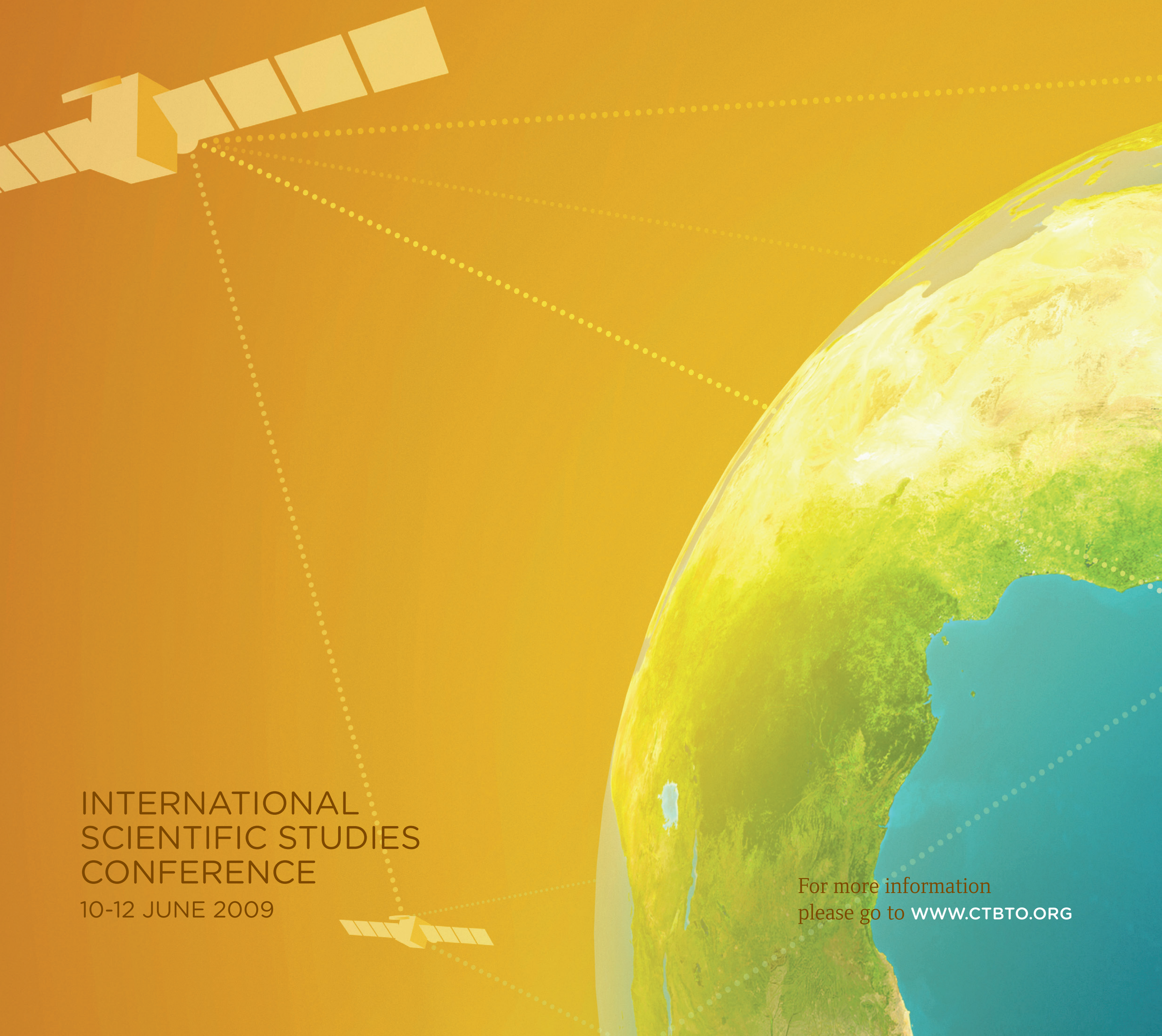
ISS09

ISS Publication

# SCIENCE FOR SECURITY

## Verifying the Comprehensive Nuclear-Test-Ban Treaty



INTERNATIONAL
SCIENTIFIC STUDIES
CONFERENCE
10-12 JUNE 2009

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THE COMPREHENSIVE NUCLEAR-TEST-BAN TREATY (CTBT) BANS ALL NUCLEAR EXPLOSIONS ON EARTH.

IT OPENED FOR SIGNATURE ON 24 SEPTEMBER 1996 IN NEW YORK.

As of September 2009, 181 countries had signed the Treaty and 150 had ratified it. Of the 44 nuclear capable States which must ratify the CTBT for it to enter into force, 35 had done so at the time of publication while nine had yet to ratify.

The Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) consists of the States Signatories and the Provisional Technical Secretariat. The main tasks of the CTBTO are to promote signatures and ratifications and to establish a global verification regime capable of detecting nuclear explosions underground, underwater and in the atmosphere.

The regime must be operational when the Treaty enters into force. It will consist of 337 monitoring facilities supported by an International Data Centre and on-site inspection measures.

# Table of Contents

# Editorial

BY OLA DAHLMAN

*Ola Dahlman has been engaged in arms control negotiations for over thirty years and spent his entire professional career at the Swedish Defense Research Institute in Stockholm, Sweden. He chaired the Group of Scientific Experts before and during the CTBT negotiations from 1982 to 1996. He subsequently headed the CTBTO's Working Group on verification issues from 1996 to 2006. Dr. Dahlman is currently leading the International Scientific Studies project.*

The Comprehensive Nuclear-Test-Ban Treaty (CTBT) has a close and long-term connection to science. For over 50 years, scientists have been working together to develop and implement the most comprehensive and complex verification regime ever created. This regime is designed to monitor compliance with the CTBT by deterring and detecting any nuclear explosions conducted anywhere on Earth.

From 10 to 12 June 2009 around 600 diplomats and scientists from 99 countries gathered in Vienna, Austria, to present and discuss results from the International Scientific Studies (ISS) project that has engaged the scientific community since early 2008. The ISS Conference (ISS09) was organized by the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) in cooperation with the Austrian Federal Ministry for European and International Affairs.

The purpose of the ISS is twofold: to conduct independent assessments of the capabilities and readiness of the CTBT verification regime; and to identify scientific and technological developments that might enhance these capabilities as well as improve the cost-effectiveness of the CTBTO's products and services.

The ISS was initiated in anticipation of an increased interest in the CTBT due to a change in the political environment and increased support for the Treaty, but there were additional reasons. The CTBT's International Monitoring System (IMS) is approaching full implementation and significant steps have been taken to increase the readiness to conduct an on-site inspection. Scientific and technological (S&T) developments have also been dramatic over the 13 years that have passed since the Treaty was opened for signature in 1996.

The ISS interacts with the scientific community through a network, the core of which are 16 senior scientists who coordinate eight topic areas which are key to the verification regime. Many hundred scientists contributed to the Conference, demonstrating the power of networking.

Is the CTBT verifiable? This crucial political question has to be addressed by each State based on its security concerns and its assessment of the capabilities and readiness of the verification regime. 150 States have so far answered affirmatively by signing and ratifying the Treaty. The ISS09 did not aim at supplying the answers to this complex and ultimately political question, but rather at providing independent scientific studies and assessments that may help facilitate national assessments.

At the ISS09 both individual scientists and groups of scientists from around the world presented more than 200 posters altogether covering all of the areas relevant to CTBT verification. This is the first time ever that such a comprehensive collection of scientific work related to the CTBT has been submitted.

Many of the scientists closely involved in the ISS project have contributed articles to this journal, which offers their summaries and analyses of the issues presented and discussed at ISS09. We hope that many more will use this valuable and extensive material to make their own interpretations and to share the results. Also within the framework of the ongoing ISS project we intend to further synthesize and interpret this material.

The recently concluded ISS Conference is not the end of the ISS process; it is rather the beginning of the next chapter. To maintain its credibility, the CTBTO has to provide products and services on a par with those that are available at any national institution. The CTBTO must thus stay closely attuned to S&T developments and maintain close links with the scientific community in order to understand the implications of these developments and their potential benefits. Ongoing collaboration with the scientific community is an essential element in this important process.

By bringing together scientists from the rapidly developing field of data mining with experts on verification data, we have already witnessed the potential for dramatic improvements in data analysis. Also, when it comes to the implementation of the technologies to be used during an on-site inspection, we recognize that much can be gained from experience already available within the scientific community.

The Comprehensive Nuclear-Test-Ban Treaty, the implementation work by the CTBTO and the ISS process are different facets of how science can be applied in support of the new broad global security agenda where non-military elements are gaining prominence. To mobilize science in support of our pending security issues is an important challenge. The way science and scientists have played and continue to play a pivotal role in relation to the CTBT should be looked upon as an inspiring example.

I want to take this opportunity to thank all of you who have contributed to this initial part of the ISS process, to the ISS09 Conference and to this journal. I very much welcome continued cooperation in further ISS activities.

# ISS promotional poster

# Facts and Figures about the ISS

**Attendance:**

600 participants including 500 scientists and 100 diplomats and journalists from 99 countries around the globe.

**Presentations:**
Eight panels with 63 panelists and 21 lecturers.

**Posters:**
212 scientific posters covering the eight topic areas of the International Scientific Studies (ISS) project outlined below.

**Best Poster Award:**
System Performance: *Sel1 vs. REB bulletins comparison*, submitted by scientists from the Istituto Nazionale de Geofisica e Vulcanologia in Italy.

## SCIENTIFIC POSTERS

| | |
|---|---|
| Seismology | 53 |
| Infrasound | 27 |
| Hydroacoustics | 18 |
| Radionuclide monitoring | 31 |
| Atmospheric Transport Modelling | 14 |
| System performance | 18 |
| On-site inspection | 34 |
| Data mining | 17 |
| Total | 212 |

## OBJECTIVES

Evaluate the readiness and capability of the verification system of the Comprehensive Nuclear-Test-Ban Treaty (CTBT) to detect nuclear explosions underground, in the atmosphere, and underwater.

Explore how scientific developments might further improve on these capabilities.

Further develop the cooperation between the scientific community and the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO).

Examine the application of data obtained from the CTBT's verification technologies for civil and scientific purposes.

Address ways of facilitating national capacity building.

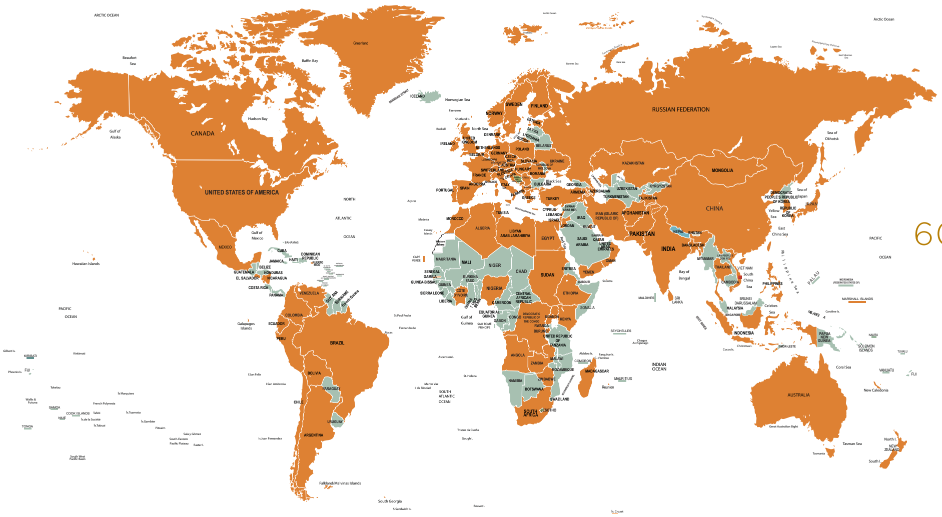
## KEY DATES AND INFORMATION

March 2008:
ISS project is launched. Open to scientific experts and institutions around the world.

March 2008 - June 2009:
Series of seminars and expert meetings related to the ISS project take place.

10 - 12 June 2009:
The ISS Conference (ISS09) is convened in Vienna, Austria, representing a milestone in the ISS project.

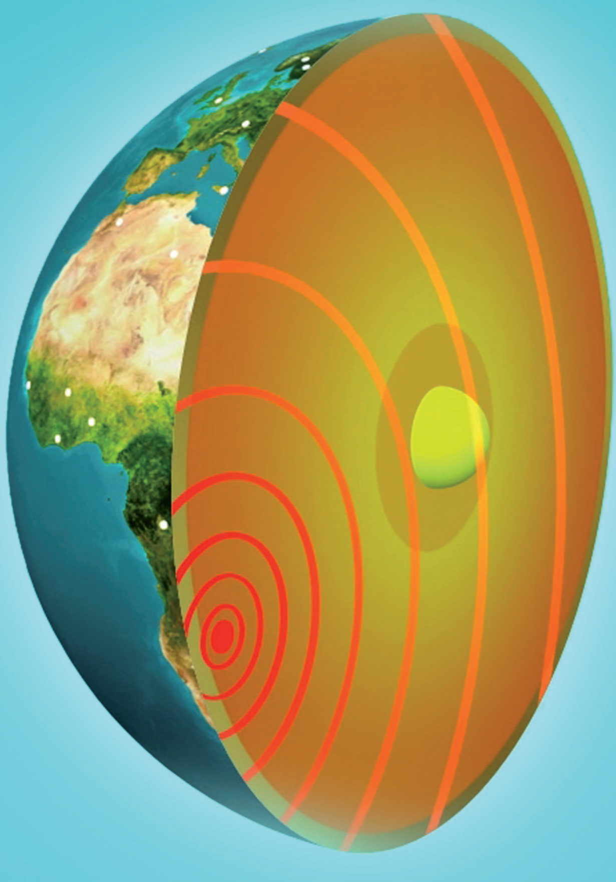
The findings of the research and studies presented at ISS09 through scientific posters are included in the DVD at the back of this publication. All ISS09 material is also available at www.ctbto.org



600 participants
from 99 countries

# Seismology

BY LYNN R. SYKES AND PAUL G. RICHARDS



# Seismology

BY LYNN R. SYKES AND PAUL G. RICHARDS

**FACT BOX**

The Seismology topic area of the ISS project has involved a series of studies concentrating on understanding and increasing the capabilities of the global detection and location of seismic events. Scientists have also explored how seismic information can be used to characterize events more fully and increase understanding of the Earth's interior.

Seismology is a key technology for verifying compliance with the Comprehensive Nuclear-Test-Ban Treaty (CTBT). By the time the CTBT enters into force, the seismic network will consist of 50 primary stations and 120 auxiliary stations that provide data for detecting, locating, identifying and determining the size of underground nuclear explosions, earthquakes and chemical explosions. Primary stations send data continuously in real time to the International Data Centre (IDC) in Vienna and are used to make the first detections and locations of events; segments of data from auxiliary stations are sent upon request.

The IDC now processes signals from around one hundred events per day, nearly all of which are earthquakes. This is demanding work that extends—for each event—from about an hour from the time of its initial automatic detection at different stations around the globe, to the production of the principal IDC product, the Reviewed Event Bulletin (REB), about one week later.

The key role of seismology was evident at the ISS Conference (ISS09) where 66 abstracts were submitted and 53 posters were displayed. Seismology was also well represented in the data mining and system performance posters. Posters and oral presentations covered the following themes:

- The detection and location capabilities of the seismic components of the International Monitoring System (IMS), both globally and regionally.
- Identification of seismic events as either explosions or earthquakes.
- Comparisons with the capabilities of national and other international agencies.
- Synergies with other IMS technologies such as hydroacoustics and infrasound.
- Seismic signal detection.
- The uses of seismic information for hazard and disaster assessments.
- Studies of Earth structure and deformation.

It is noteworthy that the ISS09 attracted representation of leading organizations engaged in seismic research and earthquake monitoring. This included the vice-president and secretary-general of the International Union of Geodesy and Geophysics; the president and secretary-general of the International Association of Seismology and Physics of the Earth's Interior; the director of the International Seismological Centre; the president and director of planning of the International Research Institutions for Seismology (IRIS) Consortium; and participation of leading seismologists from India and China as well as from Africa, Europe, Australasia, and the Americas.

## DETECTION AND LOCATION CAPABILITIES

About 70 percent of the IMS seismic stations are currently sending data to the IDC (Coyne et al., SEISMO-10/J; Kværna and Ringdal, SEISMO-15/J). Early goals for seismic detection capability of the IMS primary stations were about magnitude (mb) 4.0 and 1 kiloton (kt) for tamped (well coupled) explosions.

One of the hardest tasks in seismic monitoring, which the IDC is required to perform quickly and on a global scale, entails a series of steps to associate the correct signal detections at different stations and arrays with a particular seismic event—when their multiple signals can be interlaced at each station. There are substantial infrastructures and assets worldwide that contribute successfully to this work and they continue to improve because of needs to understand and mitigate earthquake hazard. These assets are triggered in part by the IDC's work.

A 2002 report by the U.S. National Academy of Sciences predicted that if all IMS stations were built and operated to specifications, then in the absence of evasive testing: "Underground explosions can be reliably detected and can be identified as explosions, using IMS data, down to a yield of 0.1 kt (100 tons) in hard rock if conducted in Europe, Asia, North Africa, and North America," which the report associated with magnitude 3.5 to 3.0 or lower. In some locations of interest such as Novaya Zemlya in the Arctic Ocean, capability was expected to extend down to 0.01 kt (10 tons) or better.

Kværna and Ringdal (SEISMO-15/J) report on the actual operating experience of the IMS over several years, and their figure (below)* indicates that the detection capability for the year 2007 with existing stations is mb 3.4 or better for the four areas mentioned above. It could be improved by 0.1 to 0.2 mb units for Asia and Africa if all primary stations operated. The failure of those remaining stations to contribute data to the IMS results largely from political rather than technical or logistic problems. Seismic capabilities in the southern oceans are slightly poorer but hydroacoustic stations compensate for this by providing better coverage. New IMS and other digital stations in Niger, the Persian Gulf and Afghanistan also improve detection capabilities. In summary the observed detection capabilities of the IMS today are considerably better than envisioned when the CTBT was opened for signature in 1996.

The detection capability mentioned above is not a single station capability but rather concerns detection at enough stations to provide a location estimate. The capability of individual stations is of interest, and those with the best record of detecting small events worldwide are in shield regions of Australia, Niger, North America, Kazakhstan, and South Africa (Coyne et al., SEISMO -10/J; Kværna and Ringdal, SEISMO-15/J; Estabrook et al., SEISMO-64/K).

* Dahlman, O. , S. Mykkeltveit and H. Haak (2009). Nuclear Test Ban – Converting Political Visions to Reality, Springer, ISBN 978-1-4020-6883-6

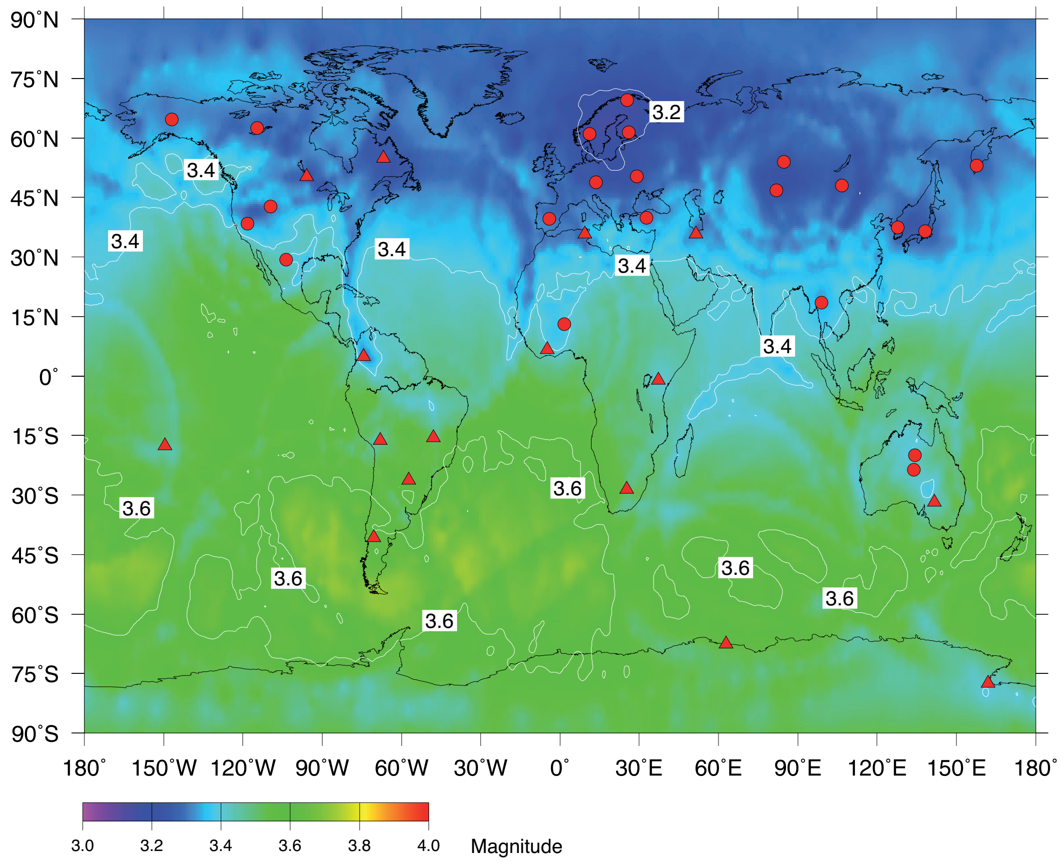



*Figure 1 showing the detection capability of the IMS primary network in late 2007, with 38 stations sending data to the IDC. The capability is represented by the magnitude of the smallest seismic event that would be detected with a 90 percent probability at three or more stations (that is, enough stations to enable a location estimate). Completion of this network (50 stations) would reduce these magnitudes by about 0.1 or 0.2 units for Asia, much of Africa, and the Indian Ocean (Kværna and Ringdal, SEISMO-15/J).*

Several ISS posters evaluated the location capability of the IMS and the IDC, either by comparison to locations determined from other networks, including local networks (Kebede and Koch, SEISMO-06/I; Giuntini et al., SEISMO-07/I), or to "ground truth" location of events subjected to special studies (Bergkvist and Johansson, SEISMO-02/I; Bergman and Engdahl, SEISMO-03/I). Location can be carried out more effectively with data from IMS stations once calibration of these stations is performed to high standards. Although the location uncertainty of events listed in the REB appears typically less than 20 km in certain studies (e.g. by comparison with locally determined locations for events in Italy), other rigorous studies indicate that the uncertainty can often be more than 20 km. This is not surprising, given that for key regional waves (notably Pn), travel times at a given distance can have values ranging over more than ± 5 percent which translates to ±50 km over a path length of 1000 km. There is room for improvement in the quality of REB event locations, and the necessary progress can come from studies to obtain appropriate travel-time calibration as a function of distance and azimuth for regional waves observed at each IMS station.

## IDENTIFICATION CAPABILITIES

The identification of nuclear explosions and problem seismic events is reserved for CTBT Member States. Nonetheless, the IDC is permitted to use several screening criteria to identify events that are earthquakes or chemical explosions. These include events in the deep oceans and deep earthquakes. Sykes and Nettles (SEISMO-26/I) and Kim et al. (SEISMO-27/I) studied the discrimination of seismic events from 2000 to 2008 within 100 km of six nuclear test sites. About half occurred near Lop Nor in China. No events were recorded near the Indian and Novaya Zemlya, former Soviet Union, sites. All of the seismic events detected by the IMS near Lop Nor, the Nevada Test Site, USA, and the North Korean test site were identified using data from IMS and other stations that are available in real or near real time. Pan et al. (SEISMO-20/J, p.106, http://www.ctbto.org/fileadmin/user_upload/ISS_2009/ISS09_Book_of_Abstracts.pdf) showed that P/S spectral ratios effectively discriminated between earthquakes and explosions in a study of more than 1000 earthquakes and 78 explosions in northwest China. Furthermore they showed that such a discriminant that worked well for medium and large events also performed well for low magnitude events (even down to around magnitude 2).

The ratio of high-frequency P to Lg waves at regional distances provides discrimination of earthquakes and explosions down to the smallest located events. Hence, a common conclusion that identification is about 0.5 mb units worse than detection is not correct when regional data are available. The two are nearly identical when adequate and calibrated regional data are available. The high-frequency technique remains to be applied to Pakistani test sites where other discriminants work for mb > 4.1. More work is needed to apply the method to areas far removed from past nuclear explosions.

Centroid moment tensor (CMT) focal mechanism solutions can identify seismic events as earthquakes or explosions and provide an estimate of earthquake depth. They can be used with seismic waves with periods of 30 to 100 seconds where earth noise is often lower than that for the older Ms-mb method. The CMT technique, which has been used for 25 years, is routinely applied to events worldwide for mb > 5.2. Sykes and Nettles (SEISMO-26/I) and Hellweg et al. (SEISMO-21/I) presented CMT solutions for events as small as mb 3.5 using data from regional stations. Materni et al. (SEISMO-22/I) applied a variety of discriminants for five test sites.

Determining that an event's depth is greater than 10 km with high confidence identifies it as an earthquake. The depths of most seismic events near the Chinese and Pakistani test sites are greater than 10 km (Sykes and Nettles). Better depth determination using the seismic waves pP, sP, Lg and Rg (e.g. Husebye et al., SEISMO-14/I) is an active area of research. Ford et al. (SEISMO-23/I) studied the numbers of aftershocks of underground explosions, which generally are not as large or as numerous as those of earthquakes. Clear downward (dilatational) first motions of P waves ( also a discriminant ), a technique that was found to be largely inapplicable 50 years ago for discrimination, can be observed today for some seismic events given the greater global distribution of stations and use of broadband sensors.

Observing clear dilatations, consistent depth phases and aftershocks and obtaining CMT solutions should be pursued more widely so as to increase the percentages of seismic events that can be identified as earthquakes. The award for the best poster in Vienna (Carluccio et al., SP-12/C), which was in the section on system performance, seeks to improve the identification of seismic events within two hours of their occurrence. T phases detected by hydroacoustic stations help to screen out many seismic events in oceanic areas. Jepsen and Fisk (HYDRO-06/H) report that over 80 percent of seismic events reported by the REB as occurring in deep water that had an unblocked oceanic path to a hydroacoustic station were screened out as being consistent with natural sources, namely earthquakes. Much more work on event identification is probably occurring at national CTBT agencies using data from the IMS, other stations and various National Technical Means.

## ANALYSES OF SPECIAL EVENTS

In general, the evaluation of monitoring capabilities emphasizes what can be achieved with routine procedures. But special events also attract non-routine procedures including the use of whatever data may be available, which for seismic methods opens up ever-growing opportunities in view of the many new and planned national and regional seismographic networks. The second nuclear explosion announced by North Korea in May 2009 is still being studied. Several posters presented special analyses of its location, how well it could be identified, and estimates of its yield. Its REB magnitudes were somewhat unusual for an underground nuclear explosion (although it was not screened out), having moderately strong surface waves given the strength of its body waves (mb 4.5, Ms 3.6). But the event was unambiguously explosive on the basis of its high-frequency spectral ratios (see Figure 2) and estimates of its moment tensor (see Figure 3 on page 10).

## SEISMOLOGY'S ROLE IN DISASTER ASSESSMENT, MITIGATION AND RESEARCH

In addition to detecting nuclear explosions the CTBTO's global coverage can offer a wide range of applications in other fields. These include tsunami warning, quick assessment of damage in large earthquakes, improving estimates of hazards and risks for future earthquakes, and research on the Earth's structure and the physics of earthquakes. History shows that seismology moves to new levels of capability following large damaging earthquakes in developed and developing countries, and this trend can be expected to continue. The importance of earthquake monitoring in the

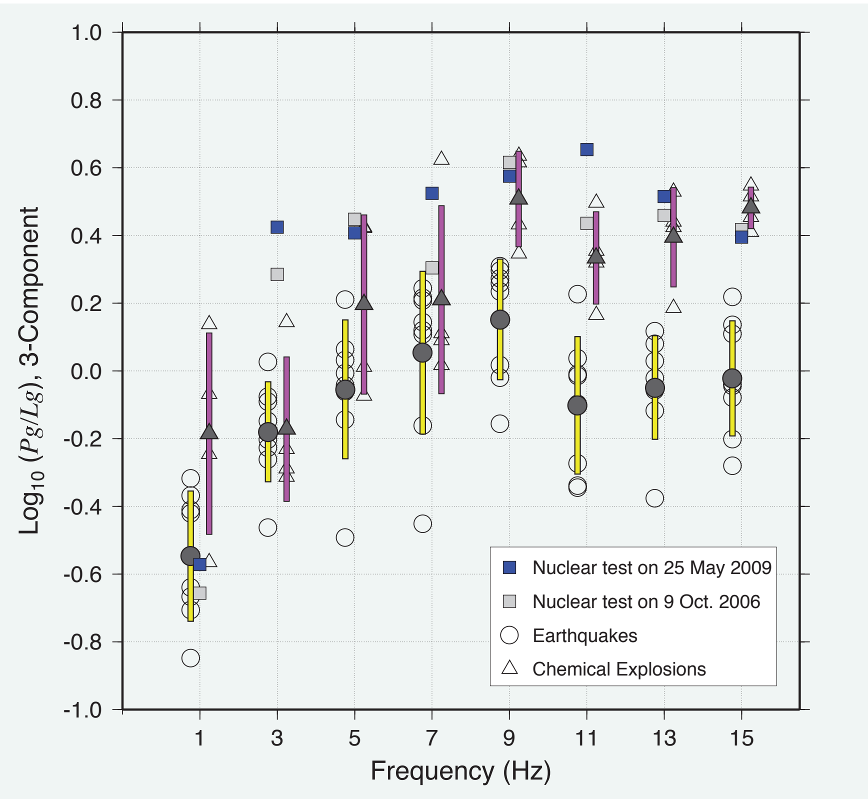



*Figure 2 showing three-component Pg/Lg spectral ratios at eight discrete frequency points used in discrimination analysis are plotted for earthquakes, chemical explosions, and the North Korea test explosions of 2006 and 2009. Data are from the open station MDJ, about 370 km north of the test explosions. This station has also recorded earthquakes and chemical explosions in the general vicinity of the North Korea test site. A mean value at each discrete frequency point is plotted for earthquakes (solid circles) and explosions (solid triangles), with their coloured arms representing the scatter (standard deviation). The explosions have higher P/S ratios than the earthquakes, and the separation of the two populations is better achieved at high frequencies. The events of 9 October 2006 and 25 May 2009 (squares) fall in the explosion population. From Kim et al. (SEISMO-27/I).*

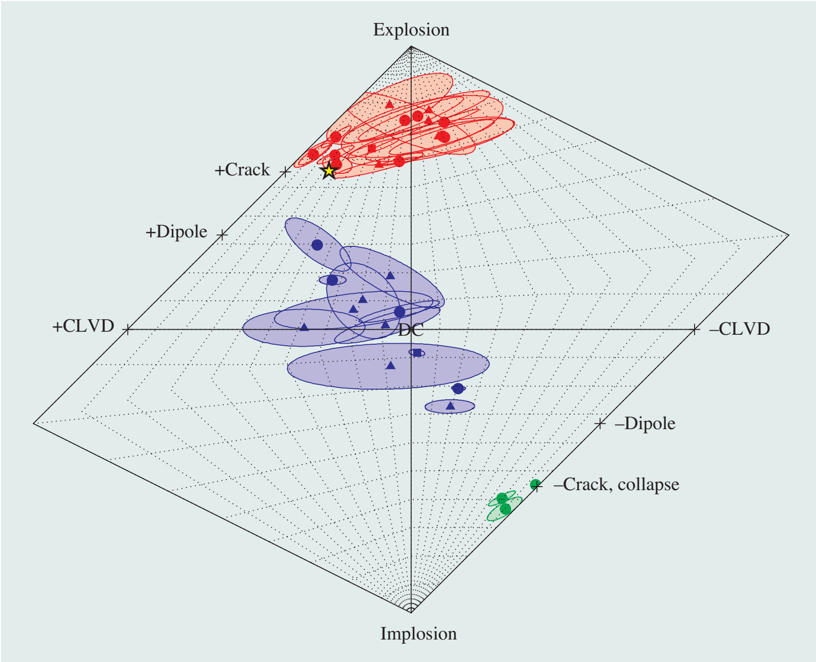
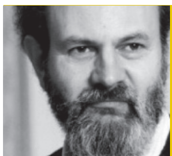



*Figure 3*
*A plot characterizing the source type of the seismic event in North Korea on 25 May 2009, based on an estimate of its moment tensor (shown here as the yellow star). The estimate was obtained by modelling seismic waveforms in the period range 10 to 15 s as recorded by four regional stations, whose data are openly available via cooperative programs between station operators in South Korea and China, and data managers in the U.S. Geological Survey and the IRIS Consortium. Source types such as earthquakes (shown in blue), explosions (red), mining collapses (green), and various cracks, all have different moment tensors and fall into different locations in this figure, which uses ellipses to indicate uncertainty. The North Korean event of 25 May falls within the explosion population. From Hellweg et al. (SEISMO-21/I). It is noteworthy that this diagram was obtained by 27 May. Subsequent efforts to improve the estimate of the moment tensor of the 25 May event (using more stations and additional analysis to update the diagram) have confirmed its location in the explosion population (Ford et al, in press with Geophysical Research Letters, 2009).*

context of seismic hazard mitigation is likely to move the entire field forward.

The U.S. Geological Survey now receives near real time seismic waveform data from about 1000 stations, and recently implemented continuous beam-forming (a signal processing technique used in sensor arrays to enhance the signals coming from a particular direction ) of 21 of the IMS arrays to improve its automated event detections, and association of detections with specific events (Buland et al., SEISMO-33/K). Helffrich and Wookey (SEISMO-47/K) used sensitive arrays to detect exotic core phases of great scientific interest (such as S-waves, apparently split by anisotropy in the Earth's inner core). Seismology and infrasound assist aviation safety by detecting volcanic eruptions along major air routes. Ito et al. (HYDRO-13/H) detected submarine volcanic activity in several parts of French Polynesia using broadband seismic arrays on the ocean floor. Seismic waves were detected from explosions and/or building collapses associated with several terrorist attacks including the World Trade Center in New York City in 2001. CTBTO Spectrum12, which appeared in April 2009, describes potential civil and scientific applications on page 28 in more detail. Key to many seismic studies is access to relevant data and the careful archiving of waveforms from long-running stations. As archives continue to grow, new seismic events that appear problematic can often be best resolved by comparing their signals with those of previously recorded events from the same region (Simpson and Willemann, SEISMO-56/K).



BIOGRAPHICAL NOTE

## PAUL G. RICHARDS

has been a professor at Columbia University since 1971, where he co-authored an advanced text on seismology in 1980 (updated, translated, and still in print).

He has researched methods of explosion and earthquake monitoring since the mid-1980s, has written about thirty professional papers on these subjects in the last ten years, and has spent two separate years in U.S. government service (on leave from academia) working on technical issues of nuclear explosion monitoring and test ban treaty negotiations.

BIOGRAPHICAL NOTE

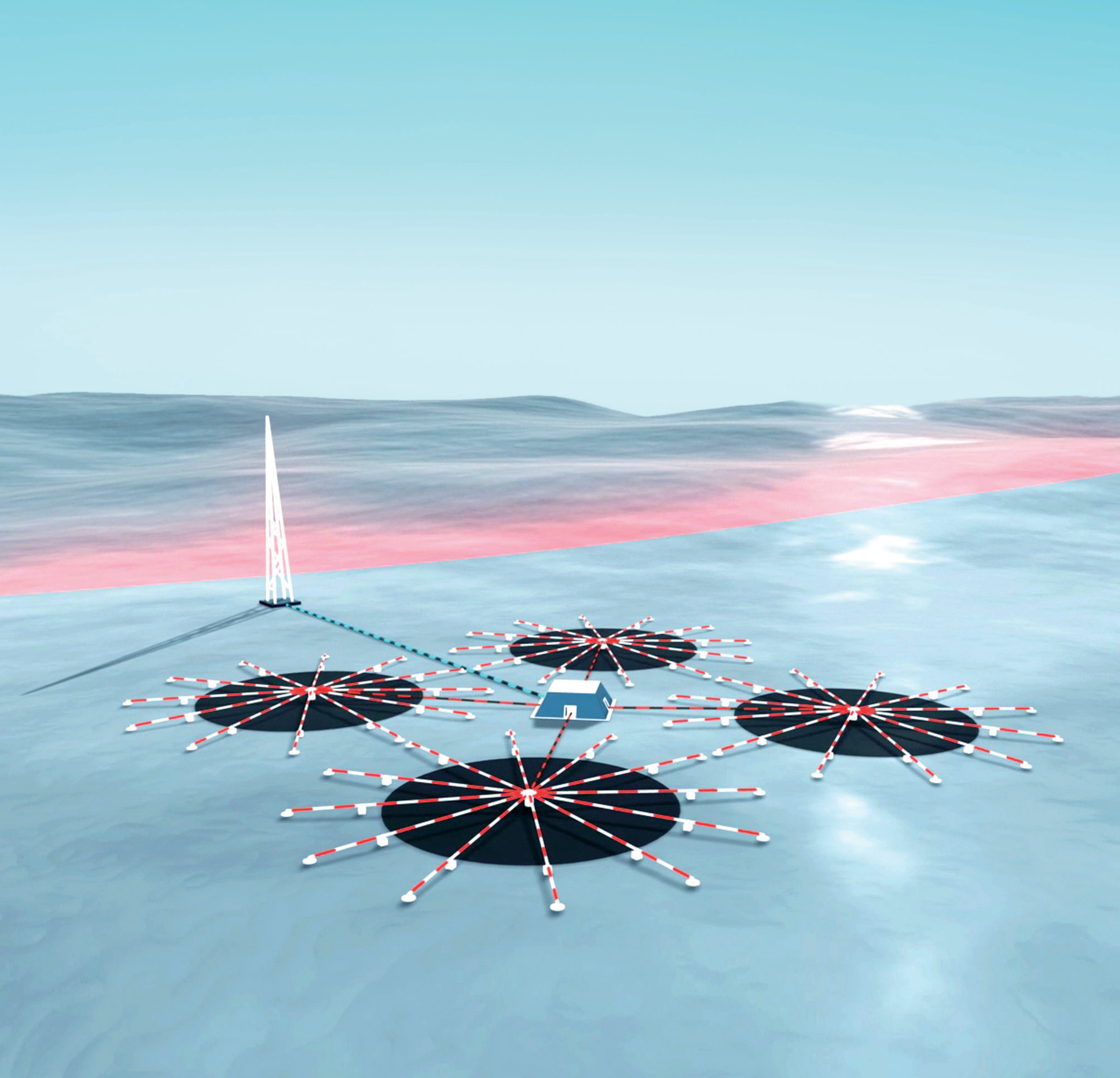
## LYNN R. SYKES

is Higgins Professor Emeritus of Earth and Environmental Sciences at the Lamont-Doherty Earth Observatory of Columbia University in Palisades, New York.

He has authored or co-authored a number of scientific papers including 40 on the verification of nuclear testing and was part of the U.S. delegation that negotiated the Threshold Test Ban Treaty in 1974. He is also a member of the U.S. National Academy of Sciences and the American Academy of Arts and Sciences.

# Infrasound

BY ELISABETH BLANC AND LARS CERANNA



# Infrasound

ELISABETH BLANC AND LARS CERANNA

**FACT BOX**

The Infrasound topic area of the ISS project has carried out a series of studies on the detection and location capabilities of the network at regional and global distances as well as exploring ways of improving these capabilities. The studies have also aimed to enhance the understanding of observed events and propagation of acoustic waves through the atmosphere.

Infrasound monitoring is an important technology for detecting and locating nuclear explosions in the atmosphere because approximately 50 percent of the energy from these explosions is released into the atmosphere as a blast wave. Such pressure pulses propagate away from the source as sound waves. Since attenuation of sound waves in the atmosphere is frequency dependent, infrasound, which is inaudible to humans at frequencies below 20 Hertz, can propagate over large distances, reaching altitudes in the atmosphere of more than 100 kilometres.

These low-frequency compression waves were first observed on a global scale after the eruption of the Krakatoa volcano, Indonesia, in 1883, when infrasonic waves circled the Earth several times. In the aftermath Infrasound technology was used intensively in the twentieth century to detect atmospheric nuclear weapon tests until the Partial Test Ban Treaty entered into force in 1963, which prohibited any nuclear test in the atmosphere.

Figure 1 shows an example of a nuclear explosion with a yield of a few kilotons (kt), conducted and recorded in French Polynesia. It clearly demonstrates the potential of infrasound recordings to identify strong atmospheric explosions.

## RENAISSANCE IN INFRASOUND TECHNOLOGY

In 1996, when the Comprehensive Nuclear-Test-Ban Treaty (CTBT) was opened for signature, infrasound technology experienced a renaissance as part of the verification regime. To fulfil compliance with the CTBT, a global network of infrasound stations was designed. This network is part of the International Monitoring System (IMS) and comprises 60 infrasound stations distributed uniformly around the globe.Currently, approximately 70 percent of the stations are in operation, providing data in near real-time to the International Data Centre (IDC) in Vienna. The first stations were certified in 2001 as meeting the CTBT's requirements, while others have been added to the network over subsequent years, constantly improving its global coverage. All of the stations are located in different environmental conditions. These range from tropical to polar regions, and from humid to arid areas which are exposed to different local wind conditions. The turbulence caused by these winds is the origin of infrasound background noise, which is reduced by spatial filters composed of pipe arrays (see cover sketch on page 11).

All the technical aspects of infrasound monitoring have been redeveloped for CTBT verification. It uses state-of-the-art advances to form a system which has never been available until now, using sensors that have been designed for the detection of small events with high sensitivity and low instrumental noise. The large dynamics of the sensors allow the observation of both very strong events close to the station and very small ones at distances of a few thousand kilometres.

Infrasound stations are mini arrays composed of four to fifteen sensors, which are spaced one to three kilometres apart to ensure the best configuration for the optimal detection of infrasound signals. These arrays act as antennas, enabling coherent signals to be detected when they cross the array, even when the signals are merged in a background of noise. The detection of coherent signals allows information about the direction from which the signals have originated (azimuth) and the speed of propagation across the infrasound array (apparent wave velocity) to be estimated. This information helps to characterize the infrasound signals and locate the source.

Along with the high quality of recorded data, initial studies have demonstrated that various kinds of events can be identified because of their wave parameters, which are measured at different stations. Over recent years, a catalogue of such events has been established, providing a database of events with well identified characteristics and known sources. However, some additional investigations on the yield of some of these sources are still ongoing.

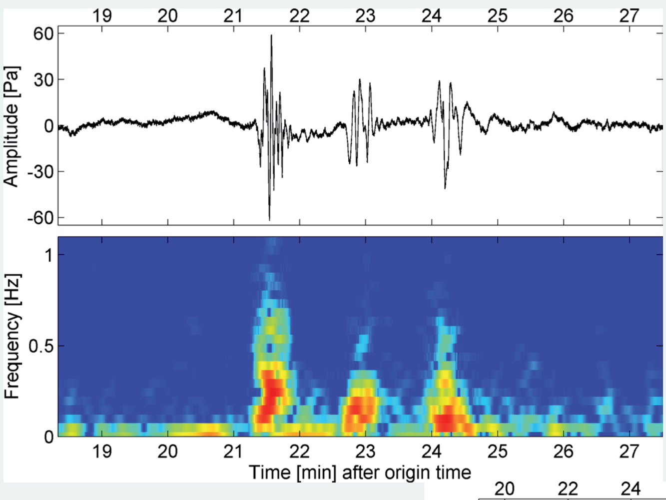
Infrasound experts benefit not only from progress in engineering sciences, but also from advances in meteorology and climatology, which have helped significantly in terms of interpreting the recordings. As shown in Figure 1, the azimuth of infrasound propagation has a strong impact on the dynamic and kinematic characterization of the signals. Therefore, precise horizontal wind and temperature profiles are required which describe the status of the atmosphere.

There is a burgeoning interest in infrasound monitoring, as evidenced by the quantity of scientific publications now dedicated to the subject and correlating well with the increase in the number of infrasound stations installed for CTBT monitoring. Moreover, this is also underlined by the 27 posters which were presented in Vienna at the International Scientific Studies Conference (ISS09) and will be summarized in the following paragraphs.

## DATA ANALYSIS AND NETWORK PROCESSING

The Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) has developed specialized software tools in order to make maximum use of the infrasound network (Campus, INFRA-01/F). Firstly, each infrasound array is analyzed individually with a cross-correlation technique for detecting and identifying coherent signals. Secondly, all detection lists are merged to form event bulletins (Brachet et al., INFRA-02/F).

In parallel to the work performed by the CTBTO, data are also analyzed at different National Data Centres (NDCs) which use their own automatic detection and location software. This processing mainly covers the analysis of events detected by



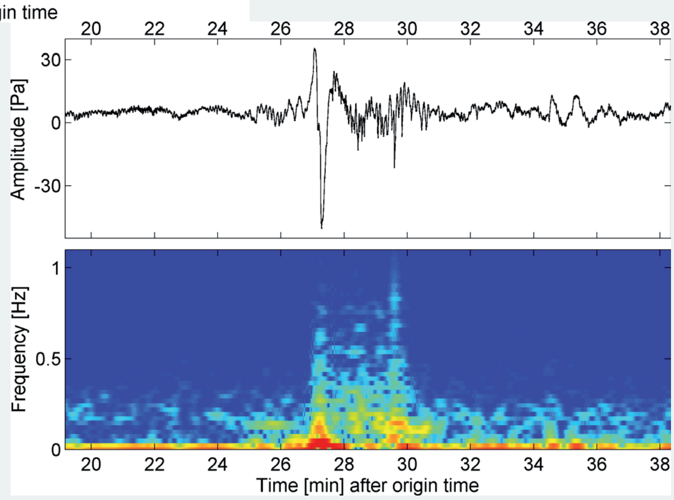




*Figure 1*
*Examples of infrasound signals recorded in French Polynesia on Hao (left) and Gambier (right) 450 km north-west and 440 km east respectively from the source of a nuclear explosion with a yield of a few kt. Time-frequency analysis (lower panels) shows dominant periods between 2 and 30 seconds.*

several stations on a regional scale with the major advantage of having a multitude of repeating events. For instance, infrasound activity in Europe is monitored by the European part of the IMS, complemented by national scientific infrasound arrays (Ceranna et al., INFRA-05/F), or on the Korean Peninsula using only scientific stations (Lee et al., INFRA-08/F). Methods for comparing and merging events detected by several stations are developed and tested using quarry blasts, accidental explosions, or supersonic activities. Moreover, this multi-station analysis includes the correction of propagation effects for the precise determination of source parameters.

Ground truth (GT) events are systematically reviewed, listed and used to calibrate the global network. Moreover, they are referenced to study infrasound propagation effects in the atmosphere, and vice versa i.e. to probe the atmosphere using data from repeating sources. Events such as the Buncefield explosion in the UK (11 December 2005), the Gerdec explosion in Albania (15 March 2008) (Vergoz et al., INFRA-06/F), and the Chelopechene explosions in Bulgaria (3 July 2008) were studied to validate propagation models and location precision (Brachet et al., INFRA-03/G; Gibson and Drob, INFRA-10/F). With regard to explosions, the synergy with seismic data allows a more detailed event analysis, especially by improving source location. Therefore, dense seismic networks are proposed to systematically identify and locate infrasound events precisely, which can be used like GT events to evaluate location methods (Hedlin et al., INFRA-07/F).

## INFRASOUND PROPAGATION AND DETECTION AND LOCATION CAPABILITY

Infrasound propagates at sound speed through specific channels (named waveguides) in the atmosphere. The sound speed varies according to temperature and is subject to the effects of the winds especially in the stratosphere (around 50 km above the Earth), which can exceed 100 metres per second (m/s). These winds vary in their direction of propagation according to the season and have a strong impact on the seasonal detection capability of infrasound stations. It is therefore important to develop tools to simulate infrasound propagation throughout the year. The increases of temperature in the stratosphere and thermosphere produce refractions and reflections of the infrasound waves, which is ducted between ground and temperature increases in the different layers of the atmosphere.

Infrasound can follow different propagation paths before being detected at an array, where different signal phases, corresponding to different arrival times, can usually be distinguished (Figure 1). Different simulation tools for infrasound propagation are now available, ranging from multi-dimensional ray tracing to full-wave solutions of the governing equations. The numerical solution of the wave equation provides a tool to describe the (infra-)sound propagation from source to receivers and to study pressure fluctuations in a lateral heterogeneous atmosphere in detail . Beside the visualisation of wave propagation, synthetic barograms are obtained using such simulation algorithms. All these tools make use of the most accurate atmospheric models, enabling a detailed analysis of recorded signals, and helping to understand atmospheric propagation effects (Kulichkov and Golikova, INFRA-11/F; Drob et al., INFRA-25/G).

Based on recordings from chemical and nuclear explosions, an empirical relationship has been established describing the amplitude of infrasound signals as a function of distance, also taking into account the effect of stratospheric winds. Using this relationship and precise atmospheric models, the network's detection and location capabilities can be determined (Le Pichon et al., INFRA-12/F; Green et al., INFRA-13/F).

Global maps providing the minimum detectable energy by the IMS infrasound network are computed. They strongly depend on the atmospheric conditions, especially wind models like the Horizontal Wind Model 1993 (HWM-93), which is an empirical model of the horizontal neutral wind in the upper thermosphere, or the European Centre for Medium-Range Weather Forecasts (ECMWF), as shown in Figure 2. Moreover, the seasonal variations of the detection thresholds for different latitude ranges can be summarized as follows: the best performances are predicted around January and July when zonal winds are stable and strong. However, during the equinox periods (April and October), winds reverse in direction and the detection capability is consequently reduced.

These variations in detection capability are stronger at high and mid latitudes and less significant in equatorial regions. Differences are also observed between northern and southern hemispheres, with lower detection levels in the southern hemisphere due to strong stratospheric jets.

Besides the detection capability, the network performance also depends on its location capability. High stratospheric winds tend to lower the detection levels; however, the location capability deteriorates since the detecting stations only cover a small azimuthal segment, making cross bearing difficult. The mean yield threshold and location error are anti-correlated. Different simulations performed by different groups provide similar results, which validate the estimations. Both models predict that the completed IMS infrasound network will provide over 95 percent global coverage for yields equal or greater than 0.9 kt, with a better detection capability in areas of dense station coverage.

Other studies have validated detection maps using GT events from accidental explosions in Europe, where the network is dense enough for such studies. Figure 3 shows the detection capability map corresponding to the Gerdec explosion in Albania on 15 March 2008. The signal amplitudes detected at each station are compared with the amplitudes predicted by the models. The explosion yield determined in this study ranges from several hundred tons up to one kt, which corresponds with the yield estimated for this explosion (~0.4 kt). Another opportunity to validate detection maps will be provided by the Sayarim calibration experiment (Gitterman et al., INFRA-09/F), where an 82 ton explosion was conducted on 26 August 2009.

## CIVIL AND SCIENTIFIC APPLICATIONS

The number of events analyzed by different scientists is increasing greatly as the number of stations in operation continues to grow. Rocket launches are detected and systematic variations of back azimuths are followed (Smirnov et al., INFRA-21/G). Infrasound from volcanoes is systematically analyzed at various sites such as in Chile, where they provide important parameters for volcanic source studies (Barrientos et al., INFRA-16/G). The detection of bolides in the United States (Hedlin et al., INFRA-07/F), Bolivia (Minaya et al., INFRA-18/G) and Africa (Edwards et al., INFRA-17/G) shows the ability of infrasound stations to detect infrasound sources at high altitudes, where bolides can be considered as GT events for high altitude explosions.

Infrasound monitoring during earthquakes provides a new image of earthquake activity which is useful for understanding ground-atmosphere coupling. Such observations can be used for studies of normal modes of atmosphere and solid earth structure. The analyses are often performed by the National Data Centres interested in the different natural infrasound sources, which are measured in their operational stations. Within the framework of the ISS project, several national centres in developing countries and countries starting research in the field of infrasound have developed new research programmes which

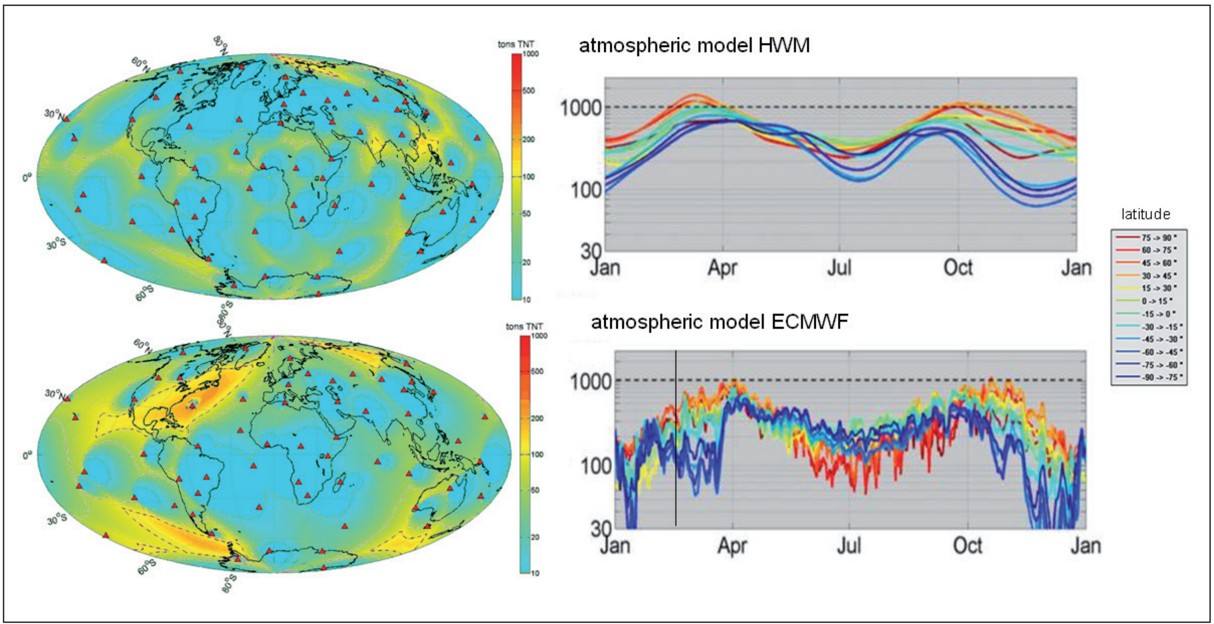
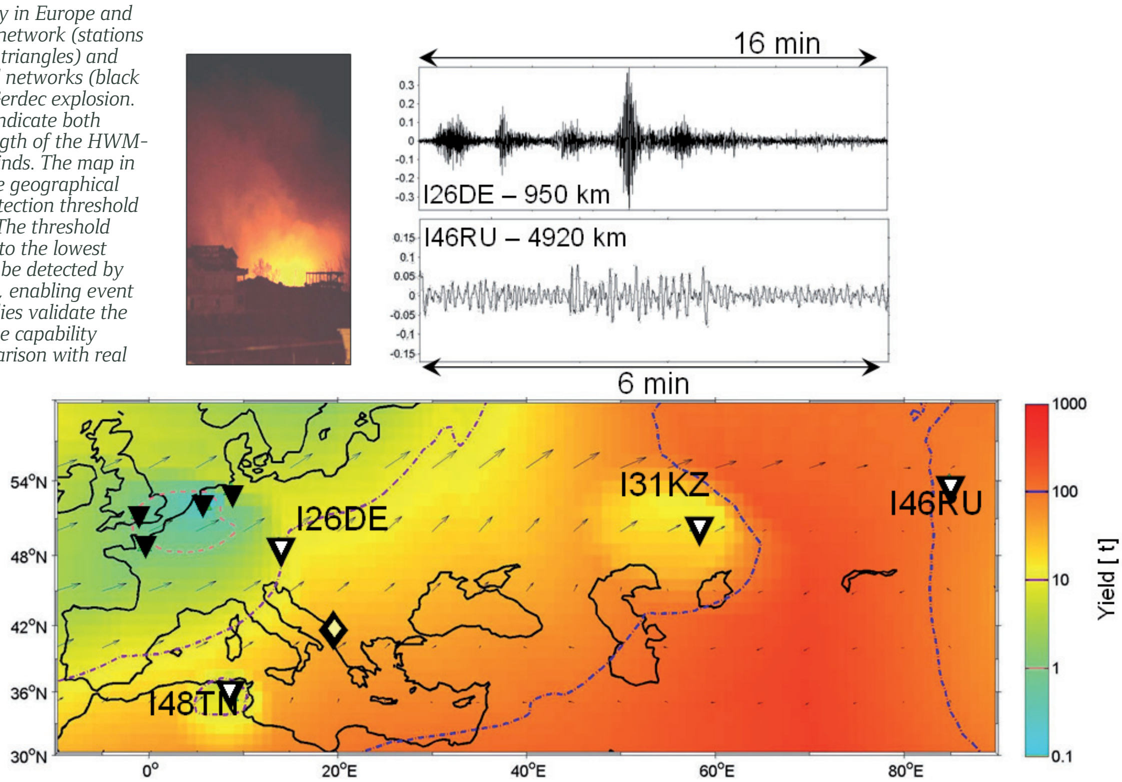



*Figure 2*
*Left: Geographical coverage of the explosive energy detectable by the full IMS network at 0000 UTC on 1st January 2003. The colour refers to the minimum energy detectable (in tons of TNT equivalent) by at least two IMS stations. The propagation effects are simulated using stratospheric winds from the HWM-93 and ECMWF models. Right: Temporal fluctuations of the minimum detectable energy in 12 latitude-dependent regions. The dashed black lines indicate the 1-kt limit. The spreading in the simulation using ECMWF model represents the fluctuations from one day to another due to the changes of the wind profiles.*

*Figure 3*
*Detection capability in Europe and Russia of the IMS network (stations indicated by white triangles) and additional national networks (black triangles) for the Gerdec explosion. The black arrows indicate both direction and strength of the HWM-93 stratospheric winds. The map in colour indicates the geographical variation of the detection threshold across the region. The threshold values correspond to the lowest energy that would be detected by at least two arrays, enabling event location. Such studies validate the computations of the capability detection by comparison with real events.*




were presented at the ISS09 (Baasambat et al., INFRA-20/G; Rambolamanana et al., INFRA-23/G). New studies show that tomography of the atmosphere can be performed using repeating sources. Additional studies reveal the possibility of using the infrasound network for imaging large scale disturbances and atmospheric dynamics in relation to climate evolution. Other studies show the possibility of using the infrasound network for imaging large scale disturbances and atmospheric dynamics in relation to climate evolution (Waxler et al. INFRA-29/G; Blanc et al., INFRA-27/G).

All these studies reveal applications much broader than the study of explosive sources for detection purposes. In return, the studies provide new software developments and new understanding of atmospheric parameters and atmospheric sources which are used to improve the operational analysis in relation to nuclear explosion detection, identification and location.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Havelock, D., S. Kuwano, and M. Vorländer (Eds), (2008), Handbook of Signal Processing in Acoustics, Part XIV – Infrasonics, Springer, Amsterdam, NL.
Le Pichon, A., E. Blanc, and A. Hauchecorne (Eds), (2009), Infrasound monitoring for atmospheric studies, Springer, Amsterdam, NL.


BIOGRAPHICAL NOTE

## ELISABETH BLANC

is a Research Director at the Commissariat à l'Energie Atomique (CEA) in France, where she has worked since 1978.

Between 1994 and 1996, Dr. Blanc was a member of the infrasound expert group mandated for the definition of the CTBT's International Monitoring System. Her areas of expertise include the study of natural and man-made disturbances and the effects of powerful atmospheric explosions.

BIOGRAPHICAL NOTE

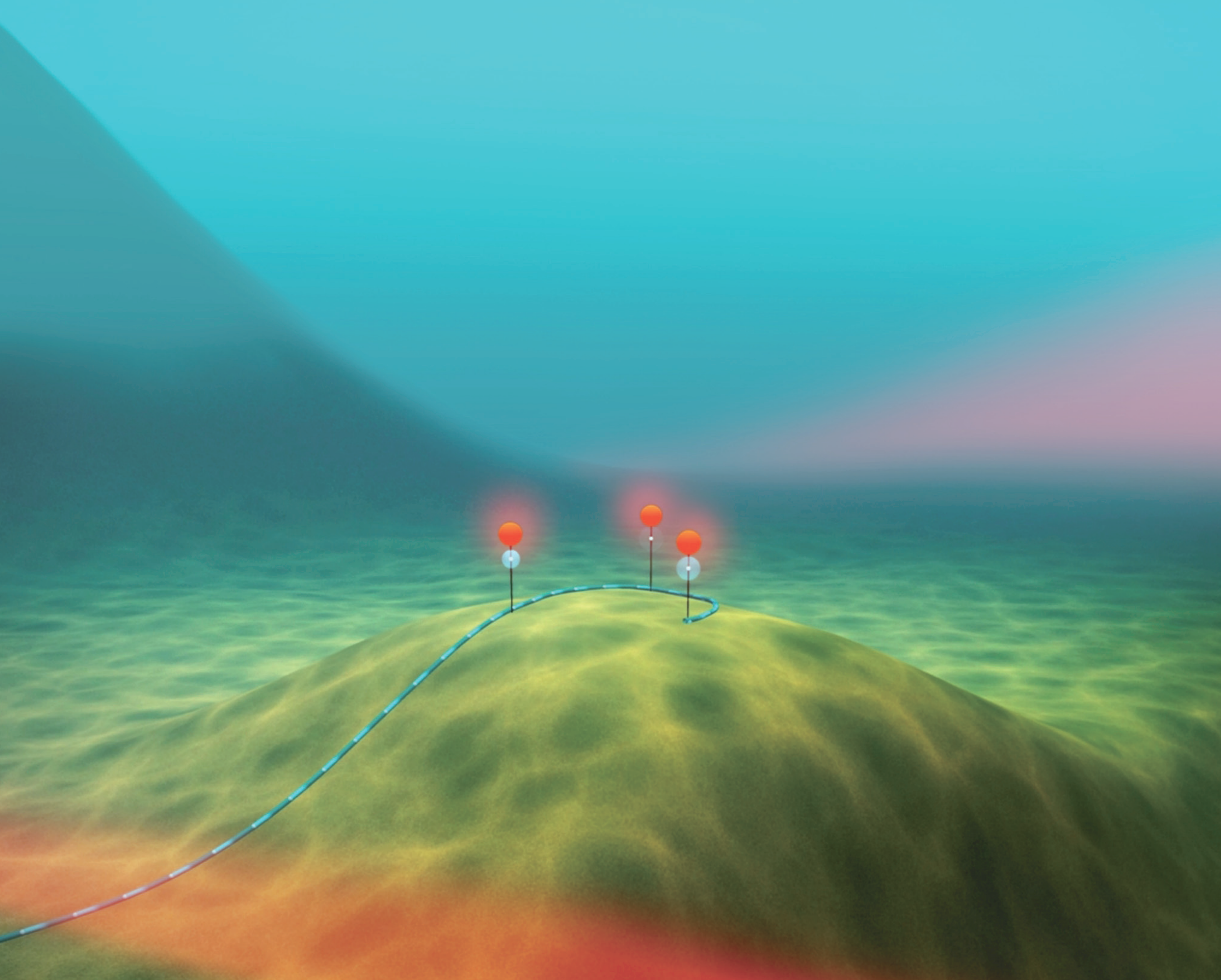
## LARS CERANNA

is a Scientific Director at the German Federal Institute for Geosciences and Natural Resources (BGR).

He is a German delegate at the CTBTO's Working Group on verification issues and provides technical advice in that regard to the German government. Dr. Ceranna is also unit head for Monitoring and Verification at BGR's section "CTBT, Seismological Central Observatory", which hosts the German National Data Centre for CTBT verification.

# Hydroacoustics

BY WOLFGANG JANS AND KIYOSHI SUYEHIRO



# Hydroacoustics

BY WOLFGANG JANS AND KIYOSHI SUYEHIRO

**FACT BOX**

The Hydroacoustic topic area of the ISS project has involved an evaluation of the detection and location capabilities of the hydroacoustic network as well as an assessment of the network's coverage. Synergies with seismic observations have also been explored.

The hydroacoustic network is a key component of the International Monitoring System (IMS). The network contains 11 stations to monitor compliance with the Comprehensive Nuclear-Test-Ban Treaty (CTBT) in the world's oceans. This is a relatively small number compared to the components that make up the other IMS networks, which include 50 primary and 120 auxiliary seismic stations, 60 infrasound, and 80 radionuclide stations. This is because the Sound Fixing and Ranging channel (SOFAR), the natural ocean acoustic channel, enables underwater sound to propagate over large distances without significant loss. It is thus possible to record underwater signals at hydroacoustic stations several thousand kilometres away from the source, provided the propagation path is not blocked by a land mass.

The network's six hydrophone stations consist of triplets of receivers placed in the middle of the SOFAR channel. Each receiver triplet comprises three hydrophones which are arranged in triangles with each point set two kilometres apart (see page 17). This setup leads to a resolution in direction. The location of an event can then be determined by identifying the intersection of bearings received from any two remote stations. Each station is linked to the shore via a cable, which allows for ocean acoustic data to be processed in real time. The other five IMS hydroacoustic stations are island-based "T-stations" and use seismometers to detect the high frequency seismic waves converted from hydroacoustic waves when they hit the island.

The hydroacoustic network is of particular significance for coverage of the southern hemisphere, which has immense ocean areas compared to the northern hemisphere with its large landmasses. Placed within the world's three major oceans (the Atlantic, Pacific, and Indian Oceans, which make up about 70 percent of "the surface area" of the Earth) this network has the capability to detect in-water, on-island or low-altitude explosions over water.

In-water explosions contain low and high frequency energy, have a short duration and normally display a bubble pulse. The signature of explosions on islands differs somewhat. Depending on the size and/or location of the explosion on the island, the signals contain less high frequency energy and no bubble pulse (see Figure 1). For low altitude explosions over the water, low frequency hydroacoustic signals of a short duration have been observed.

## EXAMPLES FOR SYSTEM PERFORMANCE & SYSTEM IMPROVEMENTS OF THE HYDROACOUSTIC NETWORK

In the case of the IMS seismic network, the performance of the International Data Centre (IDC) can be compared with earthquake information centres around the globe, for example, the National Earthquake Information Center (NEIC) run by United States Geological Survey (USGS) or the International Seismological Centre (ISC).

The situation is quite different for the IMS hydroacoustic network. Other similar networks with freely accessible data do not exist. Furthermore, there are hardly any historical records available of large nuclear in-water explosions recorded on hydrophones, whereas there are many examples of nuclear tests recorded on seismometers. Therefore, determining the capabilities of the hydroacoustic network is based on an analysis of signals received for events with known location, depth and yield. This "ground truth" information for observed events is often not available.

To overcome this problem, well documented, controlled non-nuclear underwater test-explosions are the most suitable means for performing an evaluation of the hydroacoustic network including data processing, since precise "ground truth" data like location, depth and yield of the explosion are then known. However, carrying out these kinds of tests is costly and permits are difficult to obtain. Finding a means to conduct more tests would be of great benefit to the development of the network.

Through cooperation with research institutes during the implementation of the International Scientific Studies project over the past year, the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) received information about a couple of hydroacoustic in-water events, including "ground truth" data. These events demonstrated the potential of the existing IMS hydroacoustic network in terms of sensitivity and location accuracy: on 7 and 8 September 2008, a series of low-yield explosions (estimated 20 kg TNT equivalent) on the continental shelf off the coast of Japan were detected 16,000 km across the Pacific Ocean by hydrophone triplets belonging to IMS hydroacoustic stations H03 (Juan Fernandez Island) off the coast of Chile (see Figure 4). This provides substantive evidence of the long-range detection capability of the hydroacoustic network.

The detection of these low-yield explosions clearly illustrates the ability of the sparse, global hydroacoustic network to cover the three major world oceans.

On 2 August 2006, the battery pack of a mooring of oceanographic equipment accidentally exploded off the coast of New Jersey, United States. This incident was recorded by H10 (Ascension Island) in the Atlantic Ocean (see Figure 4) at a distance of about 8000 km. The provision of "ground truth" time and location data for this event enabled the CTBTO to estimate location uncertainties in this region.

After signal processing, the observed direction of signal arrival and the real direction of the event based on its known location differed by less than 0.2 degrees. The observed travel time also agreed with the IDC-predicted travel time to within two seconds.

Although these examples are useful, carrying out comprehensive studies on a global scale will require a greater number of either controlled underwater test explosions or in-water events with sufficient "ground truth". This will take time and can only develop gradually.

During the ISS Conference (ISS09), scientists from the Curtin University of Technology in Australia presented results of their studies of transient low-frequency hydroacoustic signals in the Indian Ocean observed at IMS hydroacoustic stations H01 (Cape Leeuwin) in Western Australia and H08 (Diego Garcia) in the Chagos Archipelago, Indian Ocean (see Figure 4). Signals generated by ice rifting events on the ice shelves and iceberg calving from regions along the Antarctic coast, about 3300 km away from Australia, are of special interest to them. The temporal variations in the frequency of occurrence of such events along the coast of Antarctica reveal a noticeable seasonal component and have been related to environmental effects like climatic trends for Antarctica by this group.

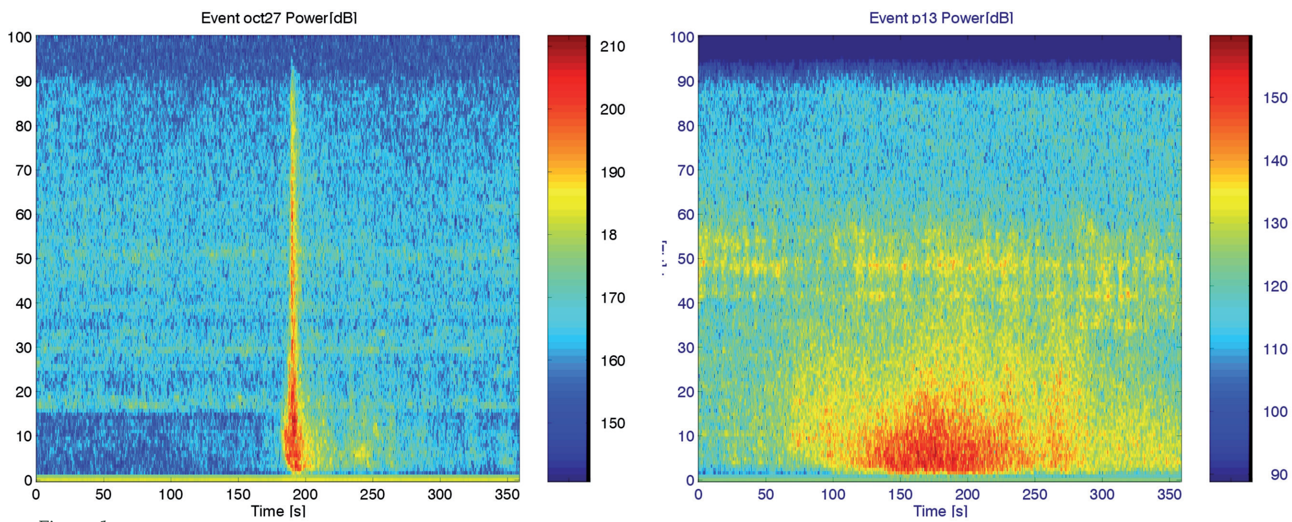



*Figure 1*
*Comparison of a sonogram (intensity versus time and frequency) of a nuclear explosion in the basement of the island Mururoa, 27 October 1995 (left) and a seaquake close to Japan (right), Peter Wille, Sound Images of the Ocean, Springer 2005, and reference therein.*

In particular, the Curtin University researchers studied the accuracy of observed directions of signal arrivals and source locations using data from the IMS stations (Li and Gavrilov, HYDRO-14/H). This has been accomplished through the modelling and analysis of the transient signals received by the stations from known ice and iceberg events. Locations of iceshelf and iceberg break-up were determined by satellite images. Using signals generated by selected long-lasting Antarctic ice tremor events, they concluded that the uncertainty of the observed direction of signal arrivals is only 0.2 degrees for IMS receivers at H01 and H08.

## SYNERGIES WITH OTHER TECHNOLOGIES

The overlapping coverage between the hydroacoustic and the seismic IMS network was also addressed during ISS09 (Prior et al., HYDRO-07/H). This overlap may enhance localization accuracy, improve knowledge about the event or fill in gaps in coverage by a single network.

Figure 2 shows the location of an event offshore from Carnarvon, Western Australia, which was detected by H08 and H01 on 10 November 2008. The signal was identified by the automatic data processing system implemented at the IDC. The spectrogram of the received signal at both stations strongly suggests that the source of the signal was an in-water explosion (see Figure 3).

The azimuths and times of the signals arriving at H08 and H01 determined a location for this event. However, this in-water event near the coast was recorded at seismic IMS stations in the Australian continent as well. Using signals from both IMS networks, the event was calculated as being located at 25.35 S, 112.13 E with an error ellipse smaller than 10 km². This small uncertainty in location is significantly less than the error ellipses resulting from exclusively processing single network signals.

This in-water event was also detected independently by the Geoscience Australia Seismic network. Locations derived by the IMS are within 20 km of the values of this local Australian network.

Another aspect to the sharing of seismic and hydroacoustic data was presented at ISS09 (Jepsen et al., HYDRO-06/H). In-water, on-island and low-altitude explosions often either contain high-frequency energy (as well as low-frequency energy) or have a short duration. In contrast, earthquakes, which are commonly observed by the hydroacoustic network, typically have a long duration and exhibit mostly low frequency energy (see Figure 1). This difference in frequency content is a clear distinguishing feature between explosions and natural earthquake sources. These features can be used during “event screening”,

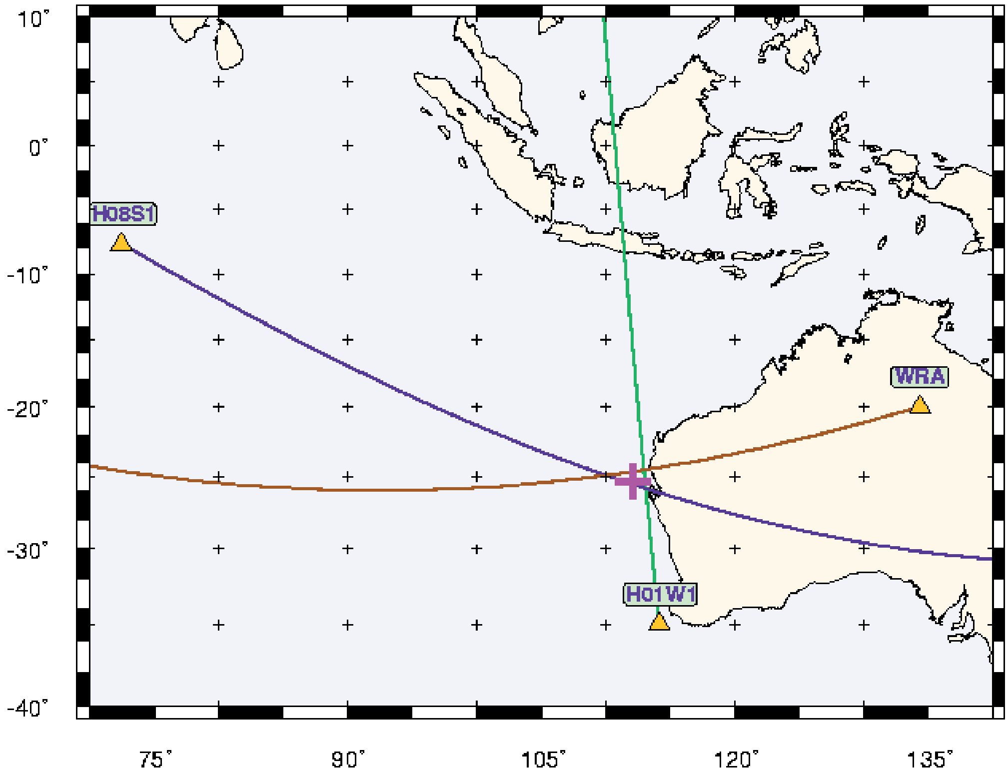



*Figure 2*
*Event formed from hydroacoustic and seismic IMS arrivals.*

the process which screens out events considered to be consistent with natural phenomena or non-nuclear, man-made phenomena and can provide a pre-classification of events listed in the IDC's Reviewed Events Bulletin (REB).

## POTENTIAL CIVIL AND SCIENTIFIC APPLICATIONS OF HYDROACOUSTIC DATA

Signals from numerous sources are observed at hydroacoustic stations. Signatures range from whale vocalizations and ship noise that are seen locally, to ice-calving, earthquakes and explosions that can be observed on an ocean wide scale.

Different posters at ISS09 presented work related to marine mammal monitoring using data received at IMS hydroacoustic stations (Harris et al., HYDRO-12/H; Flore et al., HYDRO-17/H). The population status of many whale species is sparse and difficult to obtain due to their wide–ranging distribution, extensive migration, difficult visual identification, and inaccessibility.

However, large whales produce specific low frequency, high intensity sounds year-long. Three previously described blue whale call types as well as fin whale calls have been identified in IMS hydroacoustic data.

Using passive acoustic monitoring of animals vocalizations to assess whale populations has several benefits in comparison with visual surveys. The animals can be studied continuously without any negative impact. This method is also less dependent on weather conditions than visual methods and does not rely on animals surfacing in order to be detected. It can be applied globally, including remote areas where whale studies are difficult but essential.

To carry out this kind of research, algorithms for automatic whale call detection, extraction and discrimination have been developed and used on IMS hydroacoustic data. Whale monitoring and monitoring nuclear explosions require similar techniques in some areas – in this case for detection. This is an example of how both sides – the CTBTO as well as the scientific community – benefit from close cooperation.

At ISS09 results were presented on the use of hydroacoustic data for tsunami warning purposes (Salzberg, HYDRO-16/H), which had been investigated over the last few years. For example, using data recorded at H08 (see Figure 4) it was shown that those earthquakes that produce significant tsunamis released energy of 60 Hertz (Hz) and above. This reveals, for example, the comparison of spectrograms from the two largest earthquakes that have occurred over the last 40 years: the Sumatra-Andaman Earthquake in December 2004 and the Nias Island Earthquake in 2005. The Moment Magnitude "Mw" (used to measure the size of earthquakes in terms of the energy released) for these earthquakes was 9.1 and 8.7 respectively.

The Sumatra-Andaman Earthquake generated a devastating tsunami while the Nias Island Earthquake could not generate much tsunami because of shallow water.

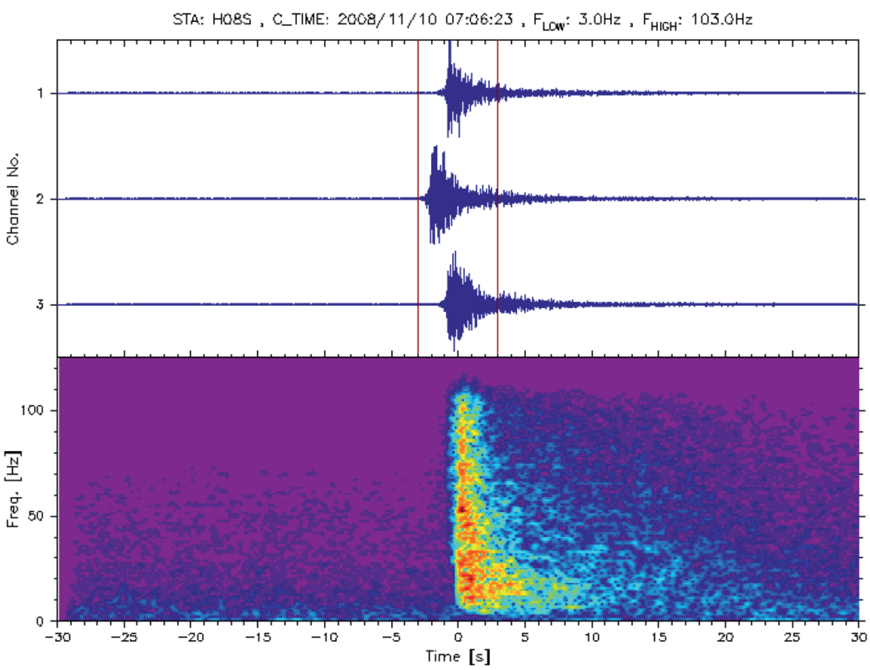



*Figure 3*
*Signal arrivals at H08 (Diego Garcia South) for an in-water event. Upper pane shows signal time histories at triad's three hydrophones. Lower pane shows sonogram (intensity versus time and frequency) of the first hydrophone's signal.*


*Figure 4 showing the hydroacoustic network.*

BIOGRAPHICAL NOTE

## WOLFGANG JANS

joined the Federal Armed Forces Underwater Acoustic and Marine Geophysics Research Institute (FWG) in Kiel, Germany, as a physicist in 1994.

Since then he has been involved in sound propagation modelling and sonar signal processing methods, was a Scientist-in-Charge for several multinational sea trials, and is currently responsible for sonar methods and signal processing for the FWG, now renamed the WTD71-FWG. He took over the advisory activities in Germany for CTBT-related hydroacoustic issues in 2005.

BIOGRAPHICAL NOTE

## KIYOSHI SUYEHIRO

spent nearly thirty years in the research field of marine seismology at Tohoku University, Chiba University, University of Tokyo and the Japan Agency for Marine Earth Science and Technology (JAMSTEC).

He is currently President of the Integrated Ocean Drilling Program Management International and oversees a unique international scientific drilling programme to study the Earth's evolution and dynamics. His recent works include establishing high quality sub-seafloor geophysical observatories to monitor the internal working of the Earth.

It should be added that in the case of the Sumatra-Andaman Earthquake, hydroacoustic data from H08 allowed tracking of the propagating rupture. This was already shown independently by the CTBTO and academia in 2005.

## CONCLUSION

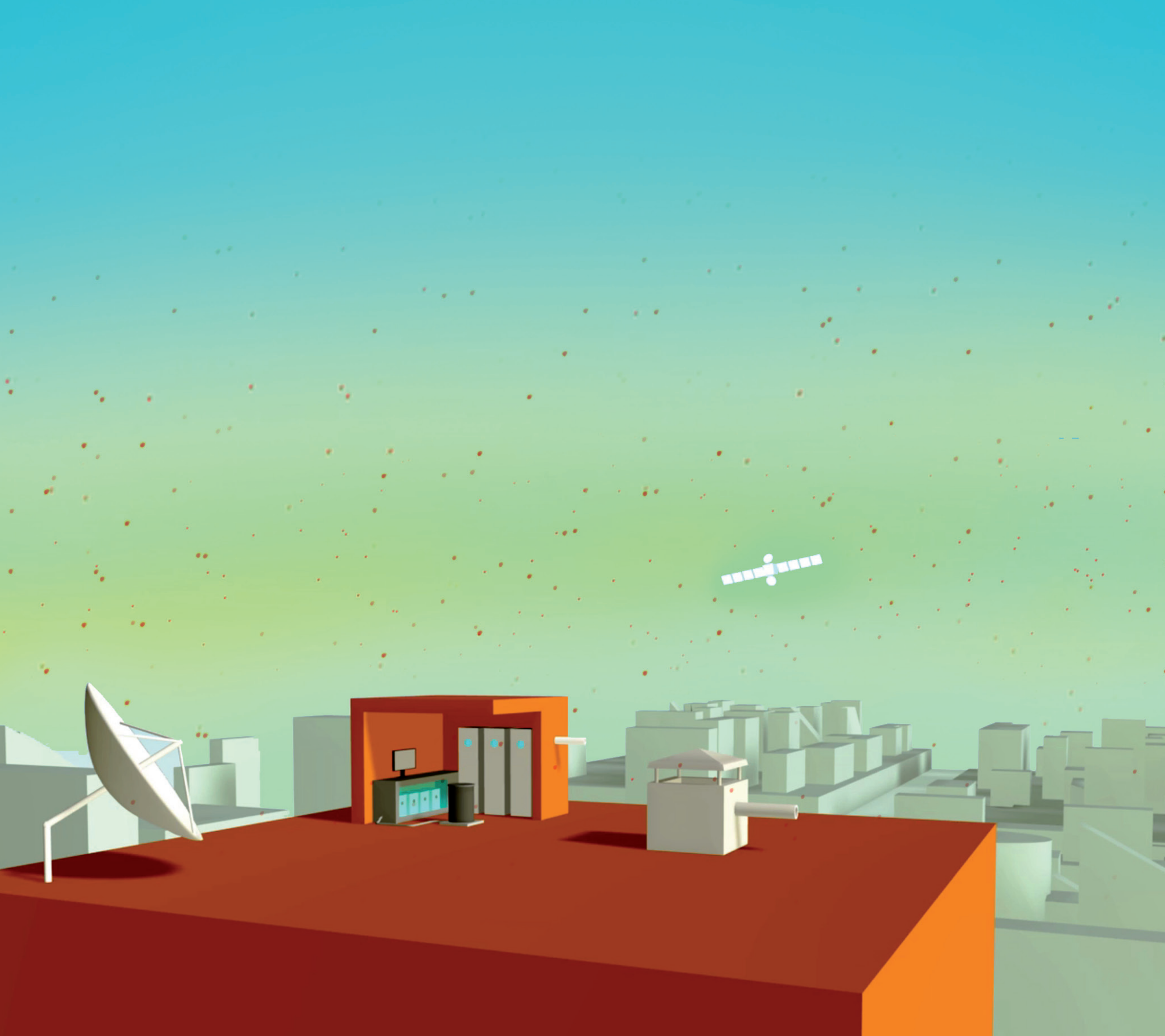
The hydroacoustic network complements the other IMS networks and is of particular significance for coverage of the southern hemisphere, as outlined on page 18.

In terms of detecting in-water events, it is unique. The existing network can most certainly detect low-yield in-water explosions, as demonstrated by the test involving only an estimated 20 kg of TNT off the coast of Japan. Location and identification capabilities will improve further with more available "ground-truth" data and with sophisticated data analysis including better understanding of wave coupling and wave propagation in 3D media with temporal variations.

The network also allows for measurements on a global scale and is therefore potentially of great value for performing studies investigating global effects. Providing data to the scientific community will initiate many different kinds of studies. To realize their research goals, scientists will develop approaches and algorithms to solve their detection, localization and characterization problems, which could be applied to similar problems at the CTBTO. Some of these benefits are immediate, like those mentioned in the second section. In other cases, benefits may be more long-term and indirect.

# Radionuclide Monitoring

BY ANDERS RINGBOM AND HARRY MILEY



# Radionuclide Monitoring

BY ANDERS RINGBOM AND HARRY MILEY

**FACT BOX**

The Radionuclide topic area of the ISS project has involved a thorough assessment of the performance of the particulate and the noble gas monitoring networks in detecting radioactive particles and noble gases in the atmosphere.

The very first article of the Comprehensive Nuclear-Test-Ban Treaty (CTBT), which holds the essence of the entire Treaty, states that "Each state party undertakes not to carry out any nuclear weapon test explosion or any other nuclear explosion…" It is therefore obvious that the ability to establish the nuclear nature of an explosion must be an essential component of the CTBT verification regime. This was well illustrated in October 2006, when the Democratic People's Republic of Korea (DPRK) conducted its first nuclear test. Based on data from the CTBT seismic network, the yield could be estimated at 0.7 kilotons (kt), far less than the very first nuclear test, Trinity, conducted by the United States in 1945, which was about 20 kt. The seismic signals from the DPRK test could, in principle, have been created by a large conventional explosion, so it was not until atmospheric radioactive isotopes in the form of noble gases were captured, measured, and associated with the explosion, that the nuclear nature of the event could be established (Ringbom et al., RN-26/D)[1,2].

At the International Scientific Studies Conference (ISS09), more than 30 posters were presented which described recent investigations on the detection of radionuclides from nuclear explosions. In this article we will try to portray the development described by these posters, together with a basic description of the scientific challenges and the techniques used to meet them.

## RADIOACTIVITY PRODUCED IN A NUCLEAR EXPLOSION

A nuclear explosion creates a huge amount of radionuclides. If conducted in the open atmosphere, characteristic fission products mainly attach themselves to normal atmospheric dust. Dirt lofted by the explosion in the atmosphere or local rain can deposit a significant fraction of the particulate debris locally, but the remaining debris can travel across continents, and even around the world.

There are examples in the past when atmospheric test debris was detected on each of three circumnavigations of the globe. Since a high percentage of radioactivity is released, the detection threshold will be very low for atmospheric explosions. Studies presented at ISS09 show that the International Monitoring System (IMS) can easily detect such particulate debris (Werzi, RN-20/D).

The situation is quite different if the explosion is conducted underground, which is a scenario considered more likely today, as illustrated by the two tests conducted by DPRK in October 2006 and May 2009. In the case of an underground test, most of the radioactivity will remain in the cavity formed by the explosion. However, a smaller part of the radioactivity produced in a nuclear explosion comes in the form of noble gases, which do not react with the rock and soil and thus have a good chance of reaching the surface.

Today, scientists recognize a few isotopes of xenon ($^{133}$Xe, $^{131m}$Xe, $^{133m}$Xe, and $^{135}$Xe), and one isotope of argon ($^{37}$Ar) for the purposes of determining the nuclear nature of an event. The latter isotope is not a fission product but produced by fission neutrons which may transmute natural calcium in the surrounding rock into $^{37}$Ar.

Xenon escape has been observed many times in nuclear tests conducted over the years. There are several different modes of noble gas escape. During the first hours after a test, high temperature and pressure can create fissures in the geological or engineered containment leading to an immediate vent of radioactive gas. This can be followed by seepage for the next few days. A third mode is caused by barometric pumping, demonstrated in the so-called "Non-Proliferation Experiment" in 1993, where it was shown that periods of low atmospheric pressure tend to transport gas to the surface through faults (Carrigan et al., OSI-26/B), [3]. In this experiment, a chemical explosive of approximately one kt was detonated in a cavity at the Nevada Test Site, together with containers of non-radioactive tracer gases.

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[1] Saey, P. R. J.,et al., (2007), "A long distance measurement of radioxenon in Yellowknife, Canada, in late October 2006", Geophys. Res. Lett., 34, L20802, doi:10.1029/2007GL030611.

[2] A. Ringbom, et al., "Measurements of radioxenon in ground level air in South Korea following the claimed nuclear test in North Korea on October 9, 2006", J. Radioanal. Nucl. Chem, published online 25 July, 2009.

[3] C.R. Carrigan, et al., "Trace gas emissions on geological faults as indicators of underground nuclear testing",Nature 382 (1996) 528.

Prompt release or later seepage may release a small percentage or only a fraction of a percent into the atmosphere. In reality it is very difficult for monitoring scientists or even testers to predict the amounts released from a particular underground explosion due to the many unknown factors involved. Local geological conditions may not be sufficiently well known and the explosive energy of the explosion may be miscalculated. However, promising theoretical models tackling aspects of this problem were presented at ISS09. One example is found in Annewandter et al., OSI-25/B, where barometric pumping observed [3] was simulated by modelling the fault zones in the vicinity of the test explosion.

It should be mentioned that it is not only noble gases that have been observed escaping from underground tests. Release data from U.S. tests (Ely et al., OSI-17/B), as well as a few independent measurements (De Geer, RN-23/D), all presented at ISS09, show that small fractions of other nuclides have been observed. In particular radioactive iodine ($^{131}$I) is capable of escaping into the atmosphere, and calculations show that there is a possibility of detecting the iodine if so called ultra-low background measurements were applied (Aalseth et al., RN-09/D).

## DETECTING THE RELEASE

When complete, the International Monitoring System (IMS) radionuclide network will consist of 80 stations which collect and measure aerosol

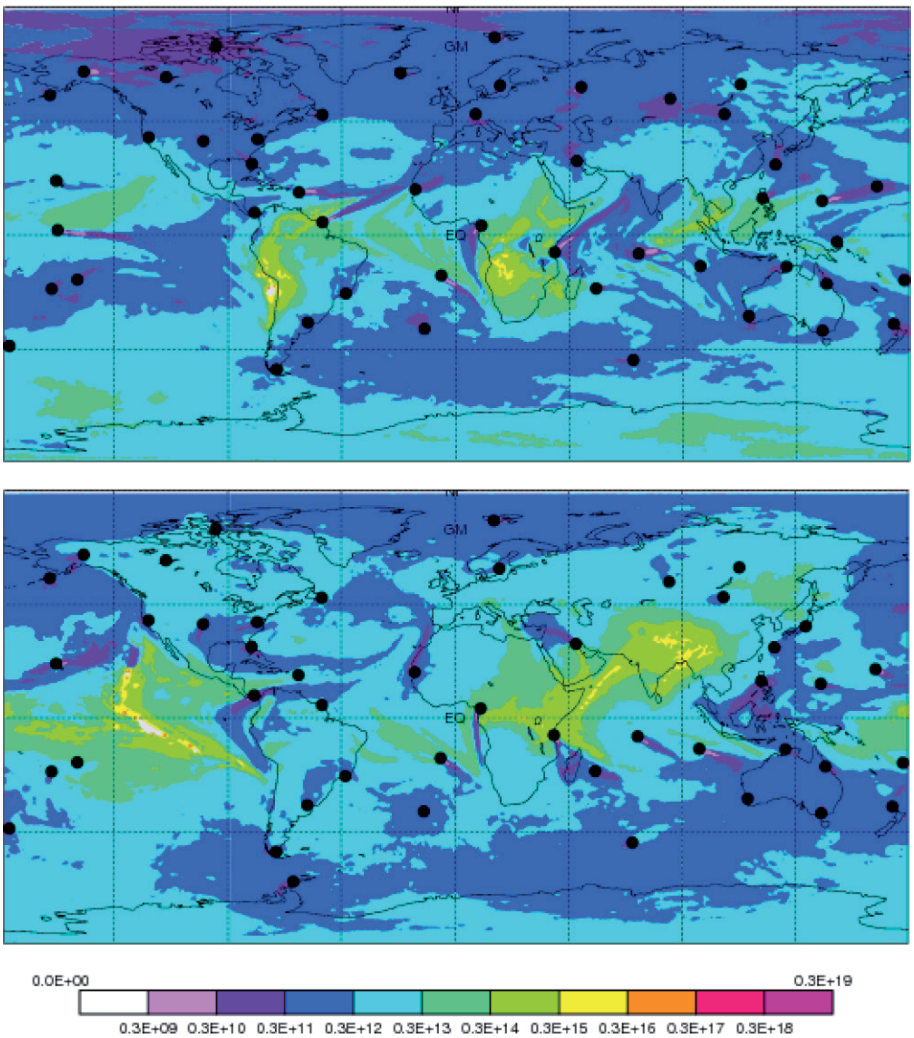


*Figure 1*
*Two months of aerosol coverage. The legend is in Bequerels of $^{140}$La, a major fission isotope found on aerosols. An atmospheric explosion of one kt would release sufficient $^{140}$La that after two weeks, 3 petaBequerels would remain. Each colour step to the left of 0.3E+16 on the legend represents a factor of 10 better sensitivity than one kt.*

particles, of which 40 stations collect and measure xenon. The systems that detect aerosols use a mature technique which has been refined over six decades. High-volume air samples are used to collect the particles on to filters that are later measured using gamma-ray detectors. Substantial progress has been made here in creating high-volume, reliable automatic systems. The combination of high volume air sampling, sensitive detection, and a dense network have resulted in a system that was assessed by the ISS scientists as fully meeting the design criteria (see Figure 1) despite the fact that it is only about 70 percent complete (Werzi, RN-20/D), and could thus withstand large outages and still detect very low-yield tests.

When the CTBT was opened for signature in 1996, mature techniques for detecting radioactive noble gases and systems for deployment in a worldwide network were not available. The lack of a demonstrated automatic technique for detecting the nuclear nature of an underground event prompted a multi-national development campaign to produce highly sensitive, fully automatic radioxenon systems with 12 or 24 hour sampling time resolutions [4]. Refined versions of those systems are now being deployed on an experimental basis. The principle for collection and purification of xenon gas is based on the physical properties that differentiate xenon from other gases like nitrogen, oxygen, and carbon dioxide.

After collection, concentration and purification, the final xenon sample is transferred into a measurement system which measures the nuclear decays of the radioactive species if they are present. The systems have an impressive detection capability corresponding to a few hundred atoms of radioactive isotopes per cubic metre of air, when the typical sampled volume is in the range of tens of cubic metres of air. Furthermore, the high time resolution results in improved accuracy when using atmospheric transport models in order to locate the source of release. By August 2009 more than 20 of the 40 planned radioxenon systems within the IMS were already operating and sending data to the International Data Centre (IDC) in Vienna.

In order to discriminate between radioxenon releases from a nuclear explosion and other sources of release, it is important to be familiar with the normal radioxenon concentrations in the atmosphere. The deployment of the new generation of xenon measurement systems has produced a unique, continuously growing data set that has led to a better understanding of this background. Studies of this data set

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[4] M. Auer, et al., "Intercomparison experiments of systems for the measurement of xenon radionuclides in the atmosphere",Appl. Rad. and Isot. 60(2004) 863.

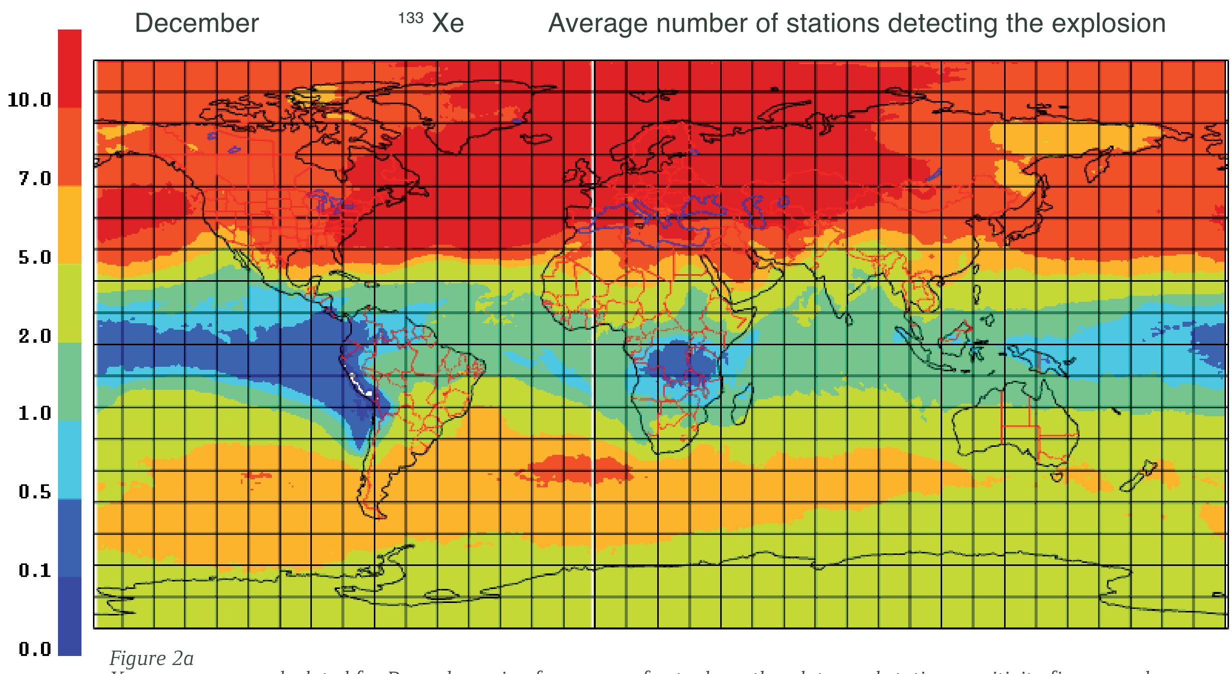



*Figure 2a*
*Xenon coverage calculated for December using four years of actual weather data, real station sensitivity figures and xenon background information. In this graph, red represents the detection by many stations and blue depicts detection by a few stations of a one kt underground test with 10 percent leakage. The colours represent the average number of stations detecting the explosion.*

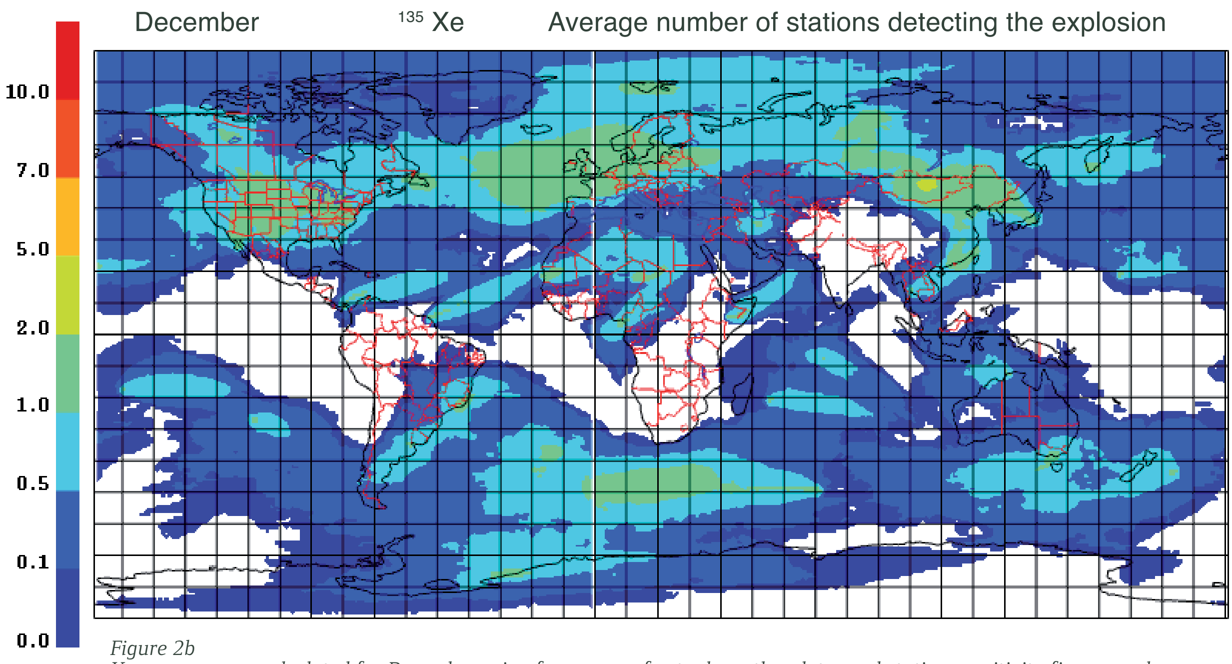



*Figure 2b*
*Xenon coverage calculated for December using four years of actual weather data, real station sensitivity figures and xenon background information. In this graph, red represents the detection by many stations and blue depicts detection by a few stations of a one kt underground test with 10 percent leakage. The colours represent the average number of stations detecting the explosion.*

(Ringbom et al., RN-19/D; Wotawa et al., ATM-16/E) as well as studies of reported radioxenon emissions (Kalinowski et al., RN-01/E), presented at ISS09, show that the atmospheric background of radioxenon today is dominated by a few isotopic production facilities, with a much smaller contribution from nuclear power reactors and a few other sources. The studies also indicate that the observed $^{133}$Xe levels at most stations can be explained using known releases in combination with Atmospheric Transport Modelling (ATM) (Wotawa et al., ATM-16/E).

The detection of more than one radioxenon isotope is important in order to be able to screen out irrelevant civilian activity. It turns out that the isotopic ratios from nuclear power plants in general are different from the ones expected from a nuclear explosion, and radioxenon experts are presently working on developing a robust categorization scheme using radioxenon isotopic ratios (Kalinowski et al., RN-24/D). ATM development also plays an important role when developing techniques for the discrimination of nuclear explosions from other sources (see ATM section on page 29).

The isotopic signature from medical isotope production facilities can in some cases be more similar to a nuclear explosion signature. This stresses the importance of controlling or closely monitoring the releases from these facilities, an area for future scientific study.

The new radioxenon background data presented at ISS09 could also enable more realistic assessments of the coverage of the planned radioxenon network to be compared to design studies conducted over a decade ago. A study presented at ISS09 (D'Amours and Ringbom, RN-16/D) reveals that while the overall detection capability of the radionuclide network for $^{133}$Xe is essentially as was anticipated, the most short-lived isotope, $^{135}$Xe, which has a half-life of nine hours, would be detected by no more than two stations (see Figure 2). This assessment strongly suggests that the network performance would be much more robust with 80 stations in operation, i.e. the same network density as used in the particulate network. Robust here means providing accurate atmospheric backtracking with maximum screening out of industrial sources.

## FURTHER DEVELOPMENT

One overall impression from ISS09 is that many of the ideas presented seem like starting points rather than ending points, and there is definitely room for scientific development in many areas. Sensor technology is developing fast, and the use of more sensitive radiation detectors is one example. If one wants to go even further, single atom counting, which exists today, could also be applied in principle. A modification that is perhaps closer to realization is the development of simpler collection and purification systems for noble gases. This could lead to even more reliable and less expensive systems, or possibly to more sensitive systems which could detect the shorter-lived xenon isotopes more often.

Another area of study discussed at ISS09 was the understanding of the transfer mechanism between underground tests and the surface. More understanding of leakage could be obtained from future repetition of the 1993 "Non-proliferation Experiment", for instance, in which controlled underground gas releases are detected at the surface, validating scientific models of seepage in different geological conditions.

## CONCLUSIONS

- The detection of radioactive products is important in order to determine whether an underground explosion was nuclear or not, as well as for detecting atmospheric tests. If the IMS does not detect any radioactive debris, an on-site inspection may be needed to determine the nuclear nature of an event.
- Aerosol detection is a very sensitive technique which has the capability to detect atmospheric explosions well below the level that was considered necessary during the Treaty negotiations. It might also be used to detect underground tests if ultra-low background measurement techniques are applied to stations and laboratories.
- Extensive development and deployment of equipment for radioxenon detection has been performed over the last decade, resulting in highly sensitive, fully automatic radioxenon systems. This development has led to a rapid increase in the knowledge of anthropogenic atmospheric radioxenon background. The main contributor to this background comes from a few medical isotope production facilities, and IMS detection levels and confidence would improve if these releases were reduced.
- A robust scheme to screen out industrial radioxenon releases is needed. Although the basic requirements for the IMS have already been met, the number of planned radioxenon stations should be increased to improve coverage for all four CTBT-relevant isotopes and thus improve discrimination.
- Further understanding of the transfer mechanisms for fission gases from the Earth's crust to the atmosphere from a nuclear explosion is required.
- The radionuclide systems of the IMS are very sensitive already but there is still room for further development, both with respect to sensitivity and reliability.

BIOGRAPHICAL NOTE

### HARRY MILEY

is a Laboratory Fellow at the Pacific Northwest National Laboratory (PNNL), USA.

Dr. Miley has worked at the intersection of pure science and science for national security for over 20 years. During the 1990s, he was a contributor to the Nuclear Explosion Monitoring (NEM) programme of which he was later appointed director. He also led a team of scientists and engineers in the development of the Radionuclide Aerosol Sampler/Analyzer (RASA), which is used today by the CTBT's verification regime.

BIOGRAPHICAL NOTE

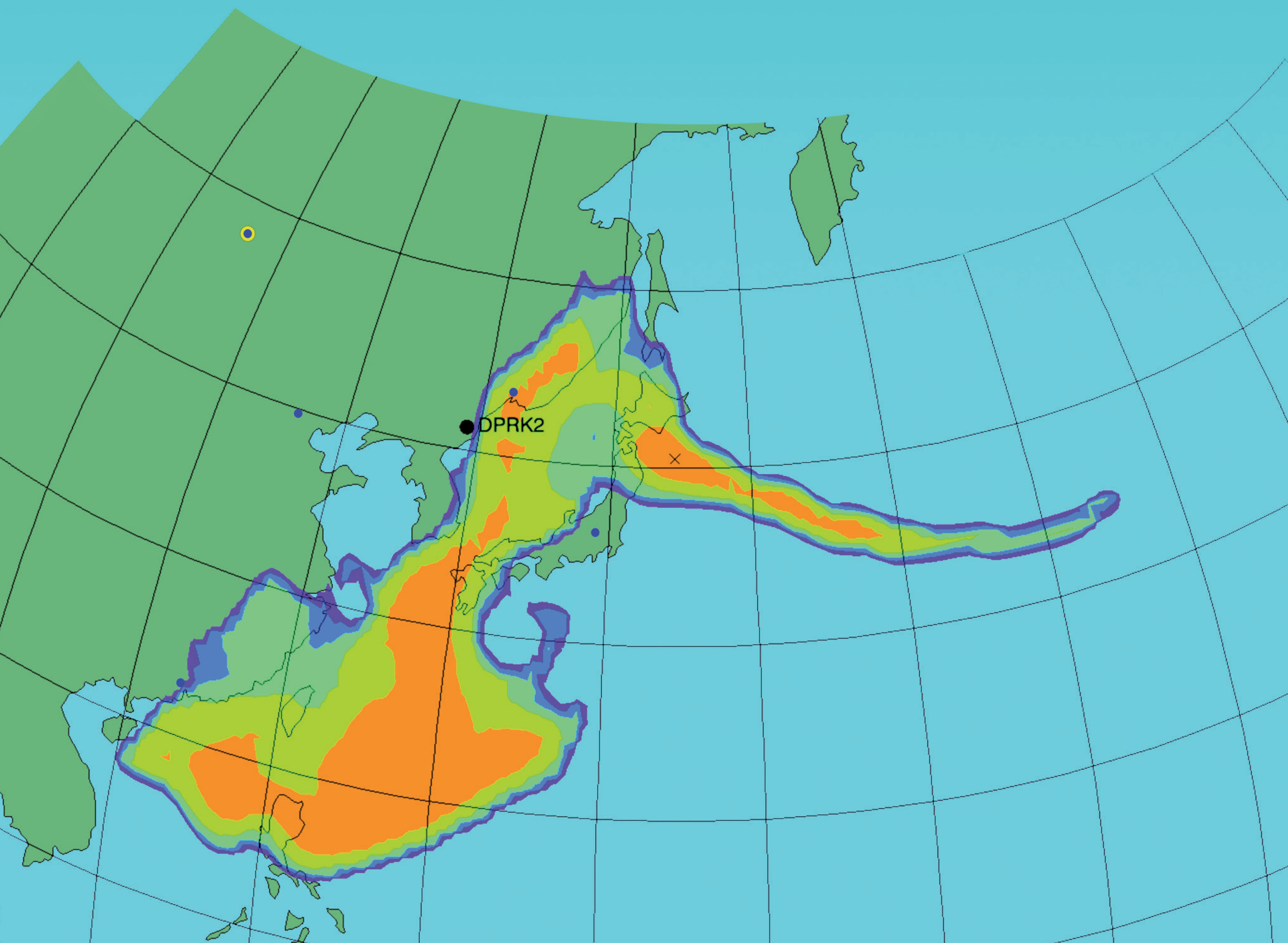
### ANDERS RINGBOM

is Deputy Research Director at the Swedish Defence Research Agency, Division of Defence & Security Systems and Technology.

Dr. Ringbom is a technical advisor to the Swedish Government and Swedish representative at the CTBTO's Working Group on verification issues. He is also manager of the Swedish National Data Centre for CTBT monitoring. He managed the development of the noble gas system SAUNA and has developed equipment and analysis techniques for radioxenon detection used by the CTBTO.

# Atmospheric Transport Modelling

BY PETER CHEN AND RICHARD HOGUE



# Atmospheric Transport Modelling

BY PETER CHEN AND RICHARD HOGUE

**FACT BOX**

Atmospheric Transport Modelling (ATM) is concerned with modelling and tracking the movement of air volumes to estimate the locations of sources of radionuclide particulates and noble gas observations. The ATM topic area of the ISS project has conducted a series of studies designed to estimate the capabilities of present ATM models and procedures, and to explore ways to further improve their accuracy.

ATM technology can be used for tracking radioactive particles and noble gases produced from atmospheric or underground explosions and dispersed by the atmospheric winds. In order to link a measurement at an International Monitoring System (IMS) station and a possible source location, a detailed understanding of the three-dimensional movements of the air around the globe is needed. To locate a potential source, the ATM's backtracking mode is used most efficiently to associate radionuclide detections at monitoring locations with possible source locations. In the opposite case, ATM can be used to forecast where the plume of radioactivity may first arrive at monitoring sites. This prediction technology was used in the daily assessments of potential station detections in the case of the 25 May 2009 test by the Democratic People's Republic of Korea (DPRK) where the spatial source location was determined accurately by the IMS seismic network.

## ATM: A KEY TECHNOLOGY FROM 1996 WHEN THE TREATY OPENED FOR SIGNATURE

The ISS Conference (ISS09) acknowledged the important role that ATM technology played during the early negotiations for the Comprehensive Nuclear-Test-Ban Treaty (CTBT) in terms of estimating the performance of various designs of a global radionuclide monitoring network for Treaty verification. ATM has advanced considerably since then.

The Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization's (CTBTO) International Data Centre (IDC) has developed and implemented a sophisticated ATM backtracking system, using real-time meteorological input from the European Centre for Medium Range Forecasts (ECMWF), one of the most advanced global meteorological centres in the world. In addition, the IDC integrates ATM estimates from the World Meteorological Organization (WMO) to increase confidence in the source location assessment. These additional estimates are computed in real-time from nine of the WMO's operational numerical weather prediction centres using global observational data, analyses, and numerical models of the earth-atmosphere system. The combined CTBTO-WMO system has been tested several times through designed exercises, as well as following the DPRK's underground nuclear test on 9 October 2006.

ATM technology has also been used extensively to study the background level of radionuclides that are detected at each of the IMS monitoring stations. Work in that area has been particularly active in improving the understanding of the noble gas measurements at the stations, which are affected by the few medical isotope production facilities in the world. These fixed sources account for most of the noble gas detections at the IMS stations. Therefore, it is important to understand the typical daily measurement signature that is due to various source emissions, in particular those from medical isotope facilities. This is often referred to as understanding the "background signature" at each station and is essential in order to interpret and identify noble gas measurements that could be associated with an emission from an underground nuclear explosion.

During ISS09, the CTBTO's capabilities to detect, locate and characterize a nuclear event were discussed. ATM technology makes vital contributions to both radionuclide particulate and noble gas event localization. In addition, ATM contributes significantly to noble gas event characterization by flagging bogus xenon detections from known fixed sources.

Overall, ISS09 noted that ATM technology is an indispensable part of Treaty verification, which connects radionuclide and noble gas monitoring data to the unambiguous identification of a nuclear explosion.

## DIFFERENT ASPECTS OF ATM TECHNOLOGY ADDRESSED THROUGH SCIENTIFIC POSTERS

Dr. Andreas Stohl, senior scientist at the Norwegian Institute for Air Research, gave a keynote lecture at ISS09 on the ATM topic area. Dr. Stohl is the main developer of the transport model (called “Flexpart”) that is used operationally at the IDC. Dr. Stohl provided a good overview of recent developments in ATM and, in particular, presented many examples of the validation of these models in the air quality modelling area such as tracking of air pollution plumes (CO, $NO^2$) and burning of biomass during large forest fires. As chemical constituents in the atmosphere follow the movements of the air, the validation process of the modelling and tracking of these elements applies directly to the use of ATM technology to track radionuclides in the atmosphere. Dr. Stohl’s presentation showed many of the capabilities of ATM technology in a wide range of successful applications, including in the Treaty verification area where the demand for ATM capability is comparatively low.

## SUMMARY OF POSTERS PRESENTED AT THE ISS09

Fourteen posters on the ATM topic area were presented at ISS09. In addition, many of the radionuclide posters made reference to subjects closely related to ATM as these two areas work hand in hand.

The posters provided a good overview of many of the areas related to ATM: operational

*Friday 21 March at 12:00 UTC*

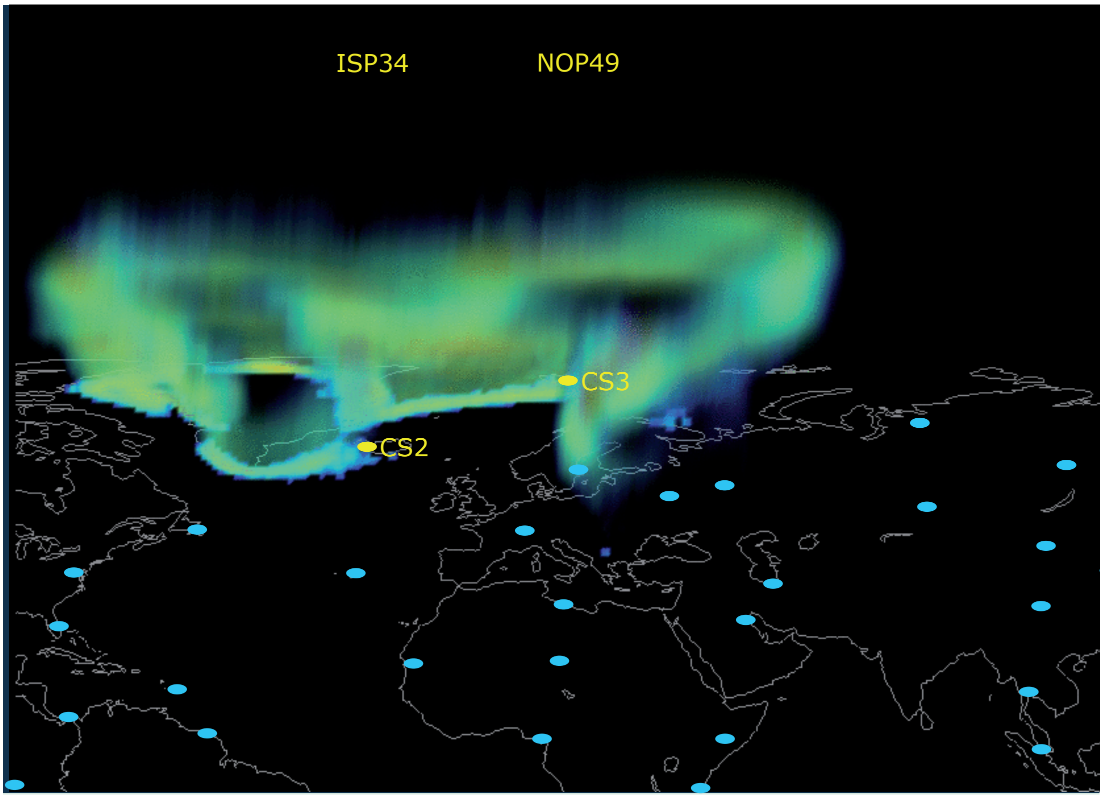



*Figure 1*
*Illustration of the complex 3D shape of a radioactive plume typically evolving from a surface level release of nuclear debris, as simulated with a CTBTO ATM tool. The related simulated IMS radionuclide measurement scenario was used for the first CTBTO-WMO Experiment in Source Location Estimationí (CTBT/PTS/TR/2004-1) conducted in March 2003.*

capabilities, case studies on CTBT-related events, improved understanding of noble gas background levels, and scientific improvements related to ATM.

The implementation of operational capabilities at the CTBTO including the close cooperation with the WMO, was well covered by several posters (Becker et al., ATM-03/E; Skomorowski and Pechinger, ATM-07/E; Wotawa and Becker, ATM-09/E). The CTBTO's ATM system is now fully functional and provides real-time reliable guidance and products to support the verification technologies. These products contain all relevant information to enable the IMS radionuclide measurements to be traced back to their source as well as information that helps determine the radionuclide network's capability in terms of network coverage and threshold monitoring. The ATM system is based on a scientifically sound and proven technology that uses the world's best atmospheric analyses available from the ECMWF. Furthermore, the CTBTO is able to access support from the WMO's Regional Specialized Meteorological Centres on a 24-hour basis. This has helped increase confidence in the CTBTO's assessments by comparing backtracking modelling with WMO results.

In-depth case studies on CTBT-related events were presented by some of the ISS posters. These included the assessment of the DPRK 2006 event (Becker et al., ATM-10/E; Stocki et al., ATM-14/E) and the study of the 2008 shutdowns of some of the major medical isotope emitters (Chalk River, Canada, and Fleurus, Belgium). These temporary shutdowns offered a unique opportunity to assess the relative impact of these production facilities on the monitoring system (Ungar et al., ATM-15/E; Wotawa et al., ATM-16/E).

ATM technology is increasingly used to further explore and understand the noble gas measurements at the IMS stations. In that regard, a few posters presented studies to enhance understanding of the background level of global noble gas measurements at the IMS stations. In particular, one study presented updated results of the global detection capabilities of the radionuclide stations to detect the various xenon isotopes by using many years of xenon measurements at the stations (Ungar et al., ATM-12/E). There have been significant contributions over the last six months alone that have helped improve the understanding of global noble gas background levels. This was one of the areas of work which was identified as needing improvement during the briefing session on the ISS project organized last December 2008 in Washington by the Center for Strategic & International Studies. The posters at ISS09 clearly demonstrated that substantial progress has been made in that field.

Finally, many of the posters covered scientific improvements to the science of ATM. Two posters specifically addressed the area of ensemble modelling methods, which aim to reduce the uncertainties in the ATM assessments. One poster (Galmarini et al., ATM-05/E) compared the performance of two approaches to generating the ensemble members (multi-model ensemble and ensemble prediction system based ensemble), while the other (Galmarini and Potempski, ATM-04/E) examined new approaches to evaluate multi-model ensemble systems. Other posters explored opportunities for improvement (Arnold et al., ATM-02/E; Panday, ATM-06/E; Seibert, ATM-08/E). These included the use of more sophisticated source terms for the emissions scenarios such as time-dependent emission profiles, the need to examine the issues related to the resolution and quality of the meteorological data input to the ATM system, and the potential application of ATM to on-site inspection (OSI) related issues. In that regard, the importance of considering the complex terrain topographies and the weather phenomena in detail at the smaller scales was well highlighted. Posters also included ongoing work to assess the added value of running higher resolution ATM systems so as to better capture the various smaller scale phenomena, in particular for the monitoring stations located near complex terrain which affect the atmospheric flows.

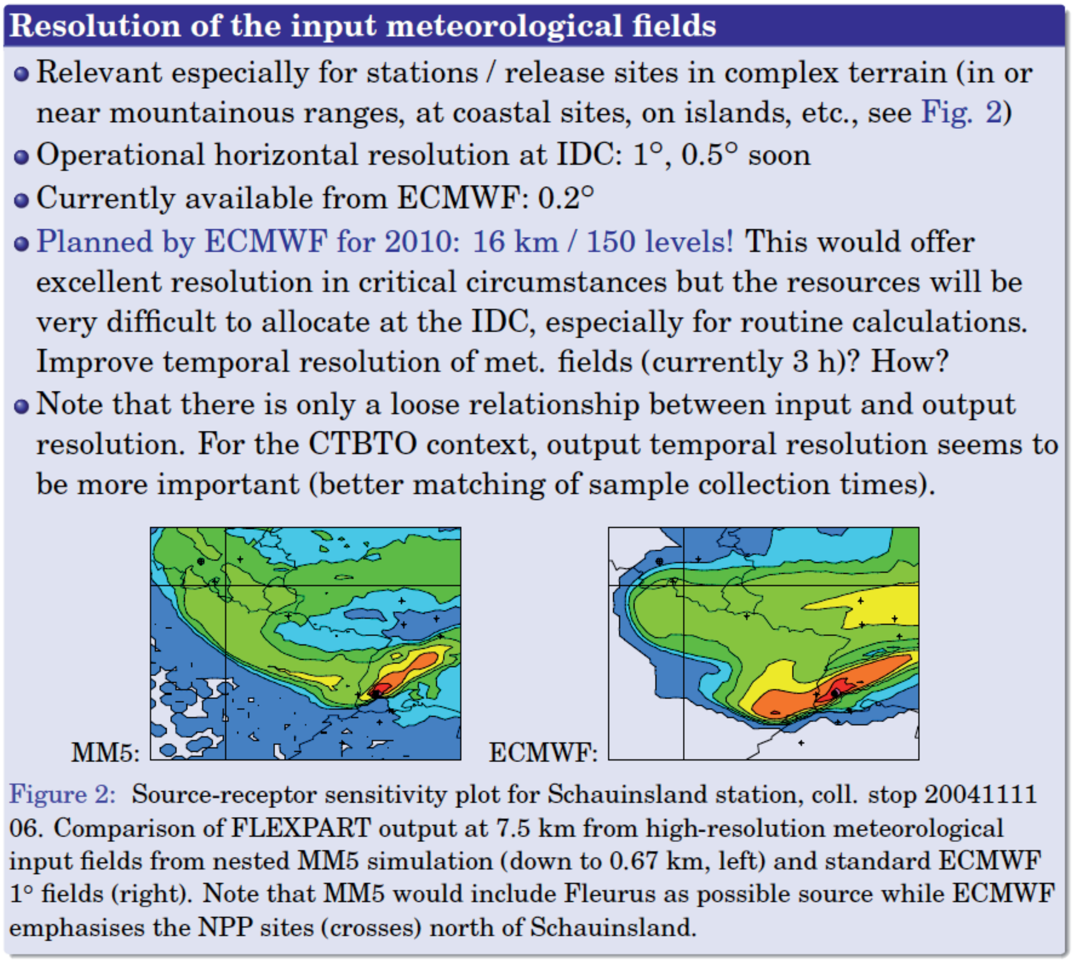
## ATM AND OTHER CIVIL AND SCIENTIFIC APPLICATIONS

The benefits of CTBT verification technologies for civil and scientific applications were strongly expressed at ISS09. The ATM scientific area profits from the availability of radionuclide datasets in order to verify and validate the atmospheric models, which is an essential part of the ATM science. Furthermore, WMO receives the weather observations from IMS stations. These observations may be used in the global data assimilation systems, which, in turn, help to improve the assessment of the atmospheric flows around the globe and improve the weather forecasts.

A well recognized civil application takes advantage of the capability to detect volcanic eruptions worldwide using infrasound monitoring. The time and intensity of the volcanic ash eruptions are important inputs to the tracking and forecasting of ash clouds in the atmosphere using ATM methods. The International Civil Aviation Organization's (ICAO) Volcanic Ash Advisory Centres (VAAC) provide timely guidance to the aviation industry concerning ash clouds. They would benefit from improved time and intensity information about the release of ash plumes to better track and forecast these plumes using ATM. Here again; this detailed information can be used to validate ATM systems more accurately (Fee et al., INFRA-28/G).

## ATM: A CORNERSTONE TO THE CTBT VERIFICATION TECHNOLOGY

The presentations and discussions at ISS09 clearly demonstrated the positive contributions of ATM to the CTBT verification regime as well as the unique collaboration with the WMO. The impressive turnout of posters presented at ISS09 indicates that interest from the scientific community will continue to grow. This is also related to the fact that ATM technology provides the link that associates radionuclide events with seismic events and improves the reliability and accuracy of infrasound event back-tracking. Many international ATM experts have expressed an interest in participating in ISS follow-up activities. Until then, the special session dedicated to 'Research and Development in Nuclear Explosion Monitoring',



**Resolution of the input meteorological fields**

- Relevant especially for stations / release sites in complex terrain (in or near mountainous ranges, at coastal sites, on islands, etc., see Fig. 2)
- Operational horizontal resolution at IDC: 1°, 0.5° soon
- Currently available from ECMWF: 0.2°
- Planned by ECMWF for 2010: 16 km / 150 levels! This would offer excellent resolution in critical circumstances but the resources will be very difficult to allocate at the IDC, especially for routine calculations. Improve temporal resolution of met. fields (currently 3 h)? How?
- Note that there is only a loose relationship between input and output resolution. For the CTBTO context, output temporal resolution seems to be more important (better matching of sample collection times).



Figure 2: Source-receptor sensitivity plot for Schauinsland station, coll. stop 20041111 06. Comparison of FLEXPART output at 7.5 km from high-resolution meteorological input fields from nested MM5 simulation (down to 0.67 km, left) and standard ECMWF 1° fields (right). Note that MM5 would include Fleurus as possible source while ECMWF emphasises the NPP sites (crosses) north of Schauinsland.

*Figure 2*
*Section snapshot of the poster by Seibert (ATM-08/E) discussing the CTBT relevant benefits of running ATM systems with higher resolved input meteorological fields.*

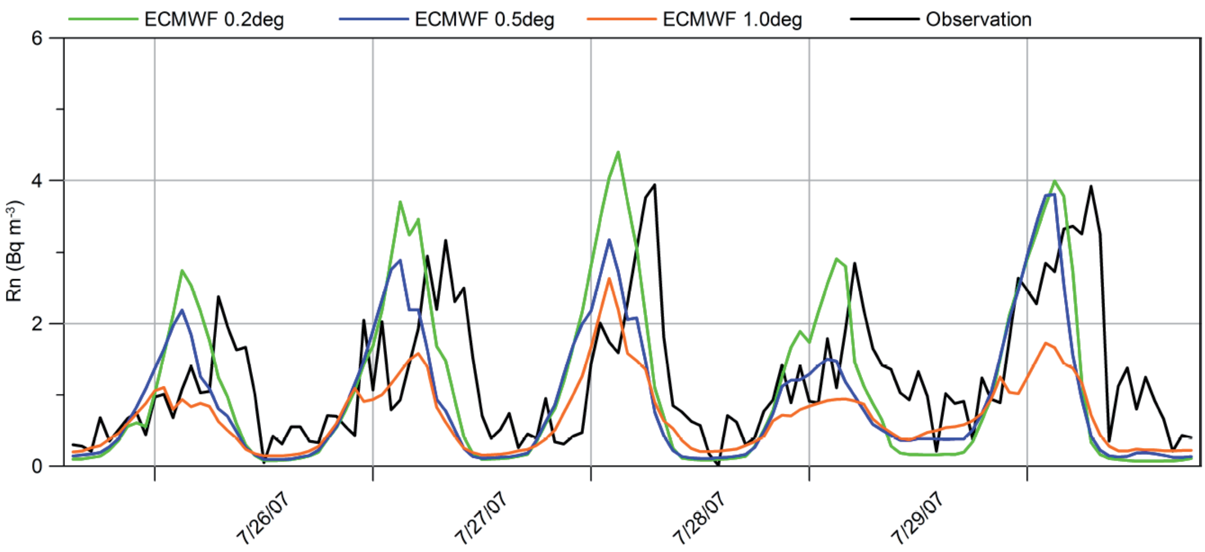



*Figure 3*
*Section snapshot of the poster by Arnold et al. (ATM-02/E) showing observed and modelled Radon-222 concentrations at a station near Barcelona, Spain, which is apparently typical for IMS stations in horizontally heterogeneous terrain. It is shown that the utilization of higher resolved input meteorological fields substantially improves the ATM system's capability to reproduce the observations.*

BIOGRAPHICAL NOTE

## RICHARD HOGUE

is Director of the National Prediction Operations Division at Environment Canada's Meteorological Service of Canada.

Mr. Hogue has been managing Research and Development and governmental operational systems for the past 15 years. Under his leadership, the Environmental Emergency Response Section manages national and international mandates to provide specialized atmospheric dispersion modelling services regarding radioactive material to various organizations such as the World Meteorological Organization (WMO) and the CTBTO.

BIOGRAPHICAL NOTE

## PETER CHEN

is Chief of the Data-Processing and Forecasting Division of the Weather and Disaster Risk Reduction Services Department of WMO. He coordinates scientific and technical matters related to operational weather forecasting for WMO Members and relevant international organizations, including numerical weather prediction, and ATM for emergency response.

Prior to his arrival at the WMO, he was Director of Operations of the Canadian Meteorological Centre for 10 years. His career has included various positions including forecaster, senior instructor, and manager of scientific services.

which was introduced at the annual European Geosciences Union General Assembly in 2007, will continue to serve as a platform for the CTBTO to exchange information and ideas with the scientific community, especially in the field of ATM.

Many participants stressed the need for an increase in the availability of CTBTO monitoring data to scientists around the world since data are best used when shared. The sharing of monitoring data would be of immense benefit to the many research projects that scientists are undertaking to improve the CTBTO's verification capacities. It would also give an impetus to further research into the civil and scientific applications highlighted during ISS09.

# System Performance

BY NICHOLAS KYRIAKOPOULOS AND THIERRY HÉRITIER

# System Performance

BY NICHOLAS KYRIAKOPOULOS AND THIERRY HÉRITIER

**FACT BOX**

The International Monitoring System will comprise 337 monitoring facilities by the time the Treaty enters into force. The System Performance topic area of the ISS has taken a holistic view of the operation of the complex global system. It has addressed issues affecting the quality, quantity and timeliness of the information that is collected, processed and distributed by the International Data Centre.

The verification regime of the Comprehensive Nuclear-Test-Ban Treaty (CTBT) is a complex system that relies on the information generated by the integration of technologies and processes to determine non-compliance with the Treaty. The major sources of the information are as follows:

- The International Monitoring System (IMS) operated by the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO).
- The process of consultation and clarification involving Member States and the Executive Secretariat of the CTBTO.
- On-site inspections.
- A set of confidence-building measures designed to help improve the capabilities of the IMS.
- National technical means, as referred to in the Treaty.

## A HOLISTIC VIEW OF THE CTBT MONITORING SYSTEM

The underlying philosophy of the regime is that the final decision as to whether or not a nuclear explosion has taken place is not made solely on the information from particular components, but the synergistic combination of all of its elements. This holistic view of verification requires that the ability to detect, locate and identify events be evaluated for the system as a whole rather than independently for each of its components.

The complexity of the verification system makes the task of performing a credible evaluation daunting but not impossible. A sine qua non condition for such an evaluation is that it be done with a scientific rigor devoid of political considerations. The International Scientific Studies Conference (ISS09) that took place from 10 to 12 June 2009 in Vienna set the stage for the continuing assessment and improvement of the system by involving the international scientific community.

As a starting point for developing a methodology to analyze the entire verification regime, the primary focus of ISS09 was the IMS. Contributions addressed topics ranging from how well the system performs as of today to how its performance could be improved and sustained. From a functional perspective, the focus is on the ability of the system to detect, locate and identify events, while the focus of the operational perspective is on the impact of the performance of the system components on the overall performance of the IMS. This paper gives a summary of the contributions in both areas.

## DETECTION, LOCATION AND IDENTIFICATION OF EVENTS

The contributions to ISS09 concerning the ability of the IMS to detect, locate and identify events addressed the topic from different perspectives. Some analyzed the performance of the system as currently deployed (e.g. Le Bras et al., SP-15/C; Le Pichon et al., INFRA-12/F; Carluccio et al., SP-12/C), while others investigated its potential performance after full deployment (e.g. Arzigian et al., SP-04/C). The primary issue addressed by the posters and presentations in these two categories was whether or not the IMS, as specified in the CTBT, would perform according to expectations. Another category of papers took a broader look at the issue of event detection and addressed the question of how the detection threshold and the location of events could be improved. While some posters in this category investigated potential improvements within the existing framework of the IMS, others took a more expanded view of verification by incorporating concepts not explicitly specified in the Treaty (Falter et al., SP-17/B).

To analyze the performance of the currently deployed system, a number of authors adopted the approach of comparing magnitudes and location of events detected by the International Data Centre (IDC) with detections by national or regional networks. Some posters limited their investigations to single regions, typically covered by the respective national networks (e.g. Chica et al., SP-02/C), while others investigated events, typically teleseismic. These comparative analyses found some differences in the magnitudes and locations of the events that were detected by the IDC and the other networks. While some differences are easily explainable by the fact that regional and national networks have a much denser coverage of a region than the currently deployed IMS, other differences need further investigation.

A significant contribution to this body of knowledge was made by posters that identified factors that have the potential to improve the detection capability of the current IMS. One example is through the use of supplemental information, such as that provided by accidental explosions (Le Pichon et al., INFRA-12/F). Another research approach that has been demonstrated to decrease the detection threshold is the integration of monitoring technologies with modeling of physical phenomena, as in the case of using atmospheric transport modeling to improve the detection capability of the radionuclide and infrasound networks.

Improvements in the detection capability are also possible within the existing framework of the monitoring system by better utilization of the available resources. Combining the 120 auxiliary seismic stations with the 50 primary stations to form a network of 170 stations would decrease the detection threshold by 0.25 units on average, with an improvement of 0.5 units for some regions (e.g. Coyne et al., SEISMO-10/J.

A number of contributions took a broader approach to the issue of verification by proposing models that combined the information generated by the IMS with that of national and regional networks (e.g. Tumwikirize, SP-08/C). The use of local and regional networks in combination with the IMS would create a global monitoring system with a much denser distribution of sensors. Although such a system would have a much lower detection threshold, it could also present a challenge in handling the increased number of detected events. However, the continuing improvements in information processing capabilities may help to make this problem manageable.

## VERIFICATION SYSTEM SENSITIVITY ANALYSIS

Of critical importance in the design of any system is the sensitivity of the performance to variations in the parameters of the system. These variations can be in the form of components that either do not operate within the design specifications or do not operate at all for extended periods of time. In addition, variations in system performance can also be caused by unforeseen changes in the environment in which the system operates. The complexity and global reach of the IMS makes it susceptible to such variations. Consequently, it is important to investigate its sensitivity to such changes.

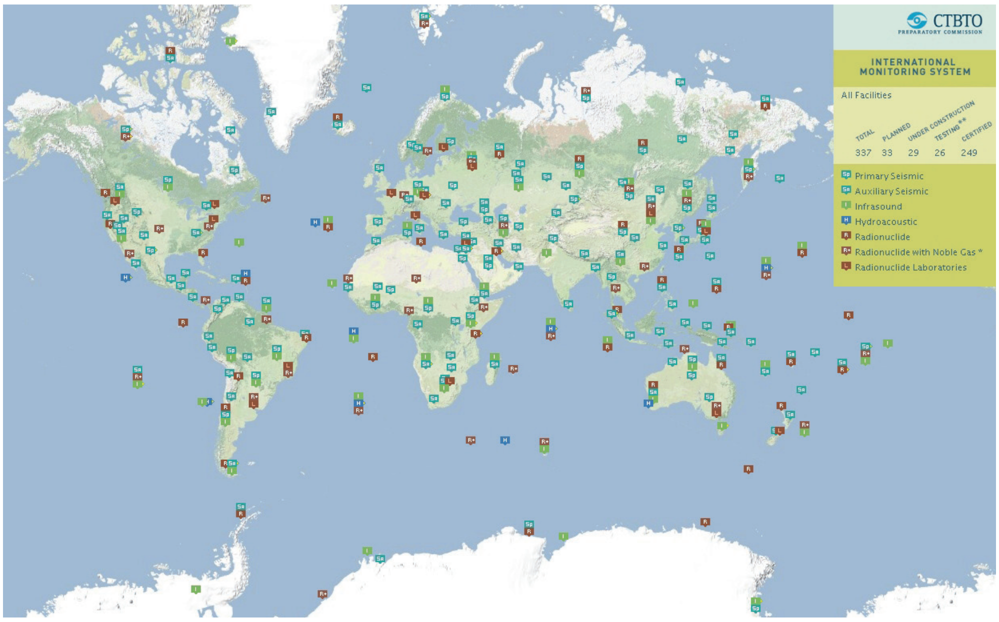



*Figure 1*
*Map showing the CTBT's International Monitoring System facilities around the globe.*

A number of authors have analyzed the effect of variations in system characteristics on the performance of the system. Some contributions examined the impact of one or more stations not being operational on the detection capability of the network. Sparse networks such as the hydroacoustic are particularly sensitive to the number of operational stations, more so if one takes into account the time it takes to repair or replace equipment in the deep ocean environment. To minimize the impact on the detection threshold some novel interim solutions were proposed, such as the use of self-contained temporary replacement sensors with autonomous communications capabilities (e.g. Ginzkey at al., HYDRO-03/H).

The performance requirements of the current system were set by taking into consideration the capabilities of the available technologies at the time the Treaty was signed. However, the Treaty makes provisions for improvements in the IMS as technologies evolve. Although the problem of evaluating the sensitivity of the entire system to changes in specific technologies is a challenging one, some formal concepts were presented that could be applied to the diverse components of the IMS. The application of analytical methods to determine the contributions of individual stations to the detection capability of the entire IMS and to evaluate the monitoring completeness of the system have produced results that can be used to improve the performance of the IMS.

Another category of posters that can be grouped under the topic of sensitivity analysis deals with variations between Standard Event Lists (SELs) and Reviewed Event Bulletins (REBs) as well as between REBs and bulletins generated by other seismic networks. The SELs are generated in near real time through automatic processing of the raw data as they arrive from the monitoring stations. The lists are updated with the arrival of new information and subsequently reviewed by analysts to generate the REBs. The sequence of processing steps introduces variations in the results that need to be understood and minimized in order to improve the detection capability of the IMS. Some posters addressed these issues by comparing detections reported in the REBs with those from national and regional networks and tried to identify factors that would explain any discrepancies (e.g. Gestermann and Henger, SP-05/C). Other posters examined the differences in detections between the SELs and the REBs and sought to identify factors that would explain those differences.

For the REBs, one potential source of differences could be the variability among the analysts (Horin and Steinberg, SP-06/C), while the differences between the SELs and the REBs are erroneous detections attributable to the phase detection algorithms used in the production of the SELs. To improve the usefulness of the first SEL, a neural network classifier was developed that can be trained to maximize the probability of detecting bogus events in the first automatic SEL bulletin (SEL1) and removing them from the subsequent lists (e.g. Carluccio et al., SP-12/C).

## MONITORING SYSTEM PERFORMANCE EVALUATION

Another perspective for analyzing the performance of the IMS is through the quality of the products and services it generates, namely the production of bulletins that list and identify the detected events. These are affected by the reliability and availability of each of its components, namely, the monitoring facilities that comprise the hydroacoustic, infrasound, seismic, and radionuclide stations including laboratories, the IDC and the Global Communications Infrastructure (GCI). The quality of the services is also affected by the quality of the data that are generated, collected, processed and distributed by the system. A number of models were presented including a framework and tools for monitoring and assessing performance (Alamo et al., SP-19/B) and specific tools (Laban and El-Desouky,, SP-13/C). Results of case studies using bulletins produced by the IDC as well as simulation experiments were also presented (Gesterman and Henger, SP-05/C, Arzigian and Damico, SP-04/C).

## SYSTEM RELIABILITY AND AVAILABILITY

The reliability of a system is defined as the probability that the system will perform specified services within a specified period of time. In the development of the IMS most of the emphasis has been on the detection, location and identification of events. Although some work has been done on identifying factors that affect the availability of the system to provide the required services additional work is needed to translate service requirements into system availability and reliability requirements and, subsequently, into component-level requirements. Contributions toward that goal included a reliability model for the entire IMS (e.g.

Gustafson, SP-14/C) as well as investigations into the reliability of some system components (e.g. Makris and Tarapore, SP-09/C).

## COMMUNICATIONS INFRASTRUCTURE

The establishment of the GCI took high priority in the development of the IMS because of the need to connect the IDC with the monitoring facilities and the National Data Centres (NDCs). Early planning and more than ten years operational experience in conjunction with advances in communications technologies have made the communications infrastructure one of the most reliable components of the IMS.

To assure high availability of the communications links between the monitoring stations and the IDC, the current design is based on the concept of a private network with access to the remote sites provided through satellite terminals. As the Internet expands to provide global connectivity, some of the data transport functions of the IMS, particularly those of lower priority, are using the evolving medium, because the savings in cost are making it an attractive alternative. Some contributors explored alternative concepts, such as Virtual Private Networks, for the GCI (e.g. Chandran and Punnekkat, SP-10/C). The rationale for such an approach was the demand for increased data communications services, not foreseen when the Treaty was negotiated, along with recent advances in the development of Internet protocols that increase the reliability of data transport.

## AVAILABILITY AND QUALITY OF THE DATA

For the IMS to detect, locate and identify events, not only must sufficient data be available, but they must also be of adequate quality in order to optimize the performance of the detector. The availability and quality of the data is affected by the performance of all components of the IMS. It is a major challenge to develop a management system that assures the sufficiency and quality of the data for the IMS to perform its primary function. An important topic that needs to be addressed is that of performance metrics for the entire IMS as well as mechanisms for measuring and evaluating performance.

The contributions on the topic of data availability and quality covered issues ranging from the effects of instrument operation on the quality of the data to concepts for high level data integration and quality control (e.g. Stead et al., SP-07/C). Some of the topics in the first category are measurements of data availability for specific stations, techniques for calibration

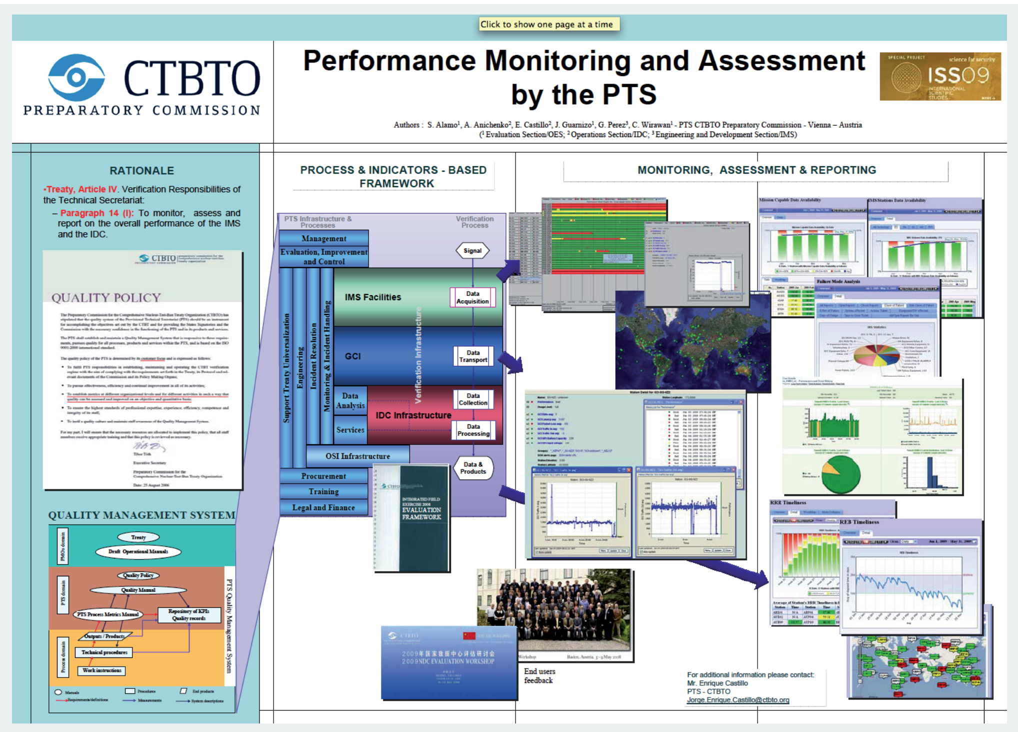



*Figure 2*
*The figure illustrates the framework used by the CTBTO for monitoring and assessing the performance of the verification system development and provisional operation. The framework is responsive to the Treaty and based on the International Organization for Standardization (ISO) 9000:2001 international quality management standards. It tracks the compliance with Draft Operational Manuals requirements as well as the supporting CTBTO processes through the corresponding performance indicators. In addition, it factors in the input of end users as a fundamental mechanism for continual improvement (Alamo et al., SP-19/B).*

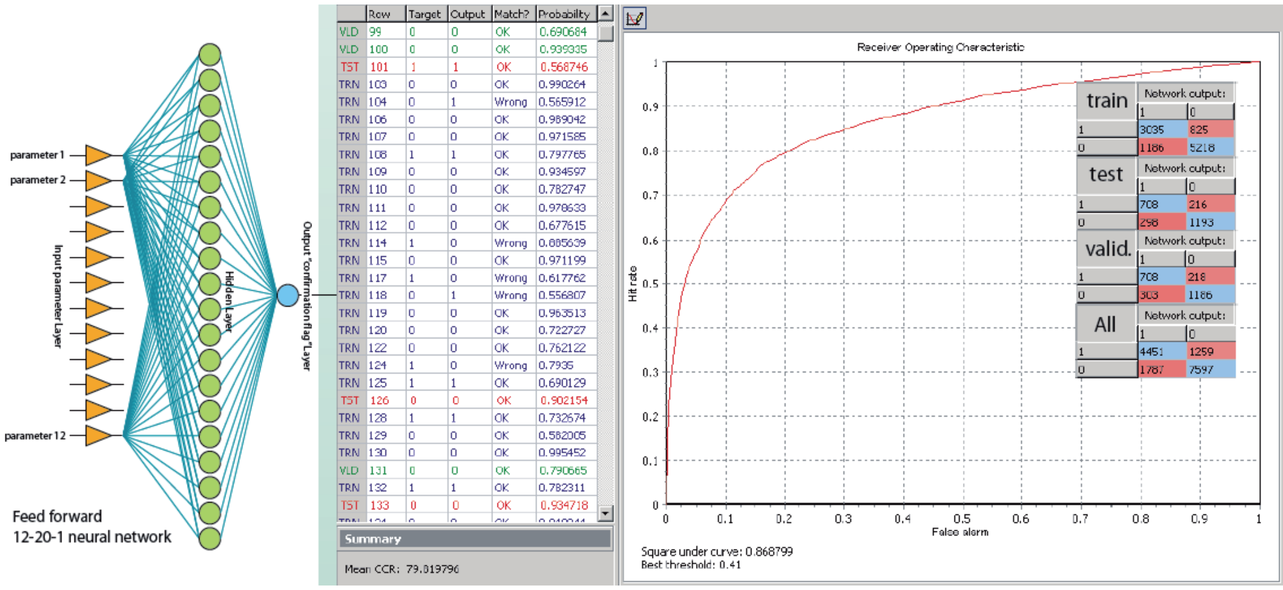



*Figure 3*
*The figure illustrates the use of advance signal processing techniques to improve the performance of the IMS. A neural network is used as a classifier to discriminate between actual and bogus events in SEL1. Bogus events are phase association algorithm artifacts. The neural network is trained using historical data from the REB. Patterns among the event definition parameters are used to train the neural network to classify each new event as real or bogus ( Carluccio et al., SP-12/C).*

of instruments (e.g. Le Bras et al., SP-15/C), measurement of responses, and measurement of the accuracy of timing of the raw data (e.g. Stammler, SP-11/C) . At the concept level, techniques were proposed for high-level integration and quality control of diverse data sets like those found in the operation of the IMS. While the techniques covered by the topics in the first category are of immediate applicability, work remains to be done in the development of concepts and methods for defining and measuring quality and availability of data for the services expected to be performed by the IMS.

## CONCLUSIONS

The significance of ISS09 lies in the fact that for the first time, the verification regime of the CTBT was the subject of a coordinated scientific inquiry outside the political constraints of the negotiating fora. Viewing the regime as a single system has laid the foundation for a comprehensive study of the performance of the IMS. Although some authors have identified specific problems in the operation of the system, the overall conclusion is that when the IMS is completed in its current form, it will exceed expectations in detecting nuclear explosions. Most important, the thrust of the contributions to the Conference was that improvements in technology and the development of new concepts would increase the sensitivity of the IMS and decrease the detection threshold.

BIOGRAPHICAL NOTE

### NICHOLAS KYRIAKOPOULOS

is Professor of Engineering at The George Washington University in Washington, DC, USA. His current research interests are in the areas of systems theory and signal processing.

For over twenty five years he was associated with the US Arms Control and Disarmament Agency and subsequently the US Department of State as an expert on monitoring systems and participated in arms control negotiations. Dr. Kyriakopoulos is currently involved in applying system-theoretic concepts to modeling and evaluation of verification systems for multilateral treaties.

BIOGRAPHICAL NOTE

### THIERRY HÉRITIER

is a research engineer at the Comissariat à L' Energie Atomique, France. He is currently an adviser to the Departement Analyse, Surveillance, Environnement.

He has been involved in numerous international complex system engineering projects and research programme development. Dr. Héritier has provided expertise in the field of project management, environmental monitoring as well as treaty verification for over twenty years.

# On-Site Inspection

BY ZHENFU LI

# On-Site Inspection

BY ZHENFU LI

**FACT BOX**

An on-site inspection (OSI) can involve a number of geophysical techniques. Noble gases such as xenon and argon are also measured on-site. An important task of the OSI topic area of the ISS project has been to explore how recent scientific and technical advances in these technologies can be applied to an OSI.

On-site inspections (OSI) are an important element of the Comprehensive Nuclear-Test-Ban Treaty's (CTBT) verification regime, which should be established and ready at the entry into force of the Treaty. During the recent International Scientific Studies Conference (ISS09) in Vienna, 34 posters were submitted which addressed various aspects of the OSI regime, ranging from the triggering event, inspection deployment, conducting an inspection and so on. Conference participants agreed that the 25 May 2009 nuclear test announced by the Democratic People's Republic of Korea (DPRK) highlighted the need for a robust and capable OSI regime.

## SIGNIFICANT PROGRESS TO DATE

Over recent years, the buildup of the OSI verification regime has made progress: the second round reading of the draft OSI Operational Manual has been completed; the "test manual" and the "Model Text" have been developed; some essential techniques and related equipment have been identified and developed; some inspection equipment has been purchased and tested; many potential inspectors have received training; a number of directed and integrated exercises have been conducted; and many important lessons have been learned. This progress culminated last year in the largest exercise conducted by the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) to date.

## INTEGRATED FIELD EXERCISE 2008

In September 2008, all OSI elements available to the CTBTO were tested in synergy for the first time in the Integrated Field Exercise 2008 (IFE08). IFE08 took place at the former Soviet nuclear test site Semipalatinsk in Kazakhstan. It was a simulated exercise involving a team of 47 inspectors who used OSI techniques to examine an area of 1000 square kilometres for technical evidence to determine the nature of the triggering event, namely, whether or not there had been a recent underground nuclear explosion in the fictitious state of Arcania. It was acknowledged at the ISS09 that the IFE08 had demonstrated the feasibility of deploying an inspection team in a hostile environment, and the implementation of the inspection techniques. Based on the IFE08 experience, it seems likely that the preliminary capability needed to conduct an OSI is now in place, i.e. the CTBTO possesses the basic capability to conduct an OSI once the Treaty has entered into force, in

*IFE08 base camp*
*For the Integrated Field Exercise 2008 a group of 200 experts, diplomats and support staff took up camp at a very remote location, the former Soviet Union nuclear test site Semipalatinsk in Kazakhstan.*

the event of a conventional-type underground nuclear test being conducted.

Admittedly, the OSI regime is not as advanced as the other CTBTO verification components, namely the International Monitoring System (IMS) and the International Data Centre (IDC). This is due to the fact that OSI-related verification techniques and equipment are wide-ranging and complex and that many of the science and technology research and development (R&D) projects are not as developed as those for the IMS and IDC. IMS and IDC techniques, especially seismic monitoring, have been developed for several decades, but some OSI techniques need to be researched from scratch. R&D projects, especially in the field of radionuclide detection, including noble gas sampling and analysis techniques and related equipment, are in urgent need of further development. The methodology or strategy of conducting an OSI has to be more clearly refined. To keep the balance among the elements of the CTBT verification regime and to improve the readiness of the OSI regime, the scientific and technical basis of the CTBT's OSI regime needs to be intensified.

## TECHNIQUES EMPLOYED DURING THE IFE08

OSI inspection techniques and equipment need to keep abreast with technological developments. During the ISS Conference, Boris Kvok, Director of the CTBTO's OSI Division, explained that several techniques employed during the IFE08 need to be further developed, including multi-spectral imaging and active seismic surveys. In addition, some of the more intrusive techniques for the continuation phase of an OSI, such as deep penetration geophysics, need to be further developed. In particular, greater efforts are required in the area of drilling for radioactive samples in order to make necessary progress.

Many posters were devoted to the IFE08 and examined the exercise from various perspectives. These included the logistical challenges of conducting a large scale exercise in a remote location, the deployment of different OSI techniques, the operational aspects, and testing the Inspection Team's operational procedures. Many lessons were learned from this exercise. However, there is a clear need for more input

*Over 50 tons of equipment were shipped to Kazakhstan by air. The shipment included these prefabs to house the radioactive laboratory where environmental samples were examined for their levels of radioactivity.*

from scientists on the techniques and issues related to an OSI, including on the phenomenology and signatures of nuclear explosions.

## PHENOMENOLOGY OF A NUCLEAR TEST EXPLOSION

The effects or phenomena of a nuclear explosion are the basis of OSI technique applications. The effects of a nuclear explosion are closely related to the device yield, test environment and emplacement techniques. For low-yield nuclear test explosions conducted underground, the effects may not be so obvious and collapsed craters, surface cracks and aftershocks may not occur. Furthermore, the radioactive release may be very low. This will make the OSI's factual evidence collecting activities more challenging. The explosion event which occurred in the DPRK on 9 October 2006 has already made this issue obvious.

There is a lot of information about the effects of a nuclear explosion in open scientific literature. It is worth collecting and assessing this information and further developing training courses in order to help familiarize future inspectors with the nuclear explosion phenomena.

## EFFECTIVENESS AND LIMITATIONS OF INSPECTION TECHNIQUES

The availability and limitations of techniques used during an OSI were also addressed by some posters (Arndt et. al., OSI-01/B; Han et.al., OSI-11/B; Riechmann et. al., OSI-13/B). The limitations of each inspection technique will have many effects on the procedures and inspection processes in a real OSI. The planning and arrangements of the inspection activities in the field and the search logic will depend heavily on the effectiveness and limitations of each inspection technique in a specific OSI scenario. Assessments of inspection techniques should be vetted.

A number of posters ( e.g. Joswig, OSI-30/B; Hegedus et. al., OSI-31/B) proposed ways of improving the effectiveness of an OSI through the use of seismic aftershock measurement systems and also explored seismic monitoring of aftershocks during an OSI to provide geological background information about the inspection area.

## VISUAL INSPECTION TECHNIQUES

The role of the visual inspection techniques is very important in an OSI and was addressed during the ISS09 and by the poster by Han et. al., (OSI-11/B). Despite the visual inspections which were conducted during the IFE08, experiences are still limited, and the visual inspection procedures should be further developed to follow a certain standard inspection approach. Visual inspections include overflights and ground-based observations. Overflights can rapidly cover the whole inspection area, recording any visual findings or information which may help to clarify signatures associable with a recent nuclear test explosion. The ground-based visual observations can confirm possible source mechanisms and document the geological alterations in order to guide other inspection techniques by locating possible surface ground zero and identifying permeable pathways for gas release.

Visual observations should target the visual features of underground testing. Further work on the in-field procedures, design of search logic, the sequence of inspection activities and corresponding training are all required to improve the capabilities of the inspection team. This is set against the reality that the previous nuclear tests which generated geological effects, signatures and other artifacts, were either poorly documented or unpublished, requiring the visual observation procedure and approach to be established by careful assessment of the available nuclear testing knowledge base.

## RADIONUCLIDE TECHNIQUES

A popular theme amongst the posters was how an OSI's search and detection capabilities can be improved through the use of new radionuclide measurement methods, such as local monitoring systems, to cover the inspection area and additional radionuclide detection means (Prah and Tanaka, OSI-06/B; Ely et. al., OSI-17/B; Friese et. al., OSI-18/B). The OSI's methodology and the application of radionuclide monitoring, detection, sampling and analysis techniques are different from those for the IMS. The IMS radionuclide stations are basically concerned with monitoring the different environments, i.e., underground, the atmosphere, and under water, but the scenario faced by the OSI is the locality of the inspection area in question in terms of the source region and the local environment in this particular area. In this regard, the noble gas sampling and analysis technique is essential for an OSI and needs to be further researched and developed. The noble gas system for an OSI should be capable of searching for and collecting factual evidence rapidly and effectively. For the detection techniques of radioactive noble gases, the physical mechanisms* of underground gas transport should be further studied. Characteristic criteria need to be established to distinguish a nuclear explosion from natural events. The sampling and analysis techniques of gaseous radionuclides, especially the portable system for the detection of the radioactive noble gases xenon and argon, need to be further researched and developed.

## GEOPHYSICAL TECHNIQUES

The continuation phase of an OSI was addressed by various posters. These included the importance of understanding the phenomenology of an underground nuclear test, the potential sources of geological anomalies, and their signatures detectable in the field. Other techniques that were addressed included geomagnetic techniques and modelling of possible testing cavity configuration, as well as the techniques of gamma-spectrometry during drilling. Research and exercises have demonstrated that the geophysical techniques and related equipment are capable of reaching the inspection targets in shallow layers or at a limited depth of up to 100 metres. The OSI regime's capability to detect deep targets has not been sufficiently or effectively tested yet.

The essential task of the geophysical techniques is to accurately locate the underground detonation point in order to guide the radionuclide sampling and drilling from the surface. Further development should focus on two areas: those geophysical techniques that can detect and accurately locate deep targets; and on characterizing geophysical anomalies related to different targets in different scenarios. For deep underground targets, those geophysical techniques allowed for an OSI should be able to detect and locate with accuracy at a depth of up to 1000 metres. The data processing techniques (synergies with other technologies, data fusion, etc.) should be further developed to improve the efficiency and integration. The effectiveness and limitations of each geophysical technique in various OSI scenarios should be further assessed. To develop a good approach for geophysical techniques during an inspection, it is important to make an appropriate assessment of the effectiveness and limitations of each geophysical technique in various OSI scenarios.

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* The leakage of radioactive gas by venting or seepage. The travel time for gas to reach the surface is affected by many factors, such as cavity pressure, geology around the cavity, and local weather environment etc.

*Visual observation is very important at the outset of an inspection. It helps inspectors to narrow down the search area by identifying anomalies in the environment that could have been caused by a nuclear explosion.*

*An OSI inspector prepares to measure the electrical conductivity of the ground to identify metal objects or other disturbances.*

## OTHER TECHNIQUES

Several posters addressed the application of information techniques (Carrigan and Johannesson, OSI-10/B; Vila, OSI-35/B). In order to achieve the optimal inspection efficiency and effectiveness, the existing Field Information Management System (FIMS) may need to be expanded to include such functions as probability inference to search-area reduction*, and the evaluation of the inspection activities for planning and implementation etc.

* Application of the probability theory such as Bayesian approach to reduce the search area.

BIOGRAPHICAL NOTE

### ZHENFU LI

has been a senior expert at the Northwest Institute of Nuclear Technology (NINT) of Xian City, China, and an expert member of the Chinese delegation to the CTBTO's Working Group on verification issues since 2000.

Prior to this, Dr. Li was the director of the NINT. His main professional fields are data acquisition and processing and arms control verification techniques. He was engaged in the physical diagnostics of nuclear testing before 1996. Since 1997, his work has focussed on CTBT verification research, especially on the on-site inspection science and techniques.

## COLLABORATION BETWEEN THE CTBTO AND THE SCIENTIFIC COMMUNITY

Speakers acknowledged the close cooperation between the CTBTO and academic institutions in the development of OSI equipment and recommended continuing and broadening this collaboration. During a key lecture by Dr. Demetrius Perricos, former acting Executive Chairman of the United Nations Monitoring, Verification and Inspection Committee (UNMOVIC), participants were informed that lessons can be learned from the experiences of the Organization of the Prohibition of Chemical Weapons (OPCW) and the International Atomic Energy Agency (IAEA). Cooperation between these organizations and the CTBTO and the exchange of information and techniques could be valuable for the increased effectiveness of an OSI. Dr. Perricos also emphasized the key role played by the inspectors in terms of knowledge, initiative, experience and diplomacy. However, challenges that need to be addressed are primarily time-related due to the rapid decay and subsidence of evidence near any perceived event location. This is particularly the case with radionuclide data and aftershocks.

Much scientific and technical work remains to be done. The capability to conduct an OSI is benefiting from many scientific and technical advances in other applications. The science and techniques related to the CTBT's OSI regime will continue to make progress through further collaboration with the international scientific community.

# Data Mining

BY HEIDI KUZMA AND SHEILA VAIDYA

# Data Mining

BY HEIDI KUZMA AND SHEILA VAIDYA

**FACT BOX**

The development of modern IT-based analysis methods, data mining, has been outstanding over the last decade. The Data Mining topic area of the ISS project has explored if and how such methods might be applied to the analysis of data in all stages of station and network processing as well as in event categorization and screening.

Each day, the facilities making up the Comprehensive Nuclear-Test-Ban Treaty's (CTBT) International Monitoring System (IMS) collect approximately 10 gigabytes of seismic, hydroacoustic, infrasound and radionuclide data, which are relayed via a secured satellite network to the International Data Centre (IDC) in Vienna, Austria. An automatic processing system sifts through the data, flagging all potential events which could be related to a suspected nuclear explosion, reporting them in a series of Standard Event Lists: SEL1, SEL2 and SEL3. The events in the final list, i.e. SEL3, must be carefully examined by a team of highly trained professional analysts before they are published in a Reviewed Event Bulletin (REB). In the process of putting together the REB, analysts discard roughly half of the SEL3 events and make many more corrections. The data, lists and bulletins are stored in a database at the IMS, which is large enough to archive 10 years worth of data. As technology evolves, the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) mandates the incorporation of new techniques into IDC data processing to continually improve the quality of its products.

Computing techniques have improved dramatically over the recent past and are constantly evolving. A variety of algorithms have been developed for data mining, a catch-all phrase for the use of automated algorithms such as clustering, classification, and statistical inference to find patterns and relationships in large amounts of data. Data fusion algorithms synergistically combine different types of related data so conclusions drawn from a large data set can be greater than sums of its parts. Data management systems intelligently store, retrieve and distribute processing in order to facilitate access to and interpretation of enormous amounts of data.

During preliminary International Scientific Studies (ISS) meetings in 2008, it was recognized that up-to-date algorithms for data mining, data fusion and data management could be used to improve many aspects of the data processing pipeline at the IDC. In addition, it was established that these algorithms could help in furthering the IDC's mission to make available its data, infrastructure and global sensing environment for other scientific, humanitarian and security related efforts. A direct dialogue was opened between the IDC and computer scientists. As a result, many posters were presented at this year's ISS Conference (ISS09). Topic coordinators Dr. Sheila Vaidya from Lawrence Livermore National Laboratories and Professor Arno Siebes from the University of Utrecht reflected on the role of Data Mining in two separate panel sessions and Professor Stuart Russell, chair of the Computer Science Department at the University of California, Berkeley, gave a well received keynote speech.

## DATA MINING: GENERAL THEMES

The dominant theme of the Data Mining posters was to recognize that analysts are learning patterns in data that the automatic system at the IDC currently ignores. In an introductory poster, Pearce et al. (DM-12/A) pointed out that analysts build up empirical knowledge of specific source-station paths. This allows them to better recognize meaningful signals, discard events and make use of negative data, that is, the absence of expected signals at particular distances or types of stations. Selby and Bowers (DM-10/A) showed that the seismic station ARCES in Norway did not detect the 2006 Democratic People's Republic of Korea (DPRK) explosion because station-specific correlated noise masked the signal to the automatic processing system, but not to a trained human analyst who knew where to look for it.

Much of the work presented at ISS09 involved training automatic algorithms to find patterns in the SELs in order to better classify events as “true“ (i.e. the event will be retained by the analyst and finally reported in the REB) or “false“ (the event will be discarded). Figure 1 illustrates an overlay of events from 2008 that were discarded by the analysts (blue), retained by the analysts although often in modified form (green), or added to the REB by an analyst (red), often incorporating information from discarded events.

Carluccio et al. (SP-12/C) plotted features of events in the SEL1, such as latitude, longitude and error ellipse, against similar features in the REB in a poster which won the overall Best Poster Award. By examining patterns of true (green) and false (red) events in a set of graphs, they motivated the training of a neural network to distinguish between events. Other off-the-shelf, quickly implemented modern classification methods also easily discriminated between true and false events (Kleiner et al., DM-02/A; Schneider, DM-05/A; Procopio et al., DM-07/A; Gaillard et al., DM-14/A ). The authors of these posters tested a number of state-of-the-art classification algorithms including Support Vector Machines (SVMs), Naive Bayes Classifiers and Decision Trees, to achieve correct classification rates on the order of 80 percent to 85 percent. Kleiner et al. pointed out that obtaining an 84 percent correct classification rate could potentially reduce the current analyst culling effort by as much as 57 percent.

Analysts currently spend a considerable amount of time evaluating, re-labeling, and re-associating seismic detections listed in the SEL3. If these phases were more correctly listed, the automatic event associations and origins would also be more accurate. Using the same techniques as they did for false event detection, Kleiner et al. and Schneider showed that algorithms can be trained to automatically test SEL3 phase labels with over 90 percent correct classification accuracy. Kuzma et al. (DM-03/A) trained an SVM for regression instead of classification in order to learn

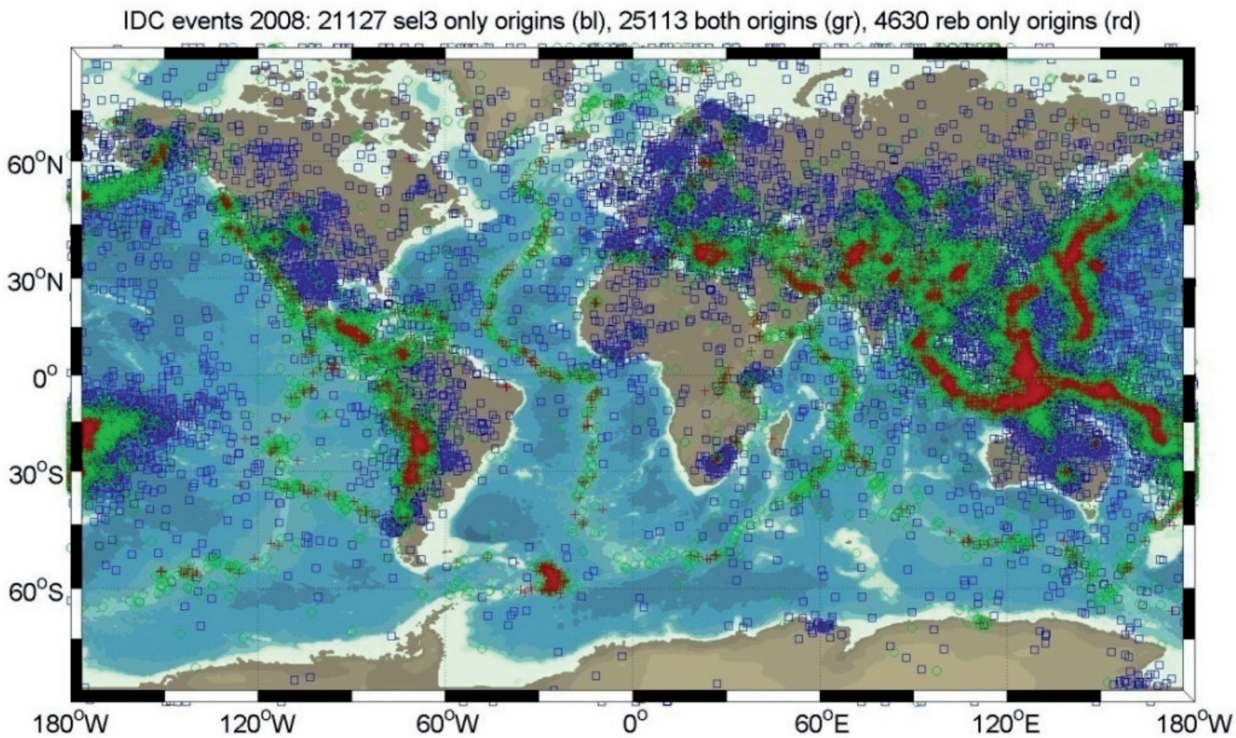



*Figure 1*
*Human analysts must carefully review each event produced by the automatic processing system at the International Data Centre (IDC) and reported in the Standard Event Lists (SEL) before it can be included in the Reviewed Event Bulletin (REB). Approximately 47 percent of SEL3 events are discarded by the analysts. Another 13 percent of the events in the REB are added, often making use of information from discarded events. In this figure reproduced from Procopio et al., (DM-7/A), blue squares indicate events that were listed in the SEL3 but discarded by an analyst. Green circles are events that were retained, albeit generally in modified form. Red stars indicate REB events that were added.*

regional effects on travel times and improve phase identification and SEL3 event classification. Ohrnberger et al. (DM-04/A) designed an algorithm to detect and accurately label the phase of arrivals using features derived from a continuous wavelet transform of the raw waveform data. Because seismic phases tend to occur in a precise order, they borrowed techniques from the automatic speech recognition community to build "grammar" constraints into their model.

The final product from the IDC is a Screened Events Bulletin (SEB), which does not include events from the REB that are likely of natural origins (earthquakes). Tuma and Igel (DM-06/A) used SVMs to discriminate between natural events and explosions in hydroacoustic data. Materni et al. (SEISMO-22/J) applied discriminant analysis to low-frequency regional seismic surface waves in order to distinguish between natural vs. man-made events. Horin and Steinberg (SP-06/C) tried to find patterns in the relationships between SEL3 and REB which could be identified as the work of individual analysts.

Several purely scientific posters mined IDC data sets to further understand the Earth and its inhabitants. It was shown that patterns in hydroacoustic data can be used to identify the songs of whales and follow their seasonal migrations (Flore et al., HYDRO-17/H). Harris et al. (HYDRO-12/H) tracked the calls of Antarctic, pygmy and Sri Lankan blue whales.

## STATISTICAL INFERENCE

Instead of simply classifying events, a second set of posters used techniques of statistical inference to mimic an analyst's intuitive grasp of what constitutes a "high probability event," i.e. a pattern of detections that is probably a true event given the measurement characteristics of the IMS network and physical properties of the Earth. The basic method of statistical inference (also known as Bayesian inference) is to compute the posterior probability of an event taking into account all the variables that contribute to the evidence for that event. The output of a Bayesian inference algorithm is a probability distribution which can be interpreted as a set of likely outcomes. Assembling a probabilistic model is not as straightforward as applying a general purpose classifier, but it holds the promise of being able to interpret data in a way that incorporates experience, physics and eventually, multiple types of data.

In a set of posters which also formed the basis for the keynote speech on data mining by Stuart Russell, Arora et al. (DM-08/A and DM-09/A) used Bayesian inference to find patterns of detections in the SEL that, with high probability, are consistent with seismic events of given locations and magnitudes, explaining that the inference process works by continually postulating events, and then creating, modifying, and deleting these events using an approach known as Markov Chain Monte Carlo (MCMC) sampling. As reproduced in Figure 2, peaks in the posterior probability density correspond to events that were confirmed by analysts in the REB. False SEL3 events, which had to be discarded by the analysts, were not generated by the inference engine.

Myers and Johannesson (DM-11/A) presented a software package called *Bayesloc* which uses a similar technique to locate multiple events from a stream of automatic detections. By studying the posterior distribution of various factors pertinent to event location, they were able to decompose measurement error into various components so that data from stations with high quality detections could receive more weight, producing events with half of the error of conventional processing.

Also using Bayesian methods, Schorlemmer (SEISMO-42/K) derived the probability distributions of events at each station in the IMS so as to produce probability maps for the detectability of eartquakes. Liszka (DM-15/A) created a probabilistic propagation model to improve the interpretation of infrasonic observations. Carrigan and Johannesson (OSI-10/B) used posterior probability as a means of narrowing the search area for Surface Ground Zero during an On-Site Inspection.

## DATA FUSION

Despite general consensus that the evidence from all IMS sensors should be used in concert, seismic, hydroacoustic, infrasonic and radionuclide data are currently processed independently, making data fusion a manual task and consequently a fertile area for research. A few authors addressed the need for data fusion directly. Jepsen and Fisk (HYDRO-06/H) recognized that a lack of high-frequency hydroacoustic energy indicated that the seismic events were more likely to be natural earthquakes than nuclear explosions. Maceira and Ammon (SEISMO-52/K) fused gravity and seismic data, and, in an unusual poster, Bossu et al. (SEISMO-28/K) correlated the IP addresses of traffic on the website of the European Mediterranean Seismological Centre to the geographical areas in which an earthquake was felt.

## DATA MANAGEMENT

A consistent thread which permeated many of the informal discussions at ISS09 was the need for faster and more comprehensive access to the IDC database. Simpson and Willemann (SEISMO-56/K) detailed the Incorporated Research Institutions for Seismology (IRIS) consortium Data Management Center as an example of a seismic data centre providing free and open access to many global networks through a common set of tools. Pesaresi et al. (DM-13/A) presented *Antelope*, a commercial software suite which can be used for real time data exchange.

An entirely new paradigm for the storage and exploitation of seismic data was suggested by Liu (DM-16/A). Currently, seismic records can only be retrieved from the relational tables in the IDC database using a fixed set of attributes such as station name, channel number, latitude, longitude etc. It is not possible, for instance, to ask the database to retrieve all waveforms that correlated well to a particular set of arrivals from a particular event. In order to ask this type of question, the entire database must be downloaded to a researcher's own computer where the correlations must be computed locally. Liu proposes developing a distributed database using a framework similar to ones used commercially (by Google in particular), which take advantage of parallel processing and multiple nodes to return records based on complicated and

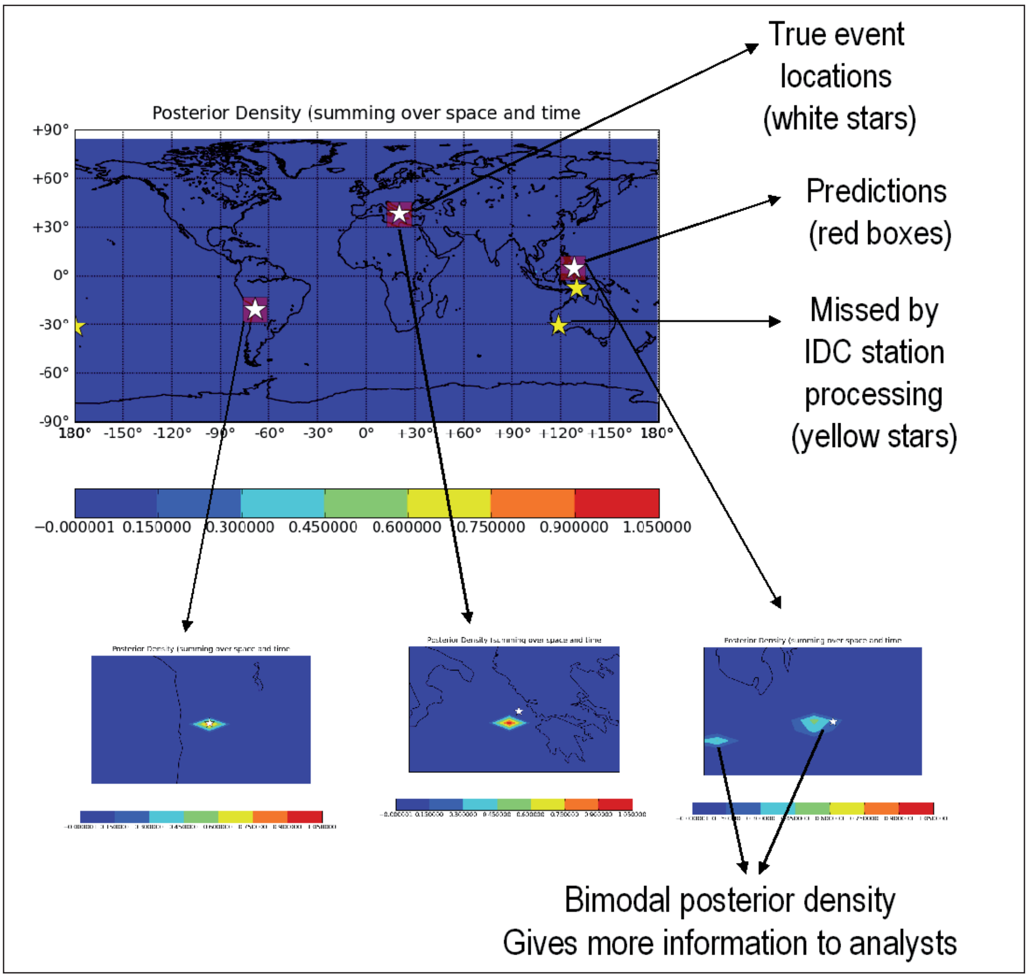



*Figure 2*
*Bayesian inference can be used to provide a posterior probability distribution giving the probability that events occurred given features in the IDC data. Using this technique, events show up as regions of high probability (in red on the large map). In Arora et al., (DM-08/A), two hours of SEL3 data were analyzed. In this example, reproduced from the poster, the algorithm is able to postulate new events (yellow stars) that were missed by the automatic processing but were confirmed by the REB.*

flexible queries and which are easily scalable to accommodate large amounts of data in different formats.

## MOVING FORWARD

Zhongliang and Suhadolc (SEISMO-32/K) liken the role of the IMS to that of the Hubble Space Telescope: it provides a well-functioning global observation facility with the potential to make fundamental contributions to basic research. At present seismology is in a period of fast development, which they credit to several factors among which are the "continuous accumulation of high-quality data and the application of new technologies in observation and data analysis." By extension, the effort which is now clearly underway to apply leading-edge technologies for data mining, fusion and management at the IDC promises not only to significantly improve its automatic processing system, but also to lead to a new and better understanding of the Earth. In addition to helping fulfill the present mission of the CTBTO, this effort will advance science and serve humanity worldwide.

Many fruitful areas for research were identified at ISS09. These include but are not limited to:

- The establishment of the best features to use for automatic event classification, including the generation of new features;
- The refinement of probabilistic inference algorithms to take many different kinds of data into account;
- The application of data mining to the CTBT's On-Site Inspection regime;
- The use of data mining to learn about effective regional corrections for seismic data;
- The development of systems with the capability of analyzing full-waveform data;
- The design of fast, effective databases for the storage and distribution of IDC data;
- The establishment of a centre to champion, coordinate and support advanced research and data analysis.

Such a virtual Data Exploitation Centre (vDEC), proposed by Vaidya et al. (DM-01/A), would create an incubating environment for ISS research. A vDEC would also provide a development clearinghouse for software and hardware infrastructure in support of the IDC and OSI missions, seeking contributions from participating Member States as well as forming strategic partnerships with national agencies with synergistic agendas.

BIOGRAPHICAL NOTE

### SHEILA VAIDYA

is Deputy Programme Director of Non-proliferation at the Global Security Directorate, Lawrence Livermore National Laboratory (LLNL).

Dr. Vaidya has over 28 years of applied research and industry experience in nucleating, building and managing programmes in areas ranging from video and imagery exploitation, remote sensing, machine learning, high performance embedded computing and streaming data analytics, to semiconductor equipment, photo-mask and integrated circuit manufacturing, quantum electronics, circuit design, devices and materials.

BIOGRAPHICAL NOTE

### HEIDI KUZMA

is a Senior Geophysicist with East Donner Research llc and a frequent collaborator with Lawrence Livermore National Laboratory (LLNL) and the University of California, Berkeley.

In addition to projects related to CTBT verification, Dr. Kuzma has developed machine learning methods to find the source of atmospheric contaminants, interpret seismic data for hydrocarbon exploration, and to use motor vehicles as a seismic source for detecting tunnels and bunkers.

# Global Security and Future Cooperation

# Cooperation between the scientific community and the CTBTO

BY HARSH GUPTA

The recently concluded International Scientific Studies Conference (ISS09) in Vienna, Austria, show-cased the capabilities and the work being carried out by the International Monitoring System (IMS) of the Preparatory Commission for the Comprehensive Nuclear-Test–Ban Treaty Organization (CTBTO). The international scientific community responded enthusiastically with over 200 posters (about 600 authors) and the attendance of around 600 delegates.

In this well organized assembly, the first day was dedicated to 'CTBT Verification Today', the second day focussed on 'Science and the CTBT', and the third day was devoted to 'Dialogue for the Future'. There was a healthy mixture of about 60 specialists who addressed key topics through a number of presentations and by participating in panel discussions. The ISS topic areas included Seismology, Hydroacoustics, Data Mining, Data Exploitation and System Performance, Infrasound, On-Site Inspection, Radionuclide and Atmospheric Transport Modelling. A special feature of the Conference was 'Reflection on the Poster Sessions' where eight panelists summarized what was conveyed in the posters and the possible future direction of work.

From the above, it can be seen that the global scientific community is interested in collaborating with the CTBTO in terms of understanding and addressing questions in several key areas.

In this article, I shall try to address the important issue of future cooperation between the scientific community and the CTBTO.

## LONGSTANDING COOPERATION BETWEEN THE CTBTO AND THE IUGG

The International Union of Geodesy and Geophysics (IUGG), comprising eight international associations on different aspects of Earth, atmospheric and ocean sciences (http://www.iugg.org), has been collaborating with the CTBTO for a long time. Way back in 1970s, the International Association of Seismology and Physics of the Earth's Interior (IASPEI) (one of the IUGG associations) participated in the Group of Scientific Experts to design a global seismological system for the verification of a comprehensive nuclear test ban. The IUGG considers that the activities of the CTBTO are very important to mitigate global change effects, including climate change. Enhanced cooperation between the CTBTO and the IUGG is in the interests of the global community.

## PROMOTING FUTURE COOPERATION

In addition to IASPEI, other IUGG associations, e.g. the International Association of Hydrological Sciences (IAHS), the International Association of Meteorology and Atmospheric Sciences (IAMAS), the International Association for the Physical Sciences of the Oceans (IAPSO) and the Union Commission on Data and Information, should be involved in this cooperation in the following ways:

- Through experts' evaluations of the CTBTO's scientific activities in relevant disciplines.
- Development and participation in joint research programmes.
- Organization of joint international scientific meetings.

The first step in enhancing this potential cooperation could be to organize a joint symposium (an open forum) at the IUGG XXV General Assembly in 2011 in Melbourne, Australia.

## DATA SHARING: THE EXAMPLE OF TSUNAMI WARNINGS

Another aspect of cooperation is data sharing. Under the IMS, high quality data are collected globally. Sharing of these data is very desirable. The availability of some of these data in real time can be extremely beneficial for addressing some very important problems.

Let me give an example. Tsunamis are generated when the fault rupture of an underwater earthquake extends to the bottom of the sea, where it causes an elevation change. This results in the displacement of the entire column of water above the rupture. Oscillation of the displaced column of water results in the generation of a tsunami. In addition to the lateral and vertical extent of the elevation change at the bottom of the sea, the height of the water column above the elevation change is a crucial parameter contributing to the size of the resultant tsunami. If the water depth is shallow, say a few tens of metres, the tsunami would only be a local one. In case the depth is of the order of a kilometre or more, a tsunami affecting the entire ocean basin can be caused. Therefore, the precise location of the earthquake source becomes a very important parameter in estimating the size of the resultant tsunami.

This issue becomes very critical when the ocean bed slope is steep and the depth of the water column increases from tens of metres to several hundred metres or more, within a few kilometres. For example the magnitude 8.6 Nias Island earthquake of 28 March 2005 and the magnitude 8.5 Bengkulu earthquake of 12 September 2007 (both in the Sumatra region, Indonesia, where the disastrous magnitude 9.3 earthquake occurred on 26 December 2004, causing the deadliest tsunami ever witnessed), generated small tsunamis, as the water column depth was only about 130 m and 200 m respectively. However, if you move the source of the Bengkulu earthquake by 10 km towards the ocean, the water depth increases from 130 m to 600 m and the size of the tsunami becomes five times bigger.

Tsunami alerts are issued on the basis of the location of the earthquake and its magnitude. For countries located close to the source of tsunamigenic earthquakes, there is often insufficient time to determine whether a tsunami has indeed developed. Availability of the seismic data from the CTBTO seismic monitoring stations in real time can improve the location of the source and improve the accuracy of tsunami alerts.

False alarms cause a lot of inconvenience. Let me quote the International Oceanographic Commission (IOC) communiqué on the subject of false tsunami warnings: " ... it is important to improve the science of issuing tsunami warnings to reduce false alarms given the inordinate inconvenience and disruptions to normal life caused by false alarms, especially given the high population densities and intensive operations in coastal areas in the Indian Ocean, and also to continuously improve forecasting." *

## COOPERATION MUST CONTINUE

The CTBTO has some unique data, such as array data, that can be "pointed" to study the deep structure within the Earth at high resolution, in particular for fundamental studies of the still poorly understood solid inner core. Likewise, there are methodologies that have been developed by the scientific community over the last 10 years that could benefit the CTBTO, if applied systematically to source detection, location or characterization. Similar examples of the usefulness of the CTBTO data can be found in almost all disciplines. Therefore, sharing of data with the global scientific community becomes an important goal for the CTBTO.

—

* IOC's 1st International Coordination Meeting, Paris, 3 to 8 March 2005 on the Development of an Indian Ocean Tsunami Warning and Mitigation System.

BIOGRAPHICAL NOTE

### HARSH GUPTA

is a geophysicist who specializes in the development and application of geophysical techniques to address problems on continents and oceans.

Dr. Gupta is currently President of the Geological Society of India, Vice President of the International Union of Geodesy and Geophysics, and Raja Ramanna Fellow at the National Geophysical Research Institute. Prior to this, he was Secretary to the Government of India looking after the Department of Ocean Development. After the 2004 Indonesian tsunami, he designed the Indian Tsunami and Storm Surge Warning System, which became fully operational in August 2007.

# Nuclear Renaissance and Global Security

BY EVGENY N. AVRORIN

One of the main threats to global security is nuclear proliferation, especially the increase in the number of countries possessing nuclear weapons and the possibility of terrorist groups acquiring them.

The nuclear non-proliferation regime is maintained mainly by two agreements: the Non-Proliferation Treaty (NPT) and the Comprehensive Nuclear-Test-Ban Treaty (CTBT), with their respective verification mechanisms. The danger of nuclear proliferation and the importance of these agreements increase significantly in relation to the projected "nuclear renaissance", i.e. nuclear power expansion.

In the future, it is expected not only that new nuclear power plants (NPPs) will be constructed and many more countries will use nuclear power, but that nuclear power technologies will also expand with the construction of different types of fast neutron reactors and the development of closed fuel cycle technologies (dry spent fuel recovery, long-lived transmutation, waste disposal etc). This will also involve the use of other nuclear technologies, for example, for medical diagnosis and therapy, or for material processing.

## CONTROL SYSTEM FOR NUCLEAR MATERIALS IS ESSENTIAL

This nuclear renaissance will require both legal and technological non-proliferation measures to be strengthened and developed. It will be crucial to ensure the reliable control of nuclear materials, which need to be as comprehensive as possible in order to keep us informed at all times as to the location and the amount of any nuclear material. Such a comprehensive control system must be integral to any nuclear power facility in any country. It is much more important and effective to control nuclear materials at the places where they are used than to equip every point that might be involved in nuclear material transportation with control systems that are rather unwieldy and inconvenient and do not guarantee success.

Unfortunately, the NPT does not bind all countries that use nuclear technologies to control and secure nuclear materials in a reliable manner. Such an amendment seems imperative. This would require the development of mechanisms for financing the verification and security systems in addition to the appropriate technical means.

It is desirable to initiate international research to help identify the root causes of proliferation as well as measures to contain it. It is also advisable to develop an internationally accepted, all-embracing list of requirements for countries that use nuclear technologies, regardless of their form of government or social structure. In addition, a legal agreement is needed ensuring that any potentially hazardous civil nuclear facility in any country is subject to verification, irrespective of its nuclear status, type of government and geographical setting. The double-standard policy must be abolished.

Not only should "sticks" (sanctions and other enforcement measures) be applied to achieve this aim, but the use of "carrots" (incentives) should also be particularly encouraged. These incentives include the guaranteed continuity of nuclear material supplies (possibly at preferential prices), and technical and financial support regarding the control and security of the material.

The nuclear "haves", i.e. the NPT nuclear weapon States, did not pay much attention to the protection of information related to nuclear weapons technology. The publication of such sensitive information poses a danger to the world as such.

## WAYS OF IMPROVING VERIFICATION MECHANISMS

The NPT's verification system should be improved mainly through the development of a means for continuous remote monitoring with real-time data transfer to an international centre. In the case of the CTBT's International Monitoring System (IMS), over 70 percent of its 337 facilities are already capable of transmitting data to the International Data Centre (IDC) in Vienna.

State-of-the-art detectors based on different physical principles can, when used in synergy, make the verification mechanisms resistant to intentional and unintentional "noise", i.e. interfering signals.

The CTBT's verification system, which uses four technologies in synergy – seismic, hydroacoustic, infrasound and radionuclide monitoring - is a perfect example of a well-orchestrated verification effort.

On-site inspections would play an important role in the routine checks and maintenance of monitoring systems as well as in emergencies. The close coordination of the different treaties' verification systems, gaining experience and the unification of some of their technical means could be very useful.

## IAEA AND CTBTO EXPERIENCES ARE MUTUALLY BENEFICIAL

So, satellite observations and radiation monitoring could be used jointly. International Atomic Energy Agency (IAEA) safeguards could be improved using the experience of the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) in the development of its global monitoring system and information technologies. And vice-versa, the experience of IAEA inspections in instrumentation and logistics could be used for the planning of on-site inspections under the CTBT, which will be possible once it has entered into force.

What could greatly contribute to non-proliferation efforts are elements of nuclear power internationalization – international centres for uranium enrichment, fuel fabrication, spent fuel recovery and waste disposal, and international fuel guarantee funds. The non-discriminatory participation of all interested countries in these centres and funds could constitute a part of the "positive stimuli" to contain the proliferation of nuclear weapons.

None of the individual aspects of the non-proliferation regime can guarantee non-proliferation in itself. These elements are of a political nature (in the form of agreements and their verification, and sanctions), economic (fuel prices, verification and protection costs) and technological nature (proliferation resistance). It would be naive to assume that, for example, some technologies ensure

*Some of the CTBT's international monitoring facilities that make up its global network.*

non-proliferation or eliminate the risk of nuclear terrorism. However, the gradual removal of the most hazardous technologies will certainly reduce the risk of proliferation.

## ROLE OF SCIENTISTS IN NUCLEAR NON-PROLIFERATION

Scientists can play a key role in contributing to nuclear non-proliferation. On the side of political science, they could conduct research into the causes of proliferation and the true incentives to non-proliferation, develop models of global security threats, as well as identifying causes of conflicts and propose remedies. Regarding the more technological aspects of non-proliferation, scientists could help through the identification of critical technologies and materials, the elaboration of technical means of verification and security systems, and by defining the technical preconditions for the internationalization of nuclear power.

The role of scientists in the verification of arms control treaties is obvious. The elaborate verification system of the CTBT is the result of decades-long dedicated work by thousands of scientists from many different countries and areas of expertise. I personally had the opportunity to take part in the US-Russian Joint Verification Experiment (JVE) in monitoring international test ban treaties in 1988. The experience gained from the JVE gave both countries confidence that a test ban can indeed be verified and helped in designing the CTBT's verification system during the Treaty's negotiations in the 1990s.

## REDUCING THE PROLIFERATION RISKS OF NUCLEAR POWER

Apart from designing cost-effective and accident-safe nuclear power systems, science can play a fundamental role in ensuring that nuclear power is less prone to proliferation by creating and advancing the following:

- Proliferation-resistant innovative nuclear reactor projects.
- Creative new nuclear fuel cycle technologies (especially for the international nuclear fuel cycle centre).
- Methods to qualitatively assess proliferation risks for different nuclear power reactor types.
- Technical means for nuclear material protection, control and accounting.

One of the most important areas of cooperation is skill formation including the joint development of training courses and assistance for nuclear power workers, and student exchange programmes.

## STEPS TOWARDS A NUCLEAR-WEAPON-FREE WORLD

It is necessary to optimize the large-scale structure of nuclear power. Concentration of the most hazardous technologies in a few large centres makes it easier to protect technological facilities and it could become attractive economically, but it increases the volume and distance of transportation – the most hazardous phase of the nuclear fuel cycle, which is very difficult to protect against terrorists. On the other hand, near-station fuel cycles minimize transportation, but complicate the protection of technological facilities. The system analysis of nuclear power with a sophisticated relationship between nuclear cycle components (from uranium or thorium mining to waste disposal and decommissioned facility dismantlement) and the consideration of short- and long-term effects demand mathematical models of different levels beginning with models for individual technologies and devices to the top level models (material and financial balance calculation).

This effort will require wide international cooperation - possibly within the scope of the Global Nuclear Energy Partnership (GNEP) or the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) programmes - under the aegis of the IAEA. All these measures along with agreements on nuclear weapons' reduction would be important steps towards a nuclear-weapon-free world.

Diligent work to reduce threats to all "threshold" countries and international guarantees of protection against any aggression may finally rule out the interest in nuclear weapons. To advance the vision of a nuclear-weapon-free world, the world's conflicts must be addressed. This includes the different root causes of conflicts, whether global or local, economic or religious.

*Participants at the International Scientific Studies Conference.*

## SCIENTISTS' ROLE IN RIDDING THE WORLD OF NUCLEAR WEAPONS

Scientists devised nuclear weapons, and they have a moral obligation to work towards reducing the risk they pose for the survival of mankind. They can contribute in the many ways described above to achieve nuclear non-proliferation and disarmament. In addition, scientists also have a pivotal role to play in mitigating and eliminating the conflicts that fuel nuclear proliferation. Scientists all around the world speak the same language and are able to comprehend the many-sided nature of a problem. Thus, scientists can take the initiative in building a world of tolerance and mutual respect, a world in which nuclear weapons will play no role.

In this world, there must be no place for pretensions to exclusiveness and messianic ideas. As Russian President D. Medvedev said at the Meeting of the Permanent Representatives of the League of Arab States in Cairo on 23 June 2009, it is necessary: "… to take the experience of all cultures and traditions into account. Attempts to define some kind of 'pure' development model, establish a 'universal development model' and spread it throughout the world will either fail or result in utopian experiments that, as we know, can turn to disaster."

A good starting point in achieving this goal was the gathering of 500 scientists from all around the world in June 2009 at the International Scientific Studies (ISS) Conference in Vienna, Austria. By coming together to perform a thorough examination of the ability of the CTBT's verification regime to detect nuclear explosions, scientists demonstrated the importance of cooperation in helping to find ways to make the world a safer place.

BIOGRAPHICAL NOTE

### EVGENY N. AVRORIN

is the Scientific Director Emeritus of the Zababakhin Russian Federal Nuclear Center in Snezhinsk.

His primary research accomplishments involve the areas of high energy density physics, the development of nuclear explosion devices for peaceful application, and basic investigations on physics of nuclear explosions. Dr. Avrorin has also worked on applied problems of nuclear power engineering, non-proliferation, environmental monitoring and remediation.

# CONFERENCE IN PICTURES

1: CHLDREN'S CHOIR PERFORMING AT THE OPENING CEREMONY OF THE ISS09 CONFERENCE.
2: UN SECRETARY-GENERAL ADDRESSING PARTICIPANTS DURING OPENING CEREMONY.
3: PANEL DISCUSSION WITH DIRECTORS FROM THE CTBTO'S IMS, OSI AND IDC DIVISIONS.

1

2

»This conference is an important step in gauging our ability to detect nuclear explosions worldwide. I believe we are well on track. There have been significant advances in science and technology related to verification.«

UN SECRETARY-GENERAL BAN KI-MOON SPEAKING VIA VIDEO DURING THE OPENING CEREMONY OF ISS09 ON 10 JUNE 2009

3

4: CTBTO'S EXECUTIVE SECRETARY TIBOR TÓTH AWARDS BEST POSTER CERTIFICATE TO MASSIMO CHIAPPINI.
5: PARTICIPANTS VISIT THE ISS09 SPECIAL EXHIBITION.
6: AUSTRIAN FOREIGN MINISTER MICHAEL SPINDELEGGER AT THE OPENING CEREMONY OF THE ISS09.


4

»Given the highly specialized technological focus of the CTBT verification mandate, staying abreast of scientific developments may be our greatest challenge as an organization. The constant close interaction with the scientific community is a must.«

THE EXECUTIVE SECRETARY OF THE CTBTO, TIBOR TÓTH, ADDRESSING PARTICIPANTS DURING THE OPENING CEREMONY OF THE ISS CONFERENCE ON 10 JUNE 2009

5

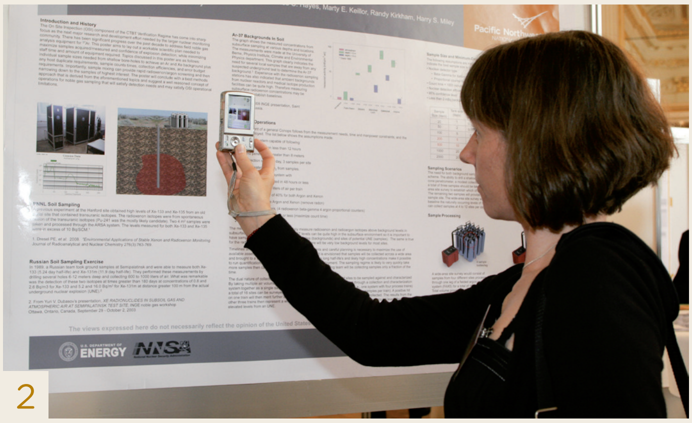
»Science gave us the atomic bomb, but science also gave us the means to control it and create a world free of nuclear weapons.«

AUSTRIAN FOREIGN MINISTER MICHAEL SPINDELEGGER DURING THE OPENING CEREMONY OF ISS09 ON 10 JUNE 2009

6

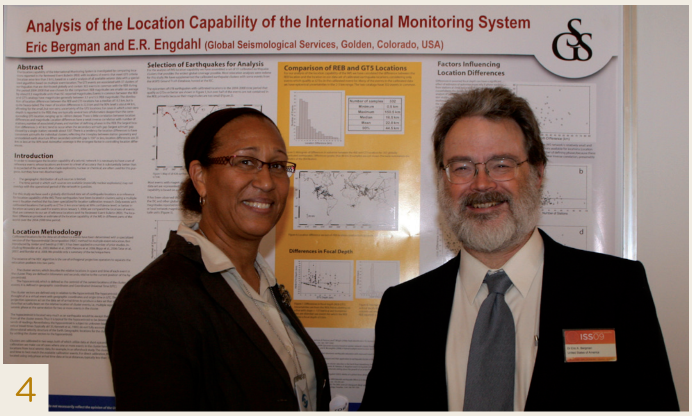
1: PANEL DISCUSSION ON UNDERWATER EXPLOSIONS.
2: PARTICIPANT STUDYING ONE OF THE 212 WORKING POSTERS ON DISPLAY AT THE ISS09 CONFERENCE.
3: AROUND 600 PARTICIPANTS FROM 99 COUNTRIES ATTENDED THE CONFERENCE.
4: PARTICIPANTS IN FRONT OF ONE OF THE SCIENTIFIC POSTERS PRESENTED AT THE ISS09.


1



2

3




4

»As a young woman scientist, I believe conferences like this one, give us (women) much needed exposure as well as a chance to make our mark in the fields of sciences - no matter how big or small. Seeing so many organizations worldwide that have partnered with the CTBTO for carrying out its mandate made me realize how much my country needs to be part of it.«

HLOMPHO MALEPHANE, LESOTHO HIGHLANDS DEVELOPMENT AUTHORITY

5: PROFESSOR RAYMOND JEANLOZ SPEAKING AT THE ISS09 CONFERENCE.
6: PARTICIPANTS NETWORKING AT THE CONFERENCE.
7: IAEA´S ANA MARIA CETTO ADDRESSING THE ISS09 CONFERENCE PARTICIPANTS.

5

»It is important to sustain the ISS momentum beyond June 2009 by strengthening links with the scientific and political communities.«

PROFESSOR RAYMOND JEANLOZ,
CHAIR OF THE U.S. NATIONAL ACADEMY
OF SCIENCES´ COMMITTEE ON INTERNATIONAL
SECURITY AND ARMS CONTROL

6

»In its daily work, the CTBTO comes into contact with institutions, scientists, researchers and data analysts from across the globe. This means that the CTBTO has a unique insight into specific science and technology issues in the developing world.«

DR. ANA MARÍA CETTO, IAEA DEPUTY DIRECTOR GENERAL,
AND HEAD OF DEPARTMENT OF TECHNICAL COOPERATION

7

# Glossary

**ANISOTROPY**
A dependence of the seismic wave speed upon the direction that the seismic wave propagates through a material.

**AZIMUTH**
A horizontal direction defined by an angle measured clockwise from true north.

**BODY WAVES**
There are two types of seismic body waves: P (primary) waves and S (shear or secondary) waves. P waves are compressional and analogous to a sound wave in air or water. They can pass through any kind of material. S waves move perpendicular to the direction of the waves' propagation and can only exist in solid earth.
"Pn" is a seismic P wave that travels along the lower boundary of the Earth's crust.
"pP" and "sP" are seismic body waves that travel upwards to the Earth's surface as a P wave or S wave respectively. They are then reflected as a P wave before travelling through the Earth for long distances. They are termed "surface reflections" and may be observed at distances of between 3,000 and 9,000 km.

**CENTROID MOMENT TENSOR (CMT)**
A method that uses the digitised seismic waves observed at a network of recording stations to estimate simultaneously the location, depth and time of a seismic event, together with its size ('moment'), and the nature of the forces acting at the source ('moment tensor'). In the case of an earthquake, this estimate would contain the orientation of the active fault and the direction that material slips along the fault as it generates the earthquake. For a large earthquake the CMT location differs from the conventional location determined from the onset times of seismic waves; the conventional method estimates the initial point of rupture, whereas the CMT method estimates the centre (or 'centroid') of the radiation of seismic energy.

**CLASSIFICATION ALGORITHMS.**
A fundamental problem in machine learning is to separate a large population of complicated objects (for example handwritten characters) into two classes (for example alphabetic characters and non-alphabetic characters). A common set of measurable characteristics or ëattributesí of each object is developed automatically (perhaps with some guidance) in order to maximise separation of the two classes. The algorithm is ëtrainedí on a set of objects (characters in this example) pre-classified by the user. In real examples (including this one), the number of attributes required to achieve a reliable separation may be very large, and large computing resources are required to optimise the attributes and classify the objects. Many approaches to solving this type of problem have been developed, including Support Vector Machines (SVMs), Naive Bayes Classifiers,and Decision Trees.

**CORE PHASES**
Seismic body waves (see above) that have passed through the Earth's core.

**DILATATION**
A reduction in pressure (opposite of compression). The observation of one or more dilatational P-wave onsets from a seismic event may be evidence of an earthquake, since a pure explosion should theoretically give compressional P-wave onsets in all directions.

**DISCRIMINANT**
In nuclear explosion monitoring, this refers to a method which is capable of discriminating between an explosion and some other source (for example an earthquake).

**ENSEMBLE MODELLING METHODS**
A group of parallel model simulations used for the ATM based assessment. Variation of the results across the ensemble members gives an estimate of uncertainty. Ensembles made with the same model but different initial conditions only characterise the uncertainty associated with the measurement (for backward ATM) or source (for forward ATM) parameters, whereas multi-model ensembles including simulations by several models also include the impact of model differences. The latter is more interesting to access the reliability of the ATM results and is utilized in the context of the CTBTO-WMO response system.

**FISSION PRODUCTS**
Any of the lighter atomic nuclei formed by splitting heavier nuclei (nuclear fission), including both the primary nuclei directly produced (fission fragments) and the nuclei subsequently generated by their radioactive decay.

**GAMMA SPECTROMETRY AND GAMMA SPECTROSCOPY**
Methods to measure gamma ray quantities and energies. They use detectors to determine the energy of gamma rays emitted by radioactive substances. This facilitates the identification of the radioactive elements present in a sample.

**'GROUND TRUTH'**
Seismoacoustic sources whose location, depth and origin time, (together with their uncertainties), are known to high precision, either from non-seismic evidence, or using exceptionally good coverage of seismometers close to the event.

**INTERNET PROTOCOL**
A protocol used for communicating data across a packet-switched internetwork using the Internet Protocol Suite.

**NATIONAL DATA CENTRES (NDCS)**
are operated and maintained by a Member State, whose functions may include sending International Monitoring System data to the International Data Centre and/or receiving data and products from the International Data Centre.

**NATIONAL TECHNICAL MEANS**
A means of verification such as reconnaissance satellites or aircrafts and electronic surveillance and other monitoring devices available to individual States. Information obtained by National Technical Means can be used when requesting an on-site inspection.

**OSI MODEL TEXT**
The current basis for discussion by the CTBTO's Working Group on verification issues (Working Group B) in its third round of elaboration of the draft OSI Operational Manual.

**OSI OPERATIONAL MANUAL**
States Signatories are currently developing a draft OSI Operational Manual, which will provide guidelines and procedures for all operational, technical and administrative aspects of an on-site inspection. The Manual is required by the CTBT and, once adopted by the Conference of the States Parties, will provide guidance on the implementation of relevant Treaty provisions.

**OSI TEST MANUAL**
The Test Manual was used as the procedural guidance for testing during the 2008 Integrated Field Exercise (IFE08) and for related training leading up to the exercise. Lessons learned from testing during IFE08 have now been included in the draft OSI Operational Manual elaboration process.

**P/S SPECTRAL RATIO**
A method which examines the amplitude ratio of seismic P and S waves observed at various frequencies.

**RAY TRACING**
A method for calculating the path of waves or particles through a system with regions of varying propagation velocity, absorption characteristics, and reflecting surfaces.

**REVIEWED EVENT BULLETIN (REB)**
A bulletin listing events and signal measurements at each station that detected an event, derived from waveform data that have been reviewed by a human analyst.

**SEISMIC WAVES**
There are different types of seismic waves: body waves that travel through the interior of the Earth and surface waves that travel along its surface. Both types of wave are measured in order to analyze the location, strength and nature of an event.

**STANDARD EVENT LISTS**
Standard Event Lists (SELs) are generated automatically every 20 minutes 24 hours per day, every day of the year. These lists include location estimates for events formed from signals recorded at different combinations of International Monitoring System (IMS) seismic, hydroacoustic and infrasound stations around the globe. The International Data Centre (IDC) issues three SELs, with different time delays, in order to provide progressively improved location estimates as more data become available. Currently the IDC issues SEL1 within two hours of 'real time', SEL2 after about four hours and SEL3 after six hours, in accordance with the timeline envisaged after the Treaty's entry into force.

**SURFACE WAVES**
"Lg" is a high frequency seismic surface wave that is often observed at distances of up to around 1,000 km.
"Rg" is a high frequency seismic surface wave that is normally observed only for very shallow seismic events (within about 3 km of the surface) and is rarely observed beyond a distance of a few hundred km.

**TAMPED**
When an explosive device is buried, and material is returned to the hole and compressed ('tamped'), this ensures that the explosion is well coupled to its surroundings and there are no cavities which could reduce the seismic energy released. By contrast, an 'untamped' explosion might be located in a cavity, resulting in 'decoupling', and an associated reduction in transmitted seismic energy.

# Acknowledgements

WE WOULD LIKE TO THANK THE FOLLOWING MEMBERS OF STAFF AT THE CTBTO WHO HAVE BEEN INSTRUMENTAL IN HELPING TO COMPILE THIS PUBLICATION :

### SILVIA ALAMO
joined the CTBTO in 2004 as Evaluation Section Chief. Prior to that she was head of evaluation at the International Atomic Energy Agency IAEA. Ms. Alamo has held several managerial positions including at the European Bank for Reconstruction and Development.

### ALEXEY ANICHENKO
joined the CTBTO in 1998 as a Processing Engineer at the International Data Centre (IDC). He went on to become Network, Data and Systems Operations Section Chief and later the Chief of Operations Section. Prior to this, Mr. Anichenko worked as a Senior Engineer in the Russian National Data Centre.

### ANDREAS BECKER
joined the CTBTO as an Atmospheric Sciences Officer in 2001 and is in charge of atmospheric transport modelling (ATM) software development at the IDC. Before this Dr. Becker worked in Germany as a senior scientist developing and utilizing ATM systems for environmental measurement campaigns.

### NICOLAS BRACHET
is a geophysicist who has been working as an acoustic officer with the IDC since 1998. Before specializing in the field of infrasound, he worked as a seismologist at the Commissariat à L'Energie Atomique in France.

### PAOLA CAMPUS
joined the International Monitoring System (IMS) Division ten years ago as an Infrasound Officer and became the Acoustic Monitoring Project Manager in 2006. Prior to this, Dr. Campus worked as a seismologist at several European institutes including the Department of Earth Sciences, University of Oxford.

### CHARLES ESTABROOK
joined the IMS Division as a Seismic Officer in 2001 and is now an Engineering Officer. Prior to that Dr. Estabrook worked in Silicon Valley in California, and was a research scientist in seismology at the Geo Forschungs Zentrum in Potsdam, Germany.

### ANDREW FORBES
joined the IMS Division as Hydroacoustic Officer in 2004. Before this Dr. Forbes worked in Australia as a project manager and principal research scientist for Australian Climate Variability and Change Project within CSIRO* Marine Research.

### JEFFREY GIVEN
recently joined the IDC Division as Chief, Software Applications Section. Dr. Given has over 20 years experience supporting research and development for treaty monitoring for GSETT2, GSETT3*[2], the United States National Data Center, the prototype IDC, and the IDC.

### TIM HAMPTON
joined the CTBTO in 1998 and is part of the team maintaining and operating the IDC application software to generate and distribute products and services. Prior to that, he worked in the UK for 10 years on test-ban monitoring issues.

### RONAN LE BRAS
joined the IDC in 2001 and is now Head of the Software Integration Unit. Dr. Le Bras has contributed key items to the IDC system and managed projects and teams in nuclear monitoring for the past 15 years.

### MIKA NIKKINEN
joined the IDC as Head of the Scientific Methods Unit, Software Applications Section in May 2007. Prior to this he worked for the International Atomic Energy Agency (IAEA) as Safeguards Data Analyst and Inspector.

### ROBERT G. PEARCE
worked at the IDC for ten years until April 2009, latterly as Chief of the Monitoring and Data Analysis Section. Prior to this, he held appointments at three universities, including the University of Edinburgh. Dr. Pearce has also worked at the UK Government's Blacknest research group.

### MATJAZ PRAH
joined the On-site Inspection (OSI) Division in early 2009 as an OSI Coordinator, Policy Planning and Operation (Office of the Director). Prior to this, Mr. Prah worked as Director General of the State Office for Nuclear Safety, Republic of Croatia.

### MARK PRIOR
has worked at the IDC since 2007 as a seismic/acoustic officer. Before this Dr. Prior worked in the field of underwater acoustics with application to active-sonar-performance prediction and ocean-acoustic modelling.

### WANG JUN
joined the OSI Division in 1997 as Chief of OSI Documentation Section, following three years of negotiation process in Geneva that concluded the CTBT. He also worked on the OSI Operational Manual and other procedural guides for the OSI regime. Mr. Wang served as the Inspection Team Leader during the IFE08 exercise.

### ROBERT WERZI
joined the Radionuclide Monitoring Section of the IMS Division in 1998. He participated in the certification of many radionuclide stations and was responsible for the operation and maintenance of the particulate radionuclide station network. In 2008, Dr. Werzi became head of the IMS Maintenance Unit.

### MATTHIAS ZÄHRINGER
is a physicist who joined the IDC as the Senior Radionuclide Officer in 2007. Prior to that, Dr. Zähringer worked at the German Federal Office for Radiation Protection mainly on issues of environmental radioactivity monitoring and emergency preparedness.

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* Australia's Commonwealth, Scientific and Industrial Research Organization (CSIRO).

*[2] Group of Scientific Experts Technical Test (GSETT)
Technical experiments conducted by the Ad-hoc Group of Scientific Experts. This was done to test monitoring technologies and data analysis methods for the verification of a nuclear test ban. GSETT1 took place in 1984, GSETT2 in 1991, and GSETT3 in 1995.

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