclear weapons development, effectively hampers both the first-time development and the upgrading of nuclear weapons.

To date, the CTBT has been signed by 183 states and ratified by 162 of them, which makes it one of the most widely supported treaties in history. However, it will not enter into force until it has been ratified by all of the 44 states listed in its Annex 2—the states that possessed nuclear power or research reactors when the treaty was being negotiated. The eight Annex 2 states that have yet to ratify the CTBT are China, Egypt, India, Iran, Israel, North Korea, Pakistan, and the US.

Although the ban on nuclear tests is not yet legally binding, the effect of the CTBT has already been tangible. In the half century before the treaty opened for signature in September 1996, more than 2000 tests were conducted worldwide. Since then, all of the CTBT's signatory states have adhered to the no-test norm, and the seven nuclear tests that have been conducted—by India, Pakistan, and North Korea—were denounced worldwide. Part of the no-test norm's strength derives from the treaty's unique verification regime, which has proven its ability to detect even small events. When North Korea conducted nuclear tests in 2006, 2009, and 2013, the CTBT's monitoring system detected them immediately and with high precision; it narrowed down the 2013 blast's origins to within about 180 km^2. The first data pertaining to the magnitude and location of that test were made available to CTBT signatory states almost within an hour—even before North Korea declared that it had carried out a test.

A global network

To monitor compliance with the treaty, the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) in Vienna established the International Monitoring System (IMS), a global network of sensors designed to ensure that all nuclear tests are detected and located. When complete, the network will comprise 337 stations and laboratories in places as varied as sub-Saharan Africa, Alaska, the Australian outback, and the South Pole. As of August 2014, almost 90% of the network was operational.

The IMS uses three types of waveform technologies—seismic, hydroacoustic, and infrasound monitoring—complemented by radionuclide detection technology. Each station's type and location is prescribed by the treaty. Operations at most stations are automated. Each station has a state, usually the

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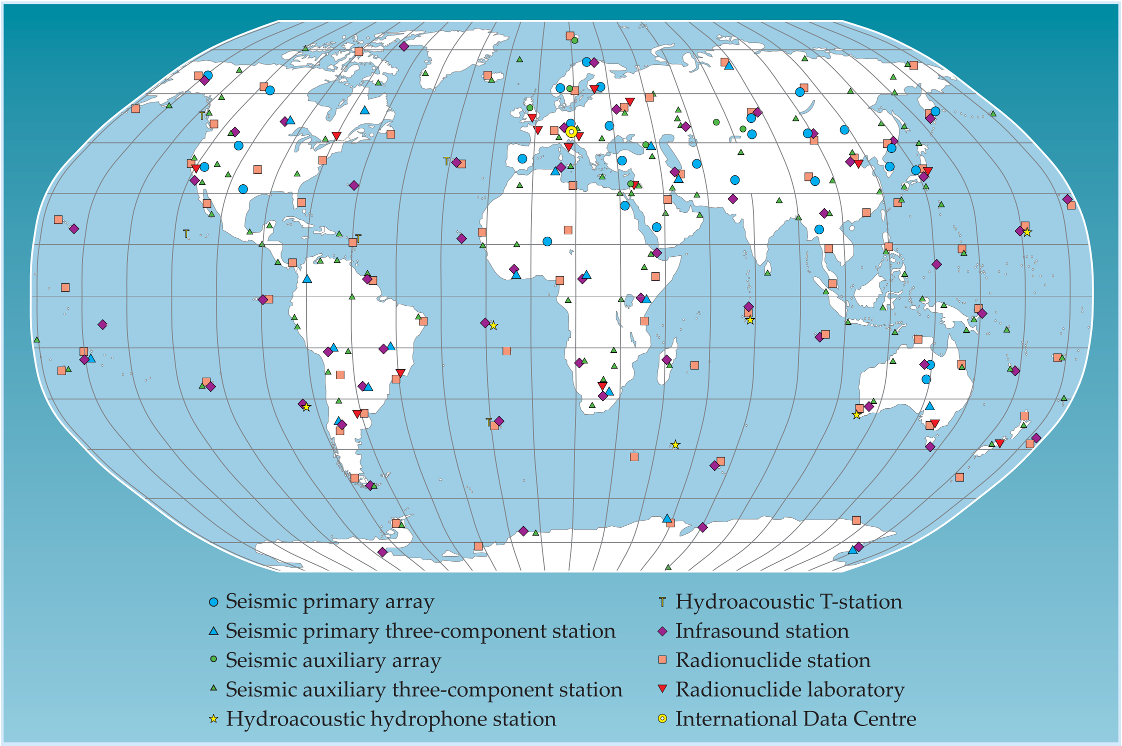


The International Monitoring System, once complete, will comprise 337 facilities: 170 seismic stations, 60 infrasound stations, 11 hydroacoustic stations, 80 radionuclide stations, and 16 radionuclide laboratories. As of May 2014, about 90% of the network was operational. (Image courtesy of the Comprehensive Nuclear-Test-Ban Treaty Organization.)

nation in which it is located, that is responsible for equipment maintenance and upkeep of the site.

By land

At the core of the IMS are its seismic monitoring stations. A seismic station may consist of a single three-component seismometer or of an array containing dozens of sensors spread over an area from a few to several hundred square kilometers. The three-component seismometers detect vertical, north–south, and east–west movements in Earth's crust; those data can be processed to give the polarization and propagation direction of seismic waves. When seismic sensors are arranged in an array, their data can be combined using beam-forming algorithms to accurately estimate a wave's direction, speed, and time of arrival.

Of the 170 seismic stations in the IMS, 50 are designated as primary seismic stations, which make the initial detection of an event, and 120 are specified as auxiliary stations, which refine estimates of the event's time and location. The two kinds of stations have the same capabilities and instrumentation; the main difference is that auxiliary seismic stations send data only on request, whereas primary seismic stations transmit data continuously.

North Korea's first nuclear test, on 9 October 2006, was detected by 22 seismic stations, including one in San Ignacio de Velasco, Bolivia, more than 17 000 km away. The event was similar in size to a magnitude 4.1 earthquake, and its location was calculated to a precision of better than 20 km. The country's second nuclear test, a magnitude 4.5 event, was declared on 25 May 2009. Due to the size of the explosion and an increase in the number of operating IMS stations, 59 stations detected the event, including one 18 000 km away in Paso Flores, Argentina. The trends of larger tests and detection by an increasing number of IMS stations continued with North Korea's third test, on 12 February 2013. Registering a magnitude of 4.9, the explosion was detected by 94 seismic stations—the farthest being in Paraguay.

By sea

The IMS uses two types of hydroacoustic stations: hydrophone and T-stations. At the six hydrophone stations, seabed cables run from a shore facility to an offshore location where three sensors are deployed in a horizontal, triangular configuration suspended beneath subsurface buoys. Time delays between signals registered by the sensors are used to calculate the direction of passing acoustic waves. The five T-stations, by contrast, use coastal seismometers to detect the vibrations caused by waterborne waves that hit the coast and convert to seismic waves.

Most hydrophones are positioned a kilometer or so below the surface, in the deep sound channel, a region of low sound speed that arises due to the cumulative effects of temperature and density. The speed of sound in seawater increases with temperature and pressure. Near the surface, temperature falls sharply with increasing depth and, therefore, so does the speed of sound. Eventually, the temperature levels off and, due to the gradual rise of pressure, the sound speed begins to increase. The depth

Workers install a primary seismic station in Torodi, Niger. It is one of 50 such stations that continuously transmit measurements to the Comprehensive Nuclear-Test-Ban Treaty Organization's headquarters in Vienna. (Photo courtesy of the CTBTO.)

at which the sound speed reaches its minimum marks the axis of the deep sound channel.

The deep sound channel behaves like a waveguide: It bends sound by refraction into paths that cycle around the channel axis and allow sound to travel long distances without hitting the sea surface or seabed. The phenomenon allows a single hydrophone station to monitor an entire ocean basin; in seismic surveys, waves emitted off the coast of Japan have been detected by IMS hydrophone stations as far away as the Juan Fernández Archipelago in Chile.

T-stations are less sensitive than hydrophone stations, largely because of the signal distortion and attenuation that occurs when waves cross the coastline. (See the article by Bill Kuperman and James Lynch, PHYSICS TODAY, October 2004, page 55.)

By air

The planned 60 infrasound stations detect airborne pressure waves at frequencies below the limit of human hearing. (See the PHYSICS TODAY article by Alfred Bedard and Thomas Georges, March 2000, page 32, and the Quick Study by Curt Szuberla and Ken Arnoult, April 2011, page 74.) Arrays comprising between 4 and 15 ultralow-frequency microphones, or microbarometers, are used to sample the acoustic field over an area of around 10 km^2. Each microbarometer sits at the center of a rosette of pipes that reduces the influence of wind noise. Choosing sites with vegetation cover can further mitigate wind noise, but that isn't always an option, given that some stations are located in high deserts and Antarctica.

The infrasound stations are designed to detect signals in the frequency range of 0.02–4 Hz, corresponding to wavelengths between a few hundred meters and a few kilometers, at distances of up to thousands of kilometers from the source. At the CTBTO's International Data Centre (IDC), the wave attributes, including the arrival direction and wave speed, are calculated by correlating signals from the different microbarometers in an array. The processing method can efficiently extract low-amplitude coherent signals from noncoherent noise such as local wind.

North Korea's third nuclear test was the first to be detected by infrasound stations; it was registered by one station in Isumi, Japan, and another in Ussuriysk, Russia. Both stations are located not far from the test site—just 1200 km and 400 km, respectively. The infrasound signals were the result of pressure waves in the air generated by the shaking of mountains in the region of the test site.

Although it is tempting to think that the three waveform technologies are each responsible for detecting a different type of nuclear test—that seismic stations detect underground tests, hydroacoustic stations detect underwater tests, and infrasound stations detect airborne tests—the signal processing used by the CTBTO is sophisticated enough to detect events that cross from one medium to another. Underground events can be detected by infrasound stations when the vibrating ground generates airborne waves or shakes microphones. Underwater explosions couple energy into Earth's crust that can be detected with land-based seismometers. Large airborne sources can generate seismic waves when their shock waves hit Earth's surface. When the Chelyabinsk meteor exploded over the Ural Mountains on 15 February 2013, for instance, it was registered by 20 CTBTO infrasound stations—including one in Antarctica and one in Alaska—for three days as waves traveled twice around Earth. But the first signal detected from the explosion was a seismic wave that arrived at a nearby station earlier, before the slower airborne waves. (For more on the Chelyabinsk meteor and its detection, see the article by David Kring and Mark Boslough on page 32 of this issue; see also A. Le Pichon et al., *Geophysical Research Letters*, volume 40, page 3732, 2013, and P. G. Brown et al., *Nature*, volume 503, page 238, 2013.)

Smoking guns

The network of seismic, hydroacoustic, and infrasound sensors is complemented by 80 stations that detect the radionuclides that are produced during a nuclear explosion. Most radionuclides condense quickly after formation and, if released into the atmosphere, attach themselves to atmospheric aerosol particles. Those aerosol-borne radionuclides are often referred to as particulates. All IMS radionuclide stations are equipped with particulate sampling and measurement systems.

Although particulate systems are well suited to monitoring explosions in the atmosphere, they are less likely to detect an underground or underwater nuclear explosion; unless a major vent of fission products occurs, only volatile isotopes—mainly noble gases and, to a lesser extent, iodine—are likely to escape into the atmosphere in significant quantities. Those isotopes typically don't condense or form particulates, but they can be analyzed using specialized analysis techniques. Whereas all of the IMS's radionuclide stations have particulate systems, only half are being equipped with noble-gas systems prior to the CTBT's entry into force. (Later, member states may decide to equip the remaining stations with noble-gas systems as well.)

Of the noble-gas isotopes, xenon-131m (here, "m" indicates a metastable nuclear configuration), xenon-133, xenon-133m, and xenon-135 are of the greatest interest for monitoring nuclear explosions.

Produced directly by fission of uranium or plutonium and indirectly by the decay of indium, tin, antimony, tellurium, and iodine isotopes, ^{133}Xe, ^{133m}Xe, and ^{135}Xe are among the highest-yield products of uranium or plutonium fission, and their half-lives (5.25 days, 2.2 days, and 9.17 hours, respectively) are long enough that they can be detected at large distances from their source. Although ^{131m}Xe has a significantly lower yield, its longer half-life (11.8 days) means that it can be detected weeks after a nuclear explosion. Under very favorable conditions, differences between the yields of uranium-235 and plutonium-239 fission may allow discrimination between the two, based on the number of Xe isotopes detected and the time at which they were detected.

Some Xe isotopes decay into particulate nuclides that can be detected by the particulate systems. The most significant among them is ^{140}Xe, which decays into barium-140. With a half-life of 13.60 seconds, ^{140}Xe is sufficiently long-lived to vent from an underground or underwater test before decaying.

Other noble gases created in nuclear explosions are less relevant for the IMS, either because their yield is too low compared with their atmospheric background concentration, as in the case of krypton-85, or because we lack the technology to measure them at the required sensitivity, as in the case of argon-37. Measuring for ^{37}Ar, which has a half-life of 35 days, can be performed during an on-site inspection—the CTBT's final verification measure. Such inspections, however, can be requested only after the treaty has entered into force.

Particulate and noble-gas samples are acquired by pumping air through filters at a rate of at least 500 m^3/h and 0.4 m^3/h, respectively, for a period of up to 24 hours. For quality assurance and in order to verify the results, samples are taken regularly and reanalyzed at one of the CTBTO's 16 radionuclide laboratories. When combined with atmospheric transport modeling (ATM), a technique that uses meteorological data to simulate the dispersion of atmospheric radionuclides, measurements made at radionuclide stations and laboratories can provide information on the timing and location of an event. The ATM calculations can be done either in a backward mode, to indicate possible source regions of radionuclide emissions, or in a forward mode, to assess the area affected by the release. The detection of radionuclides also provides significant evidence as to whether an event detected by one of the waveform technologies was a nuclear explosion.

When North Korea announced its first nuclear test in 2006, only a few noble-gas systems had been installed, none of them in the East Asian region. Nonetheless, the IMS radionuclide station in Yellowknife, Canada, detected increased levels of ^{133}Xe, consistent with a leak from an underground nuclear explosion on the Korean peninsula. That scenario was also supported by detections of ^{133}Xe and ^{133m}Xe at a mobile station deployed in South Korea.

No radionuclide releases were detected in the aftermath of North Korea's second test. But seven to eight weeks after the third test, the two stations closest to the test site—one at Takasaki, Japan, and another at Ussuriysk, Russia—collected samples with ^{131m}Xe/^{133}Xe ratios consistent with release from a nuclear test on 12 February 2013. The hypothesis that the emissions were from a nuclear test was supported by the fact that the ratios and concentrations differed significantly from previous values obtained at the same sites. The CTBTO was the only group worldwide to detect radioactivity that could be attributed to the event.

Data on the go

The IMS network is unique not only in terms of its low detection thresholds and its global coverage but also because of its state-of-the-art equipment and the exceptional quality of the data it generates. Those data are time-stamped using GPS clocks and then transmitted to the IDC in Vienna by way of a network of satellites known as the Global Communications Infrastructure. Data are transmitted in near real time—about 90% of the stations transmit data to the IDC within 30 seconds of measurement. Hardware and software devices guarantee the data's integrity. The Global Communications Infrastructure is also used to distribute processed and raw data from the IDC to signatory states.

After they have been received by the IDC, seismic, hydroacoustic, and infrasound data are entered into an automatic processing pipeline. Signals that stand out from the background noise are identified, and then the type of signal and the path by which it is traveling are calculated from the waveform shape and wave speed. Once signals have been detected in the waveform data, the next stage of processing is to identify the events that generated them. Seismic stations detect vibrations not just from explosions but from natural tremors and quarry blasts. Hydroacoustic stations detect waves trapped in the ocean sound channel that have crossed entire ocean basins, but they also detect local noises made by whales and passing ships. Infrasound stations detect signals that, among other possible paths, travel up to the thermosphere and cross the stratosphere, where wind

At a hydroacoustic station on an island in Chile's Juan Fernández Archipelago, workers lay underwater cable that will connect offshore sensors with the shore-based facility. (Photo courtesy of the Comprehensive Nuclear-Test-Ban Treaty Organization.)

Infrasound stations such as this one in Qaanaaq, Greenland, use ultralow-frequency microphones to sample the acoustic field over areas of several square kilometers. Each microphone is surrounded by a rosette of pipes that helps filter local wind noise. (Photo courtesy of the Comprehensive Nuclear-Test-Ban Treaty Organization.)

speeds can reach one-third of the speed of sound. Signals can also originate from volcanic eruptions, meteoroids, earthquakes, and space vehicle launches.

Events are identified using approaches taken from the field of global seismology; lists of detection times at IMS stations are converted to lists of hypothesized event times and locations. Because seismic, hydroacoustic, and infrasound waves travel at very different speeds, signals from even a small event may arrive at the IMS stations over the course of minutes to hours. To accommodate the staggered arrival of information, IDC processing runs in a repeated loop, with each iteration refined using new data as they become available. It is not unusual for the first estimate of an event's location to be produced while vibrations from the event are still traveling through the ground, ocean, or atmosphere.

After all signals have arrived, the automatic processing finishes and the results are sent to analysts who refine the estimates and produce the Reviewed Event Bulletin (REB), a list of the events that were detected by IMS stations. The bulletins are produced and distributed to CTBT signatory states daily and typically contain more than 100 events. All three nuclear tests by North Korea were included in an REB.

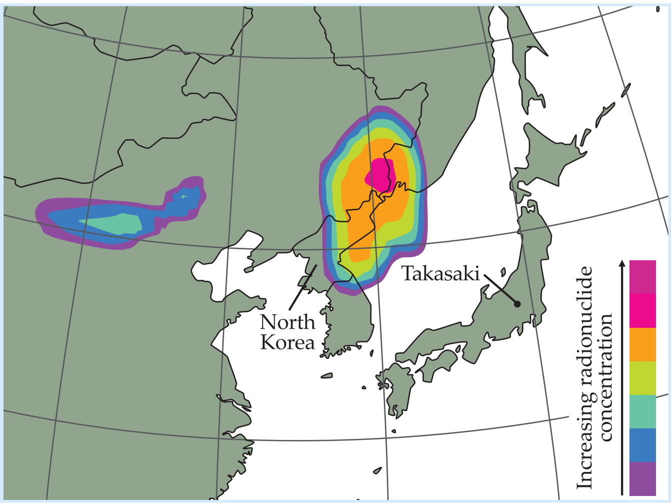
The scale and scope of the data collection and processing needed to produce the REB is remarkable. Data describing ground motion in Mongolia are combined with measurements of air pressure in Greenland to help determine the time and place of earthquakes in Asia; seismic signals from Scandinavia record quarrying in Siberia; infrasound sensors at high latitudes record very low frequency waves generated by the aurora borealis and aurora australis; underwater sensors in the tropical Atlantic record ice-breaking noises from Antarctica. Every day, gigabytes of data are recorded, transmitted across the world, and processed to produce a snapshot of global seismic activity, among other results.

The second wave

The processing of radionuclide data is substantially different from that of waveform data. Radioactive particles and noble gases may not arrive at a monitoring station until days or even weeks after an event—long after the waveform data for the same event have been analyzed.

Every day, more than 90 decay-energy spectra from radionuclide stations are transmitted to the IDC, where they are analyzed for relevant fission and activation products. For each sample, a reviewed radionuclide report is produced listing the nuclides that have been detected, with each analysis categorized according to the number of relevant isotopes detected. It takes approximately three days from the time sample collection is finished to complete the report.

One of the challenges in interpreting radionuclide data is distinguishing between radionuclides stemming from a nuclear explosion and those originating from other manmade sources. Noble-gas emissions from industrial facilities such as nuclear power plants and medical-isotope production plants are particularly common. When more than one relevant isotope is detected, nuclear explosions can be distinguished by their isotopic ratios, which are different from those of most civil nuclear activities. For example, nuclear explosions yield higher ^{133m}Xe/^{133}Xe and ^{135}Xe/^{133}Xe ratios than nuclear reactors. If the ratios are unobtainable or inconclusive, a



Atmospheric transport modeling (ATM) uses meteorological data to calculate how substances—for example, radionuclides—that are released into the atmosphere disperse over time and where and when they are likely to be detected. Backtracking ATM identifies where and when a release may have occurred based on the location of a detection. Shown here are the results of a backtracking calculation for an air sample containing radioactive xenon isotopes (^{131m}Xe/^{133}Xe) collected at the International Monitoring System's radionuclide station in Takasaki, Japan, on 8 April 2013. The colored regions represent the most likely areas for the isotopes' release into the atmosphere, had it occurred one day earlier on 7 April 2013 between 03:00 and 06:00 UTC. The measured ratios of the Xe isotopes indicate that they were the product of a nuclear fission event that occurred 50 days earlier, consistent with the time of the 2013 North Korean nuclear test. (Image courtesy of the Comprehensive Nuclear-Test-Ban Treaty Organization.)

nuclear test can often be ruled out if emissions can be traced by ATM back to known civil sources. To minimize interference with the CTBT verification regime, six producers of medical isotopes have pledged since June 2013 to reduce their emissions and to share information on emission levels.

The value of the CTBTO's global monitoring system extends beyond detecting and deterring nuclear tests. In March 2011 all radionuclide stations in the Northern Hemisphere and some in the Southern Hemisphere picked up traces of radioactive emissions from the stricken Fukushima Daiichi power plant in Japan. The data were provided to signatory states and scientific institutions, which were then able to assess the health and environmental risks caused by radiation. The CTBTO subsequently joined the Inter-Agency Committee on Radiological and Nuclear Emergencies, which coordinates the preparation and response of international intergovernmental organizations to nuclear and radiological emergencies.

After the devastating tsunami caused by the Indian Ocean earthquake on 26 December 2004, CTBTO data were made available to numerous tsunami warning centers, initially for a trial period. Since then, centers in 11 countries reached agreements with the CTBTO to receive data from around 110 IMS stations. The monitoring data enable the centers to issue more timely warnings.

A new normal?

Over the past 17 years, the CTBT's verification system has grown both quantitatively and qualitatively. As its monitoring network approaches completion, considerable scientific and technological progress has been made in the monitoring technologies. With debates over the value of arms control agreements frequently focusing on verifiability and whether would-be violators will be detected, the CTBT's verification regime has already demonstrated capabilities that meet and even exceed the parameters defined by its negotiators.

Once the CTBT enters into force, a member state will be able to request an on-site inspection to establish whether a nuclear explosion has been carried out. On-site inspections complement the other elements of the verification regime and will serve as an additional deterrent to any potential violator of the CTBT. The CTBTO has been training extensively in preparation for the treaty's entry into force and will carry out field exercises in Jordan to simulate an on-site inspection in November 2014.

One can argue that the CTBT, with 183 signatures and 162 ratifications, is already strongly embedded in the international nonproliferation and security regimes. Entry into force will provide a strong and verifiable final barrier to developing and enhancing nuclear weapons, an issue of vital importance for addressing present-day security challenges.

Additional resources

▶ M. B. Kalinowski, A. Becker, eds., *Recent Advances in Nuclear Explosion Monitoring*, vol. 2, Birkhäuser/Springer, Basel, Switzerland (2014).

▶ National Research Council, *The Comprehensive Nuclear Test Ban Treaty: Technical Issues for the United States*, National Academies Press, Washington, DC (2012). ■