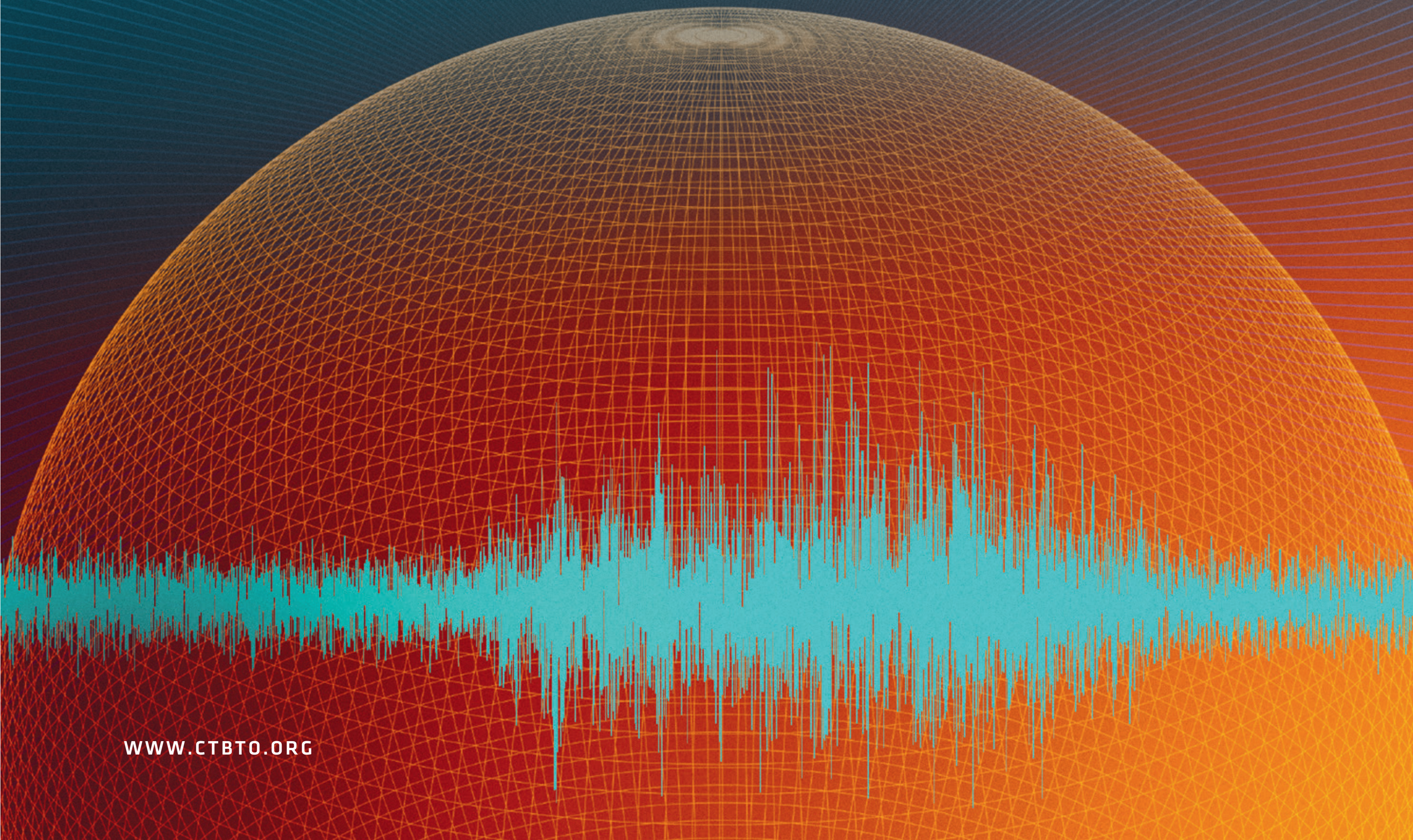
CTBTO
PREPARATORY COMMISSION

Scientific Advances in CTBT Monitoring and Verification

REVIEW OF PRESENTATIONS AND OUTCOMES OF THE **COMPREHENSIVE NUCLEAR-TEST-BAN TREATY: SCIENCE AND TECHNOLOGY 2011** CONFERENCE

8 – 10 June 2011, Hofburg Palace, Vienna



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CTBT SCIENCE AND TECHNOLOGY CONFERENCE SERIES

To build and strengthen its relationship with the broader science community in support of the Comprehensive Nuclear-Test-Ban Treaty, the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization invites the international scientific community to conferences on a regular basis.

These multidisciplinary scientific conferences attract scientists and experts from the broad range of the CTBT's verification technologies, from national agencies involved in the CTBTO's work to independent academic and research institutions. Members of the diplomatic community, international media and civil society also take an active interest.

SnT2011 was held in Vienna's Hofburg Palace on 8–10 June 2011. This report provides a summary of the scientific contributions presented at the Conference, and identifies some possible gaps in coverage and focus areas for the future.

In cooperation with the Austrian Federal Ministry for European and International Affairs

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TABLES

ABBREVIATIONS

ARISE	Atmospheric Dynamics Research Infrastructure in Europe
ARPANSA	Australian Radiation Protection and Nuclear Safety Agency
ARIX	Analyzer of Xenon Radioisotopes
ARR	Automatic Radionuclide Report
ATM	atmospheric transport modelling
BGS	British Geological Survey
BISL	Bayesian Infrasonic Source Locator
BUD	Buffer of Uniform Data
CELLAR	Collaboration of European Low-Level Underground Laboratories
CERN	European Centre for Nuclear Research
CMT	centroid moment tensor
CNF	Cooperating National Facility
CTBT	Comprehensive Nuclear-Test-Ban Treaty
CTBTO	Comprehensive Nuclear-Test-Ban Treaty Organization
DE10	Directed Exercise 2010
DLR	German Aerospace Center
DMC	Data Management Center
DONET	Dense Ocean-floor Network System for Earthquakes and Tsunamis
DOTS	Database of the Technical Secretariat
DPRK	Democratic People's Republic of Korea
DWIF	digital waveform interferometry
ECMWF	European Centre for Medium-Range Weather Forecasts
EGI	European Grid Infrastructure
EHB	Engdahl, van der Hilst and Buland
ENSN	Egyptian National Seismological Network
ESARSWG	Eastern and Southern Africa Regional Seismological Working Group
ESF	European Science Foundation
FDSN	Federation of Digital Seismograph Networks
GA	Global Association
GCI	Global Communications Infrastructure
GIS	geographical information system
GI-TEWS	German-Indonesian Tsunami Early Warning System
GEO	Group of Earth Observations
GEOSS	Global Earth Observations System of Systems
GNSS	Global Navigation Satellite System
GPCC	Global Precipitation Climatology Centre
GPR	ground penetrating radar
GPS	Global Positioning System
GRIPS	Ground-Based Infrared P-Branch Spectrometer
GSN	Global Seismographic Network
GST	Generalised Stockwell transform
GT	Ground Truth
HARPA	Hamiltonian Acoustic Ray-Tracing Program for the Atmosphere
HIFiRE	Hypersonic International Flight Research Experiment
HPGe	high-purity germanium
HUSN	Hellenic Unified Seismic Network
IACRNE	Inter-Agency Committee on Radiological and Nuclear Emergencies
IAEA	International Atomic Energy Agency
IASPEI	International Association of Seismology and Physics of the Earth's Interior
ICAO	International Civil Aviation Organization
IDA	International Deployment of Accelerometers
IDC	International Data Centre
IFE08	Integrated Field Exercise 2008
IISEE	International Institute of Seismology and Earthquake Engineering
IMS	International Monitoring System
ISC	International Seismological Centre
IOC	Intergovernmental Oceanographic Commission
IRED	Infrasound Reference Event Database
IRIS	Incorporated Research Institutions for Seismology
ISS09	CTBT International Scientific Studies Conference 2009
JHD	joint hypocentre determination
JICA	Japan International Cooperation Agency
JMA	Japan Meteorological Agency
KRNET	Kyrgyzstan Net
LEB	Late Event Bulletin
LHC	Large Hadron Collider
LIDAR	light detection and ranging
LIDO	Listening to the Deep Ocean Environment
MDAC	magnitude-distance-amplitude correction
MDC	minimum detectable concentration
MUSIC	Multiple Signal Clarification
NASA	National Aeronautics and Space Administration
NDA	nondestructive assay
NDACC	Network for the Detection of Atmospheric Composition Changes
NDC	National Data Centre
NDMC	Network for the Detection of Mesopause Changes
NET-VISA	Network Vertically Integrated Seismic Analysis
NOAA	National Oceanic and Atmospheric Administration
NORSAR	Norwegian Seismic Array
NPE	NDC Preparedness Exercise
NPT	Nuclear Non-Proliferation Treaty
NTM	national technical means
OFIS	optical fibre infrasound sensor
OGS	National Institute of Oceanography and Experimental Geophysics (Italy)
OPCW	Organization for the Prohibition of Chemical Weapons
ORFEUS	Observatories and Research Facilities for European Seismology
OSI	on-site inspection
PMCC	Progressive Multichannel Correlation
PNE	peaceful nuclear explosion
PNNL	Pacific Northwest National Laboratory
PSAC	President's Scientific Advisory Committee
PTE	proficiency test exercise
PTS	Provisional Technical Secretariat
QUACK	Quality Assurance Toolkit
REB	Reviewed Event Bulletin
REST	representational state transfer
RRR	Reviewed Radionuclide Report
RSTT	Regional Seismic Travel Time
SAMS	Seismic Aftershock Monitoring System
SANSN	South African National Seismic Network
SAUNA	Swedish Automatic System for Noble Gas Acquisition
SCSN	Samoa-China Seismograph Network
SEED	Standard for the Exchange of Earthquake Data
SEL	Standard Event List
SNL	Sandia National Laboratory
SnT2011	CTBT: Science and Technology 2011 Conference
SnT2013	CTBT: Science and Technology 2013 Conference
SPALAX	Système de Prélèvement d'air Automatique en Ligne avec l'Analyse des radio-Xénons
SRS	source-receptor sensitivity
SRTM	Shuttle Radar Topography Mission
SSI	standard station interface
SSSC	Source-Specific Station Correction
TS	Technical Secretariat
TXL	transportable xenon laboratory
UNESCO	United Nations Educational, Scientific and Cultural Organization
USAEDS	United States Atomic Energy Detection System

USGS	United States Geological Survey
VAAC	Volcanic Ash Advisory Centre
VCSEL	vertical cavity surface emitting laser
vDEC	virtual Data Exploitation Centre
VSAT	very small aperture terminal
WALPASS	Walvis Ridge Passive Source Experiment
WGB	Working Group B
WLCG	Worldwide LHC Computing Grid
WMO	World Meteorological Organization
WOSMIP	Workshop on Signatures of Medical and Industrial Isotope Production
ZAMG	Central Institute for Meteorology and Dynamics (Austria)


SCIENCE AND TECHNOLOGY 2011
CTBTO


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COMPREHENSIVE NUCLEAR-TEST-BAN TREATY: SCIENCE AND TECHNOLOGY 2011
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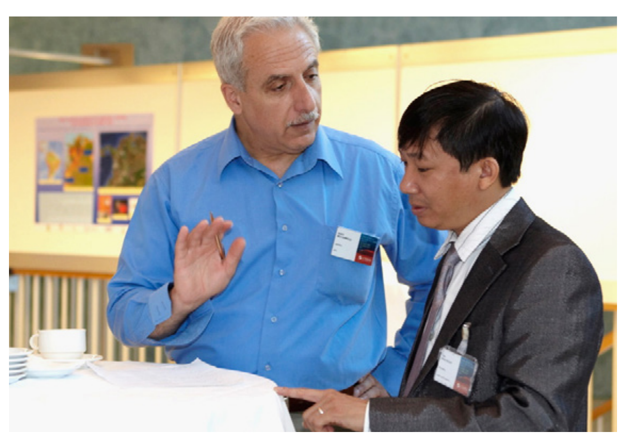


Opening Remarks from the Executive Secretary of the CTBTO Preparatory Commission

Tibor Tóth, Executive Secretary
Preparatory Commission
for the Comprehensive Nuclear-
Test-Ban Treaty Organization

Your Excellency the Vice-Chancellor of Austria, dear Michael,
Professor Garwin and Professor Strangway,
Executive Secretary Emeritus Hoffmann, dear Wolfgang,
Excellencies, Dear colleagues from the missions,
Colleagues from the Secretariat, former, present and future,
and Dear friends,

In late August 2006, less than five years ago, this organization brought together for the first time in its existence a couple of hundred scientists on the top floor of this building to look for synergies with science up to and beyond 2006. Very few of us suspected that 'beyond' would mean that by 2011 this initiative would grow into a scientific pilgrimage with around 800 participants and 350 scientific submissions and posters. A pilgrimage made possible in this amazing city, in its very heart, the Hofburg, by the generous political and financial support of Austria, for which I would like to express on behalf of all of us our most sincere appreciation, dear Michael.

I am personally humbled by the dedication of so many scientists so enthusiastically reacting to a renewed call to scientific arms. Your enthusiasm obliges me not just to announce how much we in the organization are looking forward to the scientific proceedings and discussions, presentations and poster sessions. It obliges me as well to report back to you how much this organization and its verification regime have progressed during the last half-decade or so since we launched this initiative.

I deliberately used the word 'obliges' because only together with you and thanks to you, scientists, technologists, supporters and friends of this monitoring regime and this organization, were we able to get to where we are today. Thanks to you and together with you we have now reached an 80% build-up certification readiness of the system. Together with you we improved station design, especially in the infrasound technology, resulting in an increased data availability and detection capability. We developed an effective sustainment structure for the International Monitoring System (IMS) and an integrated database called DOTS [Database of the Technical Secretariat]. We completely overhauled the computer infrastructure, installed a new state of the art Computer Centre and Operations Centre, established a new Global Communications Infrastructure unprecedented in its global reach.

Together with you we migrated all verification related applications to an open source environment, established a system-wide state of health monitoring tool, refined and improved detection and analysis methods and algorithms for processing of data, improved the configuration of automatic processing pipelines and strengthened the interactive analyst capability. Together with you we initiated the re-engineering of the operating software of the International Data Centre (IDC), introduced infrasound automatic and interactive processing into routine operations, made important advances in data fusion capabilities, decreased the time lines for the production of the various IDC products, delivering them within time lines envisaged at the time of entry into force of the Treaty.

Together with you we installed nearly 70% of the noble gas systems, introduced noble gas data into routine operations, developed software to process these data, made significant advances in using atmospheric transport modelling to backtrack dispersed radioactive material. Together with you we carried out a successful on-site inspection (OSI) Integrated Field Exercise in Kazakhstan, trained the first group of OSI surrogate inspectors, established an Equipment Storage and Maintenance Facility. Together with you we provided automated external access for States Signatories to our data and products, distributed the 'NDC in a box' software to States Signatories, created a new virtual Data Exploitation Centre (vDEC) for use by outside scientists.

And together with you we were weighed again and again. Weighed by system-wide performance tests, small scale tests and real time continuous performance monitoring. Weighed in 2006 and weighed in 2009 by the two announced nuclear tests by the Democratic People's Republic of Korea. Two tests too many. And we were tested by the forces of nature and man-made disaster. Tested by a most tragic earthquake, tsunami and nuclear accident in Japan. Tested so many times during this half-decade and still standing firm in our resolve together with you, scientists, supporters and friends of this verification regime and this organization.

During the next three days we will be looking beyond 2011. I hope that in our continued joint venture we pledge to finish the build-up of this regime and this Treaty. We pledge to put in place its elements still missing. And since "good enough" is not good enough for us, we pledge to better whatever should be improved and to look over the horizon for improvements through technology foresight. We pledge to share widely the benefits of our unprecedented monitoring system through mass collaboration, education and capacity development. All the benefits of a system and a regime which are not possessed by any of us, but belonging to all of us.

The presence of two outstanding scientists is a great source of inspiration. Professor Strangway recalled the Apollo mission. As we pledge, hopefully together with you, scientists, supporters and friends of this regime, let us use a pledge made fifty years ago by a president who dared to dream of and deliver on the unthinkable of that time, to land a man on the Moon, a pledge which I have slightly altered:

"We choose to put this Treaty in place. We choose to put this Treaty in place in this decade and do the other things, not because they are easy, but because they are hard, because that goal will serve to organize and measure the best of our energies and skills, because that challenge is one that we are willing to accept, one we are unwilling to postpone, and one which we intend to win, and the others, too ..."

Address by the Minister of Foreign Affairs of Austria

Michael Spindelegger
Vice Chancellor of the Republic of Austria

Executive Secretary Tibor Tóth, Excellencies,
Distinguished delegates, scientists
and friends of the CTBT

It is a pleasure for me to welcome you to the CTBT: Science and Technology 2011 Conference here at the Hofburg Palace. For many of you it will be a return to Vienna after the 2009 Conference "International Scientific Studies", which I had the pleasure to attend and which Austria was also pleased to support. Other participants will be here for the first time, even engaging for the first time with the CTBTO. To all of you I would like to extend a very warm welcome

Austria is a proud host to the United Nations and several important International Organizations. Many of the most pertinent issues of our time are addressed by the international community here in Vienna, be it security, energy, development, organized crime, drugs to name a few. However, it is certainly the nuclear dossier that has continuously gained in prominence among the "Vienna Issues" over the past years.

We are at a critical juncture with respect to nuclear disarmament and nonproliferation. We are faced with very serious concerns about nuclear proliferation and the risks of nuclear terrorism. At the same time, there is new political momentum towards a world free of nuclear weapons and to foster true multilateral cooperation in our collective disarmament and nonproliferation efforts. Moreover, the terrible tragedy in Fukushima has brought into clear focus the grave risks that are inherent in the use of nuclear energy. In short, nuclear safety and security are today among the key policy areas that demand a cooperative approach and coherent answers from the international community.

The Comprehensive Nuclear Test Ban Treaty is right at the centre of such an approach. It prohibits nuclear tests. It is a key instrument against the proliferation of nuclear weapons. It is a long sought-after nuclear disarmament measure. It builds confidence among Member States. It epitomizes multilateral cooperation by placing the same obligations on Member States and granting equal rights to all. It is one of the legal elements that must be in place to allow nuclear activities to be conducted in as safe and as secure an environment as possible. We are proud that this important organization is headquartered in Vienna. Austria will continue to work tirelessly with our partners to convince the remaining States whose ratification is required until the CTBT is finally brought into legal effect. Its entry into force is long overdue and necessary.

This conference, however, is not a political gathering. It is a scientific conference and as such an opportunity for the CTBTO to further strengthen its ties with the scientific community. This is not a fancy. It is a must for the CTBT and its credibility. The nexus between politics and science is particularly pronounced in the case of the CTBT. The legal aspect is but one of its pillars. Its strength and relevance also derives from the credibility of the verification regime that underpins the CTBT and its norms.

Much has been achieved in building up the verification regime since the CTBTO was set up in Vienna. By now, the build-up is almost complete and the verification regime is already fully operational. This is made clear by the daily provision of high quality and continuously improving monitoring data. It was also clearly evidenced by the performance of the CTBTO during the two North Korean nuclear tests in 2006 and 2009. Austria was a non-permanent member of the Security Council when North Korea exploded its second nuclear device. The timely and reliable information that we received from the CTBTO was of great value to us and facilitated the decision making process in the Security Council. In our view, the case has been made clearly that CTBT verification works.

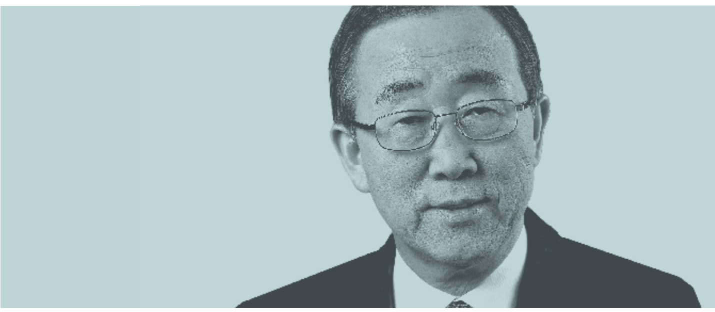
However, the credibility of CTBT verification capabilities must be safeguarded for the future. This requires a permanent and fruitful exchange with the scientific community to allow the CTBTO to remain at the forefront of those sciences and technologies of relevance for verification. In this exchange—and let me applaud Executive Secretary Tóth for his determination in this respect—we have seen some very important developments in recent years. It has become increasingly clear that the verification capabilities, in particular the global system of monitoring stations, provide additional benefits to the international community that were not anticipated. I would like to highlight in particular the contribution to tsunami warning that is now well established. The Fukushima accident gave another glimpse of the enormous potential that this system provides much beyond the originally intended use of nuclear test monitoring. I understand that we have only scratched the surface in understanding the benefits and practical application that the CTBT system could bring for a wide range of areas and issues. Many new ideas will be presented here or will be further developed as a result of this and future meetings.

In times of global financial crisis, it is imperative that scarce resources are used in the best possible way and that synergies are identified wherever possible. This is the way within our societies and it is also what we should strive for in our multilateral cooperation. I am therefore fully convinced that the CTBT assets built over the past 15 years should be used wherever they can bring added value to our common endeavours. Austria will certainly support such a trend and all such efforts.

In closing, I would like to wish you a very fruitful and interesting meeting. I look forward to hearing what new ideas emerge from this conference both those that strengthen the CTBT, strengthen the nuclear disarmament and nonproliferation regime and indeed those that develop the synergies between the CTBTO and the scientific community.

Thank you.

Message from the Secretary General of the United Nations



Ban Ki-moon
United Nations Secretary General

CTBTO Preparatory Commission Executive Secretary Tibor Tóth, Excellencies, Distinguished delegates, Ladies and gentlemen,

This is an important meeting at an important time.

The Comprehensive Nuclear-Test-Ban Treaty is widely recognized as a milestone in promoting nuclear non-proliferation and disarmament.

But above and beyond that central mission, and even before entering into force, the CTBT is saving lives.

When the devastating earthquake and tsunami hit Japan in March, the CTBTO Provisional Technical Secretariat quickly sent data to Japan and other Pacific communities, and shared valuable information with the International Atomic Energy Agency.

When the Fukushima nuclear power plant was damaged, the CTBTO Preparatory Commission tracked the spread of radioactive materials, helping governments communicate to people about possible health effects.

Since then, I have outlined a five-point strategy to enhance the global nuclear safety regime. I launched a UN system-wide study on the implications of the Fukushima nuclear accident. And I am organizing a high-level meeting on nuclear safety and security this September.

The CTBT and its International Monitoring System will make a significant contribution to this effort.

I continue to call for the Treaty's entry into force. Last year, at the NPT Review Conference, I suggested 2012 as the target year to make this happen. I am convening a special meeting in September in the hopes of generating further political momentum toward realizing this widely shared goal.

I commend your efforts to advance the science and technology that underpin the global ban on nuclear testing. I wish you a successful conference and look forward to our continued work together to rid the world of nuclear weapons and prevent their proliferation.

Thank you.

1

Introduction

1.1
LOOK TO VERIFICATION

With the Comprehensive Nuclear-Test-Ban Treaty (CTBT), as with any international treaty, comes the question of verification[1]. Indeed, the question of verification loomed large in successive negotiations[2] throughout the 40 years that preceded the opening of this treaty for signature on 24 September 1996. The final negotiations prescribed a global verification regime that was unprecedented in its extent and sophistication for an international arms-control treaty. Moreover, this would be installed and operated by an international organization set up primarily for that purpose.

As the Preparatory Commission for the CTBTO[3] prepares for the Treaty's entry into force[4], building up the verification regime represents a core activity. Most of the IMS has now been installed. The processing and analysis systems of the IDC are being tested and refined. The OSI regime is being developed and tested in major field exercises. All these activities are a means to an end, and that end is effective verification. Verification issues continue to be a focus of discussion in the ratification processes within individual States. Verification has been put to the test already, for example by the 2006 and 2009 announced nuclear tests in the Democratic People's Republic of Korea (DPRK). When the Treaty enters into force, verification will become a central activity both within the CTBTO and among its Member States.

In principle, the scope of 'verification' covers the detection, location, identification and attribution of a Treaty violation, which in simple terms includes any nuclear test explosion[5] conducted by or facilitated by a Member State. Such an explosion might be conducted in the atmosphere, underground, or in the ocean beyond the borders of any State. It could be conducted clandestinely, possibly with attempts at evasion such as cavity decoupling. So the scope of verification science and technology is broad. Verification might also be faced with a need to establish whether or not a test announced by a State was indeed a nuclear test. In that case, there might be a question as to whether a non-nuclear explosion had been combined with other actions in order to simulate a violation without one having occurred. Here it must be remembered that the credibility of verification, and hence of the Treaty itself, could be harmed not only by a missed violation, but also by a false accusation.

1.2
SCIENCE AND TECHNOLOGY AT THE FOCUS

Although any decision by a State to raise a suspected violation of the Treaty will, in the end, be made in a political setting, science and technology will be relied upon to provide the best available factual information to support the decision-making processes. The Executive Council[6] of the CTBTO, which will deal with any suspicion referred to it by a Member State, will also have its deliberations facilitated by scientific and technological information. It is also science and technology that must give credibility to the claims of verification, and to generate the deterrence value that is an essential strength of the Treaty. Scientific and technological advancement in this field lie at the heart of CTBTO's desire to engage with the scientific community; this formed the core motivation for the 'CTBT: Science and Technology 2011 Conference' (SnT2011), as well as for the 'International Scientific Studies 2009' (ISS09) conference, and the 2006 'Synergies with Science Symposium' before it.

Solution of any verification problem requires a thorough understanding of the scientific methodologies, equipment, sensors, processing methods, data transmission methods etc., that can be brought to bear on that specific problem. The methods of detection, or 'technologies', that CTBTO uses are laid down in the Treaty itself[7], and these technologies figure in many of the contributions to this conference. But the Treaty does provide for future changes to the monitoring technologies under the CTBTO's remit[8], and this has motivated many other SnT2011 contributions. Moreover, those technologies that might be used by Member States, commonly referred to as 'national technical means' (NTM), are of course unrestricted, and will grow as science and technology advance; these possibilities generated a raft of other scientific contributions to SnT2011.

The Technical Secretariat (TS) of the CTBTO and the States Parties will have distinct roles in the technical verification effort. For example, in measuring the performance of CTBTO's technical contribution, it is important to remember that its TS will not make a final judgement on the nature of any event[9]. In other words, the TS will not identify nuclear tests itself. Rather, under the terms of the Treaty, the TS will provide data, products, services and assistance to States Parties in order to support them in their responsibility to perform this task themselves. Many of the TS's obligations are already being discharged by the Provisional Technical Secretariat (PTS) before entry into force, under its current 'Provisional Operations'.

1.3 ELEMENTS OF CTBT VERIFICATION

Great strides have been made since nuclear test ban verification was first discussed in the 1950s, but it was recognized at the outset that verification, especially for nuclear tests conducted underground, would require (among other things) an appropriate global network of seismological monitoring stations[10]. In the ensuing 50 years, seismological stations have proliferated, and although most of the high-quality seismological array stations in the world are included in the IMS, there is a wealth of seismic data available from thousands of other seismological monitoring stations worldwide[11].

Today we also have the IMS infrasound network. Infrasound has enjoyed a renaissance under the Treaty after being neglected following the move away from atmospheric nuclear testing towards underground testing in the 1960s. The IMS infrasound network therefore effectively represents a new technology.

Hydroacoustic monitoring of the oceans for military purposes has been long established, but the IMS network based on triads of hydrophones supplemented by *T*-phase stations represents a major step in nuclear explosion monitoring. As with the infrasound network, many signals are being recorded that are of scientific interest far outside the network's primary purpose.

Although radionuclide monitoring also had a place in the early verification discussions, there have been major advances over the ensuing years, and the CTBTO is now able to field not only a global radionuclide particulate network as part of the IMS, but also a global network to monitor radioactive noble gas (xenon). Unlike the seismoacoustic 'waveform technologies' described above, radionuclide observations have the potential to provide unambiguous evidence of a nuclear explosion, even one detonated underground. For this reason, radionuclide observations are sometimes colloquially referred to as the 'smoking gun' of a nuclear explosion. However, alternative origins of any radionuclide observation must first be excluded, and the absence of radionuclide observations cannot itself eliminate the possibility of a well-contained underground nuclear test having occurred.

On-site inspection (OSI) poses its own set of challenges, not only technical but logistical and practical. On the technical side, the choice of suitable methods must be accompanied by the choice of, or development of, equipment to make these methods practicable, deployable and efficient in a wide range of environments within the constraints imposed by the Treaty. Operational safety is of utmost importance for OSI.

1.4 SnT2011 GOALS AND THEMES

The three Goals of SnT2011 illustrate the scope of the Conference. The scientific focus—on CTBT verification methods—defined in **GOAL 1**, is complemented by **GOALS 2** and **3** which recognize respectively the potential non-CTBTO-related applications of the verification infrastructure, and engagement with the scientific community.

THEME 1 results from the detection aspect of verification, which requires a sufficient understanding of the earth's complexities through which signals pass *en route* to monitoring equipment. **THEME 2** deals with the very specific matter of the nuclear explosion source itself, an understanding of which is crucial to the 'identification' stage of verification, while **THEMES 3** and **4** together cover the observational and theoretical aspects of verification applied to the CTBT.

The verification process requires not merely excellence in its science and technology *per se*. There is a broader context that is essential to ensure effective verification. It is not sufficient that the methodologies be known and understood by only a few specialists. If, after entry into force, a suspicious event occurs and a challenge is made, the Executive Council will need to act[6], and this will require a broad understanding of the technical issues among experts from participating Member States. So, the more widespread the understanding of verification methods, and the wider they are practised among States, the more credible will be the work of the Executive Council. This will, in turn, enhance deterrence. It is also important that Member States are able to participate actively in the work of the CTBTO and its routine verification activities. All these factors contribute to the importance of **THEME 5**.

Another contextual issue in verification concerns non-CTBT-related applications of IMS data. It has become clear that the wealth of data gathered by the IMS in support of verification can also be of great value to mankind in a wide variety of other fields, many of which already come under the responsibility of governments and international organizations. Environmental monitoring, disaster mitigation and other humanitarian applications all figure prominently here, as does a wide range of research in earth sciences and nuclear sciences. It will clearly benefit States in the long run if data gathered for one purpose at their expense can be used for other purposes without the need for duplication of effort and all the extra resources that would require, provided of course that the verification effort itself is in no way compromised. Moreover, 'research' in a broader sense using IMS data will doubtless lead to advances that will themselves benefit the verification effort. Thus there is ample motivation for welcoming contributions that use IMS data for non-verification purposes, and these mainly come within **THEMES 1** and **3**.

Goals

1. Discuss advances in science and technology relevant to test ban verification
2. Explore scientific applications of the CTBT verification infrastructure
3. Encourage partnerships and knowledge exchange between the CTBTO and the broader scientific community

Themes

- **T1** The earth as a complex system
- **T2** Understanding the nuclear explosion source
- **T3** Advances in sensors, networks and observational technologies
- **T4** Advances in computing, processing and visualization for verification applications
- **T5** Creating knowledge through partnerships, training and information/communication technology
- **JS** The 11 March 2011 Tohoku earthquake and its aftermath.

The multiple issues posed by the devastating Tohoku earthquake in Japan and its associated tsunami, together with the ensuing accident at the Fukushima Daiichi nuclear power plant, served to focus minds on a range of non-CTBT-related applications of all types of IMS data less than two months before SnT2011 began. It was decided to create an additional Theme (**THEME JS**), dedicated to contributions on these topics. These contributions serve to show that such events can have a substantial impact on the CTBT verification system. For example, the many thousands of earthquake aftershocks, and the many radionuclide observations from Fukushima, both resulted in an exceptionally high workload for CTBTO analysts reviewing IMS data. Another relevance to verification arises from the need to discriminate between a reactor accident and a possible nuclear explosion, and yet another is the transient impact that a nuclear reactor accident might have on the sensitivity of the IMS radionuclide network. Nevertheless, the contributions also demonstrate the high value of IMS data in helping to describe and understand such events.

Nuclear test identification has proved to be a non-trivial task especially for small events, despite a number of promising simple discriminants being recognized in the early days. Developments, especially in seismological monitoring, over the last half century have progressively resolved many problems in the field of earthquake/explosion discrimination. Moreover, the potential to provide conclusive evidence of a nuclear explosion, through the detection of even minute concentrations of radionuclides including isotopes of relevant noble gases xenon and argon, provides a formidable challenge to any potential violator who sees non-detection as a crucial prerequisite.

As we look forward, it is clear that scientific and technological advances may range from small incremental improvements made to existing processes offering a modest enhancement to reliability or accuracy, all the way to major advances which offer verification by whole new methods; some of the latter advances come within the scope of 'technology foresight' which will have a special place at CTBTO's next scientific conference 'CTBT: Science and Technology 2013' (SnT2013).

1.5 REPORT OUTLINE

The five Themes of SnT2011, plus the sixth Theme on the Tohoku earthquake and its aftermath, represent one attempt to divide the broad fields of CTBT-related verification and its associated data into discrete parts. Although the Themes played an important part in setting the scientific agenda for the Conference, and in planning its sessions, it was inevitable that some contributions relate to more than one Theme, and that others may not fit well into any Theme.

This report on SnT2011 is organized using the chronology of data flow as a starting point. Data Acquisition (**SECTION 3**) is followed by Data Transmission (**SECTION 4**), then Data Processing and Synthesis (**SECTION 5**). Support for data processing, as well as interpretation, must be provided by a detailed knowledge of many properties of the earth and its environment. These range from seismoacoustic wave speeds and attenuation profiles to characteristics of atmospheric transport. They also include a range of subsurface properties such as permeability and tectonic stress, which are relevant to the identification of seismic sources or the transport of radionuclides through the earth's subsurface. All work on Earth Characterization is brought together in **SECTION 6**. Interpretation, whose central purpose is to identify nuclear explosions and distinguish them from other sources of signal with which they might be confused, is considered in **SECTION 7**. Additional Sections on Capability and Performance (**SECTION 8**), and on Sharing of Data and Knowledge (**SECTION 9**), cross-cut all the earlier Sections. Contributions on the Japan Tohoku earthquake and its aftermath are fully integrated into this scheme.

This chosen way to arrange the outcomes offers several benefits. For example, it serves to emphasize the importance of pursuing an integrated approach to verification at all steps along the way, from data acquisition to interpretation. Also it avoids artificial separation of monitoring methods used for OSI from related methods used in global monitoring. Moreover, it promotes combining observations from diverse monitoring methods in order to provide a comprehensive picture in support of verification, and it helps to show how the common requirements of different monitoring technologies in terms of infrastructure, data transmission and storage, and operation and maintenance, can be exploited to simplify administration and facility management.

As a prelude, the two keynote addresses are reproduced in full (**SECTION 2**), because they each make a substantial contribution to setting the historical context and in pointing the way forward. The three statements in the scientific closing session are also reproduced in full (**SECTION 10**), in order to present these different perspectives on the future.

It is instructive to observe that the Sections have widely different lengths; this represents the research profiles and interests of the contributors, and perhaps those of their funding sources. If we consider the way ahead, it is questionable whether these contributions provide an optimum balance of effort in the respective stages of the verification process. The layout of this report facilitates enquiry into such questions. In **SECTION 11** some comments are offered on the balance of contributions, and what may be missing in the context of verification challenges. This leads to possible focus areas for the future, which are considered in **SECTION 12**. These last two Sections may provide some pointers for planning the scientific programme of future conferences.

The Report's method of presentation naturally results in some contributions being cited in more than one Section; this is done without hesitation. An **INDEX OF CONTRIBUTING AUTHORS** includes the first authors of all cited contributions, and an **INDEX OF CITED CONTRIBUTIONS** is provided for ease of cross-reference. In order to facilitate cross-referencing of outcomes referred to in each Section, an extensive **GENERAL INDEX** is also included. In the rear pocket is a **DVD** that contains electronic copies of the oral and poster presentations, and videos of the sessions.

1.6

RELATED CTBTO PUBLICATIONS

The CTBTO SnT2011 Book of Abstracts[12] is complementary to this Report, and covers all accepted oral and poster contributions; details of the Programme Committee are also included there, plus an index of all contributing authors.

Inevitably, some of the outcomes of SnT2011 overlap with those of the previous conference, ISS09. An attempt has been made to minimize repetition, and reference is made to one of the two ISS09 reports where appropriate. These are entitled "Science for Security: Verifying the Comprehensive Nuclear-Test-Ban Treaty"[13] and "Possible Projects for the CTBTO arising from the 2009 International Scientific Studies Conference, 10-12 June 2009"[14]. For brevity, these are referred to here as the external and internal ISS09 reports respectively. All the documents mentioned above are available on the CTBTO public website at www.ctbto.org.

2

Keynotes

2.1

RICHARD L GARWIN: THE SCIENTIFIC ROOTS AND PROSPECTS FOR THE CTBTO AND THE IMS

The Scientific Roots and Prospects for the CTBTO and the IMS

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I am delighted to have the opportunity to address this Science and Technology 2011 meeting of the CTBTO. Despite your essential, personal interest in your own work, the ultimate purpose is to contribute to and to advance the means available for monitoring compliance under the Comprehensive Test Ban Treaty.

It is self-evident that we would not have a CTBTO, the International Monitoring System (IMS), and the International Data Centre (IDC) without a strong interest among States, all but 13 of which are parties to the CTBT of 1996, signed by 182[15] and ratified by 153[16], and needing ratification by six signatories and adherence and ratification by India, Pakistan, and North Korea before it can enter into force as foreseen in the Treaty. The Parties have defined, created, and supported the CTBTO in a remarkable technical and political achievement to be compared with CERN, the European Organization for Nuclear Research, based near Geneva, Switzerland.

Much of the detail of the CTBTO and its detection capabilities are in the Treaty itself, the result of difficult and complex negotiations among the participants. This, in turn, draws on the very early work in several States which I want to sketch here.

Only two nuclear explosives were used in wartime, in 1945 by the United States against the Japanese cities of Hiroshima and Nagasaki. Those explosions, of 13 and 20 kiloton yield, respectively, enhanced the destructive power of individual weapons by a factor thousand or more; furthermore, J. Robert Oppenheimer in a speech in November, 1945, predicted that in a war between nuclear-armed States, such weapons would be used by the thousands or the tens of thousands.

The scientists who had created the nuclear weapon predicted that the fact of the explosions of August 1945 together with the extraordinary jump in destructiveness conferred by this new weapon would result in its acquisition by another State within four or five years, and on August 29, 1949, the Soviet Union tested a weapon of similar design and yield to the Nagasaki bomb.

Many scientists around the world had been arguing for the internationalization, control, or abolition of nuclear weapons, and the acquisition of nuclear weapons by a second State both spurred the competition and increased interest in control over nuclear weapons, especially in view of the political antagonism between the two nuclear-weapon States. The world changed, from a few nuclear weapons in the hands of the United States to possession by two political adversaries and as is shown in the figure [FIGURE 2.1], the number of nuclear weapons in the national arsenals grew rapidly.

It had long been evident that although the weapons based on nuclear fission had an upper limit to their practical yield, there would be no such limitation on a thermonuclear weapon that would obtain energy from the fusion of the lightest elements, especially the nuclear reaction of deuterium on deuterium that would yield in 50% of the cases He-3 plus a neutron and in the other half of the reactions,

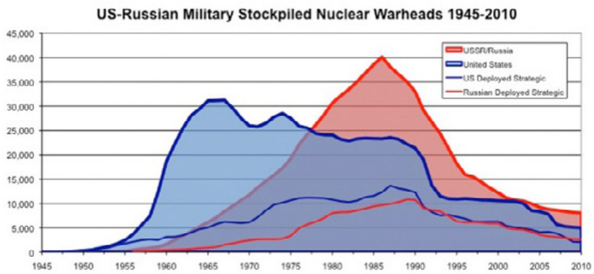

FIGURE 2.1.
USA and USSR/Russian military stockpiled nuclear warheads, 1945–2010. From H. M. Kristensen, "US and Russian Nuclear Forces: Status and Trends in Light of the 'Smaller and Safer' Article". Briefing to Panel on Smaller and Safer Article and De-alerting of Nuclear Weapons, United Nations, 13 October 2010. Federation of American Scientists and Nuclear Resources Defense Council. http://www.fas.org/programs/ssp/nukes/publications1/Brief2010_SmallSafe.pdf .

tritium (H-3) plus a proton. And it was known that at temperatures achievable with a fission bomb, the tritium would react rapidly with deuterium to form He-4 plus a neutron.

Since 1943, with the creation of the Los Alamos Scientific Laboratory with Robert Oppenheimer as its Director, the United States had a small effort on thermonuclear weapons, led by Edward Teller with a few collaborators. In January 1950, two months after his announcement of the Soviet nuclear test, US President Harry S. Truman announced that the United States would develop the thermonuclear weapon—the 'hydrogen bomb.' The first H-bomb test took place November 1, 1952, with an explosive yield of 11 megatons—almost 1,000 times the yield of the Hiroshima bomb.

Although the 1949 Soviet nuclear test was at a remote site in Kazakhstan, the nascent United States Atomic Energy Detection System—US-AEDS—detected it and acquired samples of the debris on airborne filters. Many more nuclear tests were to follow, by the United States, Soviet Union, Britain, France, and China, with a single test by India in 1974 and several more by India and Pakistan in 1998. North Korea had two nuclear test explosions underground in 2006 and 2009.

Atmospheric testing soon aroused opposition, especially because of the fallout of radioactive materials—the fission products from the bomb itself, un-reacted plutonium, and radioactivity induced by bomb neutrons in the materials of the surrounding soil and atmosphere.

Largely for reasons of public health, most nuclear-weapon testing moved underground, giving rise to a new technology to ensure containment of the debris in the explosion-created underground cavity in a horizontal 'drift' or mine shaft or at the lower end of a large-diameter drilled hole. A few explosions were conducted in space, as well, beginning in 1958 with three very small ones, launched by rocket from the deck of a US Naval ship in the South Atlantic Ocean.

With the perfection of the thermonuclear weapon, especially in the form of a two-stage 'radiation implosion' system, not only was it possible to make air-deliverable nuclear weapons with a yield range of tens of megatons, but it was also possible to make much more economical, smaller, and safer nuclear weapons in the range of yields accessible by pure fission weapons. Indeed, that was the rather unexpected major application of the concept of radiation implosion.

Although most of the effort regarding nuclear weapons was expended in testing, developing, and producing them, and especially their costly means of delivery and protection, responsible leaders and many others, especially in the scientific community, explored the possibility of limiting or banning nuclear weapon test explosions, if not nuclear weapons themselves. And that has long been a principal line of arms control.

When a responsible leader or government asks for the pros and cons of a potential ban on nuclear tests, many troubling questions are raised. Will potential adversaries comply? If not, what is the probability of detection, so that one side will not be disadvantaged by doing without nuclear tests, while the other side proceeds with clandestine nuclear tests?

In an April 28, 1958, letter to Soviet leader Nikita Krushchev, US President Dwight D. Eisenhower said the failure to achieve a ban on nuclear testing, "would have to be classed as the greatest disappointment of any administration—of any decade—of any time and of any party….".

In fact, no test ban was to be achieved before President Eisenhower left office in 1961, with the inauguration of President John F. Kennedy, for whom the nuclear test ban was also a priority. Nevertheless, the United States and the Soviet Union did impose a moratorium on their nuclear tests from October 31, 1959 to August 31, 1961, and Eisenhower had put in motion the beginning of a technical basis for a potential CTBT—a treaty completed and signed in 1996.

SCIENTIFIC BACKGROUND

The story is told well by Paul G. Richards and John Zavales[17], and in abbreviated form by Frank Press[18], Science Advisor to President Jimmy Carter.

Following the October 4, 1957 Soviet launch of the Sputnik satellite, President Eisenhower established the President's Science Advisory Committee—PSAC. The Sputnik had demonstrated Soviet capability in space, and intercontinental ballistic missile delivery of nuclear and thermonuclear weapons was an early probability. By that time the United States had had enough experience with strategic air defence to know some of the problems involved in protecting the nation against nuclear weapons delivered by aircraft, and although it was and to this day remains hopeful for ballistic missile defence, the possibility of stemming the arms race and the technical development of new weapons was appealing. In early 1958, the President's Science Advisor, James R. Killian, chairman of PSAC, appointed an inter-agency panel chaired by Hans Bethe, physicist, of Cornell University to study the technical feasibility of monitoring a test ban. In April 1958 the Bethe Panel reported that 24 seismic stations in the USSR could detect underground explosions at a level of one or two kiloton yield. As pointed out by Richards, the only prior underground nuclear explosion was the RAINIER test of September 19, 1957.

When on March 31, 1958 the USSR announced that it would impose a moratorium on its nuclear tests if the US and the UK did likewise, the Soviet Union had just concluded a series of nuclear explosion tests, while the US was about to begin one. Despite the position of the Soviet Union that a ban on tests was a political matter and should precede technical monitoring capabilities, and the view of the United States to the opposite, a Conference of Experts to Study the Methods of Detecting Violations of a Possible Agreement on the Suspension of Nuclear Tests opened on July 1, 1958 at he UN in Geneva, although not under UN sponsorship.

James Fisk, head of Bell Telephone Laboratories, chaired the US delegation supported by Robert Bacher and Ernest O. Lawrence and about a dozen physicists and seismologists as advisors to the delegation.

This first Conference of Experts found that atmospheric nuclear explosions could be well monitored, including the collection of debris, but that detection of underground nuclear explosions was much more difficult. The Soviet Union maintained that existing seismographic stations, in place for earthquake monitoring, would be adequate for the underground test monitoring role, but the UK and the US argued that many more stations would be required and that automatic seismic stations with appropriate attention to integrity of data would be needed, for instance to ensure that the detection of 'first motion' could be relied upon to separate earthquakes from explosions. The first motion from an explosion (nuclear or conventional) would be outward, whereas for an earthquake, although at some azimuth and dip angles the first motion would be outward, there would be some at which it would be inward, thus providing a diagnostic that could separate explosions from earthquakes.

The first Conference of Experts ended on August 21, with a recommended seismic monitoring system based on a UK proposal, but with the issue of on-site inspections unresolved.

Formal negotiations on a CTBT began October 31, 1958, but the two month interval saw multiple nuclear tests by the USSR, the US, and the UK. The Conference on the Discontinuance of Nuclear Weapons Tests was contentious, taking into account additional underground tests and the argument by the United States that a threshold for 90% probability of detection would be in the range of 20 kt. The detection is probabilistic, in view of the differing attenuations from the explosion site to the various detectors, and the varying level of background signal ('noise') at the various detectors.

A Panel on Seismic Improvement, appointed by Killian and chaired by Lloyd Berkner, reported in March 1959 on improvements that could be made by increasing the number of seismometers at the seismic array stations. The Panel recommended, specifically, a major increase in funding for research and basic seismology. The resulting appropriations had an enormous impact on seismology and on geophysics in general. According to Kai-Henrik Barth, "…from 1959 to 1961, funding for seismology increased by a factor of 30 and remained at this level for the better part of the 1960s."

After many adventures, the Treaty Banning Nuclear Weapon Tests in the Atmosphere, Outer Space, and Under Water (the 'Moscow Treaty') was signed by the USSR, the US, and the UK on August 5, 1963. It was ratified within a few weeks, and restricted the parties to underground nuclear testing only. It was opened to others and signed and ratified by many, but not by France and China. The last atmospheric test having been conducted by China in 1980, both France and China have signed the CTBT.

The inclusion of the fourth medium—underground—was delayed for many years in part by the technical discovery that an explosion in a sufficiently large, pre-existing cavity filled with air rather than water or rock, could reduce the signal by a factor about 70, leading to the exaggerated claim that a party to the Treaty could successfully evade detection of a 70-kt nuclear explosion, with the seismic wave similar to that of a normal 1-kt explosion, assuming a 1-kt threshold of detection for the system.

DECOUPLING OF UNDERGROUND NUCLEAR EXPLOSIONS

On page 40 of his memoir, "The Road from Los Alamos"[19], Hans Bethe writes of the

> "…possibility of deliberate concealment of explosions by a process known as decoupling, or muffling."
>
> "A very powerful method has been proposed by Albert Latter…His method consists of making an enormous underground cavity and setting off the atomic bomb in the middle of the cavity. One can calculate that the apparent size of the explosion is there by reduced by a factor about 300." [Now better estimated as a factor of about 70.]
>
> "Latter's decoupling theory was invented about January 1959, and was then checked by many scientists, including me. It was experimentally verified with small explosions of conventional high explosive in Louisiana early in 1960.…"

Bethe was at first sceptical of the validity of the Latter proposal, but writes on page 43 of "The Road from Los Alamos,"

> "I had the doubtful honor of presenting the theory of the big hole to the Russians in Geneva in November 1959 … The Russians seemed stunned by the theory of the big hole … Two of the Russian scientists presented to the Geneva Conference their supposed proof that the big hole would not work. A day or two later, Latter and I gave the counterproof and showed, with the help of the Russian theory itself, that the Russian proof was wrong, and the theory of the big hole and the achievable decoupling factor were correct. We have been commended in the American press for this feat in theoretical physics. I am not proud of it."

Soviet negotiators, according to Bethe, were extremely unhappy with the discussion of the prospects for evasion of detection of an International Monitoring System, but Edward Teller, on the other hand, without suggesting that the United States would cheat on its obligation under a treaty, recommended that the US study in great detail not only the possibility of evasion but work out the details of such evasion. Bethe writes, quoting Teller,

> "'[Teller:] We in the United States should continue determined research to find out further methods of decoupling, further methods of reducing the signal from an underground explosion.…' This may be so, but should we really spend our time and effort drawing up a blueprint for a violator of the treaty, and also do the engineering for him?"

Since the 1959 discussion of big-hole decoupling, that possibility has dominated discussions of detection of clandestine nuclear tests. It is generally accepted that the radius of the cavity for full decoupling in either salt or rock is 25 metres for a 1-kt explosive, with the volume of the required air-filled cavity increasing linearly with the yield to be decoupled. The teleseismic amplitude does not diminish further with additional increase in big-hole volume.

I suppose that is what at first led Bethe (and the Russians) to reject the validity of the big-hole decoupling approach. Imagine a cavity in competent rock, filled with air at atmospheric pressure and of

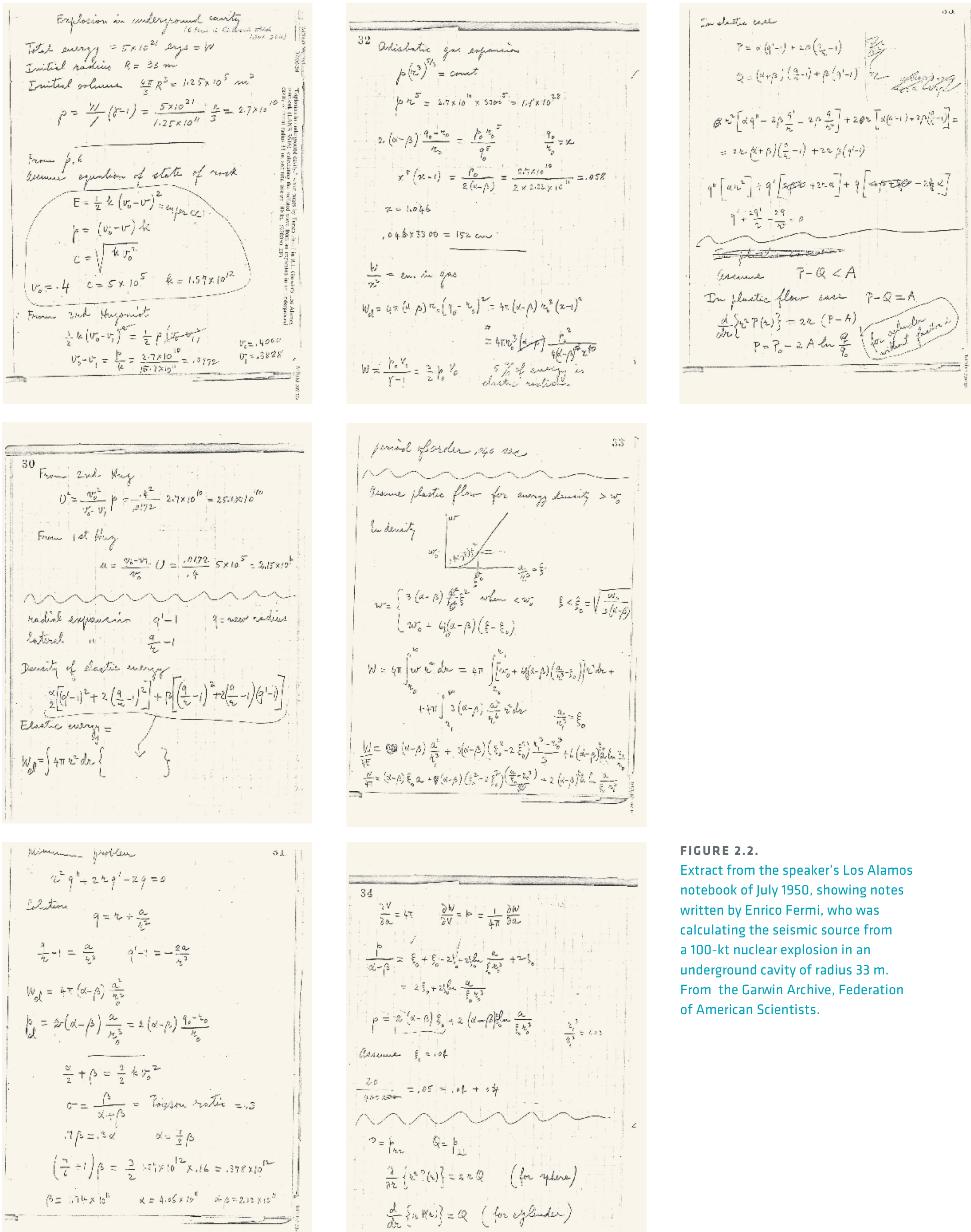

FIGURE 2.2.
Extract from the speaker's Los Alamos notebook of July 1950, showing notes written by Enrico Fermi, who was calculating the seismic source from a 100-kt nuclear explosion in an underground cavity of radius 33 m. From the Garwin Archive, Federation of American Scientists.

a size that the response of the rock to the sudden increase in pressure from a nuclear explosion is elastic. Because of the 2000:1 density ratio between rock and air, if one imagines the nuclear explosion to result in a sudden uniform heating of the contained air to a pressure on the order of 200 bar that would be contained in most rock, there is simply a step-function increase in pressure, which is the 'boundary condition' for the surface of the cavity. This is then coupled to the deformation of the rock, which in the vicinity of the cavity is a static problem, and not a wave propagation problem. However, at a radius comparable to the reduced wavelength in the rock ($\lambda/2\pi$) the near-field distortion gives way to propagating elastic waves, which in isotropic rock would correspond to a spherical *P* wave.

What happens to the wave beyond the immediate region of the cavity is determined by the layered geology and especially by the free surface between rock and free atmosphere, as well as by surface topography, and the like. But we are interested here only in the source term, and that is a local matter.

For a given yield, Y, of the nuclear explosive device, the increase in energy density in the cavity is inversely as the cavity volume. And the pressure likewise. For a cavity small compared with $\lambda/2\pi$, the static falloff of pressure, $P(r)$, in a homogeneous elastic medium between cavity radius a and $\lambda/2\pi$ goes like $1/r^3$, specifically, $P(r) = P(a)(a/r)^3$, so that $P(\lambda/2\pi) = P(a)\ \{a/(\lambda/2\pi)\}^3$. Since $a^3\ P(a) = Y_0$, $P(\lambda/2\pi)$ is independent of cavity radius, a, so long as the a is large enough for the rock to be in the elastic range. Here Y_0 differs from the nuclear yield, Y, by factors like $(4\pi/3)$ and the polytropic exponent of the gas in the cavity.

That this is true means that in this realm, a larger cavity does not provide further decoupling, and that is, perhaps, what misled Bethe. But in the inelastic realm, for a tamped explosive, the detonation of the nuclear weapon or even of a conventional explosive far exceeds the strength of competent rock. The rock is crushed, vaporized, and liquefied, and in general thrust out into a shock-heated and then frozen shell that thus corresponds to a seismic source that is a monopole. Again, there is no inherent length or time scale in this initial problem, so that the volume of the cavity thus produced by the explosion increases linearly with the yield of the explosive; so the question is to compare, for a given yield, this monopole source from the cavity creation in the rock, with the monopole source for the modest increase in pressure of the air in the pre-existing decoupling cavity. This is not a simple problem; the result is the maximum cavity decoupling factor of about 70.

I provide here [**FIGURE 2.2**], perhaps for the first time for most of this audience, a seven-page excerpt from my Los Alamos notebook of July 1950. These notes are written by Enrico Fermi, who was calculating the seismic source from a 100-kt nuclear explosion in an underground cavity of radius 33 m. Of course we have no time to follow the analysis during my talk, but I note that for this partially decoupled analysis (the cavity radius to 'fully decouple' 100 kt would be 116 m), Fermi estimated that 5% of the explosive energy would be radiated as seismic waves.

In the wave zone, for a given frequency component of the propagating wave, the pressure, velocity, and acceleration all vary alike as a function of radius. Because the area of a successive shell of rock increases as r^2, an outgoing spherical wave thus has amplitudes that decrease as $1/r$. This wave is then reflected at discontinuities, refracted at those same interfaces, just as is the case with light and sound, except that even in an isotropic solid, one has not only the waves of longitudinal motion (*P* wave) but the waves of transverse motion (shear), *S* waves. In addition, there are additional waves guided by interfaces, especially by the earth's surface.

From the advent of the big-hole decoupling analysis in 1959, it has been at the forefront of the question of effectiveness of long-range detection of underground nuclear explosions. Latter indicated also that in addition to not having pre-existing faults, the rock, which is only elastically deformed by modest pressures in the fully decoupled region, must not be put into tension. And this means that the depth to the top of the spherical cavity should be such that the post-explosion cavity air pressure should be less than half the lithostatic pressure on the rock. In fact, if the cavity pressure exceeds the hydrostatic pressure (0.1 bar per metre of depth), there would be no barrier to noble gases and perhaps other gaseous fission products escaping through water-filled cracks in the rock.

The focus on seismic detection in the early days was largely on teleseismic detection, but with the vastly increased numbers of digital seismometers, and the availability of their digital outputs continuously in real time, or in most cases by automated file transfer upon request, it is evident that regional detection of seismic waves is often practical, with the formation of regional arrays. This makes possible observations at far higher frequency than the 1 Hz typical of teleseismic observations, with greater sensitivity to short-time features such as reflection from the earth's surface.

John Tukey was on the US team at the Conference of Experts, and his work and that of others emphasized a discriminant between explosions and earthquakes based on depth. A seismic source deeper than 10 km can hardly be an explosion, so it is highly desirable to determine depth. How can this be done? For multi-station teleseismic detection, with a range of dip angles of the seismic rays from the explosion to the different stations, and with the accumulations of site-specific corrections, the travel time differences from the deep source will force the solution to 'close' at the actual depth of origin, so that the many earthquakes of focal depth of tens of km will be screened out as candidates for a nuclear test. But there is another way to determine focal depth, even on a single teleseismic detection.

Because of the very great density difference between rock and air, and the even larger ratio in stiffness between rock and air, there is almost 100% reflection of the seismic wave coming from below at the surface above the explosion or earthquake. This is determined by the acoustic impedance, $Z = \rho c$, where, substituting $c = (Y/\rho)^{1/2}$, $Z = (Y\rho)^{1/2}$. The air provides pressure release at the ground surface, and at great depths (or great distances for a teleseismic wave that curves upward for detection at distances of thousands of km) the signal is similar to that which would have been produced by the explosion itself at the initial range and position in what would now be an infinite rock medium, although with a kind of 'dotted line' to mark the boundary that existed between rock and air. The teleseismic signal, though, would be that signal from the explosion itself, plus a signal from a simultaneous anti-explosion in the rock above the initial interface—'anti-explosion' because every component of pressure or velocity would be reversed in sign.

For very short waves (wavelength short compared with the double depth of burial), there would be two time-resolved peaks in the motion detected by a seismometer. In fact, these peaks would be mirror images of one another; in the frequency domain, there would be cancellation where the double depth of burial is equal to a wavelength or some integer multiple of the dominant wavelength under consideration.

This leads to a 'scalloping' of the signal power when viewed in the Fourier domain, and if one takes the Fourier transform of the logarithm of the spectrum of the signal itself, then this cepstrum has a peak corresponding to the depth of burial. This is a powerful technique for discrimination.

Following the 1959 Berkner report, the US government created the Vela Program, conducted by the Defense Advanced Research Projects Agency. Vela UNIFORM (the initial 'U' for Underground) can be credited with stimulating much of the improvement in seismic methods over the decades. Vela HOTEL ('H' for High) resulted in the development and deployment of a series of 12 'Vela satellites' in 118,000-km orbits, that monitored for explosions in space and on the surface of the earth. Vela satellites operated from October 1963 until 1984, by which time nuclear explosion detection systems were carried on many other satellites. Vela housed detectors of neutrons, X-rays and gamma rays, as well as two optical 'bhang meters' that were sensitive to the 'double-humped' light pulse from an atmospheric nuclear explosion on the visible face of the earth, but without capability to further locate the light source.

IMS MODALITIES AND REPORTING TIMELINE

The IMS monitors with four modalities: seismic; hydroacoustic (for explosions in the oceans); infrasound (for explosions in the atmosphere); and radioactive particulates and gases (which can detect atmospheric explosions and very many underground explosions unless the test has been adequately sealed against leakage). In fact, even for skilled practitioners such as the United States and the Soviet Union/Russia, more than 50% of the underground tests leaked significant amounts of radioactive materials.

The IMS sensor results go to the International Data Centre (IDC) and are available to member countries, which have in many cases a great interest in checking, duplicating, and carrying further the analyses of the IMS. The timeline of these activities, from a presentation during my visit to the CTBTO in November, 2009 is shown on the following chart [FIGURE 2.3].

There are 50 primary IMS seismic sites, many of them arrays of several 3-component seismometers. The IMS also includes 120 secondary seismic sites, which do not report continuously in real time to the

IDC but which do record and the digital data from which can be transmitted automatically on request by the IDC. In addition to the IMS sensors, there are supplementary sensors—many thousands of digital seismometers operated by universities or national agencies primarily for earthquake monitoring and research.

Having perhaps the most difficult task, the seismic monitoring of underground explosions and the discrimination of earthquakes is probably the most advanced of the modalities of the IMS. It is continually refined by research in seismology, practically motivated by earthquake detection and characterization, and major strides have been made. For instance, the sole discriminant of direction of first motion discussed in the 1958 has been supplemented at least two other major techniques.

The first of these is depth determination, essentially by the failure of seismic records detected at different azimuths and distances all to close at a specific point on the surface. Given a full understanding of the seismic velocity versus depth of the earth, such detections typically do close at a depth equal to that of the earthquake or explosion. A source with actual depth exceeding 10 km is evidently not an explosion. Essential to the qualification of this technique has been the enormous number of digital records over the last decades of earthquakes in every part of the world. In addition, artificial signals created by 'thumpers' together with modern digital signal processing can provide such information without explosions, in giving the equivalent of an artificial explosion anywhere the thumper is permitted to operate.

The more intense production of *P* waves relative to the *S* wave by explosions compared with earthquakes continues to be exploited as a discriminant, the distortions of propagation reduced with the use of the Magnitude-Distance-Amplitude Correction (MDAC) technique. The resulting amplitude ratios are illustrated in the Figure [FIGURE 2.4]. The best-performing spectral band, 6–8 Hz, is not available for teleseismic detections. Cross-spectral ratios (not shown) show promise as well, where the high-frequency amplitude of one phase is compared with the low-frequency band of another phase.

INFRASOUND

Among the earliest systems deployed for the remote detection and location of atmospheric nuclear explosions is the microbarograph or infrasound detector in the range of 0.2–2.0 Hz. In the full IMS each of the 60 infrasound stations will consist of 4–15 gravel-covered stars of porous tubes (wind-noise-reducing system) deployed over an aperture of 1–3 km; 43 are now certified (www.CTBTO.org/map). While

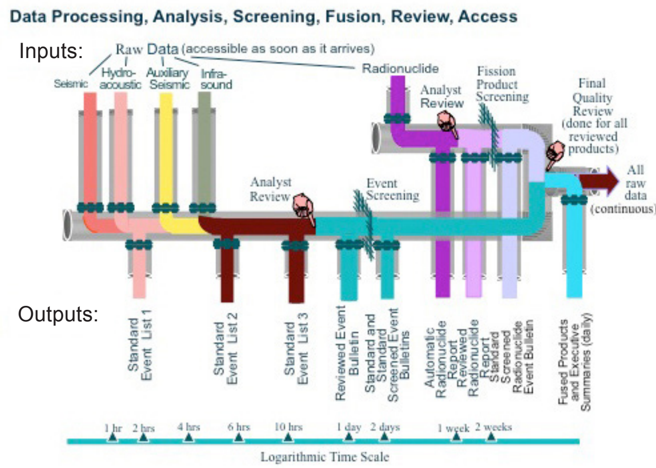

FIGURE 2.3.
Schematic of data processing and analysis of IMS data at the IDC, showing the approximate timeline applicable after entry into force of the Treaty. Source: CTBTO.

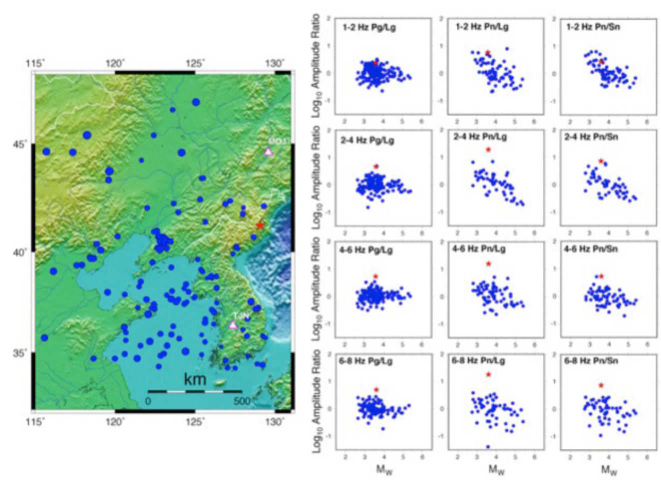

FIGURE 2.4.
The map shows earthquakes (blue circles) and the 9 October 2006 DPRK announced nuclear test (red asterisk) observed at seismic stations MDJ and TJN. The scatter plots show the MDAC path-corrected *P*/*S* ratios at each station (average when both available) for three different *P*/*S* ratios in four different frequency bands. Source: "Regional Seismic Amplitude Modelling and Tomography for Earthquake-Explosion Discrimination". Walter, W.R., M.E. Pasyanos, E. Matzel, R. Gök, J.J. Sweeney, S.R. Ford, and A.J. Rodgers, Monitoring Research Review, National Nuclear Security Administration, Department of Energy, USA (2008).

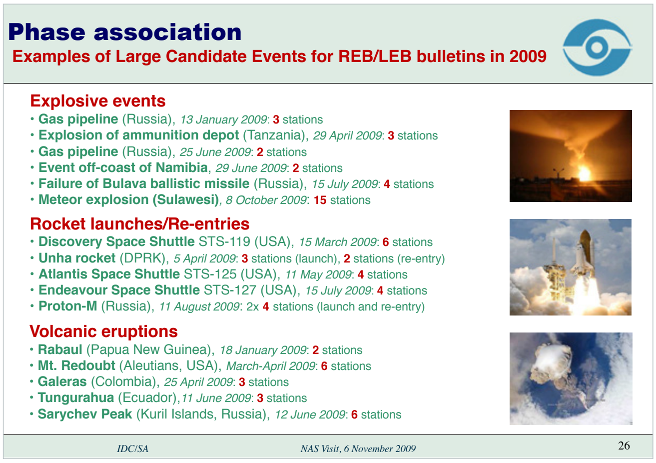

FIGURE 2.5.
Examples of sources recorded by the IMS infrasound network. Source: CTBTO.

» In general, the product of the IDC, supplemented by the national technical means of the Member States, provides a sound basis for the request for an on-site inspection of a designated area not to exceed 1,000 square kilometres in area. If such an inspection were to take place in the vicinity of an actual underground nuclear explosion test, I have little doubt that local detection of radionuclides and active seismological studies would provide hard evidence of such a test.

RICHARD L. GARWIN

awaiting signals from an atmospheric nuclear test, the infrasound system routinely detects quarry blasts, bolides, and industrial accidents as shown in this slide [FIGURE 2.5].

With no time to discuss this fascinating field in more detail, I provide here [FIGURE 2.6] a map of the sensitivity of the infrasound array to an assumed surface-burst nuclear explosion, on a particular day. Because of the thermal structure of the atmosphere and the winds aloft vary with season and with time, the detection threshold varies substantially, but is amenable to calculation as shown on the following slides [FIGURE 2.6].

The result of all of this work, both operational and developmental, with great contributions by the scientific community, is the timeline of the products of the IDC, as indicated, although I have slighted the hydroacoustic detection and the radionuclide detection network.

In general, the product of the IDC, supplemented by the national technical means of the Member States, provides a sound basis for the request for an on-site inspection of a designated area not to exceed 1,000 square kilometres in area.

If such an inspection were to take place in the vicinity of an actual underground nuclear explosion test, I have little doubt that local detection of radionuclides and active seismological studies would provide hard evidence of such a test.

POTENTIAL IMPROVEMENTS TO THE IMS AND IDC

Equally interesting science and technology underlie the three non-seismic modalities of the IMS, and much information can be deduced about these.

Furthermore, the detection and location by one modality permits the generation of a synthetic signal (for instance an explosion detected by seismic means can be taken as the source of an infrasound wave, and comparison with observed infrasound signals can augment or negate what might be a false inference in the seismic domain.)

Aside from organizational strictures, budgets, and the like, in any technical organization there is the opportunity for improvement, and that improvement can include the possibility of major reduction of effort to perform some of the existing tasks. Even so, there must be appropriate balance between initiative and approval, in order that the amount of effort devoted to automation and cost reduction be balanced against the potential improvement. Furthermore, there are no doubt competitive ideas and individuals, and again, these must be selected with good taste and judgement.

The National Data Centres [NDCs] and independent research groups perform a substantial amount of investigation into improved and more efficient technique. So exactly where these innovations originate and are tested and are provisionally deployed is an important question that I will not take up here. What might these innovations be?

1. Automation via artificial intelligence or machine learning to maintain or improve performance standards and to reduce cost.
2. Converting noise into signal in order better to discriminate amongst signals.
3. Routine incorporation of additional data into IMS processing.

I will take an example of the first two.

(1.) The digital records of the IDC provide fertile soil for work in automated 'phase' picking

(2.) In many fields of signal processing, it is desirable to emphasize the signal (for instance, from one location), while discriminating against noise. A common approach is a beamformer, and that is what is done with the individual arrays that are elements of the IMS seismic subsystem. Forming an array either in real time or later from the digital records of the individual seismometers can enhance signals (and noise) coming from a particular azimuth (more precisely, a given azimuth and dip angle). The 'array gain' is just the number of seismometers involved, if they are far enough apart to constitute independent antenna elements—a half wavelength or more.

However, a strong earthquake far off the centre of the angular beam thus formed, can leak into the side lobes of the array. But more can be done with those same seismometers in the local array, and the first step is to form an array to view the irrelevant earthquake, then to determine those array delays and coefficients, to be subtracted from the array focused on a target in the desired direction. This "sets a null" in the direction of the interfering earthquake, although the process is less effective than in the analogous electromagnetic case, with only a single velocity of propagation.

An even more sophisticated tool that can discriminate not only against earthquakes from other directions but from an earthquake source within the angular beam of the array is to form a virtual network. This provides not only the gain of a single array of seismometers near a single station, but forms a network of multiple arrays from quite different locations, with their signals time shifted so as to align at the location of interest. In this time shifting, one is greatly aided by the large numbers of small earthquake that are observed over the years, that calibrate

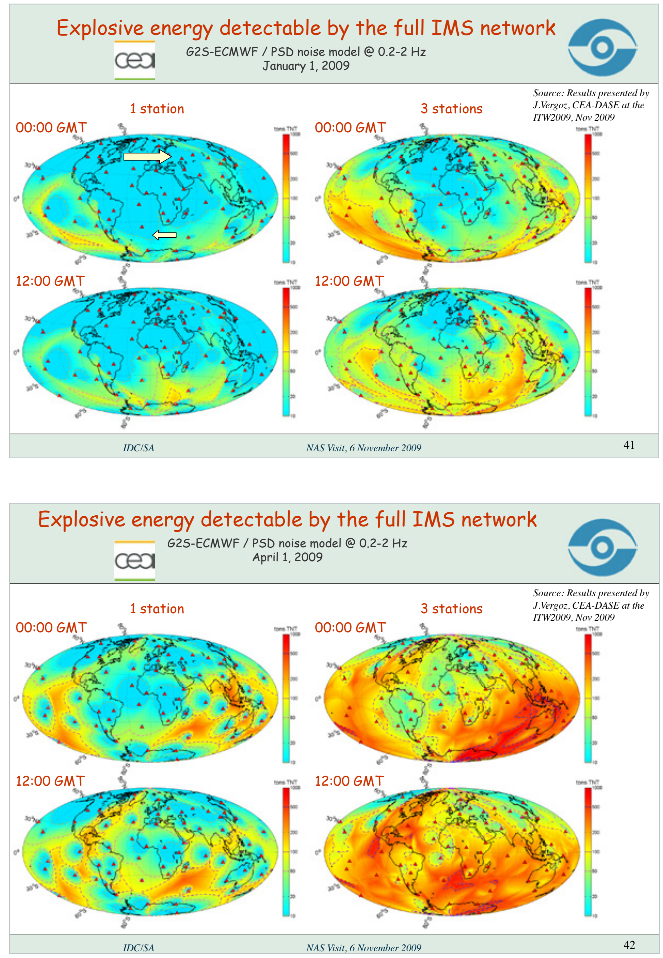

FIGURE 2.6.
Explosive energy detectable by one or three station(s) from the full IMS infrasound network on two specific days, 1 January and 1 April 2009, and at two different times, using station noise and G2S-ECMWF atmospheric specifications. Source: J. Vergoz, CEA-DASE; presented at the CTBTO Infrasound Technical Workshop 2009.

precisely the travel time from almost any location on Earth to an individual seismometer. The variation of seismic signals with azimuth and dip normally prevents the use of waveform coherence in different directions, limiting the network performance to 'incoherent' rather than coherent processing.

The virtual network does not require that from minute-to-minute the weight of the individual arrays remain constant in the virtual array. In particular, if there is a distant large earthquake on the same azimuth as the location of interest at array A (but likely at quite different range), then array A can be deleted (i.e., given zero weight) during the period of strong interference, and the other arrays used to

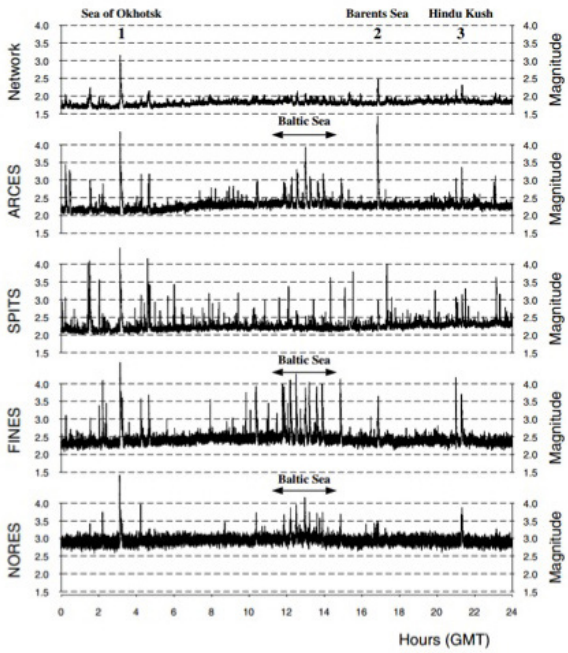

FIGURE 2.7.
Example of 'smart network' site-specific threshold monitoring for seismic events from Novaya Zemlya for 24 hours on 9 February 1998.
Source: Kværna, T., F. Ringdal, J. Schweitzer, and L. Taylor (2002). Optimized Seismic Threshold Monitoring–Part 1: Regional Processing, Pure Applied Geophysics, **159**, 969-987 (2002).

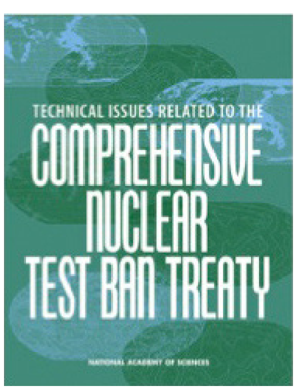

FIGURE 2.8
USA National Academy of Sciences Report: "Technical Issues Related to the Comprehensive Nuclear Test Ban Treaty" (2002).

form the virtual array—a 'smart network'. The Figure [FIGURE 2.7] shows the multiple traces of just such an experimental smart network. In the example (first panel in the Figure) the array detection threshold dropped from magnitude 3.0 or more for the static virtual array to magnitude 2.0 for the dynamic smart network.

Of course, with a vitally important system in continuous production of crucial data, it is essential to be able to operate proposed and purportedly tested improvements in parallel with the existing business practice, in order to make a considered judgement as to when 'improvement' can responsibly be made.

EPILOGUE

I was one of the authors of the 2002 report of the US National Academies of Science, Technical Issues Related to the Comprehensive Nuclear Test Ban Treaty[20]. Incidentally, from June 2, 2011 almost all 4000 reports and books of The National Academies Press can now be downloaded free from www.nap.edu.

The body of the 2002 Report contains three chapters,

1. Stockpile Stewardship Considerations: Safety and Reliability Under a CTBT
2. CTBT Monitoring Capability
3. Potential Impact of Clandestine Foreign Testing: US Security Interests and Concerns.

Although only the second is related to the CTBTO, and the remainder is very US-centric, I commend the report to your attention.

An update to this report has been prepared by a group assembled by the National Academies of Science, which has not been published in time for this meeting. I hope that it will soon be available at www.nap.edu, providing an assessment that takes into account an additional decade of stockpile stewardship without nuclear explosion tests, and the demonstrated capability of the International Monitoring System and the International Data Centre of the CTBTO. [The report has since been made available at www.nap.edu.]

2.2

DAVID STRANGWAY: EARTH AND LUNAR SCIENCE: INTERACTION BETWEEN BASIC SCIENCE AND PUBLIC NEED

Earth and Lunar Science: Interaction Between Basic Science and Public Need

David Strangway, PhD, FRSC, DC
President Emeritus, University of British Columbia and Canada Foundation for Innovation

I am honoured to be one of the keynote speakers at this Science Forum of the CTBTO. This is an organization that has not only done remarkable work on the issue of nuclear detection, but through global monitoring has made major contributions to our understanding of earth system science. As was noted in my introduction, I have been active over a long career in several aspects of earth science. These range from developing techniques for mineral exploration for mining companies, to work on returned lunar samples, to working on meteorites to determine the nature of the magnetic field that was present during the formation of the solar system. The thesis that I have chosen to pursue today is the remarkable interactions between basic science, applied science and innovation. The process of innovation is typically described in the literature as a simple linear process in which the track is from basic science, to applied science, to innovation, to applications and to adoption. Somewhere along the way, this is supposed to lead to the creation of intellectual property. Eventually the process leads to spin off companies and in a few cases to widespread adoption. If only it were so simple, it would be easy to identify and support the various parts of this linear sequence. I want to talk today, about what seems to be a more appropriate way to describe the interactions between these so-called discrete steps. The basis for innovation is much more integrated, as can be seen by the incredible revolutions that have taken place over the past two centuries. Much of today's economic and social activity can be traced to the new physics of the 1920s, as wave after wave of new impacts have affected our world. It has been estimated that some 50% of today's Gross Domestic Product in the United States has its roots in this revolution. And this is just as true in earth system science, as in any other field, as CTBTO knows better than any other agency.

A recent book on innovation by Steven Johnson describes the process of discovery and innovation in a very interesting way. The book is called "Where Good Ideas Come From—The Natural History of Innovation". He describes the process of scientific and technological development as a form of evolution and draws extensively on Charles Darwin. The first chapter is "Reef, City, Web". The last chapter is "The Fourth Quadrant". In the first chapter he compares the extensive and diverse interdependent life that accumulates and develops around marine reefs. He compares this to the vibrant life that develops on so many fronts in the dynamic cities of the world. He compares these hubs of interacting complexity to the development of the web, that has linked so many parts of the world together to create new ideas. In the last chapter, he gives a list of innovations from the last two centuries, that show the move from individual innovation to networked innovation. Sometimes I say we have moved from the Renaissance Man to the Renaissance Team with both men and women. He then further separates the list of innovations into market- and non-market driven to show the fourth quadrant. The rise of networks and complexity is key to his book. It is in this sense that he sees the analogy to evolution in which networking and communication are the drivers. The overarching theme is that interaction and communication between so many different threads of research and practice lead to innovation.

Turning now to earth science, let me describe briefly a few interactive events. The early development of the airborne magnetometer is a case in point. The airborne flux gate magnetometer was known and developed in the 1930s by Gulf Oil, that patented the device for their exploration purposes. It was soon realized that this particular airborne system could also be used for submarine detection. The patent was turned over to the US Navy. They in turn contracted the manufacture of the device to Texas Instruments.

Texas Instruments was itself already a spin-off of a seismic exploration company. The link between the private sector need and government procurement to meet a government need is evident. After the war, the instrument became available. The Canadian government, facing the prospect of mapping a very large land mass, decided to start aeromagnetic mapping of much of the Canadian shield. This they did by contracting the work out to private companies. But they still faced the problem of patent infringement. An enterprising civil servant found a modification that got them around the patent and they were in business. Here again, we see the complex interaction between technology development, meeting government needs and the creation of a private industry to meet the need through smart procurement. Much of Canada has now been mapped in this way and indeed so has much of the rest of the world. The Canadian mapping proved immensely useful in direct prospecting for iron ore deposits and a number of them were discovered. But of much greater significance, it turned out to be a truly important geological mapping tool, that set the framework for detailed ground mapping by filling in between outcrops. I was fortunate at the time to be working for a mining company and was able to compile these maps to outline the most incredible series of dike swarms. These could be traced for thousands of kilometres across the shield. This provided a fascinating insight into the tectonics of the Canadian shield.

The point I want to extract from this story, is one that comes again and again in the sciences and is relevant for this meeting with its focus on the earth sciences. Which came first, The technology of the fluxgate? The military need to detect submarines? The geologic need for mapping huge areas quickly and efficiently? The answer is all of them. As Steven Johnson points out in his first chapter Reef, City and Web, the reefs and the cities are places of intense interactions. The reef teems with life and now the web connects the world. And as we will see later, the magnetometer again played a very important role in the plate tectonics revolution.

I was fortunate, during the time I worked in the mining industry, that I was able to carry out a great deal of work on new electromagnetic techniques for mapping and searching for conducting orebodies. I was able to use artificial transmitters as well as the natural sources of audio frequencies provided by nature. Thunderstorm energy is trapped in the earth ionosphere wave guide and the electromagnetic impulses can be detected around the world.

I will turn now to what I call the planetary revolution. You will have heard in the introduction, that I was privileged to be Chief of Geophysics and of the Earth and Planetary Science Division in Houston for NASA during the Apollo lunar missions. As you can imagine, this was a very exciting time as the first full scale exploration of another planetary body was carried out. It is important to remember that the decision to land a man on the moon had nothing to do with studying an adjacent planetary body. The decision to go to the moon was not based on the need to do science. Instead the objective of the Apollo missions was to demonstrate that the United States had technical superiority and could successfully carry out such a complex technological feat. This was, in its day, an expensive mission. How many times were we asked whether landing on the moon meant that other important things were not done? My answer was to point out that the money was not deposited in a bank on the moon. It was largely spent on people and the money spent went into banks right here at home. It has always been my view, that we the scientific community, were extremely privileged to be able to participate in this exploration and to be funded to do so as a small part of the Apollo missions. Again, technology was developed to meet a very specific public need as defined by government. From this technological development flowed remarkable scientific breakthroughs. This is a reversal of the traditional linear chain model that leads from basic science to applied science to innovation.

The earth scientists had finally taken over the moon from the astronomers. We could now do actual surface experiments and work on returned lunar samples. Many experiments were carried out. Five stations were established on the surface that monitored a number of phenomena. There was at one time a network of five seismometers working simultaneously, admittedly on the front face of the moon and largely in the equatorial plane. Because the moon is so dry, seismic waves do not attenuate much and travel long distances. We were fortunate, for example, to have some meteorite hits on the far side of the moon and to detect them at all five stations on the front side. This told us that if there was any core at all, that it must be too small to be detectable with this array. There were magnetometers on board, but the moon has no overall magnetic field. The magnetometers largely detected fluctuations in the solar wind fields. These fluctuations could have caused electromagnetic induction in the moon, if it had been warm and electrically conducting. But again there was no sign of a hot core.

There were a number of surface geophysical experiments. Holes were drilled a few metres into the soil and then used to determine the heat flow. A very insulating, powdered soil in a perfect vacuum made an almost perfect thermal blanket. The wide surface temperature variations from day to night hardly penetrated. This confirmed the earth based mapping of thermal emissions in the infrared and microwave frequency ranges. There were shallow seismic refraction profiles carried out. There were lots of signals bouncing around due to the very low absorption characteristics of the dry soil, and the highly fractured subsurface. There were no coherent reflectors. I was fortunate that on Apollo 17 I was able to send an electromagnetic sounding experiment. This was of course quite different than my earlier experience on the earth, since the moon, like ice is quite transparent to radio waves. A transmitter was placed near the lunar module and the receiver was mounted on the Rover. Signals clearly penetrated to a depth of over one kilometre, but again there were no reflectors. There was a lot of scattering from the crushed near-surface material, especially at the higher frequencies. We were able to determine the electrical properties of the surface. This experiment followed my experience earlier in mining exploration, where electromagnetic sounding had reached a highly developed level. The earth based testing for the lunar work was done on glaciers. The glaciers were good analogues since ice is highly transparent to radio waves. This in turn formed the basis for later developments in Ground Penetrating Radar, now widely used.

The orbiting spacecraft had minor variations in velocity, that were detected and measured with the result that significant gravity anomalies could be mapped. And with laser and radar altimeters there could be robust interpretations. These became even more detectable along with local magnetic signals when subsatellites were left behind in low orbit.

Perhaps most importantly, through much work on the returned lunar samples it was possible to determine much of the evolutionary history of another planetary body. The lunar highlands had been intensely fractured by bombardments from the earliest days of the solar system, formed 4.6 billion years ago. This early bombardment by meteorites slowed down about 4 billion years ago. Subsequently, there was some limited volcanic activity, that filled some of the mare basins on the front side of the moon from about 3.8 billion years to about 3.3 billion years. And then even these lava flows ended. Following my own earlier work on terrestrial samples, we were able to measure the presence of a small field that had existed in the early stages of the moon's history. This small field is likely related to the field that was present during the accretion of the solar system.

The moon is in a perfect vacuum. This means that it was possible to do a considerable amount of geochemical mapping from orbit. This included X-ray spectrometer mapping as well as Gamma Ray spectrometer mapping and alpha particle detection. Since the lunar surface is under steady bombardment from solar particles, there is steady emission of secondary X-rays. This emission could be detected at orbit levels and so geochemical maps of elements such as aluminium, magnesium, silicon and others such as oxygen, iron, sodium, potassium and calcium could be made. From the gamma ray spectrometer, it was possible to map the distribution of uranium, thorium and potassium, as well as some elements activated by cosmic rays. The alpha particle spectrometer detected radon and polonium.

It seems to me, that this is a case in which a major undertaking to meet a national goal led to immense technological capacities to go and come from the moon. As a result the science of the moon and planets was taken to a new and revolutionary level. This has led on to learning more and more about the other planets and satellites as well as about comets and asteroids. There is little doubt that this new understanding of the origin and evolution of the moon was the basis for a revolution in Earth and planetary science.

Now let us turn to the other scientific revolution. Plate tectonics. Once again this new approach to earth system science has many parents. Sea floor mapping was one of the keys. And much of this was financed by several agencies, in particular the US Navy. This demand by the Navy, stemmed from many needs including how to hide submarines in the ocean. Systematic mapping of the magnetic anomalies of the sea floor was one of the critical needs. Fortunately again, the scientific community was given the opportunity to study these records for their intrinsic scientific value. This was at the very time that regular reversals of the earth's magnetic field had been widely recognized and documented. It was an important conceptual step to make the link between the time sequence of reversals and the recognition that this could be closely correlated to distance from the mid-ocean ridges. Suddenly, the translation from distance from the mid-ocean ridge to being a measure of the time since the upwelling of the ridge became obvious. It is interesting that the first paper to make this link was rejected by the journal Nature. It was by the same person who many years earlier had initiated the use of aeromagnetic mapping of the continents. People at the CTBTO will know better than anyone about the major investments made in an attempt to do earthquake prediction. It was at least in part, because of this need that the idea of the global seismic network was started. And of course there was the need to detect nuclear explosions that might be set off clandestinely. This massive investment in the worldwide network, was a key to the Plate Tectonics revolution. It was now possible to systematically map earthquake distribution around the globe. This clearly identified the mid-ocean ridge spreading centres in spectacular fashion and the nature of the activity at colliding plate boundaries. These maps and the nature of the various types of earthquakes have been integral to the plate tectonics revolution. Massive investments to meet well determined needs for military purposes and human security needs have been one of the key planks in the evolution of earth system science. Basic science has benefited from the need to solve problems and from the advances in technology driven by global monitoring by CTBTO.

The links I have been describing go far beyond the earth sciences. Much of our modern world is the beneficiary of the many interactions between applications and need-driven efforts. New technologies may derive from basic science, but cutting edge science also derives from the opportunities provided by new technologies. Yes, scientific breakthroughs and revolutions do not arise from the linear chain as is so often depicted.

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DAVID STRANGWAY

Now I want to turn my attention for a few minutes to some of the thinking that might drive the next steps in on-site inspection. It is interesting to contemplate that seeking ground truth of nuclear underground explosions has some comparisons to the search for ore bodies or to the search for suitable disposal sites for nuclear and other wastes. Kimberlite pipes are where diamonds are found. The diamond explorer is always searching for ways to detect the presence of these pipes. The scale of these pipes is comparable to the signature left by a nuclear explosion and would be good test sites. In the sedimentary basins of Western Canada, there are a number of buried palaeocraters or astroblemes as they are called, resulting from meteorite impacts hundreds of millions of years ago. These are detected from time to time during seismic reflection exploration. These would also be interesting test sites. There are a number of geophysical techniques that are in widespread use, which are clearly adaptable to the search for nuclear explosion sites. These are both airborne and ground based.

Magnetic mapping can be done from ground based surveys and from airborne surveys. The signature of material that has been heated above 580°C, the Curie point of magnetite, the predominant magnetic mineral, is likely to be distinctive. Just as it is, in the case of explosively implanted kimberlite pipes which also became magnetized as they cooled. Magnetic mapping is one of the major methods that has been used to detect often hidden kimberlite pipes. This has largely been done using airborne magnetometers, using fixed wing or helicopter borne aircraft. We are of course today, all aware of the use of manned drones for surveillance. But a whole new generation of small, unmanned aircraft are now in use. These are both fixed wing aircraft and helicopters that can readily carry magnetometers and other devices and follow a predetermined track, as they conduct very low level surveys, just above the ground. Tracking by use of GPS provides accurate locations. Magnetometers can be mounted on all terrain vehicles or towed behind them.

There are other approaches that can be taken. In the past few years, it has become possible to conduct gravity mapping on aircraft and it is only a matter of time, before the weight of these devices will be suitable for unmanned aircraft. The use of GPS and laser ranging to provide the topographic information needed to interpret gravity data is readily at hand. This approach will help greatly in detecting underground cavities for example.

There is a wide range of electromagnetic sounding techniques in common use. These are typically used for detecting electrically conducting parts of the shallow crust. In this case, a source of audiofrequency energy is transmitted from a transmitter and received by a receiver looking for the induction due to eddy currents. Again ground based and aircraft based systems are in common use. Changes in the electrical structure resulting from an underground explosion could be detected in this way. Another electrical technique in common use is the induced polarization technique. In this case not only is the electrical conductivity measured, but the polarization associated with disseminated metals or clay particles in the subsurface is mapped. It seems possible that a nuclear underground explosion will disturb the natural polarization and might thus be detected.

Ground Penetrating Radar systems could also be deployed and can be rapidly and efficiently used. GPR does not penetrate very far in the presence of near-surface conducting material such as many clay deposits. In many terrains it can usefully be employed for shallow mapping and detecting subsurface disturbances. These can easily be mounted on surface vehicles.

There are of course many other approaches including shallow seismic mapping. And it may be that the use of infrared thermal mapping could be useful. A great deal of work has been done to search for the thermal signature of oxidizing ore bodies, by over flights at the earliest hours of the morning when the effect of the sun is at its lowest point. This could be supplemented by microwave thermal emission studies that are less sensitive to the very surface temperature and provide an average of the top few metres. And of course synthetic aperture radar together with emission data is a powerful combination. Perhaps there will be disturbance in the thermal properties that can be actively exploited.

And finally there is gamma ray spectrometry which is widely used for mapping of naturally radioactive minerals in the mineral exploration field, as well as in geological mapping.

And now I conclude. My principal point is that innovation is a process that involves many different ideas and participants. It knows no discipline boundaries and can come from unexpected and unpredicted directions. Sometimes it is driven by basic research, but just as often it is driven by specific needs to solve problems. Often innovation comes from national or international demands. And that activity in return is often the source of breakthroughs in basic science. No one knows this better that than the CTBTO. The work of nuclear detection has in one sense derived from basic science, but the CTBTO has played an enormous role in the development of earth system science. Yes, indeed we live in an interconnected world, in which innovation is a form of evolution. No doubt we will hear a lot about this in the next two days.

3

Data Acquisition

INTRODUCTION

The acquisition of appropriate, reliable and high-quality data is arguably the most important stage in any monitoring exercise. Sophisticated data processing methods may be applied *post hoc* in attempts to extract useful information, but if the required signals are not contained within the raw data, they can never be recreated. Moreover, while data processing can be repeated at leisure, and new processing methods tested on the data at any time, there is no possibility of recording missed observations once the moment has passed. Of course, this applies equally to data recorded by the IMS, and to data recorded in the course of an OSI.

CTBTO gathers data from the global IMS network of seismic, hydroacoustic, infrasound and radionuclide detectors. After the Treaty enters into force, a diverse but very specific set of approved methods[21] may be used to acquire data during an OSI from the Inspection Area of no more than 1,000 km^2 [22]. Of course, States Signatories or other entities are at liberty to also use any other monitoring methods consistent with international law, perhaps using satellites. Following from the Treaty's Article IV paragraph 118, referred to in **SECTION 1.2**, it is possible that additional methods may be considered for incorporation into the CTBT verification mandate sometime in the future, after entry into force.

This Section covers contributions on sensor technology, the design and configuration of sensor arrays and networks, and the associated ancillary equipment required to digitize and record the data collected. Data acquisition includes measurements performed on samples, and measurement methods at radionuclide laboratories are thus included. Methods to reduce noise at the point of data collection constitute an important design criterion for sensors and sensor configuration for any data type. Contributions on this are included here, while contributions on the measurement of background signals/noise and their effect on network detection thresholds are considered in **SECTION 8**.

Contributions on the establishment and improvement of IMS stations and laboratories (which are together referred to conventionally as IMS facilities) are included, together with contributions on the establishment of non-IMS stations and station networks. (The establishment of NDCs is considered in **SECTION 9**.)

Although some relevant data acquisition methods are not represented (for example gravimetry and magnetometry, both permitted under OSI), any contributions on the processing or interpretation of data from such technologies are considered as appropriate in later Sections.

3.1
SENSORS AND MEASUREMENTS

3.1.1
SEISMIC

Technology tends to move forward in a series of small refinements, interspersed with major changes in concept. Probably the largest conceptual advance in seismometry during the last few decades has been the emergence of broadband feedback seismometers which can record movement in a single data stream across a wide range of frequencies. A hint of perhaps another major advance comes with several presentations on sensors whose output is recorded optically. *Berger and Zumberge* (**T3-O5**) present a seismometer whose signal is registered as fringes generated by an optical interferometer. This promises several major advantages over existing seismometers, including superior dynamic range and absolute measurement of displacement. The absence of electronics in the sensor package is said to offer several benefits for borehole emplacement, and the response is governed only by three parameters that can be easily measured, simplifying calibration.

A miniaturized version of an optical seismometer, which might find use in OSI applications, is presented by *Garcia* (**T3-P42**). Miniaturization is achieved using an interferometer comprising a vertical cavity surface emitting laser (VCSEL) and diffraction grating. The device is packaged as a geophone with a two-gramme tungsten moving mass, and provides an output that is flat to acceleration.

Although the design of seismic detectors has a long history, with major advances achieved during recent years, several developments are nevertheless presented. A broad-band force-feedback seismometer for recording teleseismic signals is described by *Matcievsky et al.* (**T3-P11**), with a response flat to velocity from 15 Hz to 360 seconds, or optionally 600 seconds. A two-dimensional tilt meter with a sensitivity of 10^{-4} arc seconds is also presented (*Matcievsky et al.,* **T3-P10**); this could potentially find use for soil deformation studies in the OSI context, but was still at an early stage of testing.

An important property of a seismometer is its self noise, being noise generated within the detection system as opposed to external seismic noise. The self noise is important because it determines the ultimate detection limit at each frequency in an ultimate low-noise environment, but it is difficult to measure because externally-generated seismic noise is omnipresent. *Rademacher et al.* (**T3-P4**) present tests of a method to measure self noise using identical adjacent seismometers configured in various ways to maximise the similarity of external seismic noise, which can then be subtracted. This 'three sensors side-by-side' method is being widely used in seismic instrumentation for self noise estimation. It has been shown that effective insulation of sensors to minimise the effect of external atmospheric temperature and pressure variations on the components of the suspended mass is essential for proper evaluation of self noise.

The IMS is a major user of borehole seismometers, which have special requirements in the development cycle, not only in relation to their design but also in relation to installation methods. For example, improved hole-locking devices are needed, as well as reduced sensitivity of the sensor to thermal convection in the borehole. Special attention also has to be paid to the evaluation of the self noise of borehole seismometers, because special methods of installation are required if the side-by-side technique reported above is to be used.

Most seismic stations designed for regional or global seismology consist either of a single site recording the three orthogonal components of ground motion, or a seismic array comprising vertical-component seismometers. (A seismic array is usually accompanied by at least one three-component site, not used in the array processing.) *Gibbons et al.* (**T4-O5**) argue that all sites at small- and medium-aperture arrays should be equipped with three-component seismometers, to achieve improvements in the signal-to-noise ratio of secondary phases as demonstrated in their contribution. Such a development would be especially relevant to the reliable detection of small signals using a sparse network such as that of the IMS.

3.1.2
HYDROACOUSTIC

No contributions focus explicitly on the IMS hydroacoustic detectors. The presentation by *André et al.* on the Listening to the Deep Ocean Environment (LIDO) initiative (**T3-O1**) describes plans to establish a seafloor observatory and in-water detection systems whose purpose includes recording seismic and hydroacoustic data in support of tsunami warning. Although the project is focused on the Mediterranean and neighbouring Atlantic waters, the detection technology has general applicability. It could potentially contribute as a source of 'data of opportunity', and could also provide useful information on modular station design.

3.1.3
INFRASOUND

A novel approach to the detection of infrasound waves, with some design features similar to those of the optical seismometers referred to in **SECTION 3.1.1**, is reported by *Zumberge et al.* (**T3-07**). By shining a laser through a pair of optical fibres helically wound on a linear compliant tube, the change in diameter resulting from the passage of infrasound can be measured by optical laser interferometry. This type of detector, which is still in the development stage, is referred to as an optical fibre infrasound sensor (OFIS), and is said to offer a number of advantages including superior wind-noise reduction and azimuth resolution, improved linearity over a wide dynamic range, and improved high-frequency response.

3.1.4
SEISMIC, HYDROACOUSTIC AND INFRA SOUND AS A GROUP

It is customary to assume a one-to-one correspondence between sensor type and the type of signal to be recorded, in which seismic sensors record seismic waves, infrasound sensors record acoustic waves in the atmosphere, and hydrophones and *T*-phase stations record acoustic waves in the oceans, including both *T* phases and *H* phases. Experience in the IMS has revealed that this is an overly narrow view. IMS infrasound arrays, as well as IMS hydrophones, have been shown to record seismic signals through coupling at the sensor location. *T*-phase stations, being seismometers, naturally record any seismic signal. Moreover, there is a further cross-cutting as a result of the partitioning of seismoacoustic energy between the ocean, atmosphere and solid earth, with the generation of infrasound from earthquakes being an obvious example. The net result is an enhanced role for all types of IMS seismoacoustic station.

This theme is taken up by *Okal* (**T1-03**), who presents a range of examples in which natural phenomena are recorded on sensors not designed to register them. Examples illustrated include tsunamis recorded not only by hydrophones, but also by infrasound arrays, magnetometers, long period seismometers, ocean bottom seismometers and seismometers located on floating ice. The author also points out that a tsunami must couple to the atmosphere, where it can be detected via ionospheric perturbations. *Poplavskiy and Le Bras* (**T3-P40**) show that variations in strain field caused by the passage of a tsunami can be recorded by the seismometers of IMS *T*-phase stations, which are installed on islands and in the coastal regions of land masses. The possibility of using *T* phases recorded on ocean-bottom seismometers to detect and locate small seismic events that would otherwise remain undetected is considered by *Tsuboi et al.*, (**T3-P3**), using observations made on ocean-bottom seismometers of the Dense Ocean-floor Network System for Earthquakes and Tsunamis (DONET), shown in **FIGURE 3.1**.

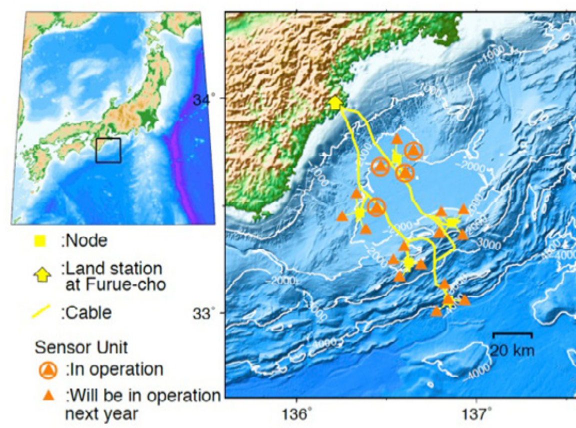


FIGURE 3.1
Status of DONET, offshore Japan, in May 2011.
From *Tsuboi, Nakamura et al.* (**T3-P3**).

3.1.5
RADIONUCLIDE

Improvements to the radionuclide particulate collection system used at IMS stations are suggested by *Toivonen* (**T2-03**). Proposals include the replacement of the current large-area filter with a 'pancake' system of small filters that can be stacked, allowing advanced nondestructive assay (NDA) analyses in which the filter sample is neither physically nor chemically altered. Alpha and beta gated gamma spectroscopy is also suggested, as used in the Finland national air sampling network. *Toivonen* also points out that electrostatic samplers are available which use oppositely charged collector plates, removing the need for a filter; the author recommends this as a research priority, with the overall goal to improve sensitivity via increased air volume and more compact sample measurement geometry. Also suggested in the same contribution are further steps to reduce signals from natural radioactivity, in addition to the standard precautions of choosing a low-background measurement site and using lead shielding with a cosmic-ray veto detector above the sample.

The reduction of cosmic-ray-associated background radiation in a gamma-ray detector by lead shielding is limited because adding such shielding increases cosmic secondary reactions in the neighbourhood of the detector. *Burnett and Davies* (**T3-P29**) report on the use of plastic scintillation plates surrounding the lead shielding that operate in anticoincidence with the germanium detector used to measure the sample. A reduction in the detector background of a factor of up to four may be achieved for such a cosmic veto device, reducing the count time required to achieve the specified minimum detectable concentration (MDC).

Methods to improve the sensitivity of the IMS radionuclide particulate network are also proposed by *Nikkinen et al.* (**T3-P36**), including IMS laboratories with detectors constructed of radio-pure materials, operated underground, and with the decay time before measurement extended from one to seven days. Tests using the Collaboration of European Low-Level Underground Laboratories (CELLAR) are reported, with systems shielded by earth and stone of thickness equivalent to thousands of metres of water.

The radionuclide laboratories of the IMS perform laboratory re-analysis of radionuclide samples in which significant Treaty-relevant radionuclides are detected. The desirability of reducing background by placing such laboratories in modest underground facilities at about 30 metres water-equivalent depth is discussed by *Forrester et al.* (**T3-08**) in the context of the upgrade of the IMS radionuclide laboratory RL16 (USL16) (**FIGURE 3.2**). Their reported measurements and projections lead them to estimate that a modest underground location and an anti-cosmic veto device can give an order of magnitude improvement in sensitivity for most isotopes.

The beta-gamma detectors currently used to measure xenon samples suffer from a memory effect in which there is residual activity in the detector after measurement, due to diffusion of xenon into the beta detector, which is composed of plastic. This has a negative impact on measurement sensitivity which is currently compensated for by subtracting background counts. This results in elevation of the

FOCUS

The Role of Radioactive Noble Gases in CTBT Verification

It is commonly said that radionuclide observations can provide the 'smoking gun' of a CTBT violation. This follows from the fact that although seismoacoustic methods (seismic, hydroacoustic and infrasound) can offer detection, location and potentially the identification of an event as an explosion, only radionuclide observations can demonstrate unambiguously that an explosion was nuclear. Although there are many radionuclides which can contribute to this identification (83 particulate radionuclides and four radioactive xenon isotopes have been agreed as 'relevant' in this context), those which happen to be gaseous have a much better chance of escaping from the site of a well-contained nuclear explosion conducted underground. Of gaseous radionuclides, those which are noble gases have the additional benefit of not reacting chemically to form non-gaseous compounds during their escape from the site of an underground nuclear test.

Although the Treaty does not specify which noble gases are to be monitored, only xenon offers radioactive isotopes with suitable half-lives and detectability. The Treaty provides that 40 of the 80 IMS noble gas stations be equipped with noble gas detection equipment upon entry into force, and the way is left open for a decision to equip all 80 stations in the future[26]. For OSI, detection systems based on any radioactive noble gas are permitted under the Treaty[27], though apart from the xenon isotopes, only argon-37 is potentially useful. If an underground nuclear test is well-contained, it is possible that very little radioactive material will leak through the surface. The amount may be below the detection limit of IMS stations. In this case an OSI will be the ultimate tool to detect radioactive noble gases at the site. As well as providing for air sampling[28], the Treaty permits drilling to obtain radio-active samples[29] during an OSI.

SnT2011 offered a good opportunity to consider current status of noble gas detection and measurement, and future plans for the technology.

FIGURE 3.2
PNNL underground laboratory facility, housing IMS Radionuclide Laboratory RL16 (USL16). From *Forrester et al.* (**T3-08**).

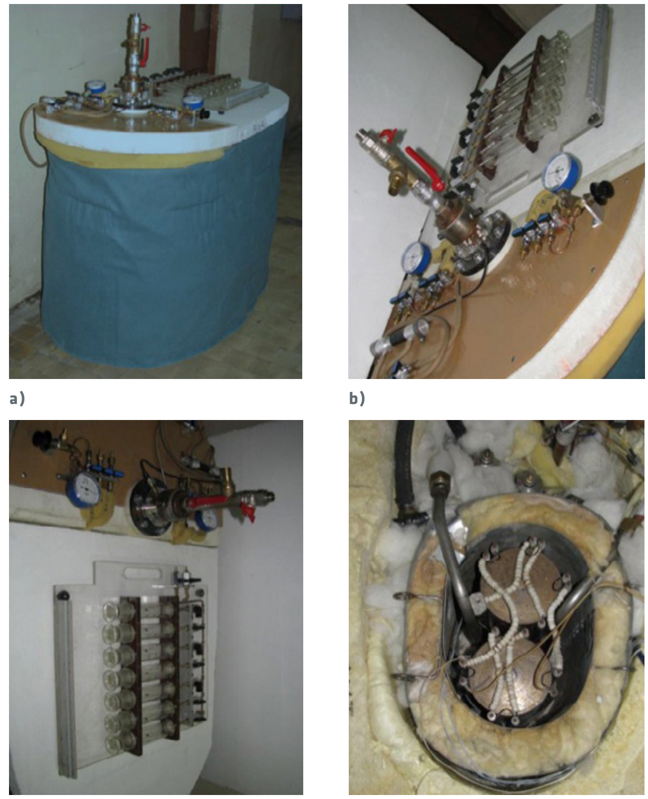
detection threshold and the uncertainty estimate of any measurement. *Toivonen* (**T2-03**) mentions the possibility of investigating the use of silicon dioxide (SiO_2) or aluminium oxide (Al_2O_3) coatings to reduce xenon diffusion. This question is considered by *Bläckberg et al.* (**T3-O11**), who conclude that several coatings tested decrease the memory effect with no degradation of resolution, with Al_2O_3 being the most promising.

Several contributions focus on the special needs of radionuclide sampling for OSI. *Berglund* (**T3-P30**) describes developments of the Swedish Automatic System for Noble Gas Acquisition (SAUNA) II. This is a detection system for radioactive xenon which includes a mobile atmospheric or soil sampling unit for field use, and a container-based portable xenon laboratory developed by the USA Pacific Northwest National Laboratory (PNNL) (**FIGURE 3.3**). This portable xenon laboratory is described more fully by *Stewart et al*. (**T3-P20**); the container includes all necessary infrastructure elements such as power and positioning. *Köble et al.* (**T2-P12**) present a mobile neutron and gamma-ray detection system that can be mounted in a car (station wagon) or small van. A system of natural background rejection is used, taking account of the shape of the complete energy spectrum. A mobile gamma-ray spectrometer which can be installed in an aircraft, helicopter or car is described by *Nikkinen and Kettunen* (**T3-P34**). It utilizes a low-resolution sodium iodide detector together with a high resolution high-purity germanium (HPGe) detector.

FIGURE 3.3
SAUNA II equipment for the acquisition and measurement of radioactive noble gas.
a) Fully automatic system for continuous monitoring.
b) Extended laboratory system for data analysis.
c) and **d)** Container solution for a portable SAUNA laboratory (TXL), developed by PNNL in 2009. From *Berglund* (**T3-P30**).

For OSI, noble gases other than xenon are also relevant. *Toivonen* (**T2-O3**) proposes an argon-37 detector using technology transferred from space applications (in particular on the NASA Messenger mission to Mercury). In addition, he proposes applying novel spectrometry technology for use in an unmanned aircraft (drone) with a real-time link to an operations centre. Mobile equipment for detecting both radioactive xenon and krypton, developed by the State Atomic Energy Corporation ROSATOM, Russian Federation, is described by *Pakhomov and Dubasov* (**T3-P6**). This equipment is self-sufficient in infrastructure and requires no liquid nitrogen; detail is shown in **FIGURE 3.4**. *Purtschert and Riedmann* (**T1-O7**) point out that argon-37 may be useful for global monitoring, as well as in an OSI.

Global monitoring for radioactive xenon has developed rapidly since it was included in the Treaty as part of the IMS. As the network has evolved and experience has been gained, the question of whether the network design is optimal, or conversely deficient, has become a focus of investigation. *Hoffman et al.* (**T3-O14**) report a new assessment of the network design in view of advances since 1998. It should be remembered that although the locations of all IMS stations are specified in the Treaty's Protocol, the decision as to which 40[26] of the 80 radionuclide stations should be equipped to monitor noble gas at entry into force was made by the Preparatory Commission, which therefore has the potential to modify it. This question is covered more fully in **SECTION 8.2.2**.



a) b) c) d)

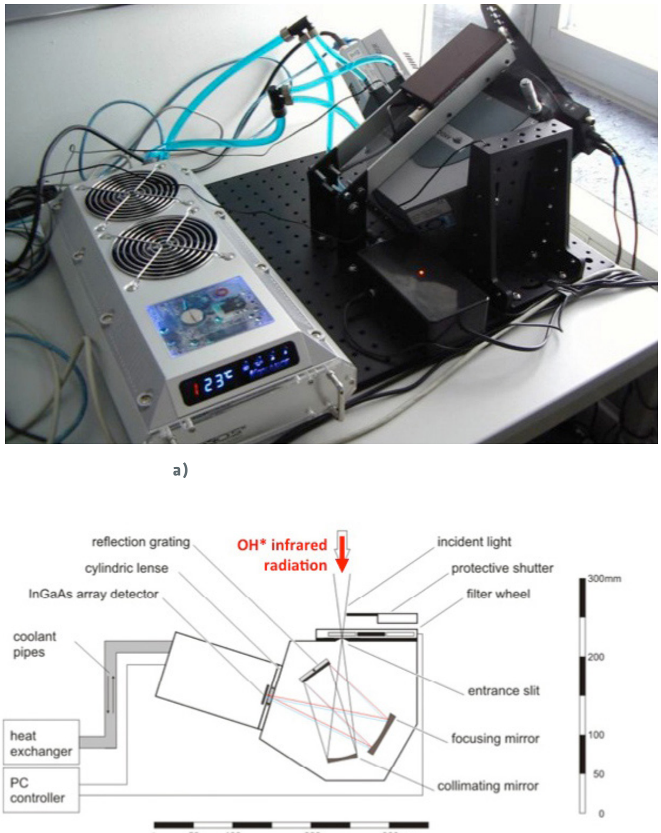
FIGURE 3.4
Detail of improved radioactive noble gas monitoring equipment developed by the State Atomic Energy Corporation, ROSATOM, Russian Federation.
a) new sampling installation, assembled,
b) view showing control systems,
c) block of syringes for krypton and xenon sampling,
d) view beneath top cover showing absorbers in thermoshield.
From *Pakhomov and Dubasov* (**T3-P6**).

3.1.6
SATELLITE-BASED AND OTHER

Surface observations of the vertical gravity gradient represent a well-established geophysical exploration method, offering the possibility of detecting density contrast between different rock types. *Wang et al.* (**T2-P4**) consider the application of this method to the detection of subsurface cavities. As a method permitted[21] during an OSI it would be relevant to the detection of anomalous subsurface structures. However, it must be remembered that a void created by an underground nuclear test conserves mass in the subsurface, and if the associated mass transport is spherically symmetric, potential field theory holds that no gravity anomaly would be observed outside the deformed zone. A practical example of a localized gravity survey is presented by *Martha* (**T1-P5**), who investigates the subsurface origins of the Lusi volcanic mud blast in Indonesia.

Geomagnetic surveying is another geophysical method permitted[21] as part of an OSI. An outline of the application of this method to the detection of underground man-made structures is provided by *Zaoui et al.* (**T4-P20**). *Sagaradze and Rachkova* (**T2-P7**) consider geomagnetic anomalies created by ferromagnetic tubes as part of a vertical drill-hole emplacement scenario. Geomagnetic surveys, together with field resistivity surveys, also permitted[21] under an OSI, are used by *Aregga* (**T1-P12**) to investigate water-level rise of Lake Beseka in the Ethiopian Rift Valley.

Some contributions on novel monitoring methods of potential relevance to CTBT verification focus on remote imagery for OSI, and the measurement of disturbances in the upper atmosphere associated with the passage of infrasound waves. Multispectral



a)

b)

FIGURE 3.5
The Ground-based Infrared P-branch Spectrometer (GRIPS), for detecting infrared airglow. **a)** General view. **b)** Schematic. From *Bittner et al.* (**T3-O13**).

imaging, either from satellite or from the air, offers the potential to differentiate between different surface properties to a much greater extent than observations at a single frequency, and allows surfaces to be characterized by their frequency-dependent reflectance profile. *Henderson et al.* (**T3-O6**) consider the application of this method to OSI, including differentiation between weathered and unweathered rock surfaces. When used together with infrared imaging, small variations in surface or near-surface temperature can be measured; this is offered as a method to narrow down the area of interest in an OSI. In common with other potentially useful methods for OSI, the lack of past data recorded at relevant sites is problematic, and these authors use Landsat imagery of several past nuclear explosion sites to investigate the feasibility of detecting relevant signatures.

The potential for exploiting satellite imagery in the context of OSI is echoed by *Gopalaswamy and Niemeyer* (**T3-P48**), who suggest that such imagery may be useful for preparing activities at the point of entry as well as in the inspection area. Optical and radar imagery are proposed for examining infrastructure changes associated with nuclear test preparation, or surface deformation after such a test. These authors also suggest how satellite imagery could be used as a complement to IMS, by confirming results deduced from IMS data.

Bittner et al. (**T3-O13**) describe a method of detecting infrasound waves at altitudes of around 90 km (the boundary of the mesosphere and the thermosphere, referred to as the mesopause). Pressure perturbations corresponding to the passage of infrasound create a temperature perturbation which can be measured by observing changes in the infrared airglow emitted by hydroxyl ions produced from the interaction of ozone and hydrogen. The authors describe the Ground-based Infrared P-branch Spectrometer (GRIPS) as an instrument used to detect this radiation (**FIGURE 3.5**). Seasonal variations, and those resulting from earth tides, are detected as well as infrasound waves at periods of between 200 and 300 seconds. Instruments are deployed globally at 50 sites as part of the Atmospheric Dynamics Research Infrastructure in Europe (ARISE) project, and the method has also been applied to the German-Indonesian Tsunami Early Warning System (GI-TEWS).

The possibility of detecting electromagnetic disturbances created by the passage of infrasound waves through the ionosphere is considered by *Park et al.* (**T3-P22**), with ionospheric electromagnetic disturbances attributed to the acoustic wave. They point out that a Global Navigation Satellite System (GNSS), of the type used for a Global Positioning System (GPS), can continuously monitor ionospheric behaviour through total electron content, with a temporal resolution of a few seconds or less. As evidence that this method may be useful in CTBT monitoring, they present data recorded at the time of the 25 May 2009 DPRK announced nuclear test.

Another approach to the detection of infrasound waves, exploiting their effect on the ionosphere, is reported by *Sindelarova et al.* (**T1-P9**), who use a Doppler sounding system to measure changes in the height of the ionospheric reflector at 3.59 MHz. Using a network of ground transmitters and receivers in the Czech Republic, signals correlated with severe weather events and geomagnetic storms are presented. Among several novel methods which may potentially be useful in OSI reported by *Ingraham and McIntyre* (T2-P15) is the analysis of micro-fauna or micro-flora which may act as bio-concentrators of radioactive isotopes of medium half lives, which might allow the detection of a recent nuclear test.

Monteith and Whichello (T2-O13) explore potential areas of common interest between CTBTO and the International Atomic Energy Agency (IAEA) in the fields of data acquisition, and research and development. They point out that current overlaps in data acquisition activities include radiation detection, the application of geographic information systems (GIS), environmental sampling and the use of geophysical methods. Among specific IAEA activities mentioned are field-portable mass spectrometry systems, field-portable laser surveying and position-logging equipment, antineutrino detection, remote mapping using multiple sensor types, noble gas monitoring using krypton-85 and xenon, and passive microseismic monitoring (used to monitor activity in an underground waste repository). These technologies may be especially relevant to OSI.

3.2 MONITORING FACILITIES

3.2.1 IMS STATIONS AND LABORATORIES

The installation of IMS stations and radionuclide laboratories has been in progress since the CTBTO began its work in 1997. Many of the seismic stations existed previously and were upgraded to IMS specification, whereas most non-seismic stations have been built from new. Relevant contributions to SnT2011 therefore represent a small sample of the recent IMS build-up activity.

Arzumanyan (T3-P7) describes the IMS auxiliary seismic station AS003 (GNI) in Armenia, and *Leavasa and Talia* (T3-P8) describe the installation at the Samoa station AS095 (AFI). A description of the primary seismic array PS36 (PETK) in Kamchatka, Russian Federation, is provided by *Kugaenko et al.* (T1-O17), and that of PS45 (AKASG) in Ukraine is provided by *Kachalin and Liashchuk* (T3-P24). In a presentation on the activities of the Turkish NDC, *Ozel et al.* (T2-P6) describe the IMS seismic array BRTR (PS43). *Lushetile and Hutchins* (T5-P28) report on the establishment of the IMS auxiliary station AS067 (TSUM) and the infrasound station IS35 (I35NA) in Namibia, while *Wallenstein et al.* (T3-P49) report on the establishment of the infrasound station IS42 (I42PT) in the Azores (Portugal). An example of the installation of a radionuclide station is provided by *Musa et al.* (T5-P2) who report on RN42 (MYP42), Malaysia.

The recent upgrading of the IMS radionuclide laboratory RL16 (USL16) at PNNL in the USA is described by *Forrester et al.* (T3-O8). This laboratory (FIGURE 3.2) incorporates an upgraded detector system placed in a new underground facility offering lower background levels and higher sensitivity; a factor of ten improvement in sensitivity is anticipated.

3.2.2 NON-IMS NETWORKS

Stations and networks outside the IMS are often associated with an IMS station in some way, and many IMS seismic stations form part of another network in addition to that of the IMS. Data from non-IMS monitoring networks are of special interest because such networks are usually local or regional, and thus may offer greater event-detection and location capabilities in specific regions than the more sparsely distributed stations of the IMS. Such locally superior capabilities provide one method of estimating the true detection thresholds of the IMS (see SECTION 8.1). Non-IMS networks also provide the bulk of data used to generate improved seismic wave-speed models essential for reliable sub-surface event location (SECTION 6.1), and they may be incorporated into a special event analysis[23] after entry into force.

TABLE 3.1 lists some of the diverse non-IMS networks presented in SnT2011. Although infrasound may not appear to be well represented, presentations on national and regional infrasound networks reveal an increased interest in infrasound monitoring which is not restricted to IMS stations. Their geographic distribution spans the Czech Republic (*Sindelarova et al.*, T1-P9), Utah, USA (*Burlarcu et al.*, T3-P31), Kamchatka, Russian Federation (*Gordeev et al.*, T1-O4), Romania (*Ionescu and Ghica*, T3-P17), the Republic of Korea (*Park et al.* T2-P8) and Ukraine (*Kachalin and Liashchuk*, T3-P24). This last example describes a non-IMS infrasound station co-located with IMS primary seismic station PS45 (AKASG). The largest non-IMS seismic network presented is USArray (*Woodward et al.*, T3-O12), shown in FIGURE 3.6, which comprises a large transportable network of seismometers, and

NAME	LOCATION	DESCRIPTION	PRESENTATION
Kamchatka network for volcano monitoring	Russian Federation (Kamchatka)	Five seismic and three infrasound stations	T1-O4
Czech microbarograph network	Czech Republic	One three-element infrasound array plus two single-element stations; also high-frequency Doppler sounding network comprising five transmission and two receiving stations	T1-P9
Dong-bei Broadband Seismic Network	China (DPRK border area) (**FIGURE 3.7**)	16 portable broadband seismic stations	T2-P2
Earthscope USArray	Continental USA (**FIGURE 3.6**)	450 portable broadband seismic stations with 1,680 sites occupied to date; infrasound being added	T3-O12
Dense Oceanfloor Network System for Earthquakes and Tsunamis (DONET)	Sea bed, SE of Japan (**FIGURE 3.1**)	Seismic and hydroacoustic; 20 cabled ocean-bottom observatories with seismic and acoustic sensors and hydrophones	T3-P3
Samoa-China Seismograph Network (SCSN)	Samoa	Three permanent broadband and three portable short-period seismic stations	T3-P8
Plostina Seismoacoustic Array (PLOR)	Romania, Vrancea area	Seven-element seismic and infrasound array	T3-P17
Malin experimental infrasound array	Ukraine	Infrasound array co-located with IMS station PS45 (AKASG)	T3-P24
Hellenic Unified Seismological Network (HUSN)	Greece	Umbrella for several seismic networks covering Greece	T3-P26
University of Utah Seismograph Stations (UUSS)	Utah, USA	200 seismic stations and nine infrasound arrays	T3-P31
Parsian Seismograph seismic stations	Iran	72 seismometer or accelerometer stations	T3-P39
Kyrgyzstan Net (KRNET)	Kyrgyzstan	18 broadband seismic stations, augmenting existing 10-station network	T5-P11
National Seismic Network	Namibia	7 seismic stations throughout Namibia with more planned	T5-P28
National Earthquake Monitoring and Tsunami Early Warning System in Thailand	Thailand	15 seismic stations and six accelerometers (Phase I); 25 seismic stations, 20 accelerometers, 9 tide gauges and 4 GPS stations (Phase II)	T5-P29

TABLE 3.1
Some non-IMS networks of monitoring stations presented at SnT2011.

now also infrasound detectors, which is being progressively migrated across the entire continental USA from west to east, and forms part of the Earthscope initiative.

Some new or upgraded non-IMS seismic networks result from capacity-building partnerships (**SECTION 9.2**); examples are in Kyrgyzstan, in collaboration with the organization operating the Norwegian Seismic Array (NORSAR) (*Berezina et al.*, **T5-P11**), and in Samoa in collaboration with China (*Leavasa and Talia*, **T3-P8**). Other non-IMS networks result from a unification of pre-existing stations or networks, such as the Hellenic Unified Seismic Network (HUSN) (*Papanastassiou et al.*, **T3-P26**) and seismic stations in Iran (*Safepour and Rezaei*, **T3-P39**). *Abd El-Aal* (**T3-P5**) describes work using stations of the Egyptian National Seismological Network (ENSN), including the Egyptian National Strong Motion Network, the Aswan network, and the Japanese network around the Gulf of Suez. The emerging national seismic network of Namibia is described by *Lushetile and Hutchins* (**T5-P28**).

The oceans place a major restriction on the distribution of seismic stations in a global network, especially since seismic stations installed on remote islands tend to suffer from high seismic noise. Ocean-bottom seismometers, perhaps installed as part of multisensor ocean bottom observatories, offer a potential solution to this problem of global station coverage. One step in this direction is DONET, a network of ocean-bottom seismometers and hydrophones south-east of Japan (*Tsuboi et al.*, **T3-P3**), shown in **FIGURE 3.1**. This takes advantage of cabled ocean-bottom observatories. A range of preliminary observations is presented, including *T* phases from unidentified events following a large Marianas Islands earthquake which are thought to be from aftershocks. The cabled observatories permit continuous real-time data transmission, and the technology may offer prospects for future installations more remote from land.

Prachuab (**T5-P29**) describes the development of the national earthquake monitoring and tsunami early warning system in Thailand, developed after the tsunami associated with the large 26 December 2004 earthquake in the Sumatra region. In addition to seismic stations and accelerometers, a network of GPS stations and tide gauges is reported.

A near-regional investigation of the announced nuclear tests in the DPRK, described in **SECTION 7.3.3**,

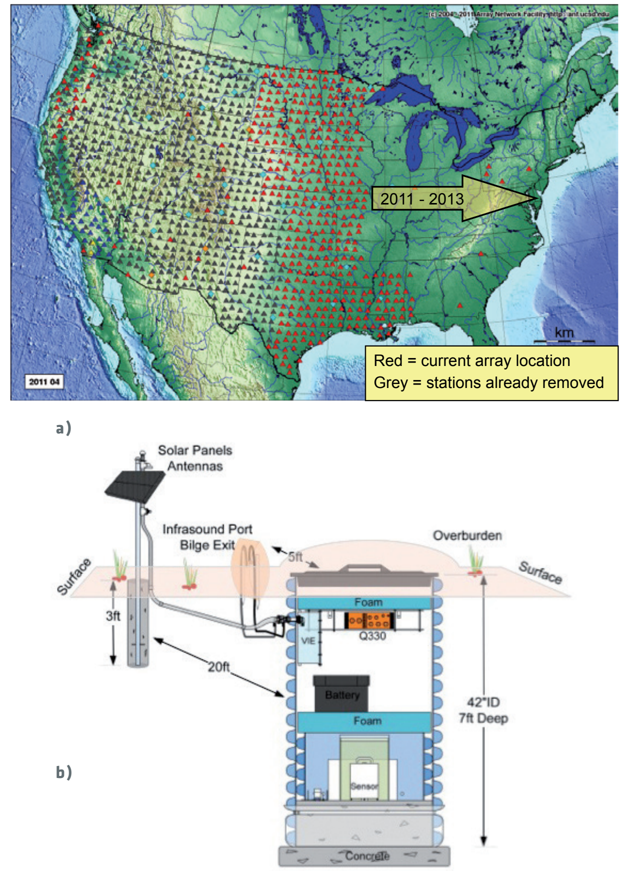


FIGURE 3.6
The Earthscope USArray transportable array.
a) Status in April 2011. **b)** Schematic of a station installation including infrasound detector. From *Woodward et al.* (**T3-O12**).

utilizes the Dong-bei Broadband Seismic Network (*Chun*, **T2-P2**), shown in **FIGURE 3.7**. This network is shown to offer an important contribution to seismic monitoring, by allowing the calibration of *Lg* propagation in the region, and it has demonstrated the validity of using *Pn*/*Lg* ratios for event screening in the region.

3.3 STRATEGIES FOR ON-SITE INSPECTION

Data acquisition during an OSI poses particular challenges. Activities and techniques are restricted by the Treaty[24] and by the OSI Operational Manual currently being prepared. The process is time-limited by the terms of the Treaty[25] and by the transient nature of some observables such as relevant radionuclides and seismic aftershocks. An inspection area of up to 1,000 km^2 [22] poses additional challenges to field op-

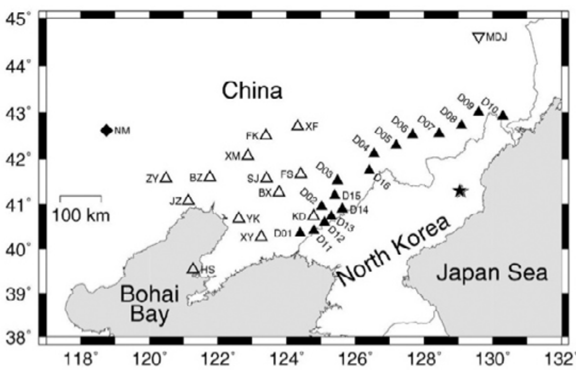


FIGURE 3.7

Stations of the Dong-bei Broadband Seismic Network, China, (solid triangles), and adjacent stations used in the study of *Chun* (**T2-P2**). From *Chun* (**T2-P2**).

erations. The climate, topography, surface conditions and other environmental factors cannot be predicted, and all approved equipment must be transported to the point of entry, checked for consistency with agreed specifications, and then must be transported further to the inspection area. The number of inspectors is strictly limited, and they will need to be conversant not only with the data acquisition process but also with the processing, interpretation and integration of data, at least inasmuch as this influences the continuing conduct of the inspection.

These challenges have resulted in a focus being placed upon strategies for acquiring data during the course of an OSI. These strategies address such issues as the utilization of remote sensing data to assist in designing the data acquisition programme; the prioritization of different methods at each stage; optimization of the speed and spatial resolution of observations with a view to progressively narrowing the area of focus, and assistance with intelligent data acquisition decisions based upon the interpretation of initial results. Bearing in mind that much still has to be done to finalize the list of methodologies to be used among those permitted[21], and to develop the equipment to be deployed, this topic will be the subject of substantial work in the future.

One approach is offered by *Tuckwell and Gaya-Piqué* (**T2-P19**), who describe an information-led search logic for use during an OSI. 'Reconnaissance missions' and 'hypothesis-testing missions' are distinguished, and requirements are outlined to facilitate the dynamic introduction of new missions and lines of enquiry, and the re-prioritizing of missions, with these decisions based upon the results of earlier missions or other newly acquired information. The Integrated Field Exercise 2008 (IFE08) and the Directed Exercise 2010 (DE10) are used as case studies to illustrate the methodology. Another contribution on the planning of OSI data acquisition (*Rizzo and Bartolomei,* **T2-P10**) emphasizes the modelling of likely sub-surface scenarios and uses this to devise sampling strategies.

Other contributions apply OSI data acquisition strategy to specific methods. For example, *Carrigan et al.* (**T2-P16**) describe strategies for noble gas monitoring, and *Ford et al.* (**T2-P13**) impose constraints by applying earthquake statistics to nuclear explosion aftershocks. A range of the permitted geophysical methods is considered by *Kakas et al.* (**T3-P21**), who point out the need to speed up acquisition and processing of OSI data, and who suggest a number of test sites in Hungary, including an impact crater and spherical cavern that offer different characteristics.

The data acquisition platform can be a major factor in the data collection strategy, because this can have a major influence on the speed and flexibility of sampling. Methods may be suitable only for static measurements, or for mounting on a range of mobile platforms such as a car, truck, helicopter, aeroplane or unmanned drone. *Köble et al.* (**T2-P12**) describe a car-borne system for radionuclide measurement for use in OSI, while *Toivonen* (**T2-O3**) points out the potential value of a drone for collecting radiation spectroscopy measurements. Other radionuclide-based developments described above may also find applications in OSI as the technology develops.

Given the specialized nature of any OSI, questions arise as to the availability of suitable equipment, and the extent to which existing commercial methods and data acquisition hardware can be used. The answers to such questions have a major impact not only upon development costs, but also upon the costs of operation and maintenance of OSI equipment, and of training. *Melamud and Gaya-Piqué* (**T3-P41**) believe that there is very limited scope for using off-the-shelf equipment. The possibility of more synergy with the methodologies used in geophysical exploration, environmental monitoring, archaeological prospecting and hydrology may be given further consideration in the future. It is also natural to consider the experiences of inspection regimes from other treaties where these may be relevant, and this issue is explored by *Abushady* (**T5-O13**) in the context of the IAEA and the Organization for the Prohibition of Chemical Weapons (OPCW).

4

Data Transmission, Storage and Format

INTRODUCTION

Rapid, secure and reliable transmission of data from station to IDC, and from IDC to States Signatories, was seen as a high priority during Treaty negotiations. One outcome was the Global Communications Infrastructure (GCI), which provides for the transmission of authenticated (though not encrypted) IMS data and IDC products over secure data channels via satellite. High data availability and near-real-time data transmission are key requirements of the GCI, and under Provisional Operations (prior to entry into force of the Treaty) the GCI is one of the few parts of the verification system that is operated with a contractual requirement of maintenance 24 hours per day seven days per week.

Communications technology, and with it the technology of data storage, have changed rapidly since the Treaty was negotiated, perhaps more rapidly than any other technological aspect of the verification regime. Moreover, these technological advances have been accompanied by a massive reduction in unit cost[30]. One consequence of this has been the emergence of large open-source data centres (for example in seismology) which can receive data in near-real-time and store it for users to access at their convenience. With data so easily retrievable by scientific researchers, the choice of data format becomes a crucial factor in determining ease of data access by users, and data exchange between users. It is therefore interesting to see the methodologies and experiences of designers and users of data centres external to IDC. Rapid advances and cost reduction will surely continue, and this will pose important strategic questions for the future of the CTBTO data transmission and storage infrastructure.

The apparently pedestrian matter of continuous data formats used for waveform data is of special interest. CTBTO uses a customised format, while in the academic community an open-source format has become the *de facto* standard for the exchange of seismic data within that community. Given that the Treaty provides that States may require CTBTO to incorporate non-IMS data into the analysis of special events[23], the question of format compatibility is as important for CTBTO as it is for external users of IMS data for civil and scientific purposes.

Advances in data transmission and storage have fostered the development of massive data archives over the last two decades, and these are typically open source and free access. Many of these facilities are highly relevant to CTBT verification, and SECTION 9 includes the relevant SnT2011 contributions.

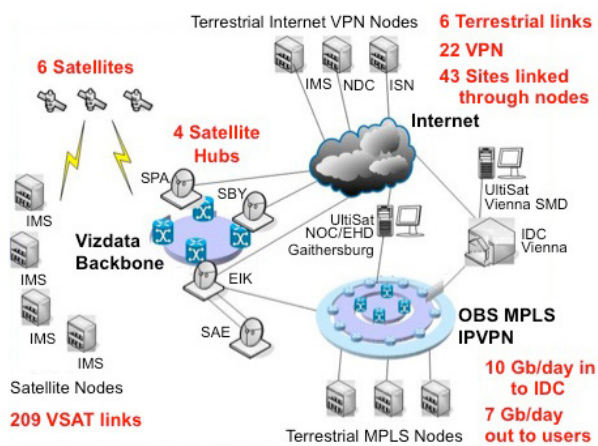


FIGURE 4.1
Main components of the CTBTO Global Communications Infrastructure (GCI). From *Daly et al.* (**T3P37**). Adapted from GCI-II System Design Specification (document FDD-001), 6 April 2011, Ultisat Inc.

4.1
DATA TRANSMISSION

To replace the first ten-year GCI contract, 'GCI II' was implemented in 2007-8, and is described by *Crichton* (**T3-P44**). Each transmission point (usually an IMS station or NDC) uses a very small aperture terminal (VSAT) to transmit data to a satellite. The current GCI utilizes six geosynchronous communications satellites together with associated ground-based data-receiving hubs and terrestrial communications links.

The scale of the CTBTO data transmission task can be gauged from the work of the IDC Operations Centre, which is responsible for monitoring the state of health of all elements of IMS stations and IDC processing, including the transmission of IMS data and IDC products to authorized users at National Data Centres or other establishments designated by the State. *Daly et al.* (**T3-P37**) describe the six satellites, four satellite hubs, six terrestrial links and 209 VSAT links at the core of the GCI (**FIGURE 4.1**), and reports that 10 Gb per day of data were being received at IDC in 2011, with 7 Gb per day sent out from IDC to authorized users including station operators.

4.2
DATA FORMATS

Difficulties arising from multiple and incompatible formats have long been a feature of data exchange and portability, and *Mohammad* (**T5-P1**) considers the consequent diversion of resources from core research activity. The benefits of using standard and widely-used formats in the transmission and storage of data are emphasised by several authors, and is summed up succinctly by *Jones* (**T4-01**) in his statement "Groups should produce data products that can readily be integrated into other systems". One example of this approach, of direct relevance to CTBT verification, is the Data Management Centre (DMC) of the Incorporated Research Institutions for Seismology (IRIS), presented by *Ahern* (**T5-P15**). More discussion of this and other data centres appears in **SECTION 9.3**.

The standardization of data formats has long been promoted in the seismological research community, especially by the international Federation of Digital Seismograph Networks (FDSN), as reported by *Suarez and Haslinger* (**T5-07**). Many network operators transmit data using formats other than the CTBTO's continuous data format, most notably using the SEEDLINK format based on the Standard for the Exchange of Earthquake Data (SEED) format for data exchange originating from FDSN. In some cases SEEDLINK is used by CTBT National Data Centres for their own networks; an example is the Romanian infrasound network presented by *Ionescu and Ghica* (**T3-P17**). However, seismic processing software is increasingly designed to handle a range of formats, overcoming what has emerged as a significant impediment to convenient data exchange. As example is the Earthworm software, described by *Hellman et al.* (**T3-P47**).

5

Data Processing and Synthesis

INTRODUCTION

This Section concerns the transformation of observations and measurements into a form suitable for interpretation. For seismoacoustic waveform data, this includes the detection of signals, the association of signals common to each event, the location of events, and the determination of characteristic parameters of each event which may be useful for interpretation, including source depth, body-wave and surface-wave magnitudes and frequency content. The determination of such parameters has been called 'event characterization'. In CTBTO, the identification of events believed to be of natural, or anthropogenic non-nuclear origin is referred to as 'event screening'[31]; because this is part of interpretation, it is deferred to SECTION 7.

For radionuclide observations, data processing and synthesis includes the processing of measurements made on gamma-ray spectra in order to identify peaks, and to estimate the concentration of radioactive isotopes represented by these peaks. Similarly, beta-gamma data processing used in noble gas data analysis covers the analysis of coincident beta and gamma radiation and subsequent analysis based on energy ratios. The processing of data from other types of measurement, including all methods used in OSI, are also included in this Section.

All the steps in the processing and synthesis of IMS data are either automatic (referred to conventionally as 'data processing') or are performed interactively by data analysts or other staff; in the preparation of standard IDC products this is referred to conventionally as 'interactive analysis' or 'data analysis'. The term 'expert analysis' is often used when referring to the analysis of special events[23].

Data processing and synthesis covers many topics that may not appear to be verification-related. For example, the study of earthquakes contributes crucially to any CTBT verification effort in view of the predominance of earthquakes among events recorded by seismic stations.

Correct processing and interpretation of observations rely strongly upon knowing the static and dynamic properties of the earth. For example, the location of events in the earth's subsurface relies upon accurate seismic wave-speed models, and the location of events in the oceans and in the atmosphere relies equally upon knowledge of acoustic wave speeds in those media. By analogy, the determination of the origin of anomalous radionuclide observations depends upon our ability to track atmospheric motion using atmospheric transport modelling (ATM). Contributions on these and other earth properties which impact upon the processing and interpretation of verification-related observations are considered in SECTION 6.

Studies of ambient noise levels, for example of microseismic noise in the solid earth, microbarometric noise in the atmosphere, or the global background of radionuclides, all relate to the detectability and performance of verification methods; these are deferred to SECTION 8.

5.1
CREATING SEISMOACOUSTIC EVENT LISTS

5.1.1
INTRODUCTION

The traditional method of building a list of seismoacoustic events involves a serial process beginning with the detection and measurement of signals from waveform data recorded at each station, followed by the association of signals which belong to the same event, followed by the location of each event using the detections associated with it. This process can be applied equally to events recorded globally, or to passive seismic monitoring for an OSI; indeed almost all automatic systems use a variation of this process, although the approach does suffer from a number of systemic deficiencies. With the introduction of machine learning, new methods are being developed in which these stages of processing are either combined, or repeated by means of a feedback loop. Such methods seek to use probabilistic inference to find those event hypotheses that best fit all of the observed data (which may include the absence of signals at some stations as well as their presence). These new approaches will require major changes in the way that waveform data and associated event parameters are stored and retrieved. They will also require a new approach to validation and testing, with clear goals and quantitative measures for improvement, as pointed out by *Kuzma and Le Bras* (**T4-P22**).

Perhaps the biggest motivation to improve event-building algorithms is the imperative for analysts to review, and substantially improve, current automatically generated lists, especially in relation to smaller events. The CTBTO verification mission drives a unique combination of requirements for seismoacoustic event lists, in that they are global, and must also focus on small events globally. Normally an event list either covers only one region or, if it is global, it focuses only on larger events. The workload imposed on CTBTO analyst staff by deficiencies in automatic processing has been a major source of concern, some aspects of which are considered by *Pearce and Kitov* (**T4-P38**).

The quality of an event list is indirectly related to its completeness. Many event lists use criteria to determine which events to include (in CTBTO these are referred to as 'event definition criteria'). Usually these criteria are related to the quality of the event location, including the number of signals contributing to the location and their azimuthal distribution. In the event lists prepared by IDC using IMS data, the event definition criteria are not easily justified on this basis, and *Pearce et al.* (**T4-P30**) investigate alternative criteria which have the potential to improve the overall quality and completeness of the IDC's Reviewed Event Bulletin (REB) without increasing the workload of analysts. *Spiliopoulos et al.* (**T4-P37**) also conclude from a study of the IMS seismic event detection threshold (see **SECTION 8.2.1**) that the event definition criteria are in need of review.

In the IDC, automatic processing and the interactive analysis of waveform data from seismic, hydroacoustic and infrasound stations are integrated, so that the automatic events lists, and the reviewed bulletins, include events created from signals at all three types of station. This is unusual because few other agencies are responsible for processing infrasound or hydroacoustic data in addition to seismic data. Nevertheless, this integrated approach has the benefit of allowing events to be built from signals recorded on multiple stations types, and there are many such events. For example, *T* phases from earthquakes are recorded on hydroacoustic stations, and surface explosions typically generate both seismic and infrasound signals. In CTBTO, events recorded on more than one station type are termed 'fused events', and *Johansson and Mialle* (**T4-P31**) present a study of such events included in the IDC REB between February 2010 and March 2011. Out of a total of 50,018 REB events during this period, they find 1,464 events with associated infrasound phases and 11,749 with associated hydroacoustic phases; of the total they find 61 events which include seismic, infrasound and *T*-phase observations. Although seismoacoustic waveform data processing is integrated, the following subsections show that the signal detection and association methods may differ.

5.1.2
EVENTS FROM SEISMIC DATA

IDC waveform analysts often detect signals manually when they review events generated by automatic processing. This confirms that signal detection, which is the first stage in detecting, locating and identifying a seismic 'event', is not always well-performed automatically. *Selby* (**T4-O2**) describes improved signal detection using a generalized *F* detector, which uses prior information to weight the frequency-wave-

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The Impact of Smaller Seismic Events

It may be obvious that smaller seismic events generate smaller seismic signals, with a consequent degradation of the quality and distance range of the signals recorded; this applies equally to seismic array stations which are designed for the recording of small signals. But low signal amplitude is not the only difficulty faced when smaller seismic events are to be detected and located. Seismic events are dominated by earthquakes, and there are many more small earthquakes. The number of earthquakes above a given magnitude, plotted on a log scale against magnitude value, shows a linear relationship over the magnitude range that the bulletin is complete.

The slope, which is referred to as the seismic *b*-value, is close to unity; this corresponds to an approximately tenfold increase in the number of earthquakes as each successively lower magnitude unit is included. This observation was documented by Gutenberg and Richter, and is perhaps the best-known empirical relation in earthquake seismology. The magnitude below which the linear relation fails corresponds to the magnitude threshold below which many earthquakes remain undetected. Above that magnitude the bulletin is considered to be complete, and few if any events escape detection. The Gutenberg-Richter relation is used to examine bulletin completeness in **SECTION 8.2.1**.

One obvious consequence of the Gutenberg-Richter relation is an increase in the number of events to process and analyse as the magnitude threshold is lowered. But this is not the only burden resulting from a focus on small events. The greater the number of events, the greater is the pool of signals recorded at stations throughout the network, and all of these signals must be associated to the correct event if events are to be correctly located. The computational effort required to correctly associate signals increases dramatically as their number increases; the process also becomes more error-prone.

CTBTO uses only signals recorded by its network of IMS primary seismic stations to detect seismic events for its IDC standard event lists and bulletins, though signals recorded by stations of the IMS auxiliary seismic network are used to refine event locations and other source parameters. The number of events reported in this way is therefore limited by the number of primary seismic stations, of which the Treaty defines 50. As data processing methods improve, and the network approaches completion, the number of events increases, with the burden described above becoming more demanding. Moreover, any event list computed using additional stations will also see an increase in the number of events.

number spectra and equalize detection thresholds. The station-specific prior information that is used comprises array aperture, signal bandwidth, number of channels in the array, noise power spectrum, and noise correlation between the array sensors; the noise is adaptively whitened to reduce false detections. Test results are presented for 10 days of data at 13 small IMS seismic arrays.

Further improvements in signal detection at seismic arrays may potentially be achieved if each array site were to record three-component signals. Traditionally, seismic array processing uses vertical component sensors, but *Gibbons et al.* (**T4-05**) show that three-component array processing at the small (1-km aperture) IMS auxiliary seismic array AS072 (SPITS), which does have three-component sensors at six sites, can improve signal detection and identification of regional phases. It is argued that, since many later arriving regional phases are *S*-type, and so tend to have higher signal amplitude on the horizontal components, these components can be used to generate a phased array sum (beam) which has higher signal-to-noise ratio than that of a beam generated from vertical components. This also allows ray direction (vector slowness) to be estimated using frequency-wavenumber (*f*-*k*) analysis on the horizontal components. Using examples it is also shown that a comparison of signal coherence across the array for the horizontal and vertical components can offer a powerful means of discriminating between *P*- and *S*-type regional phases, with *S*-type phases consistently showing relatively greater coherence on the horizontal components.

Rigglesen (T4-P13) considers the problem of signal detection at three-component stations, which lack the potential of combining signals recorded across an array of sensors. The need to take account of seasonally-dependent noise is one issue highlighted. A wavelet-transform approach is used by *Gravirov and Kislov* (T4-P2), who are concerned with the automatic detection of seismic phases in high noise conditions for single-sensor early warning of earthquakes in the 20–600 km distance range. ('Early warning' seeks to warn of a potentially damaging earthquake after its onset, but before the potentially destructive seismic waves have arrived at a neighbouring locality shortly afterwards; see also SECTION 6.1.4.) The system is described by *Kislov and Gravirov* (T3-P9).

Once a signal has been detected, its onset time must be measured as accurately as possible, since this influences the event location estimate. Statistics show that IDC analysts re-time a large proportion of signals, suggesting that automatic signal onset timing is in need of improvement. *Gravirov et al.* (JS-P4) use an adaptive algorithm for the detection and refinement of onset times for aftershocks of the Japan Tohoku earthquake. *Gunawan et al.* (T3-P2) also consider the problem of rapid and accurate onset-time determination in the context of tsunami early warning.

Identification of the type of signal, and its raypath through the earth, are essential prerequisites for the use of any signal in event location. Signals following different raypaths, referred to as different seismic 'phases', may exhibit characteristic waveform features that can be used to discriminate between them. Such features, including signal envelope, are used by *Zhang et al.* (T4-P32) to perform phase classification and association using neural networks.

One way suggested to improve signal detection, especially for earthquake aftershock sequences, is to exploit the expected similarity between the waveforms of closely spaced events recorded at the same station. *Slinkard et al.* (T4-P42) use a library of master waveforms for previously defined origins. After recognizing that an aftershock sequence has started, their procedure determines which stations to use and from which region to retrieve archived waveforms for the application of the detector. Variables include the window length, filter band and correlation threshold. For aftershocks of the Kashmir earthquake of 8 October 2005, used as an example, 47% of aftershocks in the REB are identified as 'family', plus 183 new events. *Akhouayri et al.* (T4-P14) use cross-correlation as a detector, by measuring abrupt changes in signal stationarity with time. Array-based waveform correlation is used by *Semin et al.* (T1-P10) for the detection and identification of low-magnitude seismic events near Bala, central Turkey. Assessment of detection capability is made using the earthquake sequence. Cross-correlation using a signal-envelope model is considered by *Russell et al.* (T4-P19), and is compared with the double-difference method.

The expected similarity between waveforms recorded from co-located sources of the same type is also represented in the source scaling law presented by *Ziolkowski* (T2-O8). This author proposes to correct for the source spectrum when correlating sources of different magnitude, for example in an earthquake aftershock sequence. The use of cross-correlation methods for signal detection and association is also referred to by *Ingraham and McIntyre* (T2-P15).

In the OSI context, passive seismic monitoring uses a local network of seismometers arranged in mini-arrays covering no more than 1,000 km^2. Detection and classification of signals must be highly automated in view of the large data volumes and time pressure imposed by the inspection timeline, and efforts must be made to detect the smallest of signals, at very low signal-to-noise ratios. *Sick and Joswig* (T4-P6) describe a software module integrated into the CTBTO's Seismic Aftershock Monitoring System (SAMS) which is designed to detect small aftershocks with the aid of sonograms. *Ford et al.* (T2-P13) report several examples of aftershock sequences recorded from past underground nuclear tests at several locations.

Under the traditional method of building seismic events, signal detection is followed by signal association, which seeks to group detections belonging to the same event. For a global network of stations the association process is complicated, especially in view of the need to build the smaller events. The extensive modifications made during analyst review show that automatic association is unreliable. Errors in association result in the inclusion of unrelated signals into the location process, degrading the validity of event locations. The algorithm used to perform association in the IDC applications software is referred to as Global Association (GA), and *Kværna et al.* (T4-P9) propose improving GA by incorporating amplitude data and detection probabilities into the automatic process. The aim is to assess the validity of events built automatically, and the consistency of individual phases associated with such events.

Detection probabilities are already calculated by the Threshold Monitoring subsystem of the IDC applications software, and these results are utilised in the process. Maximum likelihood estimates are used to avoid bias caused by signals that are not detected. Although GA is a part of automatic processing, these authors also envisage interactive use by analysts of their improved process.

Signal association forms part of network processing, because it involves the measurements made on data from multiple stations. Network Vertically Integrated Seismic Analysis (NET-VISA) is an alternative to GA based upon a signal-based Bayesian model, which is one of the projects resulting from the machine learning initiative begun following the CTBTO's Synergies with Science Symposium in 2006. *Arora et al.* (**T4-O6**) describe the method, and compare the analyst review required to produce the Late Event Bulletin (LEB)[32] from the existing automatically produced Standard Event List 3 (SEL3), with the difference between the NET-VISA results and the LEB. Based upon this use of the LEB as 'ground truth', an improvement is reported, and it is also found that NET-VISA correctly builds many events that are not in the LEB but are in national bulletins. The authors report the continuing testing and evaluation of this method on vDEC.

The location of seismic events, given a list of arrival times and possibly azimuths and slownesses, together with adequate travel-time information, follows a standard procedure long used in seismology. However, refinements to the method are needed to deal optimally with shortcomings in travel-time information and measurement errors, especially when combining regional and teleseismic observations as is the norm for IDC processing. A number of improvements to event location are proposed. *Husebye and Matveeva* (**T4-O11**) suggest using the regional phase *Lg* to enhance epicentre location. It is pointed out that its emergent onset precludes its use in location, whereas its maximum amplitude can be used for magnitude estimation (M_L). These authors suggest using a maximum amplitude arrival time determined using an envelope function derived from the signal multiplied by its Hilbert transform. They apply the method to selected ground-truth events (in this case earthquakes with epicentres known to a precision of 5 km, referred to as GT5). *Husebye and Matveeva* (**T4-P4**) propose determining focal depth from the polarization of the coda of the regional phase *Pn*. They propose picking *pP* and *sP* in the *Pn* coda, and then using waveform correlation. Progressive multichannel correlation (PMCC) is used by *Munkhuu* (**T1-P23**) to compute improved locations for seismicity in the Ulaanbaatar area of Mongolia.

For events of special interest[23], special methods may be used to improve location accuracy, or to determine improved relative locations between two or more events. In general, relative location between neighbouring events can be determined more accurately than absolute location, which is degraded by 'bias' caused by an inadequate wave-speed model. One example of such analysis is presented by *Kohl et al.* (**T2-P21**) for the two announced nuclear tests in the DPRK in 2006 and 2009. These authors use cross-correlation of common event-station phase pairs (digital waveform interferometry (DWIF)), plus the double difference method and joint hypocentre determination (JHD). They obtain a relative location of 2.5 ± 0.25 km, with the 2009 event west-northwest of the 2006 event. Topographic data are then used together with depth and relative location constraints to obtain absolute locations, in part using *Pn* spectral ratio to constrain depths. A depth of 180 m is inferred for the 2006 event, and 600 m for that in 2009.

Regarding the relative location of the 2006 and 2009 DPRK events presented by *Kohl et al.* (**T2-P21**), it may be noted that Richards[33] reported at the ISS09 conference, two weeks after the 2009 event, that Kim[34] had estimated a relative location of 2.6 km, with the 2009 event at an azimuth of about 286° from the 2006 location, using 83 seismic travel-time pairs observed at regional distances.

An automatically generated seismic event list, such as that of the IDC, typically includes a significant proportion of events which are not real. *Tang et al.* (**T4-P34**) propose a set of rules based on signal-to-noise ratio, station distance and other parameters to help reduce the proportion of such events[35].

The International Seismological Centre (ISC) have been issuing the world's most comprehensive global earthquake bulletin for many years. ISC waits for up to two years before issuing its final bulletin, in order to ensure the inclusion of the maximum number of observations from the largest possible number of stations. Recent improvements to their event location algorithm are described by *Bondár et al.* (**T5-P5**).

The back-projection of signals from an array of sensors, or in principle from a whole network of sensors, to estimate the spatiotemporal emission of seismic radiation at the source, provides a method which can potentially locate an event and characterize the seismic source, given an adequate description of the wave-speed model along the ray paths. *Meng and Ampuro* (**T4-O13**) apply this approach to seismograms from earthquakes observed at regional distances. Their method, referred to as Multiple Signal Clarification (MUSIC) is applied to examples including the Haiti earthquake of 12 January 2010. *Nissen-Meyer et al.* (**T4-O7**) consider the general problem of applying non-linear methods to invert for seismic source and earth structure parameters using large datasets, and consider the computing power required to perform calculations in real time for realistic datasets.

With interactive analysis remaining as an essential step in the preparation of high quality seismic event bulletins, the improvement of analyst tools is an issue of concern. For seismic arrays, the validation of automatically detected signals, and the detection of missed signals, are both assisted by a trace which shows the degree of correlation between signals on different channels when the array is aligned to a given vector slowness. The product of two traces, each representing the beam computed from one half of the array elements, has traditionally been used for this purpose, usually at linear cross arrays with each half corresponding to one of the arms of the array. Traces derived from an *F* detector have more recently been used, and *Miljanovic et al.* (**T4-P23**) report on the implementation of such a tool within the waveform data analysis package Geotool, which is provided by the CTBTO to NDCs. Geotool windows are also used within the IDC analyst environment for specific purposes.

Efficient use of analyst time relies heavily on the design of the interface between the data and the analyst. The data and associated parameters must be presented to the analyst in a form that promotes the rapid identification of important features, the rapid correction of errors made in automatic processing, and the detection of signals that have been missed. *Kuzma and Arehart* (**T4-P11**) suggest presenting seismic waveform data as an audio signal to analysts as an additional tool, and they compress the data in time by a factor of 200 for this purpose. Examples show that in some circumstances *P* and *S* waves are discernible on audio but not on visual traces, and this is suggested as a possible method of scanning for missed signals. For seismic array data, a visual spectrum view is presented which allows the analyst to align signals manually, while the replay speed can be adjusted to bring signals into the audible range. It is also proposed that array data could be presented in a stereo audio environment in which signals can be aligned by analysts. These authors also consider the possibility of including audio-derived signal features in machine learning algorithms.

Particular problems arise with the analysis of large aftershock sequences following high-magnitude earthquakes, when analyst workload may increase greatly. The largest aftershock sequence so far faced by CTBTO was that following the Tohoku earthquake of 11 March 2011. The analysis of that sequence is described by *Spiliopoulos et al*. (**JS-P5**), who report that the REBs between that date and 18 April contained 10,750 events including those from this sequence. A comparison is drawn with the 38,000 events for the whole of the previous year. With the initial days of the sequence having almost six times the average analyst workload, they report that the latency in issuance of the daily REB was increased from its scheduled maximum of normally ten days to 30 days, before the normal schedule was progressively regained. Some ideas are considered for addressing this issue, which will become especially relevant after the Treaty enters into force, since it is foreseen by the draft IDC Operational Manual that a normal latency for REB issuance of only 48 hours will then apply.

The processing of passive seismic data from a local seismograph network to detect and locate potential aftershocks in an OSI context involves the same basic steps as for a global network, but on a much smaller scale and hence at much higher signal frequencies and lower seismic magnitudes. *Ford et al.* (**T2-P13**) present a statistical model for the occurrence of such aftershocks. *Rozhkov et al.* (**T4-P5**) describe a method of locating low-magnitude events from OSI passive seismic data in the presence of high noise, which draws on the methods used for hydrofracture monitoring. *Sick and Joswig* (**T4-P6**) present an OSI passive seismic data processing method which emphasises the use of sonograms to enhance the recognition of small signals in high noise. *Gorschlüter and Altmann* (**T4-P29**) present a method of reducing periodic noise in seismic data acquired for OSI.

5.1.3
EVENTS FROM HYDROACOUSTIC DATA

Correct association of signals requires that their ray-path through the earth first be correctly identified.

A hydroacoustic signal may be noise, or a *T* phase (having travelled as a seismic wave along part of its path) or an *H* phase (having travelled wholly in water), and discriminating among these using signal characteristics has been problematic. *Tuma et al.* (T4-P15) describe recent improvements in discriminating between these phases using kernel-based classifiers.

5.1.4 EVENTS FROM INFRASOUND DATA

Automatic processing to generate events from infrasound data, followed by interactive review by analysts, was introduced into IDC Provisional Operations in its current form in February 2010, following six years during which routine infrasound processing was excluded and new infrasound processing software was developed. The first year's experience with analysing results from the new software is reported by *Bittner et al.* (T4-P18). It is reported that 3,500 infrasound events were validated and included in the LEB during the year, of which 2,000 met the REB event definition criteria; of these, more than 350 were infrasound-only events, 80% had detections at three stations and the largest had 12 identified phases.

A number of issues are identified by *Bittner et al.* (T4-P18) requiring further work to optimize the automatic processing of infrasound data. These include a number of complications in the analyst event-validation process, one of which is the dearth of associated phases due to the sparseness of the IMS infrasound network, and another is the difficulty of automatically identifying and classifying infrasound phases. Three other issues are the uncertainty in source-detector distance associated with uncertainties in the wave-speed model, the rapid fluctuation of ambient noise level at stations, and rapid changes in meteorological conditions (and hence wave speed) along the propagation path. Some of these issues are recognised as intrinsic to the differences between the seismic and infrasonic propagation media and are considered in SECTION 6.3. For example, range-dependent travel-time residuals varying from tens to hundreds of seconds are allowed in IDC for infrasound (compared with 2.5 s for seismic), whereas the back azimuth of infrasound signals can typically be resolved to within 2°. The authors note the importance of the Infrasound Reference Event Database (IRED) in drawing comparisons when validating events; IRED contained more than 750 events in 2011, with more being added. A further issue of concern, as experience is gained with the new infrasound software, is that many events must be built manually by analysts because they were missed during automatic processing.

An example of infrasound processing unrelated to that used at IDC is presented by *Arrowsmith and Whitaker* (T4-O10), who use an adaptive *F* detector, and who treat the phase association problem stochastically. Their location method, referred to as the Bayesian infrasonic source locator (BISL) is applied to regional infrasound monitoring in Utah, USA. *Selby* (T4-O2) also reports that he has tried using a generalised *F* detector for the detection of infrasound signals. *Ionescu and Ghica* (T3-P17) report on their processing of data recorded at the Romanian infrasound array in the Vrancea region, using IDC software including PMCC. Another infrasound processing system, reported by *Burlacu et al.* (T3-P31), is that of the University of Utah infrasound network.

The automatic classification of infrasound signals also receives some attention. *Kulichkov et al.* (T4-O12) focus on source identification by attempting to classify infrasound signals using cross-correlation. Their method aims to classify signals into two populations, one including volcanic and explosive sources, and the other including aurora-related signals, mountain-associated waves and microbaroms. *Gaillard et al.* (T4-P21) work on a different aspect of signal classification, by attempting to improve the current state of signal categorization using a clustering algorithm to delete mis-classified signals from detection lists.

The process of locating events in the atmosphere using infrasound signals is complicated by the complexity and intrinsic time dependence of atmospheric acoustic wave speed (see SECTION 6.3.1), and by any high-altitude winds, in particular stratospheric winds, whose speed is significant compared with the wave speed. *Wüst et al.* (T1-O6) consider the uncertainty radius for backtracking infrasound signals caused by atmospheric wave activity. They estimate planetary wave and gravity wave temperature fluctuations, and quantify their influence on infrasound propagation on a case study basis. They explore near-real-time observations of wave activity, pointing out that satellite measurements are currently only sufficient for the activity of planetary waves, not gravity waves, for which a climatological approach must be used.

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An Integrated Approach to Seismoacoustic Data

Acoustic waves (sound waves) are transmitted through the oceans and the atmosphere, and seismic waves are transmitted through the solid earth. Together, these may be called seismoacoustic waves, and in the CTBT context they give rise to what are conventionally referred to as 'waveform' methods, using data recorded by hydroacoustic, infrasound and seismic sensors. Before the IMS, the absence of a global network of either infrasound or hydroacoustic stations inevitably meant that studies involving seismoacoustic waves focused on the wealth of data available from an ever-increasing number of seismic stations[11].

The introduction of global infrasound and hydroacoustic networks in the IMS has broadened the 'view' of geophysicists who use seismoacoustic methods. Although the seismic, hydroacoustic and infrasound networks were envisaged as a means to monitor CTBT compliance in the solid earth, oceans and atmosphere respectively, this is an oversimplification. Sources in the solid earth give rise to signals recorded at hydroacoustic stations in certain circumstances. Sources in the atmosphere may be recorded by seismometers. Moreover, the six so-called *T*-phase stations in the IMS hydroacoustic network are, in reality, seismic stations, and it has become clear that more can be obtained from IMS waveform data as a whole by exploiting the full range of signals recorded at each type of station.

The addition of infrasound and hydroacoustic networks has enabled researchers to look at the three sources of waveform data in an integrated way, revealing a whole new range of earth observations recorded by this collective system of sensors. In the parlance of verification, the integration of observations of one source recorded on stations of multiple IMS 'technologies' is referred to as 'data fusion'. SnT2011 contains some novel accounts of sources recorded on multiple types of IMS station, and these offer glimpses into some possible future ways in which data fusion may be achieved in the verification context. An important application of data fusion that needs attention concerns suspicious events that may occur on or close to the boundaries between the three media, for example on the land surface, on the sea surface, or on the sea bed.

5.1.5 FUSING SEISMOACOUSTIC OBSERVATIONS

In IDC automatic processing, seismic, hydroacoustic and infrasound signals are associated if they are assessed as being from the same event. Arrival time, back azimuth and/or slowness may be used as evidence in the association process, with a dependence also upon the correct identification of the signal raypath (phase name). IDC analysts normally review all associated signals; the inclusion of multiple signal types in an event may result in arrival time differences of many minutes for different associated phases, and tools are available to assist in the convenient display of such signals, both for review and for manually adding signals not associated to an event in automatic processing.

Following the introduction of infrasound processing into IDC Provisional Operations in February 2010, the number of fused events rose significantly; statistics on events recorded at seismic and hydroacoustic as well as infrasound stations are provided by *Johansson and Mialle* (**T4-P31**) (**FIGURE 5.1**).

An example of an infrasound event in the REB that also includes seismic observations is the infrasound calibration explosion of 26 January 2011, reported by *Mialle et al.* (**T5-P23**). This surface explosion was detected at three IMS infrasound stations at distances of up to 6,250 km, and at three IMS auxiliary seismic stations at regional distances, all of which were used to determine the location. Another example of data synergy, which includes hydroacoustic as well as infrasound and seismic observations, is the study of the South Sarigan submarine volcanic eruption of 2010 reported by *Green et al.* (**T1-O8**). Infrasound signals from meteorites are considered by *Edwards et al.* (**T4-P27**) in their contribution on seismoacoustic waves coupled between the atmosphere and the solid earth. They consider various methods by which infrasound energy may be coupled to the solid earth.

5.2 RADIONUCLIDE DATA PROCESSING AND ANALYSIS

Contributions relating explicitly to the processing of radionuclide data include methods to automatically detect and identify peaks in observed gamma-ray spectra, and tools to assist in the interactive review of these spectra. As with all CTBT-relevant monitoring, there is a special interest in small signals and their discrimination from background noise. This problem is considered by *Rivals et al.* (**T4-04**), who use Bayesian inference to detect low radionuclide concentrations in gamma-ray spectra of xenon isotopes, which are of special relevance in CTBT monitoring. The correct detection of small peaks above background noise must be based on a statistical test, and this contribution adds rigour to the process, taking due account of prior knowledge.

Toivonen (**T2-03**) points out that the conventional process, by which the sample is measured once and the resulting spectrum processed automatically and then interactively analysed, does not provide for a 'second look' at the sample using additional methods of analysis. This author advocates multiple analyses of these measurements in order to address many sources of uncertainty including calibration, peak definition, peak association, radionuclide identification and radionuclide concentration ratios. He also points out the unreliability of conventional methods used to determine the uncertainty of the peak area (and hence concentration), and proposes an alternative method which gives emphasis to well-founded statistics. It is pointed out that the process of defining peak areas (by curve fitting) should itself return not only the peak areas but also their uncertainties. Recently designed software for the automatic analysis of spectra in Finland is reported which uses the covariance matrix in uncertainty estimation.

The processing and analysis of samples obtained from IMS noble gas stations has been progressively developed over the last few years, and this development continues. The status of these activities in IDC Provisional Operations is described by *Nikkinen et al.* (**T4-P35**), who report on the status of software for automatic processing and interactive analysis of noble gas spectra from the three types of equipment used in IMS for noble gas acquisition, namely the Analyzer of Xenon Radioisotopes (ARIX), SAUNA, and the Système de Prélèvement d'air Automatique en Ligne avec l'Analyse des radio-Xénons (SPALAX).

Gohla (**T3-P28**) present a statistical approach to comparing measurement of noble gas samples made at the station with those made at an IMS radionuclide laboratory. They observe a bias in activity concentration at some stations, and conclude that the number of noble-gas-capable IMS radionuclide laboratories will need to be increased from its current four in order to support a well-founded quality assurance programme for IMS noble gas measurements.

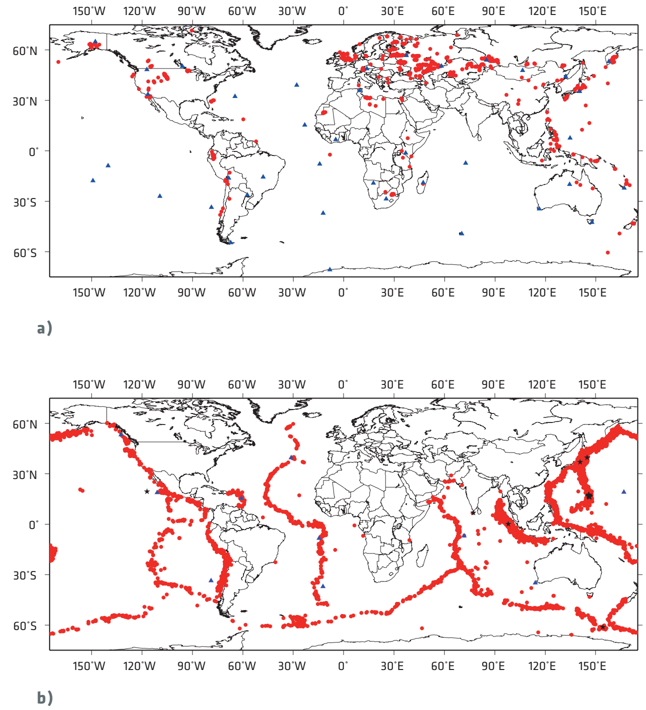

FIGURE 5.1
a) The 1,464 events (red circles) out of a total of 50,018 in the REB for the 14-month period February 2010 to March 2011 that include associated infrasound phases. Blue triangles denote infrasound stations in IDC Provisional Operations. **b)** The 11,749 events in the same period that include associated hydroacoustic phases. Red circles denote those with *T* phases (11,708 events) and black stars those with *H* phases (42 events). One event includes both. Blue triangles denote hydroacoustic stations in Operations. From *Johansson and Mialle* (**T4-P31**).

6

Earth Characterization

INTRODUCTION

Many properties of the earth have an impact upon the processing and interpretation of verification-related data, and our imperfect knowledge of these is a major factor limiting the accuracy and reliability of results derived from verification-related observations. This applies equally to observations made by the IMS, during an OSI, or using NTM. This Section is dedicated to contributions on the determination of those earth properties which may be relevant to verification, including the methods used to determine those properties and their validation.

For the location of events using seismoacoustic methods, the most fundamental requirement is an accurate knowledge of the relevant wave-speed fields. The solid earth, the oceans and the atmosphere are very different media, and determining the speed of seismoacoustic waves in these media poses a range of different issues. For the solid earth, the *P* and *S* seismic wave-speed fields are static under normal conditions, and are well-known on a large scale, but regional and local variations in the top few hundred kilometres, especially in subduction zones and other plate-boundary regions, can be large, and these local variations continue to challenge seismologists. The determination of wave speed in the earth's crust and uppermost mantle is therefore an important subject in the quest for more accurate locations of earthquakes and underground explosions. For passive or active seismic methods used in an OSI, seismic wave speeds must be determined on a local scale, and the values may be refined using the seismic data acquired during the OSI itself.

Acoustic wave speeds in the oceans pose less of a problem, with the vertical wave-speed profile well known and effectively constant throughout the oceans for the purpose of event location. Small temporal variations, in particular long-term trends, may provide potentially valuable information on climate change because marine acoustic wave speed is a proxy for ocean temperature.

The determination of acoustic wave speed in the atmosphere poses a very different set of problems. Although the atmosphere is more accessible to direct measurement than is the solid earth, the wave speed varies not only spatially, but also on a range of timescales from diurnal to seasonal, with variations often rapid and having a major impact on travel times, signal classification and event location. Accurate location of events in the atmosphere recorded by infrasound stations will therefore require separate determinations of the wave-speed field for each time interval; this demanding requirement forms one active area of investigation.

Anelastic attenuation of seismic waves within the solid earth is another important property for verification because it strongly affects the amplitude and frequency content of seismic waves, which in turn control the estimation of event magnitude and the ratio of magnitudes measured at different frequencies. Seismic magnitudes are important in source identification and have implications for estimating the yield of any underground nuclear explosion. Although the Treaty is comprehensive (so in principle the determination of yield will not be required to establish a Treaty violation), anelastic attenuation remains a major factor controlling the detectability of small signals at individual seismic stations, and hence network capability.

Attenuation of acoustic waves in the oceans is negligible, as evidenced by the detection of very small in-water events at very long range. Attenuation of acoustic waves in the atmosphere is, however, important in the transmission of infrasound, and studies have to consider also its directional dependence resulting from its relationship to (especially stratospheric) wind direction.

The distribution of earthquakes in space and time, referred to as seismicity, is another characteristic of the earth which is important in verification, if only because global seismic monitoring is dominated by signals from earthquakes. Seismicity is closely related to earthquake hazard, whose estimation is one of the many potential civil applications of IMS data. This is highlighted by the large number of contributions on earthquake hazard, and they are included in this Section. Contributions on earthquake focal mechanisms (moment tensors) form part of source identification, so are considered in **SECTION 7**; they are also included in this Section if the results are used to estimate tectonic stress, since this itself is an aspect of earth characterization.

In order to estimate the origin of any observed radionuclide, or to predict where and when a radionuclide emitted from a real or supposed source may be subsequently detected, an appropriately detailed knowledge of the three-dimensional pattern of atmospheric motion is required. For the global network of IMS stations, this information is required on a global scale, and for OSI there will be a similar requirement at a much smaller spatial scale in the region of interest (that is, an inspection area of up to 1,000 km^2 [22]). These requirements are addressed using ATM. Patterns of air circulation are retrieved from the simulations of global meteorological models, which are merged with the massive datasets of meteorological observations made continuously or at regular intervals of time throughout the world. These measurements are processed to generate uniform grids of values at successive time intervals, which are retrieved by CTBTO routinely. They constitute a crucial input to an atmospheric transport model run either in a backward mode ('backtracking') or forward mode; these modes are designed to trace respectively the origin, or the fate, of atmospheric air content, as explained in this Section.

The identification of a well-contained underground nuclear test using radioactive noble gas depends upon the ability of this gas to escape from the detonation point to the earth's surface. This ability may be influenced by many factors, including the state of the surrounding material after detonation, pre-existing and explosion-generated fractures, the permeability of the local geology, the barometric pressure prevailing at the time, and the locality of the test. So this represents a further use of meteorological data in verification, and requires estimates of permeability and other properties of the rock in the neighbourhood of the explosion site.

6.1 SOLID EARTH

6.1.1 SEISMIC WAVE SPEED

Wave-speed variations resulting from subduction zones and crustal heterogeneities result in maximum travel-time anomalies for signals recorded at regional distances (less than about 2,000 km). Many investigations of these anomalies are therefore local investigations, designed to measure these anomalies and hence calculate travel-time corrections in the region of one seismic station or a local seismic network. For example, *Midzi et al.* (**T1-P14**) invert travel times computed for events recorded by the South African National Seismic Network (SANSN) to obtain a one-dimensional wave speed model for South Africa. In another contribution, *Nguyen et al.* (**T1-O14**) determine crustal thickness and the ratio of *P*- and *S*-wave speeds from teleseismic observations, and *Kugaenko et al.* (**T1-O17**) determine the crustal wave speed structure beneath Petropavlovsk, where IMS primary seismic station PS36 (PETK) is located.

Wave-speed anomalies can alternatively be computed using seismic surface wave observations, and *Boschi et al.* (**T1-P22**) present a method to determine

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Determination of Seismic Wave Speeds

The speeds at which seismic waves travel within the earth must be known if events such as earthquakes and underground explosions are to be accurately located. Bearing in mind that the maximum area for an OSI will be 1,000 km^2 [22], it is clear that any potentially suspicious event must be located as reliably as possible, and to an accuracy that is itself measurable.

Event locations and their origin times are estimated from the arrival times of signals observed at different seismic stations; information on the direction along which these seismic waves emerge at each station (expressed as 'back azimuth' and 'slowness') may also be used, especially at seismic arrays. An event is located by optimizing the fit of distances and directions to each station, which are computed from the observations. Because seismic signals provide time rather than distance information, the importance of wave speed arises from the requirement to convert time to distance using one of the basic equations of physics:

distance = speed × time.

The essential difficulty in measuring seismic wave speed is that we cannot get inside the earth to measure it directly at each point. So a reformulation of the same equation, speed=distance/time, must be used to estimate the average wave speed along paths from events with known locations to observing stations (whose locations are, of course, also known). If observations from many intersecting paths sampling the whole earth's interior were available, then in principle the wave speed at each point within the earth could be resolved. Such a process forms the basis of 'travel time tomography'.

Unfortunately, many factors conspire to limit the success of this and other approaches to determining the wave-speed field within the earth. One factor is that the raypaths available are not uniformly distributed, and fail to sample adequately many parts of the earth. Seismic stations are almost exclusively on land (comprising only one fifth of the earth's surface) and the distribution of earthquakes is even more restrictive, being mainly confined to the well-known boundaries of tectonic plates. Moreover, augmenting the data with experiments using chemical explosions can only scratch the surface of the deficit. This under-sampling imposes a fundamental limitation. Another problem is that events are not at 'known locations', except perhaps for a few explosions. To determine wave speed it would be desirable to use signals from events (normally explosions) whose location and origin time are precisely known; there are very few such events and they are not well-distributed.

Even for suitable combinations of seismic source and recording station there are difficulties in measuring both the travel time and the distance along the ray. Difficulties measuring the travel time begin with the measurement error of the arrival time observed on the seismogram. This is always measured in the presence of background noise, and the signal may emerge slowly from that noise. Subtraction of the origin time to obtain the travel time reveals the fact that the origin time, at least for earthquakes, is never known exactly, and has to be determined together with the location using a redundancy of observations. For an explosion, the event time may be precisely known, but the sparse distribution of large explosions over the globe makes the use of earthquake observations essential in the determination of wave speeds at depth.

The measurement of distance along the path poses different problems. The path is not straight, but curves through the earth in a way that is itself determined by the spatial variation in wave speed: the path is refracted towards high-speed regions and away from low-speed regions within the earth.

To minimise errors in wave speed calculations arising from inadequate knowledge of source location, seismologists make a careful selection of those events whose locations are known most precisely. Such 'ground-truth' (GT) events are classified; for example, GT0 is reserved for explosions whose location and origin time are precisely known, and GT5 is used for events whose location is known to within 5 km. A reference list of such events is maintained under the auspices of the

International Association of Seismology and Physics of the Earth's Interior (IASPEI) and can be accessed through the ISC (see also SECTION 9.4).

The various issues touched on above give rise to what is referred to as an 'under-determined problem'; there is a deficit in the data required to obtain a well-constrained and unique result. Geophysicists, especially seismologists, are very familiar with such problems, and have devised ways to tackle them.

Despite the difficulties, a rough profile of seismic wave speed within the earth has been known since the 1930s. One factor in particular has made this possible. Except near the surface, seismic wave speed tends to depend only upon depth, to a very good approximation. This gives rise to a 'one-dimensional model'; throughout the history of seismology, the determination of location using a global network of stations has used such a one-dimensional wave-speed model as a starting point. To refine this, it has been standard practice to allow for local deviations in wave speed by applying a correction to the travel time measured at each seismic station, and perhaps another time correction for each event location. In CTBTO, an example is the Source-Specific Station Correction (SSSC), which represents a combined correction for event location and station. Such corrections are most important for rays which sample the top few hundred kilometres of the earth's interior (so-called 'regional observations'), and this corresponds to station-event distances of less than about 2,000 km, or an epicentral distance of about 20°.

There is a large gap between the partial solution offered by a one-dimensional model refined by specific corrections, and the rigorous solution which would be provided by a comprehensive sampling of the earth by experimental ray paths. Various approaches are being used to reduce this gap from both ends—by enhancing the concept of travel-time corrections applied to a one-dimensional model, and by improving the methodologies and data used to determine three-dimensional models.

The process of estimating wave-speed models is perhaps less fraught than the process of validating them. At the end of the day, any wave-speed model is an imperfect estimate of the true picture. This imperfection gives rise to errors in location. This source of error is referred to as 'model error'. Another, and wholly separate source of error results from measuring the signals on seismograms recorded from the event that is to be located. This is referred to as 'measurement error'. The 'confidence ellipse' assigned to an event location estimate takes account of the measurement error, but (at least directly) does not account for the model error. This is worrying, because model error tends to increase 'bias', in which the location estimates of all events in one area deviate systematically from their true location. It is especially problematic if bias is not reflected satisfactorily in the confidence ellipse, and this places particular importance on the process of validating new wave-speed models. The ellipses assigned to event locations at CTBTO attempt to allow for model error, and these are sometimes referred to as 'coverage ellipses'.

upper mantle seismic wave speeds using surface wave tomography. The method is capable of spatially varying resolution depending upon available data, and can take account of the directional variation of wave speed (seismic anisotropy). A three-dimensional model for Europe is presented for the top 500 km. Seismic wave-speed anisotropy is a distinct field of study on account of its importance in investigating other properties such as the orientation of fluid-filled cracks and the orientation of the ambient stress field; it is usually not taken into account in models used for the determination of event location. In a study based on the Fiji area, *Bokelmann* (T1-P7) discriminates between different characteristics of seismic anisotropy in the fore-arc and back-arc regions.

Wave-speed anomalies have traditionally been represented as station-specific travel-time corrections applied to a standard wave-speed model which usually varies only with depth (a 'one-dimensional model'). *Lin and Russell* (T4-P17) compute travel-time corrections for a range of IMS stations for use with the NET-VISA algorithm.

Although wave speed may vary gradually, either with depth or laterally, of equal importance is the presence of discontinuities in wave speed, which represent seismoacoustic boundaries and give rise to reflection and refraction of signals, and hence to additional signal arrivals. *Helffrich et al.* (**T1-P27**) use reflected phases observed from earthquakes at teleseismic distances by stations of the local virtual seismic network in northeastern Italy operated by the National Institute of Oceanographic and Experimental Geophysics (OGS); these observations are used to identify and locate upper mantle discontinuities.

Crucial to the validation of wave-speed models, as well as to their determination, are those events (either earthquakes or explosions) whose location and/or origin time are precisely known. Lists of such 'ground truth' events are compiled, and under the Treaty they can form part of 'confidence-building measures'[36]. A global list of such events is maintained as the IASPEI Reference Event List, and is described in **SECTION 9.4**. *Mikhailova and Sinyova* (**T5-P6**) describe two proposed ground-truth chemical explosions, one in Kazakhstan and the other in Kyrgyzstan.

With a focus on regional distances, which are most in need of wave-speed model refinement, and recognizing that regional observations can degrade the quality of event locations, *Myers et al.* (**T4-O3**) introduce a new platform intended as a starting point for the introduction of improved regional wave-speed models (and hence travel times) in different regions of the world. Referred to as Regional Seismic Travel Time (RSTT), this provides for a three-dimensional variable-thickness crust, above a laterally varying upper mantle underlain by a wave-speed gradient. A variable-resolution global tessellation allows for varying data coverage. Travel-time tomography is used to prepare models for Eurasia and North America, and it is intended to compute models for other regions as suitable datasets are made available.

Nissen-Meyer et al. (**T4-O7**) review the issues involved in the inversion of seismic waveforms to yield three-dimensional earth structure and source mechanism. He describes a method which offers high-frequency three-dimensional full-waveform modelling, and back-projection of waveforms to yield source parameters.

For the purpose of improving event location, studies focus mainly upon *P*-wave speed, because *P* waves provide the vast majority of, and the most accurate, arrival time observations. The speed of *S* waves is related to that of *P* waves, and for a Poisson solid, which has equal Lamé parameters and a Poisson's ratio of 0.25, the ratio of the *P*- and *S*-wave speeds is equal to the square root of three. Attempts have been made to observe a temporal variation in this ratio as a precursor to large earthquakes. *Sodnomsambuu* (**T1-P24**) considers this in the neighbourhood of Ulaanbaatar, Mongolia, where active faults and recent seismicity have raised questions about seismic hazard.

6.1.2 ANELASTIC ATTENUATION

Anelastic attenuation is the loss of energy from a propagating waveform due to internal friction resulting from the propagation medium not being perfectly elastic. This results in a progressive decrease in the amplitude of the travelling waveform. In a given medium, a proportion of energy is lost per wavelength; this loss is proportional to $1/Q$, where Q is the quality factor. It follows that higher frequencies attenuate more over a given distance, so a transient signal is progressively deprived of its higher-frequency components. There is ample experimental evidence for this behaviour, and the lower frequency of an attenuated signal may be more noticeable to a casual observer than the reduction in amplitude. If the proportion of energy lost per wavelength is independent of frequency, this results in a 'constant Q model', but over a wide frequency range evidence suggests that Q increases with frequency.

Anelastic attenuation, together with various scattering mechanisms, can have a major effect on the measured signal amplitude, and hence upon the calculated event magnitude, though few contributions are devoted to its study. The presentation by *Al-Hussaini and Al-Noman* (**T1-O10**) includes an attenuation model for Bangladesh determined from seismic intensity isoseismals, but this is derived for seismic hazard estimation and is restricted to the upper crust. Similarly, *Chafwa* (**T1-P2**) presents an attenuation relationship for Zambia, and *Semin and Ozel* (**T1-O15**) consider attenuation in central Anatolia, Turkey; in both cases these are for earthquake hazard estimation. *Rezaei and Safepour* (**T1-P40**) consider attenuation parameters for the Iranian Plateau, Iran.

The contribution of *Chun* (**T2-P2**) illustrates the importance of anelastic attenuation in source identification, through the determination of magnitude. This author's near-regional investigation of the announced nuclear tests in the DPRK includes the determination of an attenuation model for *Lg*, which reveals much higher attenuation than in previous estimates. Estimates of attenuation with distance for *Lg* is complicated by the effect of source depth, but in any case the author reports a major implication for the magnitude-yield relation applied to a supposed nuclear test, and for any discriminant based upon the magnitude of *Lg* (see **SECTION 7.3.3**).

6.1.3 TECTONIC STRESS

One method of measuring the orientation of large scale stresses within the earth associated with plate tectonics is to examine the focal mechanisms of earthquakes. In the past, 'earthquake fault-plane solutions' were used to estimate tectonic stress, under the widely accepted assumption that the earthquake mechanism could be represented by a double-couple equivalent force system. Methods utilising whole-waveform data led to the computation of 'moment tensors', in which the equivalent force system is generalized to any set of three orthogonal dipoles.

Wéber (**T3-P16**) presents moment tensor determinations for earthquakes in the Pannonian Basin (Hungary and the surrounding region). His method solves also for the isotropic (volume-change) component of the moment tensor, which is found to be insignificant as expected for an earthquake source. The moment tensors are also reported to be consistent with the onset polarities, which would be used to determine a classic fault plane solution. Moreover, he reports that the principal stress axes of the moment tensors, which indicate pure strike-slip or strike slip with a thrust component, agree with the stress pattern determined from other data. Another study using earthquake mechanisms is presented by *Quoc et al.* (**T1-P16**), who present historical fault-plane solutions for the Manila subduction zone (Philippines) to estimate tectonic stress and recent crustal movement. Focal mechanisms of earthquakes in the Azerbaijan region are presented by *Babayev and Gadirov* (**T1-P44**), with a stress map for the Caucasus region.

6.1.4 SEISMICITY AND SEISMIC HAZARD

The worldwide distribution of earthquakes, referred to as seismicity, has a major impact on the effort required to detect underground nuclear tests simply because such tests must be detected against a 'background' of many earthquakes large and small. Earthquake seismicity is itself a characteristic of the earth. It has provided crucial evidence of plate tectonics. Indeed, the characteristic linear pattern of earthquakes following tectonic plate boundaries provides the most obvious link to plate tectonics. But earthquakes can occur anywhere, so the location of an unidentified seismic event either in a region of high seismicity or of low seismicity cannot of itself say anything about the likelihood that such an event is a nuclear test. Of more importance in CTBT verification is that all possible events must first be detected and located, as a prerequisite to the identification of potential Treaty violations, and the highly non-uniform distribution of earthquakes may have implications for the design of the optimum global seismic network.

The study of earthquake seismicity leads directly to the estimation of the seismic hazard posed by earthquakes, on which there are several contributions relating to different localities. For example, *Al-Hussaini and Al-Noman* (**T1-O10**) describe ground-motion studies for critical sites in northwest Bangladesh, presenting seismicity and probabilistic seismic hazard analysis. *Babayev and Gadirov* (**T1-P44**) describe the seismic hazard in Azerbaijan, and present maps of maximum past seismic intensity and peak ground acceleration, as well as of maximum expected earthquake magnitude. *Chafwa* **T1-P2** present seismicity and a seismic hazard map for the Zambia area. The IMS auxiliary seismic station AS003 (GNI) at Garni, Armenia, is used by *Arzumanyan*(**T3-P7**) for earthquake hazard studies in that area, and *AllamehZadeh* (**T1-O11**) uses artificial neural networks for pattern recognition to investigate the spatiotemporal distribution of earthquakes with reference to pre-earthquake quiescence and paired earthquakes in Iran. He explores the 'Mogi doughnut' concept[37], which has been used in an attempt to predict earthquake aftershocks.

Many approaches are used to gather observations relevant to seismic hazard estimation. *Shanker et al.* (**T1-O16**) describe many geological incidents that have occurred in Kerala State, India during 2001, ranging from seismicity to changes in the height of the water table measured in boreholes. Reliable seismic hazard estimation requires estimates of the maximum acceleration which is likely to be suffered at a given location. *Louie* (**T1-O9**) reports on developments in the determination of shake zoning for earthquake hazard definition being carried out by the United States

Geological Survey (USGS). Three-dimensional wave propagation is applied to geological and geotechnical datasets in order to estimate wave effects observed at different locations. The quality and resolution of datasets limit the results achievable, but the example of southern Nevada, USA, is used to demonstrate the potential of the method when high-resolution datasets are available.

Earthquake hazard mapping leads to the concept of earthquake early warning (described in **SECTION 5.1.2**), which uses strong-motion seismograph signals to warn of the occurrence of a damaging earthquake before the seismic waves reach a location at some distance from the epicentre. Such a system is described by *Kislov and Gravirov* (**T3-P9**). An alternative method proposed for earthquake early warning uses remote observation of magnetic signals triggered by earthquake rupture. This possibility is considered by *Karimov* (**T3-P45**). In another contribution (**T1-P47**) *Karimov* considers the forecasting of aftershocks from anomalies in the geomagnetic record.

A specific example of a local seismicity study is provided by *Eloumala Onana* (**T1-P35**) who investigates an anomalous distribution of earthquakes along the Cameroon volcanic line, as part of an investigation into the origin of explosive release of gas from Lakes Monoun and Nyos. Among the anomalous characteristics found is a temporal change in seismic *b*-value in the Gutenberg-Richter relation. Spatial and temporal variation in the *b*-value of the Gutenberg-Richter relation is investigated by *Nugraha* (**T1-P6**) for seismicity north of Sulawesi, Indonesia, and is interpreted in terms of ambient stress in different localities. Local seismicity of the western arid (Northern Cape) region of South Africa is presented by *Malephane* (**T1-O13**), determined using observations from the SANSN.

6.1.5 SUBSURFACE GAS TRANSPORT

The release of gaseous radionuclides from an underground test is influenced by many factors, only one of which is the intrinsic permeability of the emplacement medium. In most near-surface geological conditions, the bulk permeability is controlled mainly by the presence of fractures as migration pathways, which are very specific to local geological conditions and likely to be modified by the nuclear test itself. *Miley* (**T2-O1**) considers the factors contributing to the detection of radioactive gas from an underground test, and proposes experiments designed to improve the knowledge of expected behaviour. Also proposed are experiments at the site of an existing nuclear test cavity, and in different locations and atmospheric conditions with realistic fracturing and a realistic geometry. While concluding that fractures are more significant than distance in determining the release, *Miley* points out that barometric pumping is an important mechanism in determining the size and timescale of release. He also notes that the typical dilution associated with atmospheric transport from the source location to an IMS station might be something like 15 orders of magnitude, meaning that for a release which is too small to be detected by the IMS network, there is a much greater potential for detection during an OSI.

Another radioactive noble gas isotope, argon-37, which is not a fission product but relevant for OSI, is considered by *Purtschert and Riedmann* (**T1-O7**). They describe the global background in the atmosphere and in soil, and point out that argon-37 is a very sensitive indicator of elevated neutron flux, being potentially useful both for OSI and for global monitoring (IMS). They echo the role of barometric pumping in promoting the release from an underground source, but point out that an elevated water table can have a major adverse effect on the effective permeability.

There is a lack of understanding of the processes which control the migration of radioactive gases in the subsurface, and this is identified as an active research topic by *Ingraham and McIntyre* (**T2-P15**). *Ustselemov* (**T2-P17**) considers the mechanisms which can promote or inhibit the migration of radioactive particulates and gases from the site of an underground nuclear explosion towards the surface, with several scenarios being presented together with information on the corresponding inventory of radionuclides on the surface and in the atmosphere.

6.2 OCEANS

There are no contributions specifically related to the determination of physical properties of the oceans. Variations in the acoustic wave speed and attenuation in the oceans are such a small percentage of their mean values that carefully controlled experiments are needed with very precise controls on source and receiver positions. The absence of ground-truth locations for larger underwater acoustic sources usually makes this impossible. Work on using earthquake *T*-phase observations to probe ocean structure may be reported in the future.

The rapid displacement of a large mass of water during some large undersea earthquakes gives rise to a tsunami which can propagate for thousands of kilometres across an ocean, resulting in inundation of coastal areas for up to several kilometres inland, even at such distances. Characteristics of the coastline and shallow bathymetry can focus a tsunami to create devastating high-amplitude 'run-up', for example in bays and estuaries; these effects have been known since ancient times as pointed out by *Parkes* (**T5-P30**). Researchers now attempt to predict tsunami behaviour for disaster mitigation using numerical simulations.

Shanker (**T1-P42**) describes key characteristics of a tsunami, and basic steps to be taken when designing coastal defences and recreational areas. Numerical simulation is used by *Setyonegoro* (**T1-P1**) to model maximum tsunami height resulting from a source model for the 26 December 2004 tsunamigenic earthquake in Indonesia, and *Prachuab* (**T5-P29**) describe the earthquake monitoring and tsunami warning system that was established in Thailand following that earthquake, including tide gauge stations and buoys. For the same earthquake, *Dissanayake Mudiyanselage Don* (**T1-P43**) uses remote sensing to provide observational data on inundation in Sri Lanka; such data are important for testing the validity of numerical simulations. *Takenaka et al.* (**T1-P36**) use the finite difference method to model pressure change in the sea from acoustic and tsunami waves excited by a sub-ocean earthquake. With the specific case of Japan in mind, *Setyonegoro* (**JS-P3**) points out that, for estimation of risk, predictions of run-up and inundation have to be computed for all possible earthquake source parameters and locations.

The oceans are subjected to tidal forces which create the familiar tidal periodicities of a half a day to one day. Waves on the sea surface, referred to as gravity waves since they result from gravitational forces acting to restore a planar sea surface after the water is disturbed, have much shorter periodicities of up to several minutes. *Sugoika et al.* (**T1-P3**) present evidence of coupling between these two wave types, using arrays of broadband seismometers in the deep ocean, and they support their observations with theoretical arguments.

6.3
ATMOSPHERE

6.3.1
ACOUSTIC WAVE SPEED

Blanc (**T1-01**) includes an overview of infrasound propagation in the atmosphere, emphasising the control exerted by the atmospheric temperature and wind-speed profiles on the acoustic wave-speed profile and its seasonal variation (**FIGURE 6.1**).

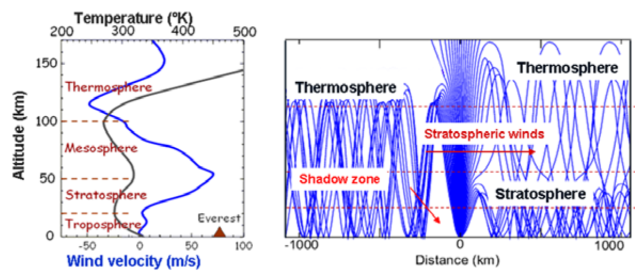

FIGURE 6.1
Acoustic ray tracing used to show the propagation of infrasound waves in the atmospheric waveguide formed by the temperature and wind variations in the different atmospheric layers. From *Blanc* (**T1-01**).

This author also shows how gravity waves and planetary waves in the atmosphere are a complication, but a welcome one to the extent that in general they serve to perturb the atmosphere in ways that increase the detection capabilities of infrasound monitoring for nuclear explosions. *Evers et al.* (**T4-08**) include a description of basic wave-speed properties of the atmosphere, highlighting shadow zones caused by wave-speed decrease with height. Their contribution considers anomalous infrasound propagation through the stratosphere (about 8 to 50 km above the earth's surface), and points out the potential for scientific advances using passive acoustic remote sensing.

Pilger et al. (**T1-P17**) also consider the modelling of infrasound propagation in pursuit of improved acoustic wave-speed information as required to locate infrasound sources relevant to CTBT monitoring. They use an improved version of the three-dimensional Hamiltonian Acoustic Ray-Tracing Program for the Atmosphere (HARPA) at the German Aerospace Center (DLR) to investigate the influences of atmospheric conditions and topography, by varying the temperature and wind profiles. A pure climatological model, independent of observational data, is used

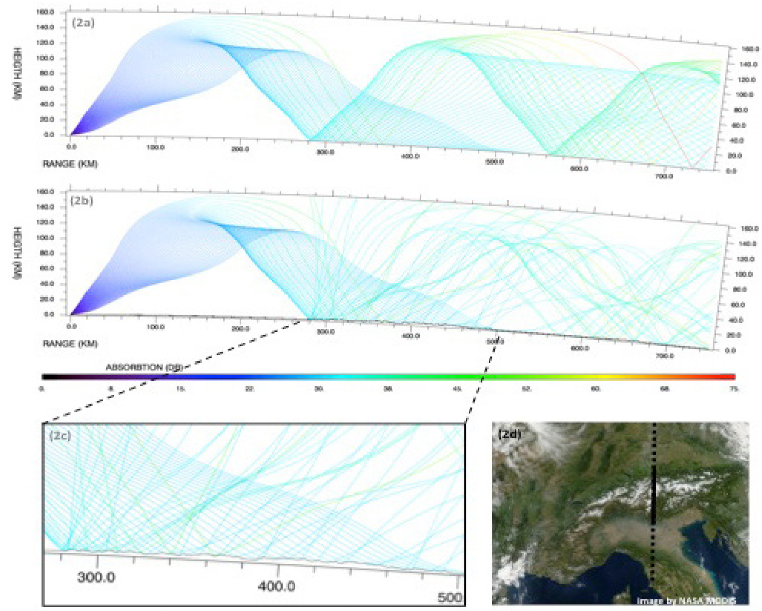

FIGURE 6.2
HARPA/DLR infrasound propagation modelling over flat and realistic terrain, for 19 July 2010 from 50.10°N, 10.58°E southwards in the German/Austrian/Italian Alps (see bottom right). Top: Orography based on flat terrain with earth curvature. Middle: Orography based on realistic terrain using the Shuttle Radar Topography Mission (STRM) terrain model for a north-south cross-section of the Alpine ridge. Lower left: detail of the terrain cross-section and infrasound ray reflections due to this orography. From *Pilger et al.* (**T1-P17**).

above 100 km. At lower levels, observational data including satellite data and numerical weather forecast profiles of wind and temperature from the European Centre for Medium-Range Weather Forecasts (ECMWF) are used. It is concluded that at these lower levels temperature and wind can be described in a more realistic way using satellite data and numerical weather forecasts, although the different models are not always compatible. These authors also consider the influence of topography on infrasound propagation arising from extensive scattering due to topographic irregularities; an example is shown in **FIGURE 6.2**. They recommend using surface topography information as well as satellite-based remote sensing in CTBT-related calculations of infrasound propagation properties.

Golikova et al. (**T1-P29**) consider the fine structure of the atmosphere, including anisotropic fluctuations in wind speed, and the effect of absorption. The importance of small-scale structures in the atmosphere is also considered by *Blanc* (**T1-01**), who points out the importance of localized reflectors complicating the wave-speed profile.

As an aid to understanding the influence of the atmosphere on the long-distance propagation of infrasound, an infrasound calibration experiment was conducted in the Middle East and the surrounding region during January 2011. Large surface chemical explosions were detonated, and were recorded by IMS infrasound stations, as well as by IMS auxiliary seismic stations and many temporary infrasound stations deployed for the purpose. The January 2011 experiment, which included a 10-tonne detonation on 24 January followed by one of 100 tonnes on 26 January, was accompanied by an infrasound workshop in Eilat, Israel, and is described by *Coyne et al.* (**T5-09**). The experiment clearly demonstrated the strong azimuthal dependence of signal propagation associated with stratospheric wind direction, in that only stations towards the east detected the signal; this contrasts (**FIGURE 6.3**) with the earlier experiment, conducted in summer, when detections were predominantly towards the west. The experiment also demonstrated the daily variation in wave-propagation characteristics resulting from the evolution of atmospheric conditions between the two detonations, as presented by *Mialle et al.* (**T5-P23**) and *Assink et al.* (**T5-P24**). The use of advanced atmospheric specifications and three-dimensional wave propagation methods appears to be essential when dealing with accurate source information, as shown by *Lee and Che* (**T3-P23**) in relation to remote volcano monitoring in east Asia. This is echoed by the work of *Wüst et al.* (**T1-06**), described in **SECTION 5.1.4**.

6.3.2 ACOUSTIC ATTENUATION

Infrasound waves suffer attenuation as they propagate through the atmosphere, and this attenuation has a major impact on the detectability of signals. *Blanc* (**T1-01**) reviews the latest measurements of

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Infrasound Calibration

The CTBTO has a strong interest in calibrating, validating, and testing its sensors and their effectiveness in detecting, locating and quantifying events. An important class of experiments measures the signals recorded on seismic, hydroacoustic, or infrasound sensors from events that are generated under controlled, or otherwise well-characterized, environments. The resulting ground-truth datasets provide important information on IMS capability.

Calibration activities related to infrasound monitoring are of particular interest, because as a relatively new technology, the IDC infrasound processing and analysis capabilities are being enhanced as the IMS infrasound network is progressively installed, and a ground-truth dataset is actively being assembled. Not only are infrasound sources highly variable, but the propagation medium itself varies significantly in space and time. Therefore, conducting atmospheric chemical explosions of known energy release under known conditions provides valuable data on the extent to which variables can be controlled in data processing.

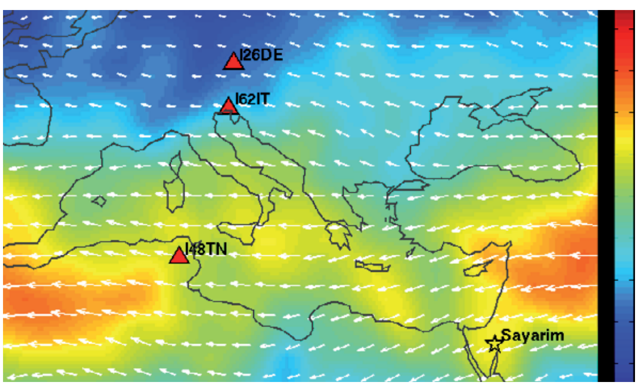
Two large-scale infrasound experiments were conducted over a wide region encompassing the Middle East, Europe, Africa, and Asia in August 2009 and January 2011. Their purpose was to test the IMS infrasound network and to verify infrasound propagation models. These experiments, which involved the detonation of surface chemical explosions at Sayarim in the Negev desert, Israel, were designed to record the contrasting consequences for infrasound recording associated with prevailing seasonally varying weather patterns, which favour recording towards the west in summer and the east in winter. In 2009, infrasound signals were observed to the west as far as Paris (3,400 km) and in 2011 to the east as far as Ulaanbaatar, Mongolia (6,300 km) (see SECTION 6.3.1 and FIGURE 6.2). International collaboration enabled temporary infrasound recording equipment to be deployed at sites up to a distance of 2,400 km from the source location. In the 2011 experiment, institutions from more than 20 countries set up a dense network of infrasound arrays in 13 countries. This work represents successful collaboration between the CTBTO and numerous institutions and States, and it demonstrates how international cooperation can provide major benefits to the development of the IMS.

These activities resulted in a comprehensive dataset in which the two 2011 explosions produced high-pressure shock waves in air in the range of 100–600 m, and infrasound signals were recorded by all near-field sensors and by numerous infrasound portable arrays deployed in the region. The infrasonic waves produced by the larger 2011 explosion were detected by the three IMS infrasound stations IS31 (I31KZ) in Kazakhstan, IS46 (I46RU) in the Russian Federation, and IS34 (I34MN) in Mongolia. Seismoacoustic signals were also detected by the regional auxiliary IMS seismic stations AS048 (EIL), AS049 (MMAI) and AS056 (ASF), and the event appeared in automatic and reviewed products of the IDC, including SEL3 and the REB.

These calibration experiments demonstrate vividly the complexity and variability of the atmosphere, and they underscore the value of large-scale calibration experiments using dense networks for improving our understanding of infrasound propagation and detection. Additionally, they provide a rich ground-truth dataset for detailed infrasound studies in the future. They are an important tool for helping to improve the calibration of IMS infrasound sensors and the enhancement of processing algorithms at the CTBTO.

However, there is still a lot to learn about infrasound propagation through a dynamic atmosphere. Current studies focus on modelling techniques, taking into account high resolution atmospheric specification and perturbation models for gravity waves, while other studies focus on propagation under specific weather patterns such as so-called ‘sudden stratospheric warming’. Such studies would benefit from future carefully designed infrasound experiments.

a)



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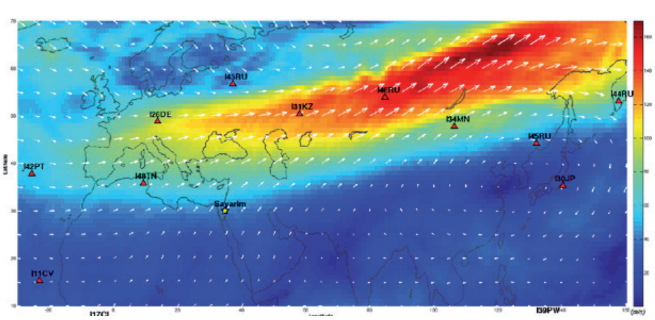

d)

FIGURE 6.3
Map contrasting the distribution of stations recording signals from infrasound calibration explosions conducted at Sayarim, Israel, in summer and winter, and its dependence upon stratospheric wind direction. **a)** The two IMS infrasound stations plus one IMS portable infrasound array (I62IT) that detected the explosion on 26 August 2009. **b)** Effective stratospheric wind speed and direction at 50 km altitude for 06:00 UTC on that day. **c)** IMS and temporary infrasound stations that detected (yellow dots) and that did not detect (white dots) the 26 January 2011 explosion. **d)** As **b)**, for 06:00 UTC on 26 January 2011. From *Coyne et al*. (**T5O9**) and the Annual Report of the CTBTO Preparatory Commission 2011.

atmospheric attenuation, which emphasize the strong dependence on wind direction, giving rise to the azimuthal variation in infrasound propagation governed by the stratospheric wind. In this regard, *Le Pichon et al*. (**T4-P39**) show the importance of using near-real-time atmospheric updates and station-specific real background noise levels when estimating the detection capability of the IMS network.

6.3.3
ATMOSPHERIC TRANSPORT

Topics of particular interest relating to the progressive enhancement of atmospheric transport capability include increasing the resolution (in both space and time) of ATM; the need to measure and allow for local effects, especially near IMS radionuclide stations in mountainous regions; the inclusion of additional factors such as rain washout, and the use of tracer experiments to validate atmospheric transport models.

Representative backtracking simulations require an adequate representation of the atmospheric circulation. For an observing station located in a region of rich topography, an adequate representation may require a mesoscale meteorological model configured at a finer resolution than the global meteorological models used for global applications. This is investigated by *Arnold et al.* (**T4-P24**) for the IMS radionuclide station RN38 (JPP38) in Takasaki, Japan, which is close to mountains with an altitude of 1 km. The standard one-degree resolution used operationally by CTBTO is compared with a nested model in which the maximum resolution is 0.67 km.

Koohkan et al. (**T3-O15**) present methodology for inverse modelling of atmospheric transport, supported by examples for which observed radionu-

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Locating the Source of Observed Radionuclides

The observation of a radionuclide at an IMS station or during an OSI leads directly to the question of its origin. As with a seismoacoustic event, this origin comprises four spatiotemporal coordinates: latitude, longitude, depth and a (possibly extended) time of release. In the atmosphere the transport of radioactive material, as with any small particulates or gases, is achieved primarily through the movement of the air mass, and the diffusive mixing that takes place as it moves. In principle, this applies both to radionuclides observed at stations of the global (but sparse) IMS particulate and noble gas networks, and to those observed during an OSI. However, the different spatial scales and various other factors pose rather different challenges in the two cases.

Central to this question is ATM, which seeks to describe the horizontal and vertical motion of airborne radionuclides as they migrate, together with the air mass, throughout the atmosphere. The three-dimensional motion of the air mass is estimated by means of a weather prediction model. Such a model uses observed weather data, together with the physical laws that govern the behaviour of the atmosphere. An atmospheric transport model can generally be configured to advance in time (‘forward modelling’) or go backwards in time (‘backtracking’). The former is favoured in a situation where the source location is known, and prediction of plume propagation is required. In order to constrain the possible origin of radionuclides detected at a station when the source is unknown, backtracking is preferred because it permits an efficient calculation of those regions within which any part of the air sample containing the observed radionuclides could have resided at successive times in the past. Multiple radionuclide detections at different stations can provide additional constraints on the source location.

For IMS stations ATM must be performed on a global scale, and CTBTO has a well-advanced capability to provide standard products and special analyses in support of the need to locate sources of radionuclides. Nevertheless, there is much scope for further improvement in resolution and precision, and the development of improved source location algorithms. The smaller-scale problem of supporting OSIs with an ATM capability is also receiving much attention. Moreover, there are many subsidiary factors affecting the transport of radionuclides which are not currently taken into account in the models calculated at CTBTO, such as wash-out by rain, and re-suspension from the earth’s surface by storms, forest fires and other phenomena.

ATM forms an integral part of investigations into the source of radionuclides observed in the atmosphere. In addition to constraining the location and time of release, ATM can also provide information on its strength, and possibly also its duration. ATM simulations can also offer negative evidence which may be of equal importance, for example by excluding the attribution of a radionuclide observation to a known radionuclide source such as a medical radioisotope production facility.

clide data are available; these include the Algeciras incident, and the Chernobyl and Fukushima nuclear accidents. Results show the potential for ATM to place constraints on the nature of the ‘source term’ (composition and time-history of the release into the atmosphere) as well as to predict the evolution of the resulting radionuclide plume. Also presented is work on the development of adaptive grids, in which the resolution of calculations is varied spatially in order to deal optimally with variations in the availability of data and the complexity of the ATM field. **FIGURE 6.4** shows an example for the IMS radioactive noble gas network. The need to pay special attention to local atmospheric transport effects in mountainous regions is exemplified by the contribution of *Regmi and Jha* (**T1-P13**), who assess the decoupling of near-surface air from regional flows in the Kathmandu valley.

Becker et al. (**T4-O9**) point out the limitations of current estimates of radionuclide concentrations

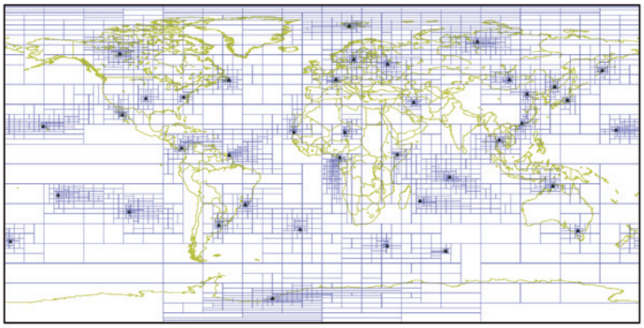
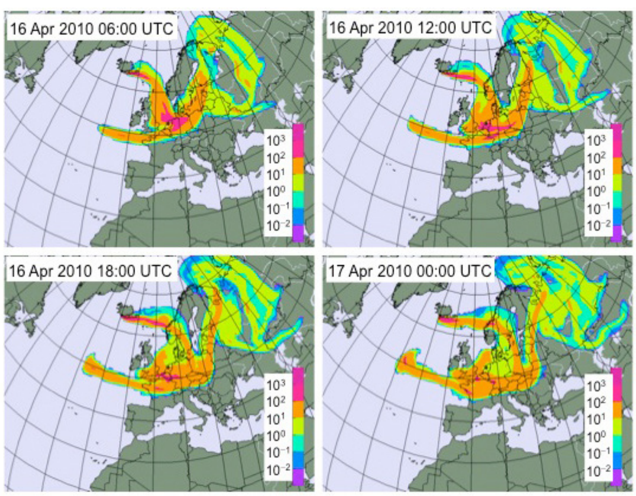
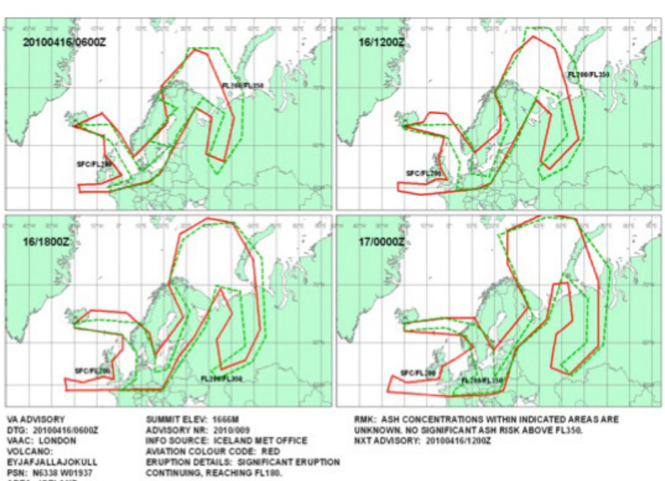


FIGURE 6.4
Adaptive model with 4096 cells of variable spatial resolution for optimum representation of variations in data density and ATM field complexity. This example is for the IMS radionuclide noble gas network, with stations shown as blue triangles. From *Koohkan et al.* (**T3-O15**).



a)



b)

within a plume, for particulate radionuclides which are susceptible to being washed out by precipitation. They present proposals for taking account of such loss mechanisms by including precipitation data in atmospheric transport calculations. They propose a new role for WMO's Global Precipitation Climatology Centre (GPCC) as a high-quality data source to parameterize the wet deposition factor.

Errors in ATM calculations lead directly to errors in the inferred source localities of observed radionuclides. *Matthews* (**T3-O4**) suggests that the occasional anomalous observations of sodium-24 at some IMS stations might prove useful in validating ATM models, since the cosmogenic origin of this isotope, combined with its favourable half life, make its observation a proxy for rapid vertical transport down the atmospheric column; such vertical transport could be compared with that predicted by ATM.

The contribution of *Elsässer et al.* (**T1-P28**) addresses the interpretation of cosmogenic radionuclide measurements made recently in the atmosphere, and those made on ice cores representing past occurrence. They point out that the interpretation of variations in terms of changing production rates requires understanding of past climatic changes which have affected deposition rates, so that the production signal can be separated from climatic modulations. These authors emphasize the importance of radioisotope ratios in resolving ambiguities in interpretation, including those of beryllium-7, beryllium-10 and lead-210. This potential example of 'civil and scientific uses' of IMS data is important to gain a fuller understanding of background signals which may be present in observations at IMS stations.

A very visible test of atmospheric transport models is provided by volcanic ash plumes (see **SECTION 7.1.3**), and the 2010 eruption of the Eyjafjallajökull volcano in Iceland offered a suitable opportunity. *Wotawa and Mitterbauer* (**T1-O5**) present ATM predictions of the evolution of the plume, which agree well with observation, as well as with the predictions of the Volcanic Ash Advisory Centre (VAAC) in London, UK (**FIGURE 6.5**).

FIGURE 6.5
a) ATM estimates of the ash plume from the 2010 Eyjafjallajökull volcanic eruption in Iceland, computed at intervals of six hours beginning 16 April 2010 06:00 UTC.
b) Official products of the London, UK, VAAC issued for the same times. Adapted from *Wotawa and Mitterbauer* (**T1-O5**).

7

Interpretation

INTRODUCTION

The interpretation of results obtained from observed data typically involves the comparison of those results with theoretical models, computer simulations, laboratory experiments or data from known sources. In the CTBT verification context, the most fundamental role for interpretation is the presentation of evidence for or against a potential violation of the Treaty. Hence, an important focus of contributions in this area is the description of the nuclear explosion source itself. Such description may be derived from theoretical studies or from observations taken from known nuclear explosions; both types of study are represented.

Interpretation not only requires knowledge of the nuclear explosion source, but also of anything which might be confused with it. For example, the identification of underground tests relies heavily on discriminating them from the multitude of earthquakes; an understanding of earthquake sources is therefore equally important. Likewise in the atmosphere, explosions need to be distinguished from other sources of infrasound such as volcanoes and bolides. It is also important that radionuclide observations can be interpreted as having originated from a nuclear test, as distinct from a medical radioisotope production facility or a nuclear power plant. So studies supporting the interpretation of verification data can cover a wide field.

It is important to remember that, at least for observations remote from the source, the seismoacoustic signature of an explosion is identical whether the source is chemical or nuclear. Although mining explosions are almost always a combination of multiple sources closely spaced in time and space, perhaps making them potentially identifiable as non-nuclear, the unambiguous identification of an explosion as being nuclear would normally be achieved using radionuclide observations—unless it were too large to render a chemical explosion feasible.

The Treaty provides that the CTBTO shall perform 'event screening' on IMS data, making the results available to Member States. Event screening is the application of standard approved methods of source discrimination to identify those events that may be confidently concluded to be of natural origin or non-nuclear man-made origin[38]. Event screening for the seismoacoustic waveform technologies begins with the computation of numerical values for 'event characterization parameters'. These parameters define characteristics of an event which may exhibit different behaviour for explosions and other sources (for example, earthquakes). One or more event characterization parameters may then be used in a formula to produce a 'score' for an event screening criterion; the formula is designed so that any positive score indicates that the event may be confidently 'screened out', with confidence increasing further for higher positive scores.

The goal of event screening is to reduce the number of events that could potentially be Treaty violations, while never to screen out such an event. This requires that the 'decision line', or threshold above which the score becomes positive, should be very conservatively defined, while at the same time endeavouring to screen out as many events as possible. A key objective of research into event screening methods is thus to reduce uncertainty so that the percentage of screened-out events can be increased without compromising the result for any nuclear test. It is important to remember, however, that although almost half of REB events are screened out with the current experimental event-screening criteria, most of the remaining events are either 'not considered' because they are believed to be too small for reliable application of the criteria, or because they have insufficient observed data.

Being 'experimental', the current waveform event screening criteria are subject to enhancement and improvement. Understanding the theory of different sources, and the observational data, will be crucial to this. It is also anticipated that additional event screening criteria will be added. For example, there are currently no event screening criteria for infrasound observations.

7.1 GEOPHYSICAL SIGNATURES

7.1.1 EXPLOSION

Since the IMS global network includes seismic, hydroacoustic and infrasound detectors, the most relevant geophysical descriptors for routine monitoring by CTBTO are seismoacoustic. Other geophysical monitoring methods may be of interest for possible future inclusion into the IMS, or for use in verification by States. A number of additional geophysical methods are permitted during an OSI, as specified in the Treaty[21].

The source-time function of an explosive source is considered by *Ziolkowski* (**T2-O8**). By invoking a scaling law in which the signal scales as the cube root of the charge size (or energy), the author is able to extract the source-time function for small explosions by releasing two shots of different sizes at the same point and recorded at the same receivers (so that the path effect can be assumed to be identical and thus cancels out).

It is expected that an underground nuclear test would create a surrounding zone of deformed and shattered rock, which could act as a scatterer of seismic waves. *Kishkina and Spivak* (**T1-P15**) aim to model this by considering the effect of such a zone on a plane wave incident from below, and thereby to observe the effect as a change in the spectral properties of seismic noise observed on closely spaced three-component seismometers at or near the surface. Such an effect might locate an observational target for passive seismic monitoring during an OSI.

The release of tectonic stress associated with underground nuclear explosions has been postulated on various occasions. In a study of the DPRK-announced nuclear tests in 2006 and 2009 using regional observations from the Dong-bei Broadband Network, *Chun* (**T2-P2**) notes that tectonic release has been postulated for the second event by some authors, but concludes that no such release is necessary to explain the observations. *Dalguer et al.* (**T2-O4**) consider whether a large explosion may have the capacity to trigger a tectonic earthquake at a distance. Using numerical simulations they show that a 150-kt explosion could in principle trigger a vertical strike-slip earthquake of moment magnitude 6.6 at a distance of 2 km from the explosion, and that an explosion of 100 kt could induce small earthquakes.

The related question of whether, and if so under what conditions, an underground nuclear test might give rise to 'aftershocks' is an important one for OSI, which includes provision for passive seismic monitoring to detect such aftershocks. It is perhaps natural to expect seismic signals from cavity collapse or other collapse phenomena at some point after the detonation, but an alternative mechanism for generating aftershocks would be made possible if adjustments to the ambient local stress field, or to the effective strength of the local rock, resulted in the triggering of tectonic microearthquakes. *Ford et al.* (**T2-P13**) apply the characteristics of earthquake aftershock statistics, including Omori's law, the Gutenberg-Richter relation, and plausible scaling factors for different emplacement rock types, to nuclear explosions of equivalent magnitude; this leads to inferred aftershock occurrence rates as a function of magnitude, time and distance from the explosion. Comparison is made with empirical data on aftershocks recorded for larger nuclear explosions at the Nevada and Semipalatinsk test sites.

Another issue of interest is the generation of shear waves (*S* waves), including *Lg* and Love waves, by explosions. A pure explosive source cannot generate shear waves, but shear waves can be observed as a result of the interaction of longitudinal waves (*P* waves) with boundaries and other structures along the path; they may also be observed if the source is not purely explosive. *Rubinstein et al.* (**T2-P14**) present analysis and modelling of explosion wavefields observed at the San Andreas Fault Observatory. Chemical explosions are observed at a distance of between zero and 20 km at surface seismic arrays and deep boreholes, especially to examine *S*-wave generation. With simple and impulsive *P*-wave arrivals, *S*-waves are observed only when *P*-to-*S* conversions have occurred at lithologic boundaries, though adding a small vertical shear component directly above an explosive source improves the fit to observations for near-surface receivers that do not observe an otherwise predicted *P*-to-*S* conversion.

An explosion at the earth's surface is special in that it occurs at the boundary between solid and gaseous media, which results in complex energy partitioning especially at local distances. *Bonner et al.* (**T2-O11**) examine the energy partitioning between earth and atmosphere for the explosions of the 2011 Eastern Mediterranean infrasound calibration experiment, involving surface explosions at Sayarim, Israel. Observations are used to validate a method of calculating energy partitioning for explosive sources at a given distance below or above the earth's surface.

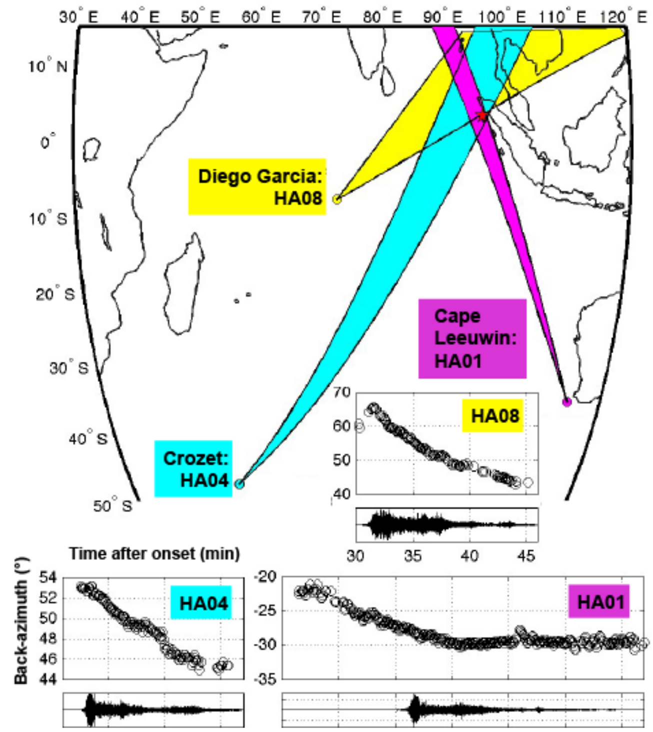


FIGURE 7.1
Back-azimuth versus time in minutes for signals from the 26 December 2004 Sumatra region earthquake observed at the IMS hydrophone stations Cape Leeuwin (HA01), Crozet (HA04) and Diego Garcia (HA08), showing the migration of the fault rupture northwards from the onset (red star on map). The map shows the corresponding azimuth ranges, indicating the mutual consistency of the observations. From *de Groot-Hedlin* (**T1-02**).

7.1.2
EARTHQUAKE

The source processes of large earthquakes typically involve the propagation of a rupture along an extended fault plane, which may extend for hundreds of kilometres in extreme cases. Several contributions study seismic recordings of the Tohoku earthquake of 11 March 2011 in order to describe its source process. *Tsuboi et al.* (**JS-01**) infer a rupture speed of 2 km s^{-1} and a slip of up to 49 m across the active fault, using synthetic seismograms calculated by the spectral element method. Teleseismic broadband data are used to determine a source rupture model. The complexity of the rupture is also studied in detail by *Meng et al.* (**JS-06**), who compare a range of source inversion results using local and teleseismic data at a range of frequencies. It is inferred that slip occurred mostly up-dip from the hypocentre (initial rupture point), and a number of possibilities are offered to explain the observation that high-frequency radiation is deep. A magnitude of 8.96 for the Tohoku earthquake is determined by *Hara* (**JS-02**) from the duration of high-frequency energy. By comparison with the Sumatra region earthquake of 26 December 2004, this author finds a shorter duration for high frequency energy, but with higher maximum amplitude.

The contribution of *de Groot-Hedlin* (**T1-02**) focuses on the value of hydroacoustic data in the study of large earthquake sources, especially in relation to earthquake dynamics. The 26 December 2004 Sumatra region earthquake is presented as the first example of hydroacoustic data used for this purpose, in which *T*-phase recordings at a hydrophone triplet of the HA08 (Diego Garcia) IMS station, 600 km from the epicentre, are used to estimate a rupture speed of

2.4±0.3 km s^{-1}, slowing to 1.5±0.4 km s^{-1} over a fault length of about 800 km. The results are shown to be consistent with observations from the two other IMS hydrophone stations in the Indian Ocean (**FIGURE 7.1**). Other studies, combining the hydroacoustic data with seismic data, are also presented. The author then reports work on the subsequent large Sumatra earthquake on 28 March 2005, together with a description of complications resulting from blockage of hydroacoustic signals by land masses and other factors. The focal mechanism and rupture characteristics of another tsunamigenic earthquake, the Mentawai (Indonesia) earthquake of 25 October 2010, are determined by *Pribadi et al.* (**T3-P1**). They confirm a predominantly dip-slip mechanism, which is typical of tsunamigenic earthquakes.

Seismic recordings offer the primary means to describe earthquake sources remotely. Earthquake focal mechanisms provide information on the local stress field, and the rupture characteristics of an earthquake lead to constraints on the physical properties of surrounding material as described in **SECTION 6.1**. Earthquake seismograms have traditionally been interpreted using the double-couple equivalent force system, which is consistent with fracture across a fault plane. More recently, algorithms which are used to estimate earthquake focal mechanisms have relaxed the double-couple constraint, resulting in moment-tensor estimations, though the double couple remains the preferred model for most earthquakes studied. Although many seismologists study earthquake sources in order to understand their properties and effects, the seismological component of CTBT verification requires only that a seismic source be identified as an earthquake, as distinct from an explosion. The focal mechanism, or moment tensor, which in essence is derived from the radiation patterns of seismic waves observed across the world, provides one potential method of achieving this discrimination. Thus earthquake mechanisms are an important topic in CTBT monitoring, as reflected in the contributions received.

Double-couple focal mechanisms for two earthquakes near Barkhan (Pakistan) are determined from teleseismic *P* and *SH* waves by *Tahir and Taiq* (**T2-P20**). They report results consistent with first-motion fault-plane solutions determined from local observations, and with the Harvard centroid moment tensor (CMT) solution. They infer the size of the fault plane from the spatial extent of aftershocks. *Wéber* (**T3-P16**) uses a Bayesian inference method to determine simultaneously location, focal mechanism and source-time function using short-period locally recorded waveforms from small earthquakes in the Pannonian basin of Hungary. Predominantly strike-slip mechanisms are obtained, with the conclusion that there is no significant isotropic (explosive/implosive) component in the moment tensor.

The triggering of (usually small) shallow earthquakes by the redistribution of ground water and its effect on pore pressure is considered by *Shanker et al.* (**T1-P4**), using examples in the Kakori area of Lucknow (17 June 2008) and Varansi, Uttar Pradesh (25 June 2008), both in India. Surface fracturing is reported from these events, which are thought to be promoted by alternate extremes of drought and flood, exacerbated by groundwater extraction.

Tahir and Grasso (**T1-P41**) discuss the suggestion that the rate of aftershocks following a large earthquake, and the distribution of their magnitudes (seismic *b*-value) depend systematically upon the class of faulting and slip direction (that is, the earthquake focal mechanism). They report a global study which suggests such a dependence, with the aftershock rate being greater than average for normal faults and less than average for strike-slip faults.

7.1.3 VOLCANO

Since a volcano can offer a source of infrasound at a known location, volcanic eruptions have the potential to be used as ground-truth events to validate atmospheric wave-speed models. Ash clouds emitted during volcanic eruptions can also be used as tracers to validate atmospheric transport models, including inversion methods to determine the coordinates of a supposed release. These CTBT-relevant topics offer a close synergy with scientific applications, especially in vulcanology.

Volcanic activity gives rise to a wide range of seismoacoustic signals; these may be recorded over large distances at seismic and infrasound stations, and in the case of submarine volcanoes, also at hydroacoustic stations. This range of signals reflects the diversity of source processes which may be associated with volcanic activity, including explosive eruption, pyroclastic flow, volcanic tremor, and microearthquakes. It follows that volcanic activity often gives rise to signals recorded on more than one type of seismoacoustic sensor, so it is a prime candidate for data ‘fusion’, or data synergy, between different recording technologies (**SECTION 5.1.5**). However, careful interpretation is required since eruptive events may be detected only on infrasound sensors, while associated but separate seismic events may be recorded only on seismic sensors.

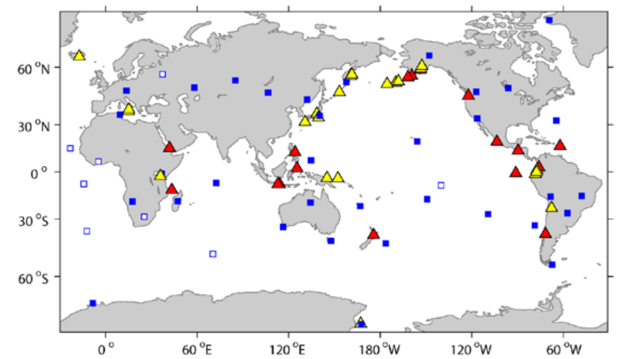


FIGURE 7.2
Volcanoes (triangles) studied by *Dabrowa et al.* (**T1-P33**) using IMS infrasound stations operating on 1 January 2010 (blue squares). Stations contributing detections are shown as filled squares, and detected volcanoes as yellow triangles.

An example of this is seen in the South Sarigan (Marianas Islands) submarine volcanic eruption of May 2010, which was recorded by IMS seismic, hydroacoustic and infrasound stations and is studied by several authors. *Green et al.* (**T1-O8**) show that the combined recordings allow a picture of the evolution of the activity to be built up, beginning with clusters of small explosive events, followed by a plume contained beneath the sea surface during which there is a progressive increase in activity. This is followed by continuous output from the vent, resulting in hydroacoustic tremor, and the plume breaching the sea surface, resulting in infrasound signals. Finally, paroxysmal activity dominated by two explosive events is reported. Requirements for correctly associating the various signals with the Sarigan activity are described, in particular the difficulty of associating infrasound signals on account of inadequate atmospheric wave-speed models.

Another study of the same South Sarigan activity by *Talandier et al.* (**T1-P18**) focuses on the paroxysmal activity and associated precursory tremors. Again, seismic, hydroacoustic and infrasound recordings are all reported, including many *T* phases, in addition to two small tsunamis recorded by a local tide gauge. *Talandier et al.* (**T1-P19**) consider the source mechanism of the main paroxysmal event and the extent to which it shows characteristics of an underwater explosion. They estimate a yield of the order of one kilotonne, with hydrophone signals that show characteristics of an explosive source but without a bubble pulse. Accordingly, they conclude that the source was not contained within the water column (as is confirmed from visual evidence of the plume).

Lee and Che (**T3-P23**) report seismic and infrasound recordings of explosive eruptions of the Shinmoe volcano, Japan from 26 January 2011 to mid-February. They use recordings at the seven arrays of the Korean Infrasound Network, South Korea, and two IMS infrasound stations. They echo limitations in event location capability arising from inadequacy of atmospheric wave-speed models. They point out a need to take account of both spatial and temporal variations in the quest to improve event location capability. They illustrate this need by refining their location algorithms using real-time atmospheric specification from ECMWF, combined with a propagation simulation tool (ray tracing).

Explosive volcanic eruptions in Kamchatka, Russian Federation, are the subject of a contribution by *Gordeev et al.* (**T1-O4**). They describe a long history of infrasound recording and signal classification in Kamchatka, with the first station installed in 1962. They point out that infrasound from a 1956 eruption was recorded at a distance of 10,000 km. Infrasound signals from the Bezymyanny eruption on 9 May 2006 are presented as an example, showing signals characteristic of explosive eruptions and pyroclastic flows. Modelling of atmospheric wave speed, together with recordings at seismic stations, is used to optimize travel times from the known volcano location.

A global study of explosive volcanic eruptions (**FIGURE 7.2**) using the IMS infrasound network is described by *Dabrowa et al.* (**T1-P33**). These authors show that detection is possible up to a range of 10,000 km, and they deduce a relationship between maximum signal range and plume height. They demonstrate the value of the IMS infrasound network in global volcano monitoring, and by implication a potential to identify volcanic sources from signal character and event location.

Infrasound signals of a more continuous nature are recorded from non-explosive eruptions. For example, in a study of infrasound signals recorded at the IMS station IS33 (I33MG) in Madagascar, *Randrianarinosy and Rambolamanana* (**T1-P20**) describe recordings from the Karthala shield volcano in the Comoros Islands.

Garces et al. (**T1-O12**) perform a systematic classification of volcano-related infrasound signals using neural networks, in order to classify the different types of eruption originating from volcanoes globally. This is motivated in part by the hazard posed by volcanic ash plumes to aviation, which is of concern to the International Civil Aviation Organization (ICAO), and is intended to provide supporting information to Volcanic Ash Advisory Centres (VAACs).

A study to determine the evolution of ash release over time as a function of height, referred to as the source term, for the March-April 2010 eruption of the Eyjafjallajökull volcano in Iceland is presented by *Seibert et al.* (**T1-P31**). A search is made to find the time-dependent vertical ash profile which, when inserted into forward atmospheric dispersion calculations, most closely matches the ash column values retrieved from satellite data. Interpretation of infrasound signals in terms of ash mass flux is also investigated, but with limited success in view of local noise and effects of local wind variations not included in the dispersion model. Estimates of the volcanic ash source term are also presented by *Wotawa and Mitterbauer* (**T1-O5**). Infrasound signals from the Eyjafjallajökull eruption, recorded at distances of up to 3,600 km, are studied by *Green et al.* (**T1-P21**), who find diurnal variations in signal that are evidently not related to the volcano source. It is concluded that diurnal variation in stratospheric solar winds caused by solar tides are a factor, though the modelling of this effect is complicated by other spatial and temporal variations in meteorological conditions. The role of volcanic ash plumes in validating atmospheric transport models is considered in **SECTION 6.3.3**.

A review of the role of infrasound in the monitoring of volcanoes and in the identification of different types of volcanic infrasound source, including some of the above examples, is included in the presentation by *Blanc* (**T1-O1**). The role of the IRED is emphasised as a platform for advancing knowledge of the infrasound signatures of different types of source, and hence identification of infrasound sources.

7.1.4
OTHER SOURCES

In a review presentation, *Blanc* (**T1-O1**) considers a range of infrasound sources in addition to earthquakes, explosions and volcanoes, including lightning, aurora, ocean swell, thunderstorms, mountain wind, sprites and meteorites. In a study of infrasound signals recorded at the IMS station IS31 (I31KZ), Kazakhstan, *Smirnov et al.* (**T4-P12**) report sources of continuous signal in addition to mining explosions. As well as microbaroms, they identify continuous signal from gas flares at a distance of several hundred kilometres. Another possible source of infrasound signals is large landslides, and this is considered by *Tumwikirize* (**T5-P27**), with reference to IMS station IS32 (I32KE) in Kenya, in a study of a landslide in eastern Uganda. The case of an earthquake triggering a landslide is considered by *Karimov and Saidov* (**T4-P7**).

A variation of the atmospheric explosive source is an explosion located at the earth's surface. Examples of this are provided by the infrasound calibration experiment conducted in the Middle East region in 2011, with surface explosion sources at Sayarim, Israel. This is described by *Gitterman et al.* (**T5-P31**). Regional infrasound observations from this experiment are studied by *Assink et al.* (**T5-P24**). The 80-tonne surface explosion was detected on three IMS infrasound stations to a distance of beyond 6,000 km, as reported by *Mialle et al*. (**T5-P23**) (see **SECTION 6.3.1**)

On meteorites, *Millet and Haynes* (**T1-P26**) point out that the earth accumulates 100 tonnes of extraterrestrial material per day. It follows that meteorites may be a significant source of infrasound signals. These authors consider infrasound signals from the Carancas meteorite of 15 September 2007 in Peru, recorded at the IMS station IS08 (I08BO) in Bolivia, 80 km from an impact crater attributed to this meteorite. They compute simulations to examine whether the primary meteor had fragmented in the atmosphere, as is normally believed to occur. They show that infrasound signals, together with other data, remain consistent with the possibility that the meteor did not fragment.

Infrasound signals from meteorites are also considered by *Edwards et al.* (**T4-P27**), in their contribution on seismoacoustic waves coupled between the earth and the atmosphere. They describe the Desert Fireball Network in Australia, which uses optical cameras to provide trajectory information on meteorites with the aim of recovering material reaching the surface. They propose to investigate infrasound as a possible additional method. The same authors report on a programme to use infrasound in the monitoring of shockwaves from launches carried out as part of the Hypersonic International Flight Research Experiment (HIFiRE).

Among the sources of infrasound signals examined by *Randrianarinosy and Rambolamanana* (**T1-P20**) using the IMS infrasound station IS33 (I33MG) in Madagascar, are lightning from thunderstorms, and microbaroms associated with two tropical cyclones that the authors are able to track for several days in the vicinity of Madagascar with the aid of azimuths determined using PMCC.

Several authors report on the recording of infrasound from large tsunamis. Although tsunamis are usually generated by earthquakes beneath the ocean, the tsunami waveform may be recorded directly by a seismoacoustic sensor, so can be regarded as a discrete type of seismoacoustic source in its own right. Tsunamis from the Sumatra region earthquake on 26 December 2004, and from the 11 March 2011 Tohoku earthquake are used as case studies by *Garces et al.* (**JS-04**); *Prior and Salzberg* (**JS-P1**) describe pressure signals recorded from the latter tsunami at the IMS hydroacoustic station HA11 (Wake Island). A tsunami can be recorded by seismometers, including ocean bottom seismometers, and by seismometers located on ice floes; examples of all these possibilities are presented by *Okal* (**T1-O3**).

Arai et al. (**JS-P7**) investigate the recording of the tsunami generated by the March 2010 Tohoku earthquake at IMS infrasound stations. They report modelling of the surface displacement of the water layer associated with the fault, which is believed to excite both the tsunami (the propagating water wave) and the Lamb's pulse (the propagating atmospheric boundary wave). The authors show observations at infrasound stations IS30 (I30JP), Japan, and at IS44 (I44RU) and IS45 (I45RU), Russian Federation. For corroboration, they compare these observations with predictions of the earthquake source mechanism and with signals observed on ocean-bottom pressure gauges.

Another source of infrasound signals is atmospheric tides, and these are studied by *Marty and Dalaudier* (**T1-P32**) using the IMS infrasound network. Atmospheric tides are gravity waves excited by diurnal solar heating of the atmosphere combined with convection of solar heat from the ground. Gravity-wave spectra are presented, and comparisons are made with other theoretical and observational data. IMS infrasound data are shown to provide high temporal resolution and accuracy, with the long duration of IMS records allowing study of tidal fluctuations from year to year. A study of gravity waves using a non-IMS network of infrasound stations in the Czech Republic is presented by *Sindelarova at al.* (**T1-P9**).

7.2
RADIONUCLIDE SIGNATURES

7.2.1
NUCLEAR EXPLOSION

Although the observation of radionuclides has the potential to provide unequivocal evidence of a nuclear explosion, it is essential to eliminate other possible origins of such nuclides, such as a nuclear reactor. The break-up of heavy nuclei such as those of uranium-235 in nuclear fission results in so-called 'fission product' atoms, which mostly have short half-lives and can provide a highly detectable explosion signal. In addition, the free neutrons produced interact with surrounding material to produce 'activation products', which include radioactive isotopes with a composition that is characteristic of the surrounding medium. So activation products will be very different for, for example, an underground test and an atmospheric one. The mix of fission products can provide unambiguous information on the nature of the source, including evidence that it was a nuclear explosion.

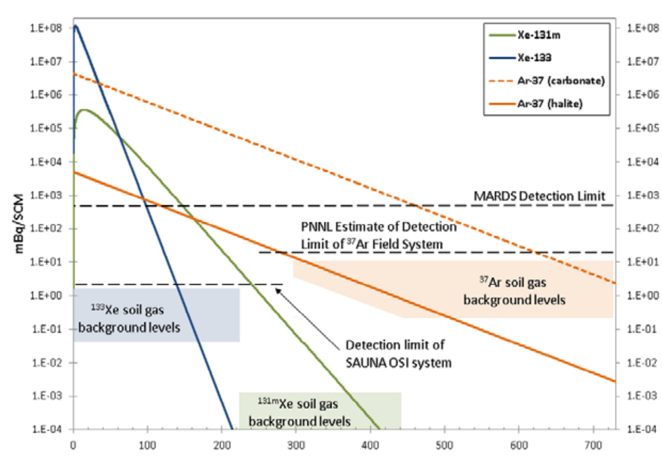


FIGURE 7.3
Potential surface noble gas activity after a 1-kT underground nuclear test, compared with relevant detection limits and background values. From *Miley* (**T2-O1**).

A contribution reviewing research publications on the fission and source terms of underground nuclear tests is presented by *Miley* (T2-O1), who highlights the fact that about one fifth of fission products decay to radioactive xenon, enhancing its importance as a tracer for monitoring underground nuclear tests. This author also considers work on the prevalence of activation products, and considers the importance of the global background level (see SECTION 8.1.2) of various relevant nuclides in affecting adversely the detection threshold of signals of interest (FIGURE 7.3).

The signature of fission products resulting from a nuclear explosion is also considered by *Kalinowski* (T2-O10), who presents calculations of fission products as a function of time, and notes that isotopic ratios can be reliable for discrimination between a nuclear explosion and other radionuclide sources, as well as providing an estimate of origin time. He also considers the temporal evolution of the xenon signature. *Nikkinen et al.* (T3-P36) present data on the release of different isotopes following underground nuclear tests, highlighting those, such as iodine-131 and barium-140, which have been observed most frequently and which have half-lives favourable for monitoring.

The possibility of using tritium observations from nuclear tests is considered by *Lukashenko and Lyakhova* (T2-P9), who investigate experimental results from former nuclear test sites. *Quintana* (T1-P37) considers the long-lived radionuclides caesium-137 and strontium-90, which are also important in environmental monitoring.

7.2.2 NUCLEAR POWER REACTOR

Contributions related to the radionuclide signature of a nuclear power plant naturally focus heavily on the Fukushima-Daiichi accident resulting from the Tohoku earthquake of 11 March 2011 and its associated tsunami. These contributions cover a variety of aspects, from the reliability of measurements made, to the inventory of radionuclide emissions, to the inferred sequence of events at the plant itself, to the effect of the incident on the detection capability of the IMS network for nuclear test monitoring during the period of elevated signals. Also considered is the adverse effect on IMS measurements caused by the contamination of an IMS station close to the accident.

Analysis by the NDC of France is reported by *Le Petit et al.* (JS-O3). They describe relying on the radionuclide stations of the IMS network to assess the severity of damage to the plant, to validate the atmospheric transport model used to predict the dispersal of radionuclides, and to estimate the radiological impact on the environment, in particular of iodine-131. They also provide an estimate of the source term (that is, the composition and time-dependent concentration of released radionuclides). The authors point out that the first xenon samples recorded had concentrations above the range of the detector system, requiring major corrections and special procedures to obtain reliable results. They also present evidence of fission products contaminating the RN38 (JPP38, Takasaki, Japan) station premises, creating difficulties for sample measurement (see SECTION 8.1.2). The authors infer from the evolution of isotopic ratios of xenon-133 and xenon-131m that no criticality occurred after the reactor shutdowns. While the authors find agreement between their ATM calculations and station observations at long distance, they attribute poor agreement at near stations to the prevalence of large particles whose transport is not adequately modelled by the ATM. They consequently argue for the inclusion of additional effects such as dry deposition and washout, in order to better model the transport of larger particles.

Hoffman et al. (JS-O5) report on the technical aspects of work done by the government authorities of Canada in support of Health Canada's lead role. The technical contribution is described under three topics: plume monitoring, source term estimation and understanding the sequence of events at the site. Although the role played by IMS radionuclide data and associated IDC products is emphasised, it is reported that collaboration between NDCs was important to achieve timely analysis of IMS data during the Fukushima accident, when IDC was unable to issue its standard products according to its normal timeline. (This delay arose from the large number and complexity of gamma-ray spectra containing multiple anthropogenic nuclides.) These authors' investigation of xenon isotopes includes terrestrial and airborne measurements in western Canada, as well as IMS data, and a xenon-133 release of between 10^{18} and 10^{19} Bq is estimated. Elevated levels of xenon-133 are also investigated using IMS data by *Bowyer et al.* (JS-O7) (FIGURE 7.4). With the aid of ATM and nuclear engineering calculations of the condition of the reactor fuel at the time of the release, an estimate of 1.2×10^{19} Bq total xenon-133 release is obtained, identified as 95% of the total inventory.

FOCUS

Tohoku and Fukushima: Their Verification Relevance

The magnitude 9 Tohoku earthquake which occurred off the coast of Japan on 11 March 2011 and its aftershocks, together with the associated tsunami and the resulting nuclear accident at the Fukushima Daiichi nuclear power plant, were appalling tragedies whose relevance to the verification of a CTBT may not be immediately apparent. As reported in a range of SnT2011 contributions, these incidents were recorded on all the types of station contained within the IMS, and they exercised all aspects of the verification regime which were in IDC Provisional Operations or otherwise under test. These incidents impacted upon the verification regime in many ways, resulting not only in an unplanned IMS and IDC stress test of unprecedented severity, but also an extensive range of lessons learnt and plans for improvement and enhancement. In addition to this, the tsunami and nuclear accident demonstrated the contributions that IMS data and IDC processing capabilities could make to the monitoring of civil disasters. Although not directly related to CTBT verification, such contributions have the potential to enhance the quality, reliability and timeliness of IMS data, and of IDC processing, by providing a broader user base and hence a broader community focusing on data and software quality and reliability.

The Tohoku earthquake was of course detected globally by the IMS primary and auxiliary seismic networks, together with 800 aftershocks on the first day and some 10,000 aftershocks over the following months. The tsunami was recorded by IMS seismic and hydroacoustic stations. The main earthquake and the largest aftershocks were also recorded at IMS infrasound stations, which also detected explosions at the Ichihara oil refinery on 11 March and the Fukushima Daiichi nuclear power plant on 12 March. The radionuclide releases from the Fukushima power plant were detected at all IMS radionuclide particulate stations in the northern hemisphere and several in the southern hemisphere, while radioactive xenon was also widely detected at IMS noble gas stations.

All these IMS detections were made in the context of CTBTO Provisional Operations, under which IDC processing and analysis is applied to generate 'IDC standard products' which are made available to authorized users from States Signatories. Although the unprecedented number of earthquake aftershocks placed a stress on the automatic processing system, and created a substantial increase in analyst workload resulting in delays to the issuance of REBs, the operational system continued to cope with the processing load. The almost-continuou signals from the main earthquake and early aftershocks resulted in a significant elevation of the event detection threshold globally, which implies a temporary reduction in the ability of the IMS (and all other seismic stations) to detect and locate other events of potential CTBT relevance.

The load placed upon automatic data processing and analyst review by an aftershock sequence following a large earthquake is well known. However, an analogous stress imposed on the IMS radionuclide network, and upon radionuclide processing and analysis, was a new experience. A daily radionuclide particulate or noble-gas gamma-ray spectrum received from an IMS station results in IDC Standard Products including an Automatic Radionuclide Report (ARR) followed by a Reviewed Radionuclide Report (RRR) after analyst review has been performed. Although the number of spectra to process and analyse remains constant, the multiple anthropogenic radionuclides released during the Fukushima accident resulted in an unprecedented number of gamma-ray peaks in each spectrum, each of which had to be measured and identified. Under the scheme used to categorise radionuclide particulate spectra, category 5 is assigned when two or more anthropogenic isotopes are identified, and in the case of Fukushima this resulted in more than 400 category 5 spectra extending over two months.

Standard CTBTO procedures provide that a sample resulting in a category 5 spectrum be split and sent to two IMS radionuclide laboratories for repeat analysis. The unprecedented number of such spectra during the Fukushima accident would have overwhelmed IMS laboratory capacity, and only some 10% were subjected to this procedure, in accordance with provisions in the draft IDC Operational Manual for situations in which many samples are linked to the same event.

The overall increase in radionuclide background, mostly in the northern hemisphere, resulted in a degradation in the ability to detect radionuclides from potentially CTBT-relevant events for up to two months. A further issue which degraded the ability to detect CTBT-relevant events during the first few days was contamination of the closest IMS station RN38 (JPP38, Takasaki, Japan), resulting in unreliable measurements of concentration.

Considerable effort was made by many authors to describe the evolution of radionuclide release during the Fukushima accident, and this is reflected in the SnT2011 contributions. All this work is potentially relevant to the identification of different radionuclide sources, and to the discrimination between a reactor accident and a suspicious event under the Treaty.

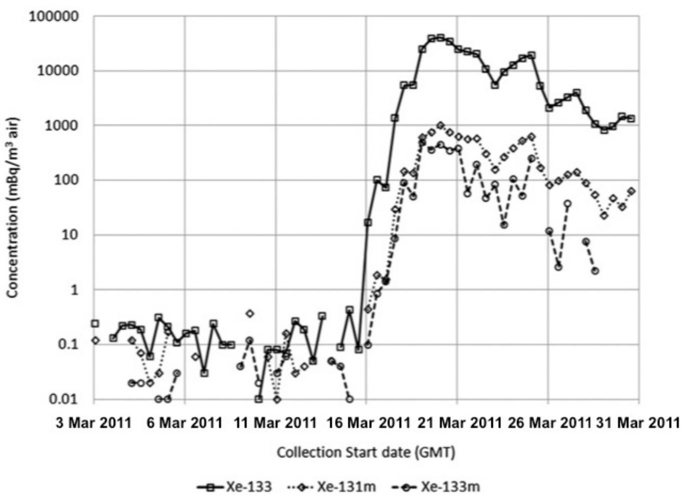


FIGURE 7.4
Concentrations of xenon-131m, xenon-133 and xenon-133m detected at the non-IMS station in Richmond, Washington State, USA during March 2011, which includes the period of the Fukushima Daiichi nuclear power plant accident. Values at or below the detection limit are omitted. From *Bowyer et al.* (JS07) and *Bowyer et al.* Journal of Environmental Radioactivity **102** 681–687 (2011).

An analysis of particulate radionuclides observed following the Fukushima accident is reported by *Miley et al.* (JS-P8), who show that isotope activity ratios provide a clear basis upon which to exclude a nuclear-test hypothesis as the source of the observations. They point out that concentrations of iodine-132 and other isotopes can be usefully compared with those of xenon as an aid to source identification, but only if meteorological effects such as washout can be correctly allowed for in the simulation of the transport of particulates. The authors also emphasise the benefits of co-locating particulate and noble gas stations.

The response of the Austria NDC and the Austrian Central Institute for Meteorology and Dynamics (ZAMG) to the Fukushima accident is reported by *Wotawa and Mitterbauer* (JS-O8). They point out that explosions at two reactors were detected at an IMS infrasound station at a distance of 240 km on 12 and 14 March. They describe the formal role of ZAMG in response to the Fukushima accident and they describe the ATM performed to predict the dispersal of the plume. The IMS radionuclide particulate and noble gas networks are seen as valuable in validating the atmospheric transport predictions, and in estimating the source term. The authors report that ZAMG was the first institute to estimate source terms for Fukushima, on 22 March. They estimate an iodine-131 release of 10^{17} Bq per day and a caesium-137 release of 10^{16} Bq per day between 12 and 16 March, with a factor of 5–10 less for the remainder of March and two orders of magnitude less in April for both isotopes.

Tinker et al. (JS-P2) reports on the Fukushima source-term estimation made by the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA). They describe their ATM used to predict the dispersal of radionuclides under various source hypotheses, and their comparison of these with observational data from IMS stations, in order to estimate the most compatible source term.

An overview of the consequences of the Fukushima accident for the CTBTO is presented by *Nikkinen et al.* (JS-O9). As well as pointing out the consequences of contamination in the closest radionuclide station RN38 (JPP38, Takasaki, Japan), he notes the unprecedented workload placed upon radionuclide analysts as a result of the large number of gamma-ray peaks that had to be reviewed in each spectrum. A summary of radionuclide observations, atmospheric transport calculations, and briefings to States Signatories is also given, plus a description of how this led to a role for CTBTO in the Inter-Agency Committee on Radiological and Nuclear Emergencies (IACRNE) of the United Nations.

The use of IMS radionuclide data and IDC ATM results by the National Center of Radiobiology and Radiation Protection of Bulgaria is reported by *Kamenova-Totzeva and Badulin* (JS-P6). The potential value of IMS data and IDC products in providing relevant information in the event of a nuclear reactor incident is evident in this and the contribution of *Balemsaga* (JS-P9).

One contribution on the source signature of nuclear reactors unrelated to the Fukushima accident is that of *Safari and Sabzian* (T4-P41), who present a simulation of the radionuclide production in a pressurised light-water reactor of Soviet design (VVER-1000) during start-up. Calculation of the inventory is seen to be necessary for assessing the contribution to natural background.

7.2.3
MEDICAL RADIOISOTOPE PRODUCTION FACILITY

A small number of installations worldwide manufacture radioactive isotopes for medical purposes, in order to produce radiopharmaceuticals. The fission process for the production of molybdenum-99 (an important isotope in this application) involves neutron irradiation of uranium-235, which undergoes nuclear fission followed by chemical dissolution. The chemical dissolution of an irradiated uranium target may result in the release of radionuclides into the atmosphere as by-products. Because of the short irradiation time, these can have a characteristic signature which may or may not be readily distinguishable from other radionuclide sources.

Friese and Payne (T2-O12) point out that the production of molybdenum-99 from fission gives rise to amounts of xenon-133 comparable to that produced by an underground nuclear test, and that the xenon isotope ratios can be similar. It is argued that although discrimination can be made using isotope ratios of, for instance, xenon-133 and xenon-135 if both are detected, it is preferable to simply eliminate radioactive xenon isotopes released during medical radioisotope production, thereby reducing the global background. The authors show that two of the five radionuclides which have given rise to the most category 4 and 5 spectra from IMS particulate stations result from medical radioisotope production (iodine-131 and technetium-99m). Issues to be confronted in any programme to facilitate discrimination between radionuclides from radiopharmaceutical production and nuclear tests are discussed, including reduction in release, increased monitoring, and the addition of tracers for identification. They report the initiative to address these issues with the radiopharmaceutical industry through meetings of the Workshop on Signatures of Medical and Industrial Isotope Production (WOSMIP). The contribution of radioisotope production to the global radionuclide background is considered in SECTION 8.1.2.

Eslinger et al. (T3-O9) argue that the understanding of releases from radiopharmaceutical plants is key to the understanding and discrimination of CTBT-relevant signals. They propose the temporary deployment of xenon monitoring stations to study releases from radiopharmaceutical plants, and they calculate a 'figure of merit' as an aid to determining the optimum location for such temporary stations. ATM is used to determine whether releases from known production facilities reach a given location, and whether the production facility is well-covered by existing IMS stations. They present data related to a list of known radiopharmaceutical plants, and conclude that there is a strong case for such additional temporary monitoring.

7.3
IDENTIFICATION OF NUCLEAR EXPLOSIONS

7.3.1
IDENTIFICATION OF EXPLOSIONS USING SEISMOACOUSTIC DATA

Many countries use seismic networks and other means to identify mining explosions for reasons unconnected with CTBT monitoring. The identification of such non-nuclear explosions is useful in the development of earthquake/explosion discriminants which might be used for event screening or the identification of a Treaty violation after entry into force. It is also useful in regard to 'confidence building measures' which are defined in the Treaty. Under these measures, Member States are invited, on a voluntary basis, to submit to the TS details of large chemical explosions within their jurisdiction[39].

One project to identify mining explosions in Kazakhstan is presented by *Sokolova et al.* (T5-P17). They use two approaches. In the first, seismic and infrasound signals are used to locate potential explosions and to investigate potential seismic discriminants between earthquakes and explosions. In the second approach, field and other evidence is used to identify quarries and map likely explosion sources, offering a basis upon which to test potential discriminants.

Park et al. (T2-P8) use the seismic network of the Korea Institute of Geoscience and Mineral Resources (KIGAM), together with five seismoacoustic arrays in South Korea (which include infrasound arrays), and seven China-Korea joint seismic stations, to attempt discrimination between earthquakes and surface explosions in DPRK based on the presence or absence of infrasound signals. The combined station network has an aperture of approximately 1,500 km. For the year 2010, they report the location of approximately 500 events of magnitude M_L between 1.0 and 2.7, of which 39.4% were discriminated as surface explosions.

FOCUS

Radionuclide Particulates and Verification

One important component of CTBT verification is the collection and analysis of radioactive traces contained within particulates which may be released into the atmosphere. The Treaty provides for a global network of 80 high volume particulate samplers that allow detection capability of less than 10 μBq m^{-3} for many relevant radionuclides. Particles in the range of one micrometre in diameter travel in the atmosphere like a gas; this allows small releases to be visible even thousands of kilometres away after a delay of perhaps a few days or more.

An IMS radionuclide particulate station collects particles for one day on a sampling medium referred to as a 'filter'. After removal, the filter is left to decay for one day in order to eliminate excess natural radiation, then gamma rays emitted from any radioactive particles are measured for a further day using a high-resolution HPGe gamma-ray detector, to obtain a gamma ray spectrum containing peaks corresponding to the energies of gamma rays characteristic of each isotope detected. The size of each peak also provides information on the concentration of each detected isotope. The gamma-ray spectra retrieved from each station for each day are transmitted to IDC for automatic processing, followed by interactive analysis to confirm which radionuclides have been detected and at what concentrations.

A nuclear explosion produces atomic fragments as a result of nuclear fission, and these are termed 'fission products'. Some of the neutrons produced by the fission process are captured by atomic nuclei in surrounding materials, producing 'activation products'. In both cases the 'parent' radioactive isotope produced may decay into a 'daughter' isotope, which may itself decay; the result is a chain of nuclear reactions with each isotope having a characteristic half-life. Fission products and activation products may provide information on the time of a nuclear explosion, and in some cases its composition, through the analysis of the parent-daughter relationships and isotopic ratios of certain radionuclides. For example, the changing ratio of the concentrations of a certain parent and daughter as time passes may provide an estimate of the time of the explosion. Such calculations can also be performed in certified IMS Radionuclide Laboratories, of which the Treaty provides for 16 worldwide. These laboratories are also used to assure the quality of the radionuclide detections made from the stations in the particulate network. An important feature of the IMS radionuclide particulate network is its ability to detect radionuclides which may have originated at any location globally. Raw measurement data, the ARR and the RRR from each spectrum are available to States Signatories.

Another contribution related to events in DPRK focuses on the announced nuclear tests in 2006 and 2009. *Kohl et al.* (T2-P21) use IMS and other data to carry out a detailed analysis of these two events, beginning with an analysis of their relative and absolute locations described in SECTION 5.1.2. They estimate a yield of 4.2 kT for the 2009 presumed explosion, assuming this depth. Finally, the authors investigate Love waves from the two events in an attempt to explain perceived unexpectedly high observed surface-wave magnitudes; no firm conclusion is drawn.

Other methods of identifying seismograms from explosions may be applied to locally recorded signals. For example, *Yedlin and Horin* (T4-P16) apply a generalized Stockwell transform (GST) to the classification of seismic waveforms recorded from an earthquake and a chemical explosion in 2005 in Israel; the Stockwell transform is a variant of the continuous wavelet transform that preserves absolute phase. Another approach to the discrimination of local seismic signals is adopted by *Ait Laasri et al.* (T4-P8), who use a supervised neural network, referred to as fuzzy ARTMAP, to attempt discrimination between earthquake and quarry-blast signals.

In the most general sense, the interpretation of seismograms consists of estimating the nature of the seismic source, together with the seismic properties of the structure through which the seismic waves have passed. *Nissen-Meyer et al.* (T4-07) consider the current possibilities for the simultaneous determination of source and structure in global seismology, including three-dimensional full waveform modelling to include high frequencies, back projection of signals to the source, and probabilistic source inversion.

7.3.2
IDENTIFICATION OF NUCLEAR EXPLOSIONS USING RADIONUCLIDE DATA

The identification of a nuclear explosion from radionuclide data, and in particular its discrimination from a nuclear reactor release, depend strongly upon the analysis of relative concentrations of radioisotopes released. Isotopic concentration ratios characteristic of the Fukushima accident are presented by *Hoffman et al.* (JS-05), including those of tellurium-132/caesium-137 and caesium-136/caesium-134. An unusual data analysis technique is used to explore correlation of isotopic data with events at the site, in particular with the spraying of reactor cores and spent fuel ponds with water. Concentration ratios of xenon-133/xenon-131m against xenon-133m/xenon-131m are plotted by *Bowyer et al.* (JS-07) as evidence of an ability to discriminate between reactor release and release from a nuclear explosion. These two contributions show the power of isotopic ratios in the quest to provide confident discrimination between civilian nuclear activity and a potential Treaty violation (FIGURE 7.5).

A different context for the application of isotope ratios to the discrimination of nuclear explosion and nuclear reactor releases is presented by *Baltrunas et al.* (T2-P11), who measure plutonium isotope ratios in soil samples taken from different sites in Lithuania. They determine a set of plutonium ratios, concluding that ratios characteristic of past nuclear tests are found except in the southwestern part of the country, where ratios are indicative of the Chernobyl nuclear reactor accident in 1986.

7.3.3
EVENT SCREENING FOR IDC PRODUCTS

The concept of 'event screening' in the CTBTO is described in the introduction to this Section. The development of these criteria depends heavily upon

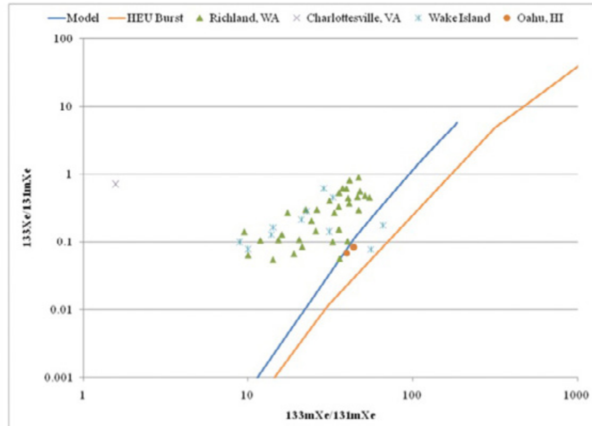


FIGURE 7.5
Comparison of xenon isotope ratios based on observations of the Fukushima accident at the IMS and non-IMS stations shown, together with discrimination lines. HEU refers to highly erriched uranium. From *Bowyer et al.* (JS-07).

research into seismoacoustic and radionuclide sources designed to identify properties that can be used to discriminate between nuclear explosions and other sources of similar signals. Even the experimental criteria already implemented, such as the m_b/M_S criterion and the regional spectral ratio criterion, are in need of further development and validation.

Richards (T2-09) considers the effect on the m_b/M_S criterion if a subsurface explosive source is not isotropic, but instead has a larger dipole along the vertical axis than along the two orthogonal horizontal axes. He points out that this makes the surface-wave magnitude smaller, and hence more explosion-like, than for a pure volumetric source. He also points out that his result may provide an underlying reason for the effectiveness of the m_b/M_S discriminant, even in situations where tectonic release is also present.

Other work of potential relevance to the m_b/M_S criterion is presented by *Mayeda* (T2-P22), motivated by a desire to extend the criterion to smaller events observed at regional distances by a sparse station network. The author notes that sparse measurements require a stable magnitude value observed at a single station, while m_b measurements based upon *Pn* and *Pg* are highly variable, and those based upon *Sn* and *Lg* are unsuitable since they suffer bias for explosions, which are depleted in *S*-wave energy. They present preliminary results for a near-teleseismic *P*-coda magnitude scale based on earthquakes and explosions at the Nevada Test Site (NTS), USA.

Work relevant to the discriminant based on spectral ratios of regional phases is presented by *Israelsson and Chun* (**T2-P5**). Observations of *Pg*, *Pn*, *Lg* and *Rg* from the two DPRK announced nuclear tests in 2006 and 2009 observed at stations of the Dong-bei Broadband Seismic Network (**FIGURE 3.7**) in the border region of China at distances of 160–360 km, are used to compare the spectra of each phase observed for the two explosions. It is speculated that evidence of tensile failure or other non-isotropic source effects observed for the 2009 explosion by some authors can be seen as a minimum in the difference spectra plotted for *Lg*. Investigation of scalloping, which would follow from interference between the direct and surface-reflected waves, is inconclusive, but the authors report that their investigation of travel time differences between *Pg* and *Pn* suggests that the 2009 explosion had a deeper hypocentre.

Evidence of discrimination using spectral ratios is also presented by *Berezina et al.* (**T5-P11**), who present *Lg*/*Pg* data from historical digitised seismograms of a Chinese nuclear test recorded at stations now replaced by Kyrgyzstan Net (KRNET) digital stations. In his investigation of near-regional seismic data from the DPRK event of 25 May 2009, *Chun* (**T2-P2**) finds that anelastic attenuation estimates higher than expected affect magnitude-yield estimates, and also affect results for discriminants such as m_b/M_S and a *Pg*/*Lg* amplitude ratio discriminant. Unlike some other authors, he does not report a tendency for this event to reside in the earthquake population according to these criteria.

The possibility of introducing an event screening criterion for atmospheric explosions based on the correlation of infrasound signals is considered by *Kulichkov et al.* (**T4-O12**). They use data from stations in Alaska and Antarctica from the 1980s, before the IMS was installed. They attempt to classify signals into the five classes, namely nuclear test, mountain associated wave, microbarom, volcanic and auroral. They are unable to classify into the five categories, but report success in classifying signals into the two sets comprising nuclear test plus volcanic, and mountain wave plus microbarom plus auroral.

Each gamma-ray spectrum measured from a radionuclide particulate station is categorized according to the prevalence of anthropogenic nuclides, and spectra not containing relevant radionuclides in anomalous concentrations are screened out. The screening of radionuclide spectra could be further improved by additional steps, such as measuring isotope ratios or source location information, which can potentially differentiate between a nuclear explosion and other radionuclide sources. A categorization scheme for noble gas spectra has also been implemented, but screening criteria would need a basis upon which to differentiate between types of source. This possibility is investigated by *Schoeppner* (**T4-P10**), who focuses on the use of ATM to constrain the location of a radioxenon source, together with knowledge of known sources including the maximum expected concentration. Several schemes for a screening criterion are presented, all of which utilize ATM information and knowledge of known sources of radioactive xenon.

8

Capability, Performance and Sustainment

INTRODUCTION

SECTIONS 3 to 7 have followed the flow of CTBT verification data from acquisition to interpretation. This Section, which is perhaps a particularly relevant Section for a non-scientist concerned with CTBT verification, considers the contributions that relate to the capability, performance or sustainment of any part of the verification system. By way of introduction, the meanings assigned to 'capability', 'performance', and 'sustainment' are outlined. This Section is mainly concerned with the CTBTO verification regime, though this restriction arises only from the substance of the submitted contributions. Those contributions that address the accuracy and validity of earth properties used in verification (such as wave-speed fields and atmospheric transport models) are considered in SECTION 6.

The capability of each element of the verification regime is central to the question of Treaty verifiability. Measuring this capability must therefore form an integral part of CTBTO operational activity, and the same motivation would apply equally to a verification programme operated by an individual State.

Capability relates not only to the quality and configuration of sensors and the processing methods applied to the data, but also to the levels of background noise associated with quantities being measured. Higher levels of seismic, infrasonic or radionuclide background in the vicinity of monitoring stations adversely affect the detectability of useful signals. Background noise is therefore one factor in the determination of capability, and its variation and complexity make it the focus of many contributions.

Although there is always some difficulty in defining background noise recorded by a sensor, and even whether to call it 'noise' or 'signal', the essential feature of background noise is that it represents a level of continuous measured activity below which it is difficult or impossible to detect and characterize a signal of interest: the background noise masks it. Seismoacoustic signals of interest are normally transient, whereas those of radionuclides may appear in one or more daily measurement periods. In all cases the fundamental importance of background noise arises from its influence on the detection threshold of relevant signals on an individual sensor or array of sensors, and on the whole network of sensors. An understanding of background noise is therefore required in order to estimate and improve the detection threshold of the verification system as a whole, and of the IMS in particular. Background noise may also arise from limitations of the detection system itself. The self noise of a seismometer and the contamination of a gamma-ray detection system are examples. Processing of data from suitably designed seismometer arrays by beam forming has long been used to significantly reduce the effect of incoherent noise from natural sources. For anthropogenic noise such as radioactive xenon resulting from radiopharmaceutical plants, or the seismoacoustic noise created by wind turbines, it may be possible to lower the detection threshold by reducing or even eliminating the source of noise.

Depending upon its origin, background noise may change diurnally, seasonally, or it may be correlated with environmental conditions such as wind or temperature. The global background of seismic noise increases after large earthquakes; this is sometimes referred to as 'signal-generated noise' (SECTION 8.2.1). The inherently variable nature of background noise leads to a need for regular, or even continuous observations, leading to time-dependent estimates of station-specific or network-wide detection thresholds; these can then be compared with the detection threshold achieved in practice.

Noise observations are also an important pre-requisite for the use of negative evidence. For example, the failure of a particular station to detect a certain signal of interest can assist in the interpretation of a network of observations, but only if the station detection threshold is known. Another application of time-dependent seismoacoustic noise measurements is in recognizing equipment malfunction, including incorrect sensor calibration. Background noise is therefore an important input into the measurement of performance.

Performance has to do with the reliability of elements of the system in carrying out the specified task. Obvious examples relate to equipment down time, computer hardware failure and telecommunications outages, but it is equally important to measure the performance of processing algorithms, for example in detecting signals or building seismoacoustic events, and the performance of interactive tasks such as data analysis.

Performance is closely allied to capability, but whereas capability is intrinsic to an element of the verification system and external factors, performance has more to do with the efficiency and reliability of the system as it is implemented. One important input to performance measurement comes from comparison of results with those of other agencies whose missions are in some way related to those of CTBTO. Several such contributions are cited in this Section.

A real system is not static, but suffers deterioration, failure and obsolescence, all of which adversely affect performance. The ability to minimise the effect of these factors on performance, by managing the life cycle of verification system elements, forms the basis of sustainment. Sustainment includes maintenance, replacement and upgrading, and so has an impact on both capability and performance.

8.1. BACKGROUND SIGNALS AND NOISE

8.1.1 SEISMOACOUSTIC

Bearing in mind the needs expressed in the introduction to this Section, CTBTO has implemented the routine calculation of background noise level four times per day as part of IDC automatic processing for every seismic, hydrophone, and infrasound sensor that is providing a stable stream of data to IDC Provisional Operations (*Brown et al*., T3-P14). A probability density function is calculated as a function of signal frequency. The 5% and 95% percentiles are extracted to give the ‘low noise’ and ‘high noise’ limits. For each station type, the highest high-noise limit and the lowest low-noise limit are used to define global high-noise and low-noise models, and these are compared with other published models for seismic, hydroacoustic and infrasound noise.

Noise levels recorded by specific seismic stations and networks form the subject of several contributions. For example, *Abd El-Aal* (T3-P5) present an analysis of noise at stations of the ENSN and other stations in Egypt. *Ghica et al.* (T3-P18) present the background noise at the IMS auxiliary seismic station AS081 (MLR), Romania, and *Ozel et al.* (T3-P15) report long-term real-time background noise monitoring around BR235 (one element of the IMS primary seismic array in Turkey, PS43 (BRTR)). *Atmani et al.* (T4-P25) describe the use of a portable three-component station to measure seismic noise at a range of sites in the neighbourhood of Agadir, Morocco, comparing the results with global noise models. *Pyle and Koper* (T1-P25) use small-aperture and medium-aperture IMS seismic arrays to investigate the body-wave energy in ambient seismic noise, and to locate its sources by back projection. For example, they identify consistent sources of microseisms in the north Pacific Ocean recorded at IMS seismic arrays PS09 (YKA) and PS49 (ILAR) .

One anthropogenic source of seismic noise which may in the future become important at many stations is that generated by modern wind turbines. This has been an issue at the IMS auxiliary seismic array AS104 (EKA) in the UK, where action has been taken to limit the development of new wind farms. *Toon et al.* (T3-P27) report new work on this problem, including consideration of small wind turbines. UK Government action restricting the building of wind farms close to this station is motivated by obligations under the Treaty[40], and under the Vienna Convention on the Law of Treaties[41], which both require host States to maintain the effectiveness of IMS monitoring facilities.

It is important to ensure that, wherever possible, the detection threshold is limited by the level of external background noise, rather than by the detection limit of the sensor itself. IMS specifications for IMS sensors seek to ensure this. For seismometers, there is always a self noise, which is hard to measure in the presence of external seismic noise. *Rademacher et al.* (T3-P4) describe a technique for determining self noise of seismic sensors for performance screening (see SECTION 3.1.1).

Regarding the measurement of acoustic noise at IMS hydrophone stations, a relevant contribution is by *André et al.* (T3-O1), who describe the measurement of acoustic noise in the oceans under the LIDO programme. Continuous real-time measurements of noise are made, with the intention of classifying and understanding a wide range of noise sources, from shipping noise to whale noises to sonar.

Background noise at infrasound stations raises special issues. Although wind noise near the sensors has traditionally been the focus of attempts to suppress noise, there are many dynamic factors that affect the amplitude of the signal reaching an infrasound station; these include topography near the station, and seasonal variations in stratospheric winds. Although signal level should not be confused with noise level, in the case of infrasound both of these have a major impact on detection threshold. *Pilger et al.* (T1-P17) consider these questions in some detail, and they are reported in SECTION 6.3.1.

8.1.2 RADIONUCLIDE

Several contributions report studies of the global radionuclide background, which has a major influence on the detection capability of the IMS radionuclide particulate and noble gas networks. *Ringbom* (T2-O2) computes theoretical estimates of the radioactive xenon background expected from known sources, and compares these with observation. He concludes that major features of background can be understood using a simple analytical dispersion model, but that more work is needed to understand fully the provenance of the metastable isotopes. Releases from isotope production facilities are shown to have a major impact on station sensitivities for several IMS sites.

The need to measure the radioactive xenon background worldwide was recognized at an early stage, and projects have been under way to perform measurements using permanent stations and temporary deployments. The transportable xenon laboratory (TXL) described by *Stewart et al.* (T3-P20), using a modified SAUNA system mounted in a container with associated power and communications infrastructure as illustrated in FIGURE 3.3, is being employed to take background measurements temporarily at different locations, with a number of collaborative measurement programmes planned.

Eslinger et al. (T3-O9) point out that the radioactive xenon background is more complicated than was envisaged when the IMS network was designed, and that new locations are needed for xenon background study. It is argued that temporary stations are needed to study signals released from medical radioisotope production facilities, which contribute substantially to the background. It is proposed that atmospheric transport calculations be used to calculate xenon transport from existing and proposed facilities, in order to locate xenon background monitoring wsites.

The argon-37 atmospheric and soil backgrounds are considered by *Purtschert and Riedmann* (T1-O7), the soil background being of special relevance to OSI noble gas monitoring. They report measurement of both the natural contribution, resulting primarily from the neutron flux derived from cosmic rays, and artificial sources including nuclear testing and nuclear reactor incidents. They consider the factors controlling background in soil, including the prevalence of the target nuclide calcium-40, as well as depth below the surface and effective permeability (which controls the rate of escape to the atmosphere). They note that in dry permeable soils, barometric pumping serves to assist gas release from the soil and thus reduces the argon-37 soil background.

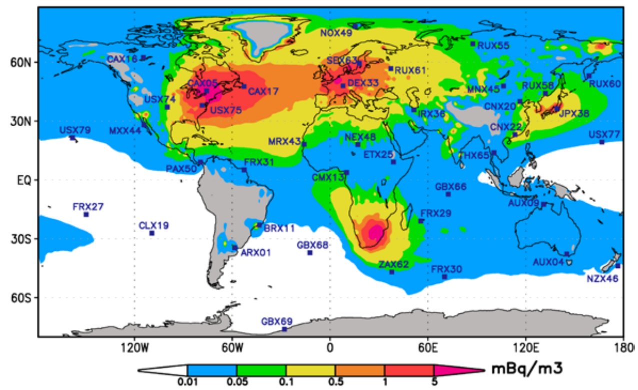


FIGURE 8.1
Calculated average background of xenon-133 calculated for the three-year period 2007 to 2009 at the earth's surface, including contributions from 195 worldwide nuclear power plants and the four major radiopharmaceutical plants. From *Achim, Gross, Le Petit, Taffary and Armand* (**T2-P3**).

Friese and Payne (**T2-O12**) consider the contribution made to the radionuclide background by medical radioisotope production. They point out that a typical production batch of molybdenum-99 for medical purposes releases an amount of xenon-133 similar to that from a typical underground nuclear test. They present a world map of the current effect of medical radioisotope production on radioactive xenon background, and they note that this is likely to increase as radiopharmaceutical production increases. They also consider the particulate radionuclide background resulting from medical radioisotope production, and the number of resulting CTBTO category 4 and category 5 spectra. Their results suggest that about 10% of category 4 and 20% of category 5 spectra result from medical radioisotope production (iodine-131 and technetium-99m). They point out the desirability of reducing this background at the source, or at least of monitoring it at the source, but note that this may be difficult in view of commercial considerations and a desire not to release proprietary information. The identification of radionuclides from this source is considered in **SECTION 7.2.3**.

The contribution of radioisotope production facilities to the global background of xenon-133 is also considered by *Achim and Le Petit* (**T2-P3**) (**FIGURE 8.1**). They compare the continuous contributions from 195 nuclear power plants throughout the world with those of the four main radioisotope facilities in Canada, South Africa, Belgium and the Netherlands, concluding that in many locations the radioisotope facilities are major contributors to the background.

Invariance of the present-day uranium-238/uranium-235 concentration ratio is questioned by *Hiess et al.* (**T1-P38**), who present high-accuracy and high-precision determinations of the ratio in a range of common uranium-bearing minerals from a variety of geological environments and ages. They report significantly lower values than the commonly accepted value. A localised contribution to radionuclide background is investigated by *Shanker et al.* (**T1-P46**) who report measurements of high natural radioactivity at a site in India which is related to uranium mineralization.

A major source of radionuclide background arose from the Fukushima-Daiichi nuclear power plant accident, in the form of a prolonged elevation of man-made radiation in the northern hemisphere and beyond. The contamination caused masking in the measurement results that can be treated in a similar way to the background. *Le Petit et al.* (**JS-O3**) report the difficulties created with measurement of samples at the IMS station RN38 (JPP38, Takasaki, Japan) from 15 March, when fission products were detected in the station premises (see also **SECTION 7.2.2**).

8.2 NETWORK CAPABILITY

8.2.1 SEISMOACOUSTIC EVENT LOCATION THRESHOLDS

Background noise limits the level of signal that can be detected at any given station. However, for the three IMS waveform (seismoacoustic) technologies, the aim is to locate the 'events' which generate the signals detected. Hence, the minimum detectable size of event is of particular interest. This is governed not only by the background noise at the detecting stations, but also by the amplitude of the signals that reach each station, and the number and distribution of those detecting stations with respect to the event. Differential anelastic attenuation of seismic waves within the earth (see **SECTION 6.1.2**) can result in a large difference in signal level at different stations (which may then be either above or below the station's detection threshold). Likewise, stratospheric winds can markedly affect the size of acoustic signal that reaches infrasound stations (**SECTIONS 6.3.1** and **6.3.2**). An important goal, therefore, is to understand the minimum size of event that can be detected and located by the IMS network (or any other network). This is referred to as the 'event location threshold'. Event location threshold varies both with event location, and with time, so it is usually displayed as a global contour map computed for a specified time window. The spatial variation arises predominantly from the non-uniform distribution of stations, their different background noise characteristics, and non-uniform propagation characteristics. The temporal variation may result from changes in background noise characteristics at each station, and in the case of infrasound, changes in the propagation medium. In the case of seismic stations, this may depend upon seasonal climatic variations (for example in wind strength or seasonal freezing of the ground), the prevalence of storms, or the level of global seismicity (since persistent signals from large earthquakes and subsequent aftershocks create 'signal-generated noise' which can elevate the event location threshold, even globally). For infrasound, the seasonal effects on propagation resulting from changes in the stratospheric wind pattern have a major influence, especially on the azimuthal variation in signal detection capability (see **SECTION 6.3.1**).

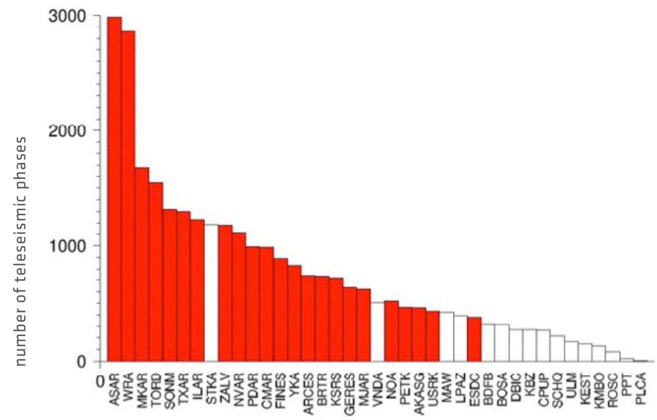


FIGURE 8.2
Number of teleseismic phases associated to REB events from each IMS primary seismic array (red) and three-component station (white) for 130 selected days, from *Selby* (**T4-O2**). The numbers for PS02 (WRA), PS03 (ASAR), and PS04 (STKA) are strongly influenced by their distance from the major seismicity to the east and north of Australia.

The number of signals detected and associated to events varies considerably between IMS stations. It is influenced by the irregular global distribution of seismicity, and we may expect seismic array stations to be used more frequently than three-component stations. Nevertheless, the variation is considerable, as shown by *Selby* (**T4-O2**) (**FIGURE 8.2**).

Software at the IDC estimates global event location threshold at hourly intervals; this is referred to as threshold monitoring, and at present is only applied to the IMS primary seismic network. Threshold monitoring uses station-specific noise levels to predict the minimum magnitude of event that will be detected at three or more primary seismic stations. *Prior and Brown* (**T3-P12**) report on a study of event location threshold using the network simulation tool NETSIM; results are based upon the magnitude at which there is 90% probability of inclusion. This is compared with the threshold of completeness of the REB inferred from the magnitude at which there is deviation from the linear Gutenberg-Richter relation applied globally. The comparison is made over several years as the IMS was progressively enlarged. As noted in the contribution, the slope of the Gutenberg-Richter relation (commonly referred to as the *b*-value—see first focus box in **SECTION 5**) is not the same for all event populations, and this can compromise adherence to its linear relationship. *Kitov et al.* (**T1-P30**) compare Gutenberg-Richter relations determined from IDC and ISC bulletins, computing different curves for different geographic regions, and they demonstrate large geographic differences in *b*-value. Comparison of the IDC and ISC bulletins has also been assisted by the establishment of a link between the IDC and ISC which is reported by *Storchak et al.* (**T5-O6**). It should also be remembered that data from a large number of seismic stations worldwide are available openly from agencies such as the IRIS DMC (see *Ahern*, **T5-P15** and **SECTION 9.4**).

Gutenberg-Richter curves for REB events are also plotted by *Lee and Coyne* (**T1-P39**), but divided by year, and this again shows marked variation that can be due to the different geographic contributions to global seismicity, caused predominantly by aftershock sequences occurring in different regions. They also show that the slope of the Gutenberg-Richter curve for REB events changes when smaller events are removed; this suggests a deviation from the log-linear relationship which again might be caused by the bulletin being incomplete, or by the superposition of populations of different *b*-value. *Lee and Coyne* also investigate the total energy release represented by seismic events in the REB over time, though this energy release is always dominated by the largest events, such as the 26 December 2004 Sumatra region earthquake and the 11 March 2011 Tohoku earthquake.

The ISC gathers parametric data, such as signal arrival times and amplitudes, from seismic stations

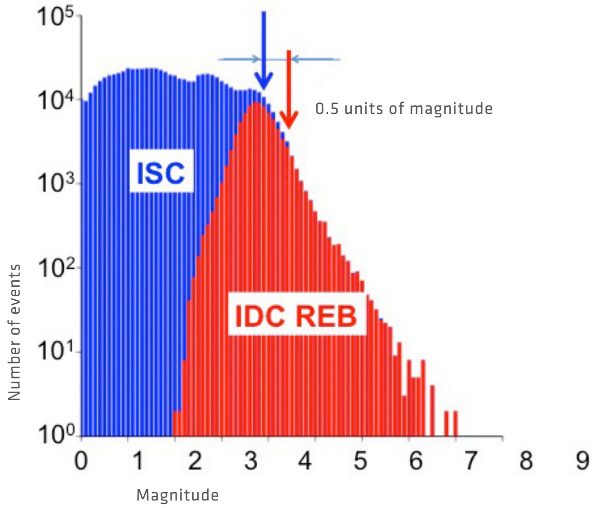


FIGURE 8.3
Cumulative number of seismic events against magnitude, for the Bulletin ISC shown in blue, and for the REB, superposed in red for the period May 2006 to April 2009, taken from *Storchak et al.* (**T5-06**). The magnitude below which the linear Gutenberg-Richter relation no longer holds gives an indication of the magnitude below which each bulletin is not globally complete, and is denoted by blue and red arrows respectively. The difference of about 0.5 magnitude units is considered by *Storchak et al.* to be small, bearing in mind the large difference in the number of stations contributing to the bulletins of the two agencies.

worldwide, for issuing perhaps the most comprehensive earthquake bulletin; a latency of two years helps to ensure that contributing data are maximized. The ISC also maintains, together with the World Data Centre for Seismology located within the USGS, the world registry of seismic stations. The mission of ISC and the completeness of its bulletins are described by *Storchak et al.* (**T5-06**), who show that, while parameters from the IDC REB now form a 'critical component' of the ISC Bulletin, the latter has a threshold of completeness one half a magnitude lower than that of the REB. This can be shown by examining the magnitude below which the linear Gutenberg-Richter relation ceases to hold, implying that the bulletin is not complete at lower magnitudes (**FIGURE 8.3**). The author reminds us that the magnitude scale used in the REB results in values significantly different from those of other agencies (because the scale was designed with a view to identifying explosions), and proposes that the REB also includes magnitudes determined using the standards specified by IASPEI; this would address the difficulty of integrating magnitude measurements based upon different measurement procedures. A database link between CTBTO States Signatories and the ISC to support the analysis of performance is described in **SECTION 9.4**.

Estimation of the true event detection threshold for the REB is complicated not only by the event definition criteria (**SECTION 5.1.1**) that events are required to meet, but also by the possibility that events which do meet the criteria are missed. A study by *Spiliopoulos et al.* (**T4-P37**) focusing on the DPRK region finds, even for this low seismicity area, a number of events which are real and can be well located using IMS stations, but which do not appear in the REB; in some cases this is because the event definition criteria are not met, but in others it is because signals were not detected or associated during automatic processing. The authors conclude that similar results would be expected for any other region.

Comparison between bulletins of the IDC and those of national networks is also instructive, since the latter are expected to have a lower detection threshold than that of the global IMS for events in their region. An example is presented by *Sinyova and Mikhailova* (**T4-P3**), who show a comparison of regional seismic phases in the REB and Kazakhstan NDC bulletins.

Although threshold monitoring has so far focused mainly on the IMS seismic network, it can also be performed for the infrasound network, as reported by *Le Pichon et al.* (**T4-P39**). They conclude that an atmospheric explosion of 550 tonnes would be detected at two IMS infrasound stations in the frequency range 0.2–2 Hz in any conditions. The associated detection capability maps are also presented by *Blanc* (**T1-01**).

8.2.2
RADIONUCLIDE NETWORK CAPABILITY

Following on from his results on the noble gas background, *Ringbom* (**T2-02**) estimates the maximum detection distance of xenon releases which contribute to it. He then considers the impact of background on detection capability. The release from the Fukushima-Daiichi nuclear power plant accident following the Japan Tohoku earthquake of 11 March 2011 is considered 'background', in that it had an adverse effect on the ability to detect a Treaty-relevant release, in much the same way as a large earthquake temporarily decreases the event location threshold by increasing the global seismic background noise level. *Ringbom* (T2-02) estimates that xenon from Fukushima is 10%–100% of one full reactor inventory at equilibrium.

Rivals and Blanchard (T4-04) challenge the idea that, when hypothesis testing, a station detection threshold indicates a deterministic level above which a signal will definitely be detected. Instead they use Bayesian inference to study low level radioactivity in the environment, and apply this to the detection of xenon isotopes. They determine probability of zero radioactivity with physically meaningful point-and-interval estimates, and prior density of radioactivity, obtained by fitting previously recorded radioactivity data. They also raise a concern about the alternative approach of *Zaehringer and Kirchner* (2008)[42].

Following their work on the argon-37 background, *Purtschert and Riedmann* (T1-07) consider the threshold in soil air (air contained within soil pores) above which a possible nuclear explosion may be suspected. They present historical data measured in Berne, Switzerland, on the prevalence of argon-37 background resulting from nuclear testing in the 1970s. They compare this with lower, more recent values, and with the high levels following the Fukushima-Daiichi nuclear power plant accident. They conclude that argon-37 is a very sensitive indicator of elevated neutron flux, even globally.

The detection capability of a radionuclide network depends upon the sensitivity of the detector and the level of background, and also crucially upon whether a release at any given point could be transported to one or more detecting stations. In view of the prevalence of characteristic large-scale atmospheric transport patterns, we may expect that a globally uniform coverage will not necessarily be achieved by a uniform distribution of stations. These atmospheric transport patterns determine what region a station at a given location can effectively monitor. *Hoffman et al.* (T3-014) assume a uniform station MDC and use source-receptor sensitivity (SRS) fields computed using meteorological fields provided by the ECMWF to measure detection capability of the current and planned IMS noble gas networks, taking into account known sources of background (see FIGURE 8.4). They show that certain equatorial regions would benefit from an increased station coverage, and they propose a modified network of 40 stations plus an additional 17 stations. They point out that in view of seasonal changes in atmospheric transport patterns, the optimum 40-station distribution also

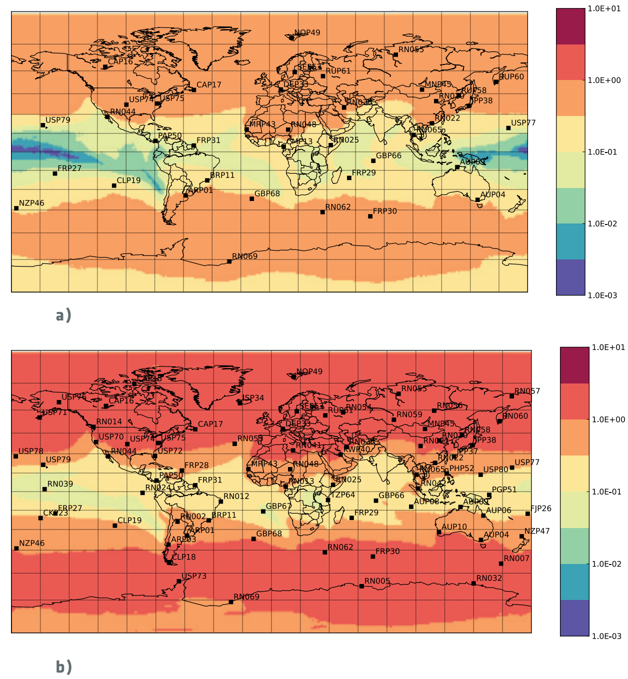


FIGURE 8.4
Estimates of the global detection capability of xenon-133 for the IMS radionuclide network.
a) The 39-station network with an assumed minimum detectable concentration (MDC) of 0.3 mBq m^{-3}, chosen by the authors as a conservative representation of the current technology. **b)** The 79-station network with an assumed MDC of 0.06 mBq m^{-3}. The relatively higher detection threshold in parts of the equatorial region is evident. From *Hoffman et al.* (**T3014**).

fluctuates seasonally. *Koohkan et al.* (T3-015) also consider the detection capability of the IMS radionuclide noble gas network, and deduce deficient coverage in equatorial areas.

Ringbom (T2-02) proposes that the IMS network density should be modified using coverage of the metastable isotope xenon-133m as a criterion. Whereas his calculations suggest that 80 stations are sufficient to provide adequate global coverage, this is only held to be so if more are moved to equatorial regions.

8.3 PERFORMANCE, QUALITY AND VALIDATION

Methods for testing and validating different elements of the verification regime are the focus of several contributions. *Starovoit et al.* (T3-P13) provide a review of testing methods used for IMS equipment in the seismoacoustic technologies. This includes testing of a new Guralp digitiser at the Sandia National Laboratory (SNL) in the USA; testing of the IMS standard station interface (SSI), and the testing of a hybrid seismometer frequency response. Testing of IMS seismic and infrasound equipment takes advantage of the facilities established by ZAMG at the Conrad Observatory in Austria. The overall aim of IMS equipment testing is to ensure that IMS equipment meets the minimum technical requirements specified in the draft IMS Operational Manuals. An example of a validation exercise for a non-IMS seismic network is presented by *Anderson* (**T3-P19**), who describes a data quality initiative for the Global Seismographic Network (GSN) that includes the verification of sensitivity, orientation and location parameters for all sensors in the network.

On the testing and validation of IMS radioactive xenon detection equipment, *Gheddou et al.* (**T4-P40**) describe the process of validating the SAUNA and SPALAX systems; this testing is being implemented progressively at the relevant IMS stations, again with the aim of ensuring compliance with the relevant draft IMS Operational Manual. *Han* (**T3-P33**) reports on the quality assurance programme for the IMS radionuclide network, through which samples are routinely sent for reanalysis at IMS radionuclide laboratories. IMS radionuclide laboratories themselves are also subject to routine quality control, and *Duran et al*. (**T2-P18**) describe the annual proficiency test exercise (PTE) that is carried out in order to assess the accuracy of radionuclide identification and measurement at these laboratories, and to trigger corrective actions where necessary. *Peräjärvi et al.* (**T3-O10**) describe a service for the production of isotopically pure xenon samples for the calibration of xenon detectors, both at IMS stations and at IMS radionuclide laboratories, and for the evaluation of software performance.

ATM provides an essential support in the interpretation of anomalous radionuclide observations, and performance evaluation of the atmospheric source location algorithm at CTBTO in the context of the annual NDC Preparedness Exercises (NPEs) is described by *Krysta and Coyne* (**T4-P26**). *Mitterbauer and Wotawa* (**T5-P9**) report specifically on their atmospheric backtracking contribution to the NPE held in 2010. The Eyjafjallajökull volcanic eruption in Iceland during 2010 provided another good opportunity for testing the performance of atmospheric transport calculations, and this is presented by *Wotawa and Mitterbauer* (**T1-O5**).

On the testing of other IDC software, *Kuzma and Le Bras* (**T4-P22**) point out the need for concrete plans to ensure the quantitative testing of new algorithms. This need has been highlighted especially as new data processing methods using a machine learning approach are being developed, and need to be tested thoroughly by comparison with existing methods. These authors refer to recommendations on the testing of wave-speed models and on location confidence ellipses which arose from the CTBTO Event Location Calibration Workshop held in Oslo, Norway in 1999, and on subsequent discussions at the CTBTO Machine Learning Workshop held in Vienna, Austria, in 2010. The authors conclude that standard metrics are required for testing new data processing algorithms, including standard training datasets and test datasets.

One area of IDC processing only recently introduced into IDC Provisional Operations is the network processing, event building and interactive analysis of infrasound data. Measurement of capability and performance in this area is therefore at a formative stage, and *Bittner et al.* (**T4-P18**) report on the first year's experience with the new infrasound processing software. It follows that the ability to form 'fused events', which include IMS detections at more than one type of station (seismic, hydroacoustic or infrasound) is also a developing field. *Johansson and Mialle* (**T4-P31**) report on the fused REB events during the 14-month period from February 2010 (when infrasound processing was re-introduced into IDC Provisional Operations) to March 2011. They report 1,464 events with associated infrasound phases, and 11,749 with associated hydroacoustic phases out of total of 50,018 REB events. They report 61 events with seismic, infrasound and *T*-phase detections, and one with seismic, infrasound and *H*-phase detections. The fusion of seismic and infrasound detections for the same event is also investigated by *Ionescu and Ghica* (**T3-P17**) for the non-IMS infrasound station IPLOR in Romania, with comparison made against REB events.

The many contributions on seismoacoustic detection thresholds and performance paint a picture of the difficulties faced in trying to measure improvement in network capability quantitatively. However, **FIGURE 8.5**, taken from *Pearce and Kitov* (**T4-P38**), does demonstrate a steady improvement. This graph shows simply the reduction in average magnitude of seismic events in the LEB which have a magnitude assigned. (The LEB contains all those events which analysts have reviewed or added[32]; some of these events are not included in the REB after application of the REB event definition criteria, as explained by *Pearce et al.* (**T4-P30**). This graph does not, in itself, demonstrate that the event location threshold has decreased since IDC has been operating, or even that the threshold of bulletin completeness has been lowered, but it does show that there has been a steady increase in the proportion of smaller events that are being located by the IDC using the IMS network. Given that the total number of REB events has increased by about 40% in this period, and given the importance of small events in the verification context, a consistent and continuing improvement is indicated. This graph may reflect the combined effect of many factors, which may include the progressive completion of the IMS network, improvement in data availability, improvement in automatic processing and scanning for missed events, and improvement in the identification of aftershocks. The fact that these authors draw a linear trend line through the data may not have any theoretical significance, but it does serve to show that there is no sign of this average magnitude 'bottoming out'. This suggests that there is much scope for further improvement in IDC bulletin completeness in the future, though this will depend to some extent on the future policy on event definition criteria for the REB (see *Pearce et al.*, **T4-P30**).

CTBTO is aiming for a comprehensive measure of network performance, and this theme is taken up by *Carter et al.* (**T4-P1**) who present theoretical and empirical network performance maps for the IMS primary seismic, hydroacoustic, infrasound and radionuclide particulate networks.

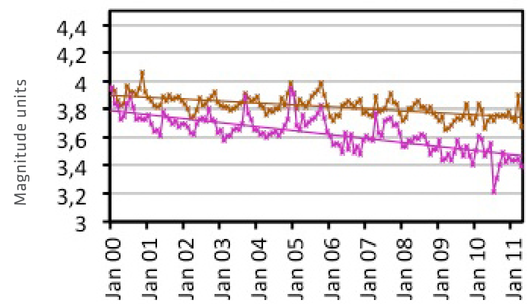


FIGURE 8.5
Average of defined magnitudes m_b and M_L for the LEB events in each month, from January 2000 to April 2011, taken from *Pearce and Kitov* (**T4-P38**). The graph shows that the average magnitude of seismic events validated by analysts has decreased steadily over the years of IDC Provisional Operations. This demonstrates a progressively increasing ability to detect and locate smaller events.

FIGURE 8.6
The IDC Operations Centre. From *Nikkinen et al.* (**T4-P35**).

8.4 SUSTAINMENT

Sustainment of the verification system includes maintenance and replacement of IMS and IDC facilities, and will in the future be equally applicable to OSI. For the IMS, ensuring that each facility continues to perform to specifications is a major logistical task. *Brely et al.* (**T5-P20**) describe a logistics support analysis tool to assist in the process of prioritizing and executing tasks that are essential to sustainment of the IMS. The integrated logistics support system of IMS is described by *Brely et al.* (**T5-P19**).

Sustainability begins in the IDC Operations Centre (**FIGURE 8.6**), where data availability is monitored and where problems with IMS facilities, communications links to stations and NDCs, and IDC processing are notified and either resolved or forwarded to responsible entities for action. The role of the IDC Operations Centre is described by *Daly et al.* (**T3-P37**). With three levels of progressive maintenance response depending upon the severity of the problem, all issues must be subject to appropriate resolution. In the case of generic design malfunctions, a review of technical requirements and the re-engineering of equipment may become necessary.

Looking further ahead, the need to explore and eventually implement solutions to existing engineering problems, and to advance the technology of the IMS in line with scientific and technological advances, is the province of the CTBTO Technology Foresight initiative. This initiative is about information gathering to explore developments in science and technology that will shape the technological future of the verification regime, and about developing a long-range vision and scenarios looking ahead to 2025. Interaction with the wider science and technology community is essential to ensure that this vision is grounded in a solid assessment of today's technology landscape. A technology foresight survey was conducted among the participants of the SnT2011 Conference. The questionnaire was primarily designed to provide information on trends and new developments in earth observation science and geophysics. In addition, there were questions exploring civil and scientific applications of CTBT technology and data, as well as questions on the positioning of the CTBT verification system in earth observation science and global monitoring. The results were distributed to the participants and posted on the website after the Conference. The Technology Foresight initiative is described in a presentation by *Grenard and Steeghs* (**T3-P43**).

9

Sharing Data and Knowledge

INTRODUCTION

SECTION 1 emphasises that a broad awareness and understanding of the CTBT verification regime serves to promote the Treaty's credibility, and will help to facilitate an informed decision-making process in the Executive Council and among Member States after entry into force. A community of well-informed and active verification practitioners widely dispersed among Member States will also contribute to deterrence, and will help to cultivate a diverse pool of experts who could potentially participate in the work of the CTBTO, or become OSI inspectors, or perform other roles in support of monitoring and verification. These sentiments have helped fuel support for the capacity building programme of CTBTO, with its training courses and its schedule of international workshops and other meetings. A central goal of these initiatives is to promote the establishment of active NDCs in as many States Signatories as possible. Many contributions in this Section focus on these aims.

The sharing of data and knowledge also involves synergies between the CTBTO verification regime and the vast range of independent outside activities which may be relevant in one way or another to verification. One example of such an outside activity is the storage of waveform data from the many non-IMS seismic stations at data centres whose main purpose lies with academic research rather than CTBT monitoring. Another is the acquisition and storage of the world's meteorological data, whose main motivation may be for weather forecasting and meteorological research, but which is also crucial to the interpretation of IMS radionuclide observations through ATM. Yet another example is the various research programmes acquiring diverse oceanographic and atmospheric datasets in support of academic research into oceans and the atmosphere, but which can also lead to improved infrasound and hydroacoustic monitoring for CTBT purposes. Contributions in this Section provide a broad sample of those ongoing activities.

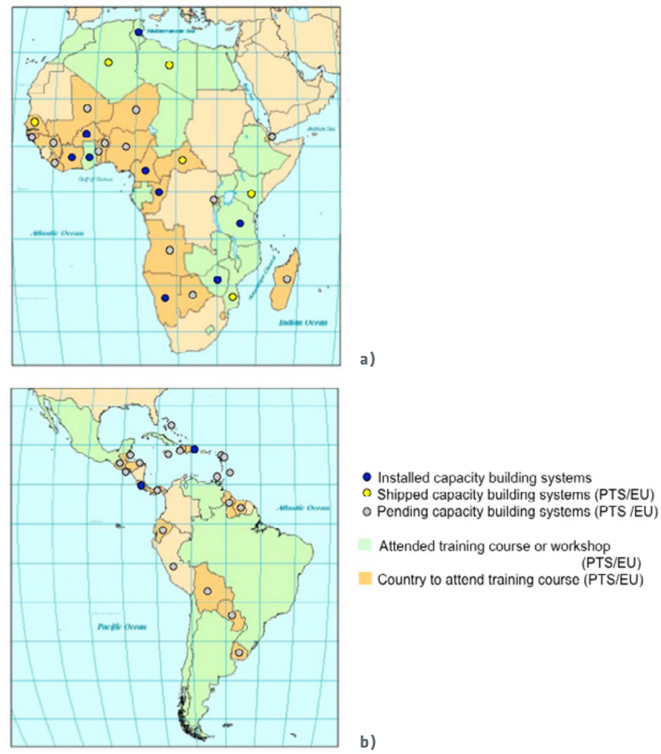


FIGURE 9.1
Capacity building systems installed by CTBTO at NDCs, with CTBTO and European Union Support. **a)** Africa. **b)** Latin America and the Caribbean. Participation in training courses and workshops is also shown. From *Zerbo et al.* (**T5-04**).

9.1 BUILDING GLOBAL CAPACITY

An overview of the CTBTO capacity building programme is provided by *Zerbo et al.* (**T5-04**). Together with statistics on the CTBTO user community within States Signatories, they describe the five elements of the capacity building programme. These are: country profiling to establish needs; NDC Development Workshops; NDC Capacity Building Technical Training Courses; equipment installation where applicable (funded through national and European Union contributions), and technical follow-up visits to assess impact and help sustain achievements. **FIGURE 9.1** summarizes the extent of these activities. The authors provide details of the e-learning component of the capacity building programme, and point out that the programme focuses on beneficiary States

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Spin-off Applications of IMS Data

The expectation that IMS data would find uses outside nuclear-test-ban verification was in the minds of the Treaty negotiators, who inserted a provision to protect the international exchange of data for scientific purposes[44]. The CTBTO Preparatory Commission was also anxious to be made aware of the potential additional uses of IMS data, and four meetings of experts were held in London, UK (2002); Sopron, Hungary (2003), Berlin, Germany (2004) and Budapest, Hungary (2006), to review the potential range of these uses. The reports from these meetings cover many obvious applications and some less obvious ones. At the same time it was self-evident that any 'dual use' of IMS data must in no way adversely affect the core mission of CTBTO or its Member States to monitor and verify a nuclear test ban.

Examples of the many potential scientific applications identified are earthquake monitoring and response, earthquake hazard analysis, research into the structure of the earth and its atmosphere, studies of physical properties of the deep oceans, research into sources of infrasound including volcanoes, meteorites and storms, studies of the atmosphere using infrasound, the potential of infrasound data in improved weather forecasting, and improved understanding of the global radionuclide background. It quickly became clear that potential applications are by no means restricted to 'scientific' ones, and there was much discussion on the potential value of IMS data in disaster mitigation, environmental monitoring and humanitarian fields, many of which are of direct concern to States. Examples raised at these experts' meetings are monitoring for destructive earthquakes, volcanoes, tsunamis and nuclear reactor accidents, environmental pollution monitoring, and monitoring for volcanic ash clouds.

Major disasters always serve to focus minds, and the Indian-Ocean tsunami arising from the massive earthquake off Sumatra, Indonesia, on 26 December 2004 resulted in a decision at the 27th Session of the CTBTO Preparatory Commission in November 2006 that allows IMS seismic and hydroacoustic data to be made available, continuously and in near-real-time, to tsunami warning organizations recognised by the Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific and Cultural Organization (UNESCO). At the end of 2012, ten tsunami warning organizations in nine countries were receiving data under this decision.

A more recent series of major disasters arose from the massive Tohoku earthquake off Japan on 11 March 2011, with its resulting tsunami and associated accident at the Fukushima Daiichi nuclear power plant. Again, the value of IMS data was revealed, and since these disasters occurred shortly before SnT2011, this gave an opportunity for an extensive examination of the value of various types of IMS data in environmental monitoring and disaster mitigation in the context of those events. As a direct result of these events, CTBTO is now a member of IACRNE. Under this arrangement international organizations can share information and support each other in decision making. CTBT data have been shown to be very useful in the case of radiological and general emergencies. These disasters apart, SnT2011 saw a number of wide-ranging contributions that address, either directly or indirectly, the non-verification uses of IMS data.

that do not currently have access to IMS data and IDC products, or are making only limited use of them. A focus on the capacity building follow-up visits in African region is provided by *Fisseha et al.* (T5-P13).

One overall consequence of CTBT capacity building is to improve confidence and trust in CTBT-related global monitoring and verification. This can also be achieved in other ways, for example by engaging the widest range of organizations in relevant activities. *Kalinowski* (T5-O8) considers the contribution of the scientific community, and offers a matrix which relates different stages of the verification process with their degree of connection to the scientific community. The announced nuclear tests in DPRK in 2006 and 2009 are used as an example, and the cells of the matrix are populated with entries relevant to this example.

The broader concept of trans-national cooperation is considered by *Wing* (T5-O3), who identifies four expected positive outcomes from international cooperation among scientists and technologists working for non-governmental entities. The first is assistance in the implementation of internationally agreed treaties or activities such as the CTBT, where in this case the desired outcome is a more effective and efficient operation of the system for detecting nuclear tests. The second recognizes that such cooperation helps countries to build useful infrastructure, and so helps to strengthen their scientific and technical capabilities. The third is that trans-national cooperation on scientific research, or in the development of data sources relevant to research, can further knowledge and understanding, thereby advancing research disciplines, either in their own right or in ways relevant to specific global problems. The fourth is that cooperation helps to inform the policy decisions of States and international organizations.

9.2 COLLABORATION AND TRAINING INITIATIVES

The governments of some CTBT States Signatories, and in some cases other organizations within these States, have initiated their own capacity building programmes, often focused on specific developing countries or geographic regions with which they have a special connection. In some cases these programmes are not CTBT-specific, but nevertheless find direct application to the technologies, methods, or equipment used to monitor for indications of possible nuclear tests remotely.

Collaboration can take the form of training courses. One example (*Mikhailova et al.*, T5-P7) is the international training centre in support of CTBTO which has been set up in Almaty, Kazakhstan with financial support from the Norwegian Ministry of Foreign Affairs and with technical support from NORSAR, and which is focused initially upon the provision of support to Central Asian countries.

Another example is the collaboration between ZAMG in Austria and the NDC of Tunisia described by *Khemiri et al.* (T5-P10). Collaboration on the use of WEBGRAPE software is reported, including its application to the 2010 NPE. This software is provided by CTBTO to NDCs for the purpose of post-processing and visualization of ATM calculations using CTBTO SRS fields. Following the establishment of the IMS radionuclide station RN50 (PAP50), *Marcos et al.* (T5-O12) refer to partnerships they are establishing between Panama and universities in the USA and Mexico to explore legal factors related to international collaboration in support of the Treaty.

Lushetile and Hutchins (T5-P28) describe initiatives by the Government of Namibia to provide training. While the Geological Survey of Namibia has been concerned with preparing an earthquake hazard map for the country, and in participating in the Africa Array programme, the establishment of two IMS stations in Namibia has introduced a further incentive to provide training in relevant fields of geophysics. The authors also describe Namibia's participation in the Walvis Ridge Passive Source Experiment (WALPASS) in collaboration with the German Centre for Geoscience (GFZ) in Potsdam, Germany, and their establishment of a Seismometers in Schools programme in collaboration with the UK's British Geological Survey (BGS). Regional cooperation in central Africa is reported by *Marimira* (T5-P18), referring to the Eastern and Southern Africa Regional Seismological Working Group (ESARSWG) and the Africa Array project.

The Samoa-China Seismograph Network (SCSN), representing a collaboration between China and Samoa, is described by *Leavasa and Talia* (T3-P8). They report that, following a memorandum of understanding signed in 2009, the design and installation of the seismic network has proceeded. They also describe a tsunami operation and seismic analysis and reporting system set up with equipment donated by the US National Oceanic and Atmospheric Administration (NOAA).

A collaboration extending for over 20 years between researchers at Michigan State University, USA, and several seismic networks and institutions in the Russian Federation is described by *Mackey et al.* (T5-P22). In addition to the accumulation of improved earthquake locations and ground-truth events (events for which the location is known to high and measurable precision), a programme of digitising and analysing seismograms from the Peaceful Nuclear Explosion (PNE) programme of the former USSR is described; this includes new temporary deployments of seismometers intended to provide ground-truth events in areas where they are currently lacking.

Hara (T5-P14) describes the annual training course in global seismology offered by the International Institute of Seismology and Earthquake Engineering (IISEE) Building Research Institute of Japan, in collaboration with the Japan International Cooperation Agency (JICA) and the Japan Meteorological Agency (JMA), since 1995. This has the specific goal of supporting the technical capacities of States in CTBTO verification. Training is provided by experts from several collaborating Japanese institutions, with the addition of PTS staff since 2003.

» Our vision is a scientific e-Infrastructure that supports seamless access, use, reuse and trust of data. In a sense, the physical and technical infrastructure becomes invisible and the data themselves become the infrastructure — a valuable asset, on which science, technology, the economy and society can advance.

ROBERT JONES, CERN
QUOTING FROM REPORT SUBMITTED TO THE EUROPEAN COMMISSION [43]

Another collaboration involving Japan is reported by *Arzumanyan* (T3-P7), who describes a programme with Armenia to study seismic risk assessment and seismic risk management, which includes the installation of instrumentation at Garni, Armenia.

The potential for technical collaboration between CTBTO and the IAEA is explored by *Monteith and Whichello* (T2-O13). They identify common areas of interest in equipment, sensors and data acquisition methods (see SECTION 3.1.6).

9.3 NATIONAL EXPERIENCES

The account of collaborative ventures in SECTION 9.2 includes many national experiences. Of particular interest under the CTBT is the experience of States Signatories who have recently established an NDC, in some instances where no similar facility previously existed.

Two projects carried out at the Philippines NDC are described by *dela Cruz et al.* (T5-P25); one is to assess the contribution of radionuclide particulates in the air to the effective dose experienced by the local population, and the other is to trace the flux of natural radionuclides such as beryllium-7 and lead-210 for the establishment of the inventory of these isotopes for the purpose of using them as soil tracers. *Castro* (T1-P8) reports that particulate samples acquired at the IMS radionuclide station RN50 (PAP50) in Panama are measured prior to dispatch to CTBTO, to seek evidence of airborne pollution particulates using Mössbauer spectroscopy. These are two of many papers which describe the use of IMS data by the host country for civil and scientific purposes.

In Africa, *Opoku* (T5-P3) emphasises the importance of natural disaster mitigation along with CTBT monitoring, in the context of the establishment of the Ghana NDC. The experience of setting up the Ghana NDC is described by *Amponsah and Serfor-Armah* (T5-O10), together with associated training events. The contribution by *Ayero* (T5-O11) focuses on how Uganda can develop capacity through education, training and research with the broader scientific community, especially by identifying centres of excellence in Africa in relevant areas of training and research. This author also identifies a need to encourage internal exchange opportunities in Africa among NDCs. *Mdoe et al.* (T5-P8) points out that in Tanzania, synthesis between the CTBT function and disaster management is important in view of the importance that disaster management holds within the country. Accordingly, the NDC is seen to be important for the monitoring of potential natural disasters as well as for the CTBT monitoring task. CTBT-related activities in Mali, including operation of the IMS auxiliary seismic station AS062 (KOWA) and the Mali NDC are reported by *Thera* (T5-P12). A different type of national experience is reported by *Blake and Campbell* (T5-O5) who describe an educational programme to install seismometers in schools in Ireland.

9.4 DATA AND INFORMATION PLATFORMS

The European Organization for Nuclear Research (CERN) may not appear to have a direct relevance to CTBT verification, but it is a prime example of an organization accumulating a massive amount of digital data which must be made available to a large number of collaborating institutions. *Jones* (T4-O1) provides a description of CERN and its computer facilities, and draws some analogies with the challenges inherent in the technical aspects of the global CTBTO verification system. With 300 Mb s^{-1} of raw data being recorded from its Large Hadron Collider (LHC), corresponding to 15 million gigabytes per year or 20 million CDs, and with a need to provide computing power 100,000 times more than today's most powerful personal computer, he suggests that CERN may have useful hints to offer CTBTO on its future challenges in computing infrastructure. Bearing in mind that CERN can provide only 20% of its required computing power, the author describes a distributed infrastructure for data processing known as the Worldwide LHC Computing Grid (WLCG). He also describes the European Grid Infrastructure (EGI), which is designed as an enabling facility for e-science in a wide variety of subjects including earth sciences, geophysics and civil protection. One example is e-science for earthquake disaster mitigation and for mitigating earthquake hazard, to include tsunamis, air pollution and social resilience. The author emphasises that, since the 'data deluge' will continue to increase, it is important that "groups should produce data products that can be readily integrated into other systems". He highlights relative benefits and shortcomings of computing grids, computing clouds, supercomputers and volunteer computing.

Referring to the 'Vision 2030' of the European Union High Level Experts' Group on Scientific Data, he quotes from one of its reports: "Our vision is a scientific e-Infrastructure that supports seamless access, use, reuse and trust of data. In a sense, the physical and technical infrastructure becomes invisible and the data themselves become the infrastructure—a valuable asset, on which science, technology, the economy and society can advance."[43]

By comparison, *Ahern* (T5-P15) describes a consortium (IRIS) that receives data from 2,100 seismic stations in a typical day, 72% of it in near-real-time, with an accumulated archive of 138 terabytes (FIGURE 9.2). The IRIS DMC is the world's largest archive of broadband seismological data, and is an asset of direct application to CTBT monitoring. He describes a 'buffer of uniform data' (BUD), making this the *de facto* standard for real-time seismic data. He also describes the 'quality assurance toolkit' (QUACK), which is of direct relevance to data quality monitoring at CTBTO. In describing the IRIS vision, the author states: "The IRIS Data Management Centre (DMC) manages the largest concentration of broadband seismological data in the world. DMC data and services are free and open. A rich variety of request tools are currently being extended using Representational State Transfer (REST) web services. These new methods of providing access to data will greatly simplify a research or monitoring group's ability to retrieve data quickly, reliably, and in a form that is readily usable."

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Combining IMS Data With Non-IMS Data

The Treaty specifies[45] that IDC standard products be derived only from data observed using facilities of the IMS, and which have been processed in the IDC or at certified IMS radio-nuclide laboratories. IMS stations offer the benefits of controlled data quality, secure and reliable data transmission, data authentication, and oversight by CTBTO, but the IMS does not exist in isolation. Apart from the many thousands of non-IMS seismic stations, there are non-IMS infrasound and radionuclide stations, and even hydroacoustic stations. Although the Treaty contains provisions for CTBTO to use non-IMS data in the investigation of special events upon request[46], the question arises as to whether, and if so to what extent, products which combine the observations of IMS and non-IMS stations might be more comprehensive and of higher quality than the products currently produced using IMS and non-IMS data separately.

This question is especially relevant to seismic monitoring, which is perhaps the most mature of the four IMS monitoring technologies, and which enjoys a prolific non-IMS inventory of stations, networks and data centres. Many non-IMS seismic networks are national or regional, offering a lower detection threshold for events in their neighbourhood, whereas most seismic arrays, which are designed to record small signals, are in the IMS. National or regional networks are useful in providing a set of reference events against which the performance of the IMS station network, or of software used to prepare automatic event lists at IDC, may be compared. After entry into force of the Treaty, they may also be useful in providing corroborative evidence of a suspicious event under the Treaty, which could be presented by a State Party, perhaps to support a challenge.

The vDEC offers a platform for experiments with event bulletins derived from combined IMS and non-IMS data. There are plans to incorporate open-source data onto vDEC, and to provide all data in compatible format.

One mechanism provided under the Treaty which can potentially overcome concerns about the quality and authenticity of non-IMS data is the concept of a 'Cooperating National Facility' (CNF)[47]. A CNF is a non-IMS station which is required to meet IMS specifications, and which is required to undergo the same certification procedure as an IMS station.

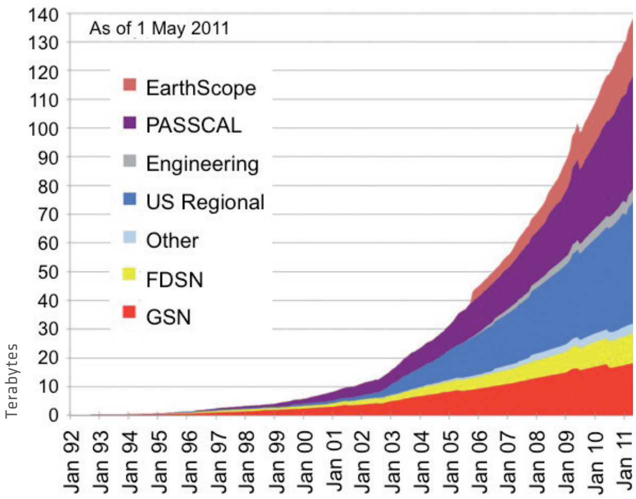


FIGURE 9.2
Growth in the size of the archive of global seismic and other data at the IRIS DMC. From *Ahern* (**T5-P15**).

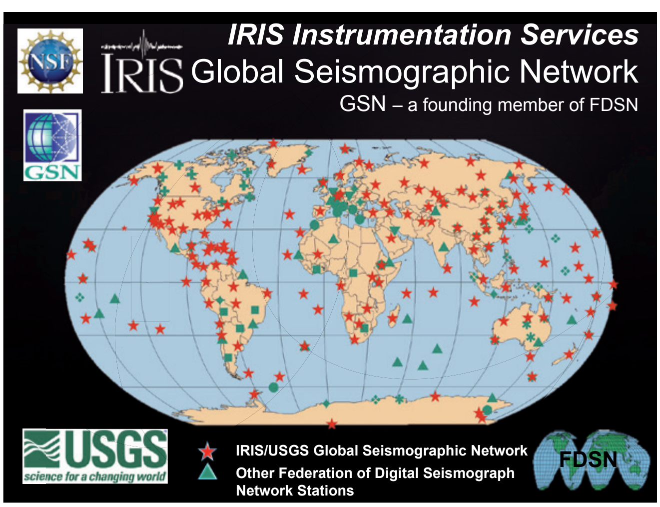


FIGURE 9.3
Digital broadband seismograph stations of the Federation of Digital Seismograph Networks (FDSN) backbone network in 2011, including those of the IRIS/GSN of the USA. From *Simpson* (**T3-O2**).

The concept of open shared data is followed up by *Simpson* (**T3-O2**), who outlines the shared data resources and shared instrumentation facilities provided by IRIS to support research in seismology. Together with earthquakes, earth structure and earth dynamics, verification of a CTBT is offered as a fourth application of these facilities. The funding base of the US National Science Foundation is described. In addition, the Education and Public Outreach Program of IRIS is presented, which has an analogue in the capacity building activities of CTBTO. Relations between seismic stations sending data to IRIS and those of the CTBTO are pointed out, including the fact that 44 stations of the planned 120-station IMS auxiliary seismic network were built as stations of the GSN of the USA, itself a joint venture of IRIS, the USGS and the International Deployment of Accelerometers (IDA) programme of the University of California, San Diego. Stations of the GSN are shown in **FIGURE 9.3**.

An open-access archive of digital waveform data from seismic stations in the European and Mediterranean region is provided by the Observatories and Research Facilities for European Seismology (ORFEUS), as described by *van Eck et al.* (**T5-P21**). They describe the role of ORFEUS in the coordination of data exchange and research infrastructure in Europe, and their involvement in a range of European Union and Europe-wide research initiatives.

A global collaborative project involving a major data archive and data sharing component is described by *Achaché and Gaetani* (**T5-O1**). The Group of Earth Observations (GEO) was formed in 2005 as an intergovernmental organization with the objective of establishing a "coordinated and sustained" Global Earth Observations System of Systems (GEOSS) "to enhance informed decision making in different areas of Society". As with other similar initiatives, its objectives include improvement and coordination of observational systems, the provision of easier and more open data access, and building capacity to use earth observation data. The author lists observational resources made openly available under GEOSS, including much satellite-based data, and describes the GEOSS common infrastructure. Again, natural hazard mitigation is one area envisaged for GEOSS, including that of flood, earthquake and volcano. The author explains that 'super sites' have been set up for access to data from specific events such as the Haiti earthquake of 12 January 2010 and the Tohoku earthquake of 11 March 2011.

ARISE is an initiative for collaboration within and outside Europe on atmospheric research, and is described by *Blanc* (**T1-P45**). ARISE aims to integrate different observational networks in order to provide three-dimensional images of atmospheric dynamics from the ground to the mesosphere (that is, to about 90 km in altitude) with much-improved resolution in both space and time (**FIGURE 9.4**). Among the goals are improved weather forecasting and climate monitoring; the intention is to bring together data from the IMS infrasound network, the Network for the Detection of Atmospheric Composition Changes (NDACC), and the Network for the Detection of Mesopause Changes (NDMC). The author points out that an ARISE data centre is proposed. In their study of the classification of infrasound signals, *Garces et al.* (**T1-O12**) dwell on the importance of extending the IRED.

For data acquired from the oceans, *André et al.* (**T3-O1**) describe the collaborative project LIDO, which collects data from sensor networks that monitor the oceans in a range of countries including Spain, France, Canada and Japan. LIDO is concerned not only with acoustic signals in the oceans, but also with the continuous monitoring of acoustic noise; this has a range of applications including the monitoring of shipping, marine mammals, seismic surveys and offshore construction. Classification of noise sources is discussed, and the mitigation of marine acoustic noise sources is one goal.

Another initiative which emphasises the free exchange of data and partnerships in scientific research is NEPTUNE Canada, which is described by *Pautet et al.* (**T3-O3**). NEPTUNE Canada includes a network of ocean-bottom data acquisition nodes housing a range of sensors including seismic and acoustic, off Canada's west coast.

The role of the European Science Foundation (ESF) as an independent organization dedicated to pan-European scientific networking and collaboration is described by *Campus and Azzolini* (**T5-P33**). Many large-scale projects with relevance to the science of CTBT verification are described.

The relevance of the ISC as a data source for CTBT monitoring is discussed by *Bondár et al.* (**T5-P5**); they present the ISC Bulletin (**FIGURE 9.5**). They also describe the Engdahl, van der Hilst and Buland (EHB) 'groomed' ISC Bulletin and the IASPEI Reference Event List (**FIGURE 9.6**), both of which find application

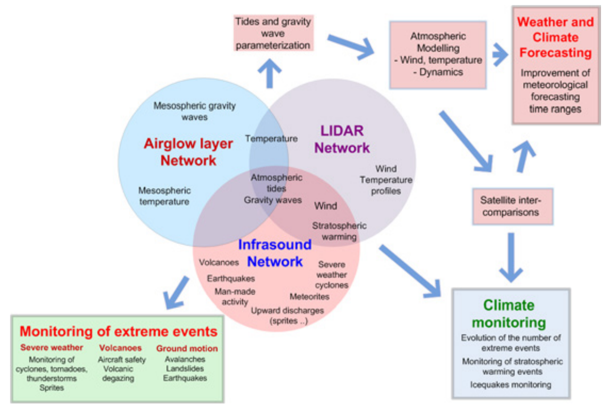


FIGURE 9.4
Objectives of the ARISE project, showing the complementary role of infrasound, LIDAR and airglow observations. From *Blanc* (**T1-P45**).

» The IRIS Data Management Centre (DMC) manages the largest concentration of broadband seismological data in the world. DMC data and services are free and open. A rich variety of request tools are currently being extended using Representational State Transfer (REST) web services. These new methods of providing access to data will greatly simplify a research or monitoring group's ability to retrieve data quickly, reliably, and in a form that is readily usable.

TIM AHERN, IRIS

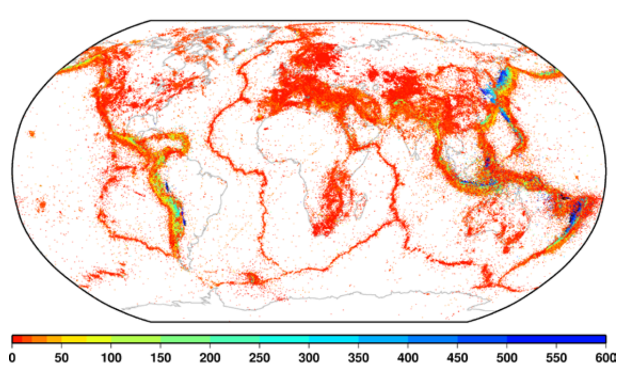
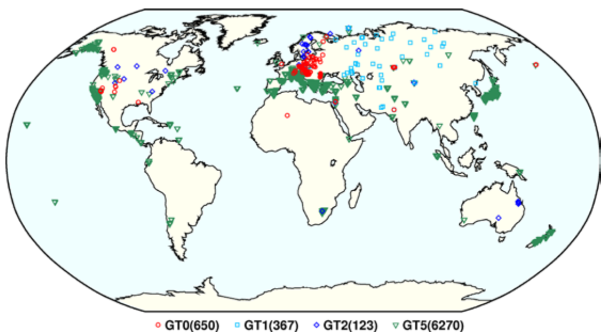
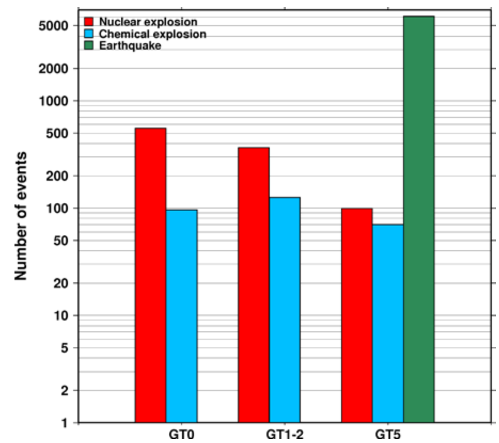


FIGURE 9.5
The full ISC Bulletin 1960 to 2011 (approximately 4 million events), with depth colour-coded in km. From Bondár et al. (**T5-P5**);



a)



b)

FIGURE 9.6

a) Geographic distribution of the 7,410 GT5–GT0 events in the IASPEI Reference Event List as at May 2011. **b)** Distribution of ground-truth events among source types. From *Bondár* et al. (**T5-P5**).

in the improvement of wave-speed models (**SECTION 6.1.1**) and hence event location (**SECTION 5.1.2**). To promote data and knowledge exchange, the ISC has developed a link from CTBTO to the ISC database, with support from the UK Foreign and Commonwealth Office and several partner organizations in Nordic countries. This link is described by *Bondár et al.* (**T5-P4**), who point out that the link enables authorised users from CTBTO States Signatories to access ISC bulletins and seismic station history information, thus offering opportunities for comparing the performance of, for example, the ISC bulletin and the REB. Relevant data available for the DPRK region are highlighted as an example. The digitizing of historical seismograms relevant to CTBT monitoring is considered by *Sokolova et al.* (**T5-P16**), who describe a database of digitized historical seismograms recorded from nuclear and chemical explosions at stations of several seismic networks in the former USSR.

In 1985 the FDSN was established to bring together the operators of digital, broadband seismic stations, which at that time represented a major enhancement in the technology of seismic data acquisition. *Suarez and Haslinger* (**T5-O7**) describe the goals of the FDSN. These include the encouragement of data exchange, the promotion of digital broadband seismic network installation at the local, regional and global level, and the coordination of the location of such stations, as well as the provision of support to national institutions and seismic networks as they moved to the new technology. The installation of ocean bottom seismometers is included in its interests. The authors point out that a 'backbone' of over 200 stations within member networks provides data in real-time to the IRIS DMC, and they describe the FDSN 'performance goals', which include the free and open access of members' data via internet, the real-time availability of data without delay or restriction, data quality control, and a continuous and complete data archive.

Seismic data acquisition and processing systems have also helped to promote data sharing, by prioritizing multiple formats and platforms. *Hellman et al.* (**T3-P47**) describe the open-source seismic acquisition and processing system Earthworm. This promotes data exchange and cooperation by offering a common protocol for networks to share data, supporting multiple data formats and operating systems. Data sharing and cooperation in South-Central Europe are described by *Pesaresi et al.* (**T3-P25**), using Antelope and SeisComP3 data acquisition and processing software. These are also used for sharing data within the HUSN of Greece, described by *Papanastassiou et al.* (**T3-P26**).

10

Closing

INTRODUCTION

The Scientific Closing Session comprised three presentations, giving different perspectives on the outcomes of the Conference, and some pointers to the future. Representatives of the scientific community, the CTBTO and its States Signatories (as represented through Working Group B of the Preparatory Commission) were invited to give closing remarks. These presentations are reproduced here in full.

10.1

PAUL G. RICHARDS: PERSPECTIVE OF THE SCIENTIFIC COMMUNITY

Paul G Richards

Special Research Scientist,
Lamont-Doherty Earth Observatory,
Columbia University, USA

Excellencies, fellow scientists, and other ladies, and other gentlemen:

I have been asked to summarize this conference from the perspective of the scientific community — and I plan to begin with a large and general point, then move on to categorize some of the different types of research we have heard and seen here, and finally to get into some specific examples of successful work that has been enabled with data and facilities of the CTBT Organization.

The largest and most general point is that those of you who have always known the CTBT networks and data centre were important — in support of a major arms control initiative to deter vertical proliferation — have now been joined in recent months by an enormous new audience, of people who have needed objective and high quality information on the great earthquake offshore Japan, magnitude 9, and information on the great tsunami waves, and on damage to nuclear reactors at Fukushima and the resulting release of potentially damaging radionuclides detected worldwide. Technically, these were three very different types of disaster.

It is not a comfortable matter to acquire data and to generate data products that are suddenly of intense interest to all humanity. Fortunately, some of the usual rules about data access were suspended, and the fact that good work was done by the IMS and the IDC is now appreciated by many other international and national agencies, as well as by scientists and the general public who will continue to make demands for more information, and more transparency.

Moving on to some of the different categories of work presented at this conference, the way I found it helpful to organize my thoughts was to invent some new acronyms and write them on my programme.

One category I'll call OTM—which stands for Other Types of Monitoring—

- the work of monitoring volcanoes, or
- the natural earthquakes near a candidate nuclear waste repository, or
- using infrasound to monitor the circulation of the upper atmosphere.

So, concerning OTM: CTBTO networks are turning out to be excellent for other types of monitoring.

Another acronym, which I wrote all over my programme, is MTL, standing for Much To Learn. For example, much to learn still, about isotopes used in modern medicine that are derived from the fission

» The largest and most general point is that those of you who have always known the CTBT networks and data centre were important—in support of a major arms control initiative to deter vertical proliferation—have now been joined in recent months by an enormous new audience, of people who have needed objective and high quality information on the great earthquake offshore Japan, magnitude 9, and information on the great tsunami waves, and on damage to nuclear reactors at Fukushima and the resulting release of potentially damaging radionuclides detected worldwide. Technically, these were three very different types of disaster.

PAUL G RICHARDS

of highly enriched uranium. Much to learn, about synergies between data derived from different types of monitoring techniques. Much to learn, about the information that can in practice be extracted from gamma ray spectra in radioisotope studies, and about using cross correlation in several different ways with seismic data (for example to manage the burden of thousands of aftershocks that typically follow a great earthquake).

Going back to the first of these MTL subjects—much to learn about medical isotopes—I was struck by the similarities here with a situation that arose about 25 years ago in seismology when it seemed that a first-class network of seismometers, operated to monitor for nuclear explosions, had the potential to be overwhelmed by the signals from hundreds of chemical explosions that occur every day in large mines around the world. It took more than ten years of work to evaluate this problem—which is real, but which in my opinion has turned out to be manageable. So may it be with the signals from special reactors making medical isotopes—which over time must become understood, in a climate where peaceful uses of fissionable materials are going to have to become more transparent if they are to gain the trust of the general public. One way or another, if necessary by site-specific monitoring, peaceful uses of nuclear reactors will have to become more transparent.

I could go on with the acronyms that I have used to mark up my programme. For example, EOC—it stands for Estimation of Capability. Many presentations addressed that subject, seeking quantitative estimates of how well we characterize the location and size, and even the very nature, of the sources whose signals the CTBTO networks detect.

But let's take a break from acronyms, and note some highlights in the five themes around which this conference has been organized.

In **THEME 1**, "The Earth as a Complex System", I was struck again and again by the renaissance in our understanding of the atmosphere, enabled by the infrasound network. One invited speaker reminded us of a paper written in 1973 that advocated a synoptic network to monitor conditions in the upper atmosphere, because of the insights it would permit into this key feature of our extraordinary and very special planet. This resonated with me, because I was on the thesis defence committee of the author of that 1973 paper. He went on to explain that great storms at sea generate microseisms, and microbaroms, and disturbances in the atmosphere that propagate up to the highest levels, and are there so active that they raise temperature by tens of degrees!

And there is feedback from infrasound research into our estimates of the capability of the infrasound monitoring network, because it is being learned that planetary waves and gravity waves in the atmosphere in general serve to perturb the atmosphere in ways that increase the detection capabilities of infrasound monitoring for nuclear explosions.

Under **THEME 1** we also heard of serendipity, when a huge natural phenomenon is detected on the wrong instrument, giving new insight into physical processes—such as when an ice floe is moved by a tsunami, and a seismometer on the ice is used to measure the amplitude of the December 2004 tsunami, out in the open ocean.

THEME 2 was "Understanding the Nuclear Explosion Source"—for example, understanding the radionuclide source term for an underground nuclear explosion, needed to develop novel technologies for CTBT radionuclide measurement and analysis as well as the radioxenon and other noble gas signatures and measurements. The conveners have told me to say that the new methods for some measurements have been implemented or proposed to be further investigated. Another topic covered during the session was related to seismic phenomena and the physics of explosion sources as well as the understanding of the seismic signals originated from nuclear explosions. It may be possible to use small-scale chemical explosions as a basis for understanding the seismic and other wave phenomena, which could serve for development of efficient verification technology.

THEME 3 was "Advances in Sensors, Networks, and Observational Technologies". We heard of

- a new wave of deployment of ocean observatories, seismic networks, and the first wave of extensive deployment of infrasound sensors
- the value for science of these long-term/densely-deployed/continuous real-time monitoring systems, was clearly demonstrated.
- new sensor developments that provide better performance, both for deployment and maintenance. Examples include an optical seismometer, and a new underground low-background radionuclide lab.

THEME 4 was "Advances in Computing, Processing and Visualization for Verification Applications". The most notable feature to the convenors was the extent to which the reported research focused directly on issues of importance to CTBTO (both IMS and OSI), while retaining a good deal of innovative 'basic research' flavour. Many of the poster presentations were by the PTS or NDCs reporting on the current performance of the verification system and recommendations for further development. A number of presenters described substantial and largely successful efforts to integrate infrasound and radionuclide monitoring into the overall IMS pipeline, despite the additional complexities of the signal propagation models. We heard of state-of-the-art machine-learning methodologies applied to the problems of detecting, identifying, and associating signals from waveform technologies. Some current work is approaching operational readiness. Novel applications continue to be proposed, such as

- improved signal detection at IMS stations, including seismometer and infrasound arrays and radionuclide detectors
- improvements in the accuracy of seismic travel-time models, and
- application of cross-correlation methods to improve efficiency of waveform analysis.

THEME 5 was "Creating Knowledge through Partnerships, Training and Information/Communication Technology". This theme started with an overview of transnational cooperation and how this cooperation has been—and can be—used effectively to advance both science and policy. This cooperation can also be seen as a confidence-building measure, through its promotion of transparency and openness. Examples include:

- capacity building programmes by CTBTO and others from the view of both the providers as well as the recipients
- international partnerships in scientific experiments—a trend that has been increasing for many years: various federations and data centres provide alternative sets of data that complement—and help to assess—the work of the CTBTO
- cooperation in gathering and disseminating a wide range of geophysical data as well as in developing tools for their analysis
- initiatives for public awareness of capabilities used by scientists working on CTBT issues.

Underlying all five themes, repeatedly, we heard of the need for data access. And here, of course, we are dealing with a difference in cultures—between the freewheeling approach of many researchers, and the prescribed activities in which the PTS is allowed to engage.

It is important for each side to understand the culture of the other if we are to work long-term on these matters, and for each side to help the other as far as may be possible, and not get too frustrated. One speaker this morning had a very useful summary of practical experience in this matter, acquired over many years. He said that "Well-exercised data are healthy data"—meaning that one of the best methods for maintaining a high-quality data flow is to have a large and active user community.

My overall conclusion from the last three days is that monitoring for nuclear explosions, today, is being done very well indeed by the PTS. And the work continues to improve.

In my opinion it will get significantly better, especially if opportunities are taken to maintain a good relationship with the vast community of potential data users, whose focus may be far from treaty monitoring. The feedback from those data users will help the CTBTO do its very important work.

10.2

LASSINA ZERBO: PERSPECTIVE OF THE CTBTO

Lassina Zerbo

Director, International Data Centre Division,
Provisional Technical Secretariat,
Preparatory Commission for the CTBTO

Dear friends and colleagues,

As the Project Executive for the planning of Science and Technology 2011 and as the Director of the International Data Centre, it gives me great pleasure to address all of you during this, the scientific concluding session.

Our three days have been spent productively and collegially as evidenced by the scores of interactions which have taken place, the scientific collaborations which have been initiated, and the information which has been transmitted. I and my colleagues at the PTS will be digesting the wealth of insights we have gained from you during this workshop for many weeks and months to come.

To review and recap our work over these past three days, I remind you that the goals of SnT2011 were to discuss advances in science and technology relevant to test ban verification, to explore scientific applications of the Comprehensive Nuclear-Test-Ban Treaty verification infrastructure, and to encourage partnerships and knowledge exchange between the CTBTO and the broader scientific community. I believe that with your help and active participation, we have met each one of these goals.

The organization of SnT2011 around five theme areas has helped clarify our thinking about technical advances relevant to the CTBTO. These five conference themes which we selected well in advance were:

- The Earth as a complex system
- Understanding the nuclear explosion source
- Advances in sensors, networks and observational technologies
- Advances in computing, processing and visualization for verification applications
- Creating knowledge through partnerships, training and information/communication technology

It is essential that the CTBTO verification effort be enhanced through the adaptation and implementation of new ideas and through the paced adoption of novel technologies; indeed Article IV of the Treaty imposes a requirement for such continuous improvement. Your contributions to the technical programme of SnT2011 have furthered significantly our progress along these lines.

SnT2011 has followed in the path of the September 2006 Symposium on Synergies with Science, and the International Scientific Studies conference held in June 2009 (ISS09). Ties between the scientific community and the CTBTO have been progressively strengthened over the past few years, and several projects are underway that show the benefits of such ties both to the CTBTO and to the broader scientific and engineering community involved. We have confidence that with this successful conclusion of SnT2011 additional ties have been formed and existing ties have been enhanced.

Over 300 research contributions and review presentations were received and a total of 282 were included at this Conference, representing a broad range of original effort. I hope you will agree with me that the reach of the conference has been truly global, and that interest was evident even among scientists from States that have not yet signed or ratified the Treaty.

A special session was held on the devastating 11 March 2011 Tohoku earthquake in Japan, its associated tsunami, and the subsequent release and dispersion of radioactive particles and noble gas from the Fukushima nuclear plant. The panel discussion which took place immediately after the presentations on the Tohoku earthquake and Fukushima accident was extremely informative and underscored the vast potential for IMS data to contribute to real-time warning systems and civil applications such as disaster management.

Our other two panel discussions covered topics highly relevant to the CTBTO's engagement with the scientific community including mechanisms for partnerships with the CTBTO and ideas for technology support programmes. This conference is part of a continuing process of engagement. I hope it has allowed you to present and discuss your work, assimilate advances that have occurred during the past two years, and interact with your peers.

Accordingly, the goals of SnT2011 have been to discuss advances in science and technology relevant to test ban verification, to explore scientific applications of the Comprehensive Nuclear-Test-Ban Treaty verification infrastructure, and to encourage partnerships and knowledge exchange between the CTBTO and the broader scientific community. It is my assessment that these goals have been exceeded, and that SnT2011 has succeeded beyond our expectations.

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Your contributions to the technical programme of SnT2011 have furthered significantly our progress along these lines.

LASSINA ZERBO

The SnT2011 Programme Committee and the project team hope that your visit to Vienna for this scientific conference organized by the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) has been productive and stimulating. The CTBTO remains responsible for developing the Treaty's verification regime, whose primary purpose is to ensure that any nuclear explosion is detected, located, and described sufficiently well for it to be identified. With your contributions to SnT2011, I believe that we have advanced the mission of the CTBTO, strengthened our connections with the scientific community, and laid the groundwork for future meetings of this kind. Thank you for your help in making this conference a success.

10.3

JAY ZUCCA: PERSPECTIVE OF THE STATES SIGNATORIES

Science and the Comprehensive Test Ban Treaty

J.J. Zucca

Programme Director for Nonproliferation,
Global Security Principal Directorate,
Lawrence Livermore National Laboratory,
United States of America,
and Task Leader for Technology Refreshment,
Working Group B of the CTBTO Preparatory Commission

Verifying the CTBT is an unprecedented technical undertaking for an international treaty. No other Treaty has the same depth of scientific expertise needed in order carry out the verification provisions. The Nonproliferation Treaty and the Chemical Weapons Convention both have scientific verification regimes but they are confined to primarily one discipline. The science of nuclear explosion monitoring crosses several disciplines from nuclear physics to seismology and acoustics to atmospheric transport modelling.

The science of nuclear explosion monitoring has been under development for over fifty years—or at least some of the disciplines have. At one end of the spectrum is the seismic method, which is relatively mature. At the other end is the Noble Gas method whose development basically started with the signing of the Treaty in 1996. Whether a monitoring method is mature or in its infancy, the development of the underlying science never stops. While we work in our community to continually improve the monitoring, we need to stay engaged with scientists in related fields outside our community. These scientists continue to develop new technologies and algorithms that can have a direct benefit to our work. Indeed it is likely that some of the most important advances in the future are likely to come from this outside community. Going forward with it will be more important than ever for us to maintain a situational awareness of the advances taking place in the broader scientific community and to have a transparent mechanism for bringing the best of these new advances into our verification systems.

Maintaining this contact with the outside community is particularly important at this point in time. The International Data Centre is undertaking a major effort to re-engineer the event processing pipeline software upon which the development of the products of the IDC is based. The pipeline and its algorithms are what make the event bulletins of the IDC possible. Many of the algorithms in the IDC were written over thirty years ago. New algorithms are available now which will run more efficiently on today's computers and produce better products from the data of International Monitoring System. For example, at ISS09 two years ago, we learned about new data mining and machine learning techniques. The result of this new knowledge has been the development of the new NET-VISA algorithm, which is being tested at the IDC now. At this meeting we have the opportunity to learn about new technology and algorithms that can potentially make their way into our monitoring and verification system.

How will this process work? How will new technology and algorithms make their way into the IDC and IMS? First off, in Working Group B, Technology Refreshment is our forum for exploring new technology and its impact on the verification system. I am the task leader for that forum. What tools do we have to get our work done? We have the radionuclide and waveform experts groups, Working Group A, the Provisional Technical Secretariat, and the outside scientific community. We need to use all these tools effectively to guarantee that the IDC and IMS are technologically relevant in the future.

Working Group B represents the technical knowledge of the States that are Signatory to the Treaty. We are the ultimate judge of the appropriateness of new technology to replace obsolescent technology in our monitoring system. As part of our meetings in Vienna, our experts meet with the experts in the PTS. These meetings are carried out in an informal setting in order to facilitate effective communication among the experts about the inner workings of the verification system. As the need for changes and new technology is identified in the expert groups, they make recommendations to Working

Group B. Then we discuss the recommendations and modify and approve them as appropriate and report our recommendations to the Preparatory Commission for possible approval.

The PTS is a key partner in this process. They are the stewards of the verification system and have the best knowledge of how it works. Although the PTS is not a research and development organization, the verification divisions are composed of scientists that have vast technical experience and insight into the verification technologies. In addition there is the Engineering and Development Section that is developing technology solutions to issues that the PTS is facing today. A current example of such development is the work to develop a reliable cryogenic cooling system for the radionuclide particulate systems. The failure of these mechanical cooling systems is the major factor in the extended downtime that has been plaguing these systems.

> » Verifying the CTBT is an unprecedented technical undertaking for an international treaty. No other Treaty has the same depth of scientific expertise needed in order carry out the verification provisions. The Nonproliferation Treaty and the Chemical Weapons Convention both have scientific verification regimes but they are confined to primarily one discipline. The science of nuclear explosion monitoring crosses several disciplines from nuclear physics to seismology and acoustics to atmospheric transport modelling.
>
> J.J. ZUCCA

The outside scientific community has a strong role to play as well. Through scientific meetings such as this one, professional society meetings and CTBTO-sponsored workshops, the national and PTS experts have the opportunity to interact with the broader scientific community. These meetings provide a forum for the broader scientific community to see the state of the art in the CTBT verification system and for the national and PTS experts to see what's new in the scientific disciplines. If an outside expert has an idea that he or she wants to try out on IMS data that interaction is possible through something called the vDEC or virtual data exploitation centre.

The vDEC was first discussed at the ISS09 and is now up and running in the IDC. The vDEC has two main functions. First it is a data access portal for the IMS data. Once a researcher gets a password on the vDEC he or she can log in and obtain IMS data. The second main function is to allow researchers to run new algorithms in a developmental version of the IDC data processing pipeline. As results are achieved they can be brought to the expert groups and discussed by the national and PTS experts. As appropriate these results can be brought to the WGB for consideration for adoption.

What about long-term scientific trends that we need to monitor in order to be able to plan for the future of the verification system? The PTS has undertaken the Technology Foresight project in order to understand the long term technology trends for our verification technologies. The results of effort are on display at this meeting.

In summary there is a well-defined process for getting new ideas into the IDC. Scientists in the PTS, Working Group B, and the broader scientific community all have an important role to play. The vDEC portal to the IDC is an important tool to facilitate the interaction of all these communities.

11

What Was Missing from SnT2011?

INTRODUCTION

The purpose of this Section is to examine the coverage of SnT2011's scientific contributions against the Conference Goals, in order to provide a perspective on how well the oral and poster presentations represent relevant research topics. The three Goals are displayed in SECTION 1. In summary, they respectively cover verification (both inside and outside CTBTO), the scientific applications of verification data and its associated infrastructure, and CTBTO's engagement with the broader scientific community. SECTIONS 3-8 of this Report cover contributions on various aspects of the first Goal, from data acquisition to interpretation and performance, and SECTION 9 includes most contributions on the third Goal. Contributions towards the second Goal are mostly covered in SECTION 6, though there is no Section dedicated to that Goal explicitly.

Gaps in the range of scientific contributions might arise in various ways. First, CTBTO's attempts to reach out to those parts of the scientific community whose activities may be relevant to the Goals may not have been exhaustive or appropriately targeted; this may be especially so for research fields whose relevance to CTBT verification is not obvious, or is yet to be established. Secondly, many factors influence what research is performed, including the priorities of industry and governments, the patterns of research funding, university research policy, and the level of intellectual challenge. Thirdly, some topics may not be the subject of active research because a need has not been demonstrated. Finally, as with any conference, those researchers with relevant contributions may simply have chosen not to participate. In the end, the papers presented at any scientific conference represent the range of research activities of the contributors who have decided to contribute, or who have been invited to contribute. So a list of gaps might include topics which are not currently the subject of research, as well as active research topic not reported.

This Section includes examples of topics potentially relevant to each of the three Goals, but which are not represented in the SnT2011 scientific contributions. There is no attempt to be exhaustive, and no attempt to sort the examples by relevance or to prioritize them. Some topics are broad while others have arisen from very specific concerns. Given the desire to seek new scientific linkages, new technological applications and new avenues for knowledge exchange, potentially fruitful advances include ones not known in advance, so any list of gaps is necessarily open-ended.

11.1
SnT2011 GOAL 1

"Discuss advances in science and technology relevant to test ban verification"

A review of SECTIONS 3-8 of this Report offers an indication of possible gaps relating to this Goal. The Technology Foresight initiative of CTBTO is set to address the longer-term need for scientific and technological solutions to monitoring and verification questions, and this is especially relevant to this Goal. Technology Foresight will be given a special focus in future conferences, and no attempt is made to list such longer-term needs here.

In SECTION 3 (Data Acquisition), there are no contributions on hydroacoustic sensors (SECTION 3.1.2), and there are few contributions on sensors relevant to monitoring methods which are outside those currently used under the CTBT (SECTION 3.1.6). There are several contributions on novel remote methods, such as airglow monitoring and total electron content, used to detect disturbances in the upper atmosphere created by infrasound (SECTION 3.1.6). Bearing in mind that infrasound is increasingly observed from seismic events, these contributions highlight the potential for underground events to generate seismic waves that couple into the atmosphere, giving rise to disturbances at high altitude that can be detected remotely. Indeed, airglow and light detection and ranging (LIDAR) are two technologies currently under investigation for technology synergy in the field of atmospheric dynamics, and there may be other work on this approach that is not reported here.

There is no focus on the use of satellite based methods for monitoring nuclear explosions, and no contributions on the monitoring of nuclear explosions in outer space. In the meantime, contributions on the calibration of infrasound stations and the establishment of infrasound instrumentation standards would reflect the emphasis that needs to be given to those topics. It was also too early to address the lessons learnt from the Fukushima Daiichi nuclear power plant accident, such as improved adaptation of the dynamic range and time resolution of radionuclide stations, and consideration of the potential for early detection of a plume.

In the OSI context (SECTION 3.3), there are few contributions on the major challenges in data acquisition faced by a time-limited inspection regime in an unknown physical environment with what may be less than state-of-the-art techniques. As pointed out by *Strangway* in his keynote address (SECTION 2.2), the mineral extraction industry faces some analogous challenges in the acquisition of geophysical and remotely sensed data during exploration, though these potential sources of relevant information are not considered by other SnT2011 contributors. There are no contributions on resonance seismometry, which is an OSI method listed in the Treaty[48].

SECTION 4 (Data Transmission, Storage and Format) is conspicuously brief. Bearing in mind the rapid and revolutionary changes in telecommunications technology and its reduction in unit costs that have taken place over the last 15 years, contributions on alternative data transmission models, perhaps using secure internet, would be potentially relevant. Models for the sharing of bandwidth to optimize the use of infrastructure and to reduce costs might also have application.

SECTION 5 (Data Processing and Synthesis) is relatively long, with many diverse contributions. These serve to highlight the challenges as well as the achievements in this field. For example, some contributions point out the shortcomings of automatic seismoacoustic data processing and the investment in interactive analysis that must be made as a result; it becomes clear that despite much effort, over 15 years of CTBTO, there is still much scope for improvement in CTBTO seismic operational data processing as it applies to the use of IMS data to compute standard IDC products. New approaches using machine learning, cross-correlation and other techniques promise improvements in the future (SECTION 5.1.2), but realization of these will depend upon thorough testing in an operational environment to demonstrate an improvement in performance, taking into account the statistics not only of real events found, but also of invalid events created. The establishment of baseline performance, and efforts to establish benchmarks, are aspects not extensively covered.

On the interactive environment for waveform data analysis (SECTION 5.1.2), there is no discussion of advances in visualisation which might assist analysts in verifying and modifying the results of automatic processing, adding missed events, or the speeding up of analysts' work. The well-known problems of excessive analyst workload during aftershock sequences also remains unmitigated in IDC Provisional Operations, not only for waveform analysts (SECTION 5.1.2), but also for radionuclide analysts (SECTION 7.2.2), as revealed by the Fukushima Daiichi nuclear power plant accident. Examples of seismoacoustic signals recorded in unexpected circumstances by sensors not designed for such signals (SECTION 3.1.4) suggests untapped potential for the fusion of data recorded on seismic, hydroacoustic and infrasound sensors (SECTION 5.1.5), which could improve the understanding of sources close to or at the boundary between different media.

The combined processing and interpretation of data recorded by multiple monitoring technologies (data fusion) is addressed insofar as it applies to seismic, hydroacoustic and infrasound data (SECTION 5.1.5). However, approaches for combining data from seismoacoustic and radionuclide observations receive little attention.

SECTION 6 (Earth Characterization) contains many contributions of direct relevance to CTBT verification, again highlighting challenges as well as achievements. The need to provide improved three-dimensional descriptions of the earth's seismic wave-speed field (SECTION 6.1.1) has long been central to the precise and reliable location of potentially suspicious events, but a comprehensive solution, especially at regional distances, remains elusive. Accordingly, novel approaches to this issue, and the broader question of optimally locating events and measuring the errors in these locations, would be valuable. For the atmosphere (SECTION 6.3.1), the source location problem is complicated by rapid temporal variations in acoustic wave speed, which will require a new wave field to be calculated from meteorological data at appropriate intervals of time. This poses its own challenges which are not addressed explicitly in contributions.

Improvements in the calculation of atmospheric transport models (SECTION 6.3.3) need complementary increases in the resolution of meteorological data fields, as well as reliable source information or emission inventories, and trustworthy measurements. Here a specific problem is identified near IMS radionuclide stations in mountainous regions, where mesoscale effects, not taken account of in uniform resolution ATM, can greatly affect the validity of conclusions (SECTION 6.3.3). A related need is to devise methods which provide well-founded error bounds on ATM; this becomes especially important when hypotheses involving known radionuclide sources are discounted using ATM evidence.

SECTION 7 (Interpretation) includes the question of source identification using seismoacoustic, radionuclide or other data. The relevance to CTBTO technical activities is important for event screening (SECTION 7.3.3), because the TS of the CTBTO will not make a final judgement on the nature of any event[9]. However, for the States Parties, identification of suspicious sources will be a crucial part of verification. There are few contributions on the discrimination of sources using radionuclide data (SECTION 7.3.2), and none on the interpretation of radionuclides from underwater nuclear explosions. Moreover, there are no contributions with specific proposals for new CTBTO event screening criteria (SECTION 7.3.3).

SECTION 8 (Capability, Performance and Sustainment) includes little material on generic maintenance and logistics issues, or on sustainability (SECTION 8.4). This may be seen as a major gap, bearing in mind the challenges that are faced in the longer-term sustainment of IMS stations, and in recapitalizing IMS facilities. The implications of the Treaty obligation to keep pace with the latest technology[8] is especially relevant in the field of IMS station equipment, where decisions must be made on the options of using older, proven technology, or the latest technology which might prove to be less reliable initially, or which may not rigorously meet all IMS specifications.

11.2 SnT2011 GOAL 2

"Explore scientific applications of the CTBT verification infrastructure"

A starting point for describing the applications of CTBT verification data is the reports from four experts' meetings on the civil and scientific uses of CTBT verification technologies organized by the CTBTO between 2002 and 2006—see first focus box in SECTION 9. The experts attending these meetings identify a wide range of potential scientific applications of IMS data covering basic research as well as environmental monitoring and disaster mitigation. Although some of these applications feature in SnT2011 contributions, many of those envisaged for hydroacoustic and radionuclide data do not. Some applications of IMS hydroacoustic data suggested at the experts' meetings are represented, such as monitoring of marine mammals, background acoustic noise monitoring and submarine volcano monitoring, while others are absent including acoustic thermometry, the monitoring of iceberg activity and the tracking of distant storms. Potential uses of IMS radionuclide data suggested at these meetings but not represented at SnT2011 mainly concern environmental monitoring and pollution research, as well as trends in microscopic fauna. These applications envisage the exploitation of material other than radionuclide particulates which are collected on the filters at radionuclide particulate stations.

Goal 2 refers not only to verification data, but also to verification infrastructure. Some IMS stations provide a source of electric power and data communications at remote sites which would otherwise not be able to support measuring equipment for long periods. The possibility of shared use of this infrastructure by research or government groups for recording other types of data for unconnected purposes would first need an elaboration as to what types of data collection programme might benefit from such a remote location. Meteorological stations might be one; environmental monitoring might be another. There are no contributions exploring this potential. Shared use of the GCI is another topic that could provide benefits to CTBTO as well as to science.

This Goal is not restricted to the IMS infrastructure operated by CTBTO. The potential uses of other data acquired by States Signatories or independent entities which may be employed for verification might also find other applications; there are no contributions on this topic.

11.3 SnT2011 GOAL 3

"Encourage partnerships and knowledge exchange between the CTBTO and the broader scientific community"

The contributions relevant to this Goal generally appear in **SECTION 9** (Sharing Data and Knowledge). There have been major developments in the field of distance learning, taking advantage of technological advances in telecommunications and their unit costs in recent years. Many examples of training and knowledge exchange involving collaborations between many entities worldwide are described (**SECTIONS 9.1** and **9.2**), but the mechanisms which might be used exploiting modern technology in this field are not discussed. This is in contrast with contributions on data exchange (**SECTION 9.4**), which describe rapid development in methods of making data available to worldwide users.

12

Possible Focus Areas

INTRODUCTION

The coverage of SnT2011 contributions, and their conclusions about the state of knowledge in various scientific topics of relevance to CTBT verification, can be used to identify topics which require additional work in the future. Outcomes of the Conference might also include new topics which have been identified as gaps, and promising new areas of investigation and novel techniques, either for the short term or the longer term.

Examples of possible focus areas for the future which emerged during SnT2011 are given in this Section. The list is not intended to be exhaustive; no attempt is made to assign priorities or to validate the examples presented. Rather, the aim is to promote discussion on some future activities and priorities in the field of CTBT verification in its broadest sense. The examples are not restricted to topics contained within the CTBTO's mandate under the Treaty, and are intended to capture the full breadth of potential CTBT verification methods. However, methodologies which are already established and not currently believed to need substantial further development are excluded.

The examples are organized according to the foregoing SECTIONS 3-9. Some ideas arising from the keynote addresses (SECTION 2), the closing statements (SECTION 10) and missing topics (SECTION 11) are integrated at the appropriate places. Cross-references to the relevant Sections of this Report are included where possible. These examples might provide useful input for planning CTBT-related activities. They may also be relevant for planning future CTBT Science and Technology Conferences and in formulating priorities for Technology Foresight. They might also offer ideas to those who may be pursuing research in cognate fields.

12.1
DATA ACQUISITION

1.
Assessment of proposed seismo-acoustic sensors that use optical interferometry to measure displacement, including broad-band seismometer, geophone and OFIS (SECTIONS 3.1.1, 3.1.3 and 10.1).

2.
Design of borehole seismometers and installation methods for them, including hole-locking devices; reduced sensitivity to thermal convection in the borehole (SECTION 3.1.1).

3.
Exploitation of ocean-bottom seismometer networks as an additional source of verification data (SECTIONS 3.1.2 and 10.1).

4.
Developments in ocean-bottom observatory design as an analogue for future modular design of IMS stations (SECTION 3.1.2).

5.
Synergy between infrasound and ionospheric observations such as total electron content, Doppler sounding and GRIPS, for seismo-acoustic signal detection (SECTION 3.1.6).

6.
Novel technologies for CTBT radionuclide measurement, including pancake filters, NDA analysis, and electrostatic samplers which could greatly increase air sample rate at a given power, thus offering increased sensitivity (SECTIONS 3.1.5 and 10.1).

7.
Reduction of cosmogenic background radiation using scintillation plates operating in anticoincidence with the detector: the so-called 'cosmic veto' (SECTION 3.1.5).

8.
Improvement in the sensitivity of IMS radionuclide particulate stations using underground laboratories and increased decay time prior to measurement (SECTION 3.1.5).

9.
Advances in noble gas measurement instrumentation, including the reduction of xenon diffusion in plastic scintillators to reduce the memory effect and thus improve sensitivity, and single isotope calibration standards (SECTION 3.1.5).

10.
Optimization of station location for the IMS radioactive noble gas network, in order to approach uniform global coverage (SECTION 8.2.2).

11.
Assessment of novel technologies such as satellite remote sensing that might be adopted by the States Parties after the Treaty enters into force (SECTION 11.1).

12.
Airborne magnetic profiling as an OSI method to detect underground nuclear testing (SECTIONS 2.2 and 3.1.6).

13.
Electromagnetic sounding and induced polarization as OSI methods to detect underground nuclear testing (SECTION 2.2).

14.
Ground penetrating radar as an OSI method to detect shallow secondary effects and signatures of underground nuclear testing (SECTION 2.2).

15.
Infrared thermal mapping and microwave thermal emission profiling as OSI methods to determine surface and near-surface temperature anomalies respectively (SECTIONS 2.2 and 3.1.6).

16.
Use of kimberlite pipes and palaeocraters as sites for OSI field exercises (SECTION 2.2).

17.
Synergies between OSI methodologies and the same methods used to detect ore bodies by the mining industry, including gamma-ray spectrometry (SECTION 2.2).

18.
Multispectral imaging as an OSI method (SECTION 3.1.6).

19.
Detection of argon-37 for OSI purposes (SECTION 3.1.5).

20.
Microfauna and microflora as radioisotope concentrators in an OSI context (SECTION 3.1.6).

21.
Potential dual-use equipment for OSI from geophysical exploration, environmental monitoring, archaeological prospecting, hydrology and other applications (SECTION 3.3).

22.
Satellite imagery as a tool in OSI planning (SECTION 3.1.6).

23.
Improved software tools for designing strategies for OSI data acquisition to meet Treaty constraints including the maximum 1,000 km^2 field area, the need to use only approved equipment and methods, the short OSI timeline, inspection team size limits, and unpredictability of field environment and conditions (SECTION 3.3).

12.2
DATA TRANSMISSION, STORAGE AND FORMAT

1.
New modalities for future CTBTO data communications (SECTION 11.1).

2.
Synergy with formats used by global data centres to support the integration of non-IMS data provided by States Parties for the purpose of expert technical analysis[46] (SECTION 4.2).

3.
CTBTO contribution to the development of standards to be used by global data centres, since they are important in the integration of

non-IMS data both at NDCs and for special technical analysis by CTBTO (SECTION 4.2).

12.3
DATA PROCESSING AND SYNTHESIS

1.
Improved automatic seismoacoustic signal detection, signal association and event building, including a machine learning approach to these processes (SECTIONS 2.1, 5.1.2, 10.1 and 10.3).

2.
Waveform cross-correlation methods applied to signal detection and event building, including their application to earthquake aftershock sequences (SECTIONS 5.1.2 and 10.1).

3.
Use of source scaling law in cross-correlation processing (SECTION 5.1.2).

4.
Seismic signal detection using a generalized *F* detector. (SECTION 5.1.2).

5.
Refinements to automatic seismic signal arrival-time measurements (SECTION 5.1.2).

6.
Improved tools for interactive analysis of seismic data (SECTION 5.1.2).

7.
Improved methods for processing and analysing earthquake aftershock sequences (SECTION 5.1.2).

8.
Improved infrasound signal detection and event validation (SECTIONS 5.1.4 and 10.1).

9.
Improved identification and classification of infrasound signals, leading to fewer missed infrasound events in automatic processing (SECTION 5.1.4).

10.
Development of synergies between data derived from different types of sensor and different monitoring methods (SECTIONS 3.1.4 and 10.1), including synthetic signals computed for one medium used to verify or discount inferences made from signals observed in another (SECTION 2.1).

11.
Exploitation of seismoacoustic signals recorded across different media in unexpected situations (SECTIONS 3.1.4 and 10.1).

12.
Enhanced methodologies for data fusion between seismoacoustic and radionuclide event location in space and time (SECTIONS 11.1 and 9.2).

13.
Novel technologies for CTBT radionuclide processing and analysis (SECTIONS 3.1.5 and 10.1).

14.
Further integration of infrasound data into IDC processing (SECTIONS 5.1.4 and 10.1).

15.
Conversion of noise into signal in order to better discriminate between signals (SECTION 2.1).

16.
Routine incorporation of additional data into IDC processing (SECTION 2.1).

17.
Enhanced array processing methods, including network-wide array processing, to suppress signals interfering with those of interest (SECTION 2.1).

18.
Review of IDC seismoacoustic event definition criteria (SECTION 5.1.1).

19.
Improved methods to determine radionuclide concentration from gamma-ray peak measurements (SECTION 5.2).

20.
Multiple measurement and analysis of radionuclide samples (SECTION 5.2).

12.4
EARTH CHARACTERIZATION

1.
Improved seismic wave-speed models, including travel-time, azimuth and slowness corrections and well-founded estimates of model error (SECTIONS 2.1 and 6.1.1).

2.
Improved anelastic attenuation models for the solid earth, leading to improved knowledge of the effect of anelastic attenuation on seismic magnitude (SECTION 6.1.2).

3.
Improved acoustic wave-speed and attenuation models for the atmosphere, including the use of near-real-time atmospheric models based on meteorological data to provide time-dependent wave-speed fields (SECTION 6.3.1).

4.
Use of atmospheric gravity waves to increase the detection capabilities of infrasound monitoring for nuclear explosions (SECTIONS 5.1.4 and 10.1).

5.
Improved atmospheric transport models for locating radionuclide sources, to operate at higher spatial and temporal resolution (SECTION 6.3.3).

6.
Variable resolution ATM to provide an adequate description of near-station effects in mountainous regions (SECTION 6.3.3).

7.
Consideration of whether to allow for the effect of washout, in which particulate radionuclides are removed from the atmosphere by precipitation, and how best to model it (SECTION 6.3.3).

8.
Use of the IMS infrasound network to improve understanding of the earth's atmosphere (SECTIONS 6.3.1 and 10.1).

9. Use of natural radioactive tracers to validate atmospheric transport models (SECTION 6.3.3).

10. Studies to help understand radioactive gas transport from the site of an underground nuclear explosion to the surface (SECTION 6.1.5).

12.5 INTERPRETATION

1. The physics of explosion sources (SECTIONS 7.1.1 and 10.1).

2. Use of chemical explosions to understand seismoacoustic signals originating from nuclear explosions (SECTION 10.1).

3. Studies to improve understanding of the radionuclide source term for underground nuclear explosions (SECTIONS 7.2.1 and 10.1) and for underwater nuclear explosions.

4. Location and characterization of observed and potential radionuclide sources, including nuclear reactors (SECTION 7.2.2), medical radioisotope production facilities and other medical facilities (SECTION 7.2.3).

5. Influence of nuclear reactor incidents on radionuclide station sensitivity (SECTION 7.2.2).

6. Refinements to existing waveform (seismoacoustic) event screening criteria including m_b/M_S and regional methods (SECTION 7.3.3).

7. Possible waveform event screening criterion for atmospheric explosions (SECTION 7.3.3).

8. Additional event screening methods, including those combining multiple seismoacoustic technologies (SECTION 7.3.3).

9. Additional screening criteria for radionuclide gamma-ray spectra (SECTION 7.3.3).

12.6 CAPABILITY, PERFORMANCE AND SUSTAINMENT

1. Noise characterization and detection thresholds of IMS stations and networks, in particular those for seismic and infrasound (SECTIONS 8.1.1 and 8.2.1), particulate radionuclide and noble gas (SECTION 8.1.2 and 8.2.2), the last being also relevant for OSI applications of noble gas detection.

2. Use of routine noise measurements as a check on data quality (SECTION 8.1.1).

3. Detailed comparison of different methods of estimating event location threshold, including threshold monitoring, applied to seismic and infrasound networks (SECTION 8.2.1).

4. Detailed comparison of IDC seismoacoustic event lists and bulletins with those of other agencies, to estimate event location thresholds and to measure performance (SECTION 8.2.1).

5. Studies to understand the effect of wind turbine noise on seismic and infrasound data (SECTION 8.1.1).

6. Methods to measure seismometer self noise for performance evaluation (SECTIONS 3.1.1 and 8.1.1).

7. Characterization and measurement of the global atmospheric radionuclide background, in particular that of radioactive noble gases (SECTION 8.1.2).

8. Studies of the effective geographic coverage of the IMS radionuclide particulate and radioactive noble gas networks, taking into account prevailing atmospheric transport patterns, and recommendations to mitigate any gaps (SECTION 8.2.2).

9. Mitigation of the radionuclide background originating from medical radioisotope production (SECTIONS 8.1.2 and 10.1).

10. Studies to understand the potential effect of a nuclear reactor accident on the detection threshold of the IMS radionuclide network (SECTIONS 7.2.2 and 8.2.2).

11. Understanding radionuclide background in soils and the shallow subsurface, in the OSI context (SECTION 8.1.2).

12. Further testing and evaluation of the IMS, IDC and GCI components of the CTBT verification system (SECTION 8.3).

13. Development of metrics and methods (including training datasets and test datasets) for measuring errors and performance associated with new processing methods and algorithms, including wave-speed models and methods for building automatic seismoacoustic event lists (SECTION 8.3).

14. Further assessment of the performance of IDC infrasound processing and analysis (SECTION 8.3).

15. Development of metrics for testing components of the IDC applications software.

16. Modalities for IMS sustainment (SECTION 8.4).

12.7 SHARING OF DATA AND KNOWLEDGE

1. Further development of the CTBTO capacity building programme including e-learning, to include training on nuclear explosion monitoring (SECTION 9.1).

2. Integration of non-IMS data sources, bearing in mind that CTBTO will be required to integrate data from such sources for the study of specific events upon request ('Expert Technical Analysis'[46]) (SECTIONS 2.1 and 9.4).

3. International partnerships in scientific experiments, by analogy with the infrasound calibration experiments of 2009 and 2011 (SECTION 10.1).

4. Further enhancement of the facilities for scientists to undertake relevant projects on vDEC (SECTION 10.3).

5. Consideration of potential partnerships with major data processing and data archiving organizations which have technical challenges related to those of CTBTO (SECTION 9.4).

6. Promotion of work using IMS data for other monitoring and disaster mitigation applications in such fields as volcanic hazard, earthquake hazard and radionuclide dispersion, in order to exercise IMS data and thereby improve performance monitoring and thus data quality (SECTION 10.1).

7. Engagement of the broader community in technology foresight endeavours (SECTION 8.4).

8. Promotion of the integration of Treaty monitoring with other national applications to harvest synergies and support development (SECTIONS 9.1 and 9.2).

Notes

1 Article IV of the CTBT describes its provisions for verification. Paragraph 1 states: "In order to verify compliance with this Treaty, a verification regime shall be established consisting of the following elements: (a) An International Monitoring System; (b) Consultation and clarification; (c) On-site inspections; and (d) Confidence-building measures." (In this context the International Monitoring System (IMS) incorporates the International Data Centre (IDC)). In essence, the purpose of verification under this Treaty is to monitor the compliance of its States Parties with the basic obligations quoted in Note **5**.

2 See, for example, the keynote address by Dr Richard Garwin in **SECTION 2.1** of this Report, and the references contained therein.

3 The Preparatory Commission for the Comprehensive Nuclear-Test-Ban Organization was set up by Resolution CTBT/MSS/RES/1 of the United Nations General Assembly, adopted on 19 November 1996. It was established to prepare for the Treaty's entry into force, and to build up the functionality specified under the Treaty, including the IMS and the IDC. Its Secretariat is referred to as the Provisional Technical Secretariat (PTS). After Entry into Force, the Preparatory Commission will be replaced by the Comprehensive Nuclear-Test-Ban Organization (CTBTO) as specified in the Treaty, and the PTS will be replaced by the Technical Secretariat (TS). For simplicity, the term 'CTBTO' is generally used in this Report for both the current and future organizations, except where distinction between the various organs is important to the context.

4 Article XIV, paragraph 1 of the CTBT specifies that the Treaty shall enter into force 180 days after all 44 States in the Treaty's Annex 2 have signed and ratified; this corresponds to those States deemed to have significant nuclear capabilities. At the time of SnT2011, three of these States had not signed (India, Pakistan and the DPRK (Democratic People's Republic of Korea)), and a further six had signed but not ratified (China, Egypt, Indonesia, Islamic Republic of Iran, Israel, and the United States of America). (Indonesia ratified on 6 February 2012.)

5 The basic obligations of the CTBT are defined in the two paragraphs of its Article I: "1. Each State Party undertakes not to carry out any nuclear weapon test explosion or any other nuclear explosion, and to prohibit and prevent any such nuclear explosion at any place under its jurisdiction or control. 2. Each State Party undertakes, furthermore, to refrain from causing, encouraging, or in any way participating in the carrying out of any nuclear weapon test explosion or any other nuclear explosion." This wording covers a ban on so-called 'peaceful nuclear explosions', as well as on nuclear weapon tests.

6 Article II, Part C of the CTBT creates the Executive Council as the Executive Organ of the CTBTO, comprising 51 Member States rotating according to specified procedures. Article II, paragraph 40, states: "[The] Executive Council shall … [r]eceive, consider and take action on requests for, and reports on, on-site inspections…", and paragraph 41 states: "The Executive Council shall consider any concern raised by a State Party about possible non-compliance with this Treaty …".

7 Article IV, paragraph 16 of the CTBT states: "The International Monitoring System shall comprise facilities for seismological monitoring, radionuclide monitoring including certified laboratories, hydroacoustic monitoring, infrasound monitoring, and respective means of communication …". Monitoring methods which may be used for On-Site Inspections are detailed in the Protocol to the CTBT, Part II, paragraph 69; see Note **21**.

8 Article IV, paragraph 11 of the CTBT states: "Each State Party undertakes to cooperate with the Organization and with other States Parties in the improvement of the verification regime, and in the examination of the verification potential of additional monitoring technologies such as electromagnetic pulse monitoring or satellite monitoring, with a view to developing, when appropriate, specific measures to enhance the efficient and cost-effective verification of this Treaty. ..."

9 The Protocol to the CTBT, Part I, paragraph 18 states: "… These [IDC standard] products shall be provided at no cost to States Parties and shall be without prejudice to final judgements with regard to the nature of any event, which shall remain the responsibility of States Parties …".

10 For further details see, for example, the Section "Scientific Background" in the Keynote Address by Dr Richard Garwin in **SECTION 2.1** of this Report.

11 A graph on page 10 of the internal ISS09 report (see Note **14**) shows that the cumulative number of seismic stations registered with the International Seismological Centre (ISC) increased from about 50 in the 1880s, to about 1,000 in the 1960s, and to about 10,000 by 2010.

12 "Book of Abstracts. Comprehensive Nuclear-Test-Ban Treaty: Science and Technology 2011". CTBTO, June 2011, www.CTBTO.org/fileadmin/user_upload/SandT_2011/Book_of_Abstracts_web.pdf.

13 "Science for Security: Monitoring the Comprehensive Nuclear Test-Ban-Treaty Organization". CTBTO, September 2009, www.CTBTO.org/fileadmin/user_upload/pdf/ISS_Publication/Science_for_Security.pdf.

14 "Possible Projects for the CTBTO arising from the 2009 International Scientific Studies Conference, 10-12 June 2009". CTBTO, May 2011, www.CTBTO.org/fileadmin/user_upload/ISS_2009/ISS_report_2011.pdf.

15 By April 2012 States Signatories had increased to 183 with the addition of Niue.

16 By February 2013 ratifying States had increased to 159 with the addition of Bruni Darussalam, Chad, Ghana, Guatemala, Guinea and Indonesia.

17 "Seismological Methods for Monitoring a CTBT: The Technical Issues Arising in Early Negotiations," at www.ldeo.columbia.edu/~richards/earlyCTBThistory.html.

18 "Earth Science and Society." *Nature* 451, 301-303 (17 January 2008).

19 Bethe, H.A. "The Road from Los Alamos". Masters of Modern Physics Series, volume 2. American Institute of Physics (1991). ISBN 0-88318-707-8.

20 Available for reading and PDF download at www.nap.edu/openbook.php?record_id=10471.

21 The Protocol to the CTBT, Part II, paragraph 69, lists the technologies that may be used during an OSI: "The following inspection activities may be conducted and techniques used, ... on collection, handling and analysis of samples, and on overflights: (a) Position finding from the air and at the surface to confirm the boundaries of the inspected area and establish coordinates of locations therein, in support of the inspection activities; (b) Visual observation, video and still photography and multi-spectral imaging, including infrared measurements, at and below the surface, and from the air, to search for anomalies or artifacts; (c) Measurement of levels of radioactivity above, at and below the surface, using gamma radiation monitoring and energy resolution analysis from the air, and at or under the surface, to search for and identify radiation anomalies; (d) Environmental sampling and analysis of solids, liquids and gases from above, at and below the surface to detect anomalies; (e) Passive seismological monitoring for aftershocks to localize the search area and facilitate determination of the nature of an event; (f) Resonance seismometry and active seismic surveys to search for and locate underground anomalies, including cavities and rubble zones; (g) Magnetic and gravitational field mapping, ground penetrating radar and electrical conductivity measurements at the surface and from the air, as appropriate, to detect anomalies or artifacts; and (h) Drilling to obtain radioactive samples.".

22 The Protocol to the CTBT, Part I, paragraph 3 states: "The area of an on-site inspection shall be continuous and its size shall not exceed 1,000 square kilometres. There shall be no linear distance greater than 50 kilometres in any direction."

23 The Protocol to the CTBT, Part I, paragraph 20(c) defines one of the IDC services as "Assisting individual States Parties, at their request and at no cost for reasonable efforts, with expert technical analysis of [IMS] data and other relevant data provided by the requesting State Party, in order to help the State Party concerned to identify the source of specific events. …"

24 Verification activities, including those of an OSI, are limited by CTBT Article IV, paragraph 2, which states: "Verification activities shall be based on objective information, shall be limited to the subject matter of this Treaty, and shall be carried out on the basis of full respect for the sovereignty of States Parties and in the least intrusive manner possible consistent with the effective and timely accomplishment of their objectives. Each State Party shall refrain from any abuse of the right of verification." OSI activites are also limited by CTBT Article IV, paragraph 35, which states: "The sole purpose of an on-site inspection shall be to clarify whether a nuclear weapon test explosion or any other nuclear explosion has been carried out in violation of Article I and, to the extent possible, to gather any facts which might assist in identifying any possible violator." OSI techniques are restricted by the Protocol to the CTBT, Part II, paragraph 69; see Note **21**.

25 Article IV, paragraph 47 of the CTBT states: "No later than 25 days after the approval of the on-site inspection … the inspection team shall transmit to the Executive Council … a progress inspection report." Paragraph 49 states that "The inspection team may request the Executive Council … to extend the inspection duration by a maximum of 70 days beyond the 60-day time-frame …, if the inspection team considers such an extension essential to enable it to fulfil its mandate."

26 The Protocol to the CTBT, Part I, paragraph 10 states: "... Forty of these [80 IMS radionuclide] stations shall also be capable of monitoring for the presence of relevant noble gases upon the entry into force of this Treaty. ... At its first regular session, the Conference [of States Parties] shall consider and decide on a plan for the implementation of noble gas monitoring capability throughout the network. ..."

27 Protocol to the CTBT, Part II, paragraph 69(c); see Note **21**.

28 Protocol to the CTBT, Part II, paragraph 69(d); see Note **21**.

29 Protocol to the CTBT, Part II, paragraph 69(h); see Note **21**.

30 Evidence is presented on page 12 of the internal ISS09 report (Note **14**).

31 The Protocol to the CTBT, Part I, paragraph 18(b) makes provision for event screening, stating that IDC products should include "[s]tandard screened event bulletins that result from the application to each event by the [IDC] of standard event screening criteria, making use of the characterization parameters specified in Annex 2 to this Protocol, with the objective of characterizing, highlighting in the standard event bulletin, and thereby screening out, events considered to be consistent with natural phenomena or non-nuclear, man-made phenomena. The standard event bulletin shall indicate numerically for each event the degree to which that event meets or does not meet the event screening criteria. … The [IDC] shall progressively enhance its technical capabilities as experience is gained in the operation of the International Monitoring System…".

32 The LEB contains the seismoacoustic events reviewed or added by analysts. Those LEB events which meet the REB event definition criteria are selected automatically to compile the REB. The LEB is not an IDC standard product.

33 Paul G. Richards. "On Seismic Monitoring of Nuclear Explosions". Keynote address, ISS-09 Conference. http://video.CTBTO.org:8080/Public_Archive/ISS-2009/ISS09_2009-06-11_0902.wmv.

34 Kim, Won-Young, Lamont-Doherty Earth Observatory, USA.

35 These authors refer to their process as 'screening out' events; this should not be confused with the same term used in connection with the event screening provisions of the CTBT.

36 Article IV, paragraph 68 of the CTBT requires Member States to cooperate with the CTBTO and with other Member States in implementing relevant confidence-building measures defined in Part III of its Protocol, one purpose of which is to "assist in the calibration of the stations that are part of the [IMS]". Part III of the Protocol to the CTBT lists several voluntary steps to be taken by a

Member State to inform the TS of the location, origin time and other details of large chemical explosions carried out on its territory.

37 This was introduced by Mogi, K. in "Some features of recent seismic activity in and near Japan (2); Activity before and after great earthquakes". Bull. Earthquake Res. Inst. Univ. Tokyo, 47, 395–417, (1969).

38 The Protocol to the CTBT, Part I, paragraph 18, states: "The [IDC] shall apply on a routine basis automatic processing methods and interactive human analysis to raw [IMS] data in order to produce and archive standard [IDC] products on behalf of all States Parties. These products ...shall include: ... (b) Standard screened event bulletins" (see Note **31**).

39 The Protocol to the CTBT, Part III, paragraph 1 states: " Pursuant to Article IV, paragraph 68 [see Note **36**], each State Party shall, on a voluntary basis, provide the Technical Secretariat with notification of any chemical explosion using 300 tonnes or greater of TNT-equivalent blasting material detonated as a single explosion anywhere on its territory, or at any place under its jurisdiction or control. If possible, such notification shall be provided in advance. Such notification shall include details on location, time, quantity and type of explosive used, as well as on the configuration and intended purpose of the blast."

40 Article IV, paragraph 6 of the CTBT states: "... States Parties shall not interfere with elements of the verification regime of this Treaty ...". Additionally, the Protocol to the CTBT, Part I, provides that IMS stations meet the technical requirements set out in the relevant IMS Operational Manual.

41 "A State is obliged to refrain from acts which would defeat the object and purpose of a treaty when: (a) it has signed the treaty or has exchanged instruments constituting the treaty subject to ratification, acceptance or approval, until it shall have made its intention clear not to become a party to the treaty; or (b) it has expressed its consent to be bound by the treaty, pending the entry into force of the treaty and provided that such entry into force is not unduly delayed." Vienna Convention on the Law of Treaties, Geneva, 23 May 1969, Article XVIII.

42 Zaehringer, M. and Kirchner, G. (2008). Nuclide Ratios and Source Identification of High-Resolution Gamma Ray Spectra using a Bayesian Point of View. Nucl. Instr. Meth. Phys. Res. A594, 400-406.

43 From "Riding the Wave: How Europe Can Gain From the Rising Tide of Scientific Data". Final Report of the High-Level Group on Scientific Data. Submitted to the European Commission October 2010. Page 4.

44 Article IV, paragraph 10 of the CTBT states: "The provisions of this Treaty shall not be interpreted as restricting the international exchange of data for scientific purposes."

45 The Protocol to the CTBT, Part I, paragraph 18, states: "The [IDC] shall apply on a routine basis automatic processing methods and interactive human analysis to raw [IMS] data in order to produce and archive standard [IDC] products on behalf of all States Parties. …"

46 The Treaty text for 'expert technical analysis' (Note **23**) refers to "[IMS] data and other relevant data provided by the requesting State Party."

47 Article IV, paragraphs 27 and 28 of the CTBT provide for 'Cooperating National Facilities': "27. States Parties may also separately establish cooperative arrangements with the Organization, in order to make available to the [IDC] supplementary data from national monitoring stations that are not formally part of the [IMS]. 28. Such co-operative arrangements may be established as follows: (a) Upon request by a State Party, and at the expense of that State, the Technical Secretariat shall take the steps required to certify that a given monitoring facility meets the technical and operational requirements specified in the relevant operational manuals for an [IMS] facility, and make arrangements for the authentication of its data. Subject to the agreement of the Executive Council, the Technical Secretariat shall then formally designate such a facility as a cooperating national facility. … (c) The [IDC] shall call upon data from cooperating national facilities, if so requested by a State Party, for the purposes of facilitating consultation and clarification and the consideration of on-site inspection requests, data transmission costs being borne by that State Party. …"

48 Protocol to the CTBT, Part II, paragraph 69(f); see Note **21**.

Appendix 1
Oral and Poster Presentations

KEYNOTES

The Scientific Roots and Prospects for the CTBTO and the IMS (Richard L Garwin)
Earth and Lunar Science: Interaction Between Basic Science and Public Need (David Strangway)

THEME 1. THE EARTH AS A COMPLEX SYSTEM

ORAL PRESENTATIONS

T1-01: Infrasound: from explosion monitoring to atmospheric studies and climate (Elisabeth Blanc)
T1-02: Rupture dynamics of large earthquakes inferred from hydroacoustic data (Catherine de Groot-Hedlin)
T1-03: Extracurricular geophysics, or tsunamis in the complex earth system (Emile Okal)
T1-04: Monitoring of explosive volcano eruptions in Kamchatka and the Kuriles Islands on acoustic data from IMS and KBGS RAS stations (Evgenii I. Gordeev, Evgenii R. Makhmudov, Pavel P. Firstov, Sergei N. Kulichkov, Viktor N. Chebrov)
T1-05: Civil applications of CTBT verification software and technologies: Volcano eruption in Iceland (Gerhard Wotawa, Ulrike Mitterbauer)
T1-06: Determination of an uncertainty radius for back tracing infrasound signals to source caused by atmospheric wave activity (Sabine Wüst, Christoph Pilger, Verena Kopp, Michael Bittner)
T1-07: Argon 37: What is the suspicious threshold activity in soil air? (Roland Purtschert, Robin Riedmann)
T1-08: The South Sarigan submarine volcanic eruption, May 2010: an example of International Monitoring System waveform data synergy. (David Green, Laslo Evers, David Fee, Robin Matoza, Mirjam Snellen, Dick Simons)
T1-09: Next-level shake zoning for modeling seismic-wave propagation in the U.S. Intermountain West (John N. Louie)
T1-010: Ground motion studies for critical sites in north-east Bangladesh (Tahmeed Malik Al-Hussaini, M.Nayeem Al-Noman)
T1-011: Prediction of aftershocks distribution using artificial neural networks (Mostafa AllamehZadeh)
T1-012: Neural classification of infrasonic signals from hazardous volcanic eruptions (Milton Garces, F. Ham, A. Iyer, D. Fee, A. Le Pichon, R. Matoza, T. Murayama, D. Brown, P. Mialle, R. Servranckx)
T1-013: Seismicity and seismic hazard assessment of the arid western regions of South Africa (Hlompho Malephane)
T1-014: Crustal thickness and average VP/VS ratio variations in northern Viet Nam from teleseismic receiver function analysis (Van Duong Nguyen, Bor-Shouh Huang, Tu-Son Le, Van-Toan Dinh)
T1-015: Scattering and intrinsic attenuation structure in Central Anatolia, Turkey using BRTR (PS-43) array data (Korhan Umut Semin, Nurcan Meral Ozel)
T1-016: Detection of earthquake hazard in southwest peninsular India–Spurt of various unusual geological incidents (D. Shanker, H. N. Singh, John Mathai , V. N. Neelakandan , A. Kumar)
T1-017: Upper crust structure under CTBTO station "Petropavlovsk-Kamchatsky" by endogenic micro-seismic activity (Yulia Kugaenko, Vadim Saltykov, Victor Chebrov)

POSTER PRESENTATIONS

T1-P1: Tsunami numerical simulation applied to tsunami early warning system along Sumatra region (Wiko Setyonegoro)
T1-P2: Seismic hazard assessment for Zambia and surrounding areas (Gift Chafwa)
T1-P3: Evidence for infragravity wave-tide resonance in deep oceans (Hiroko Sugioka, Yoshio Fukao, Toshihiko Kanazawa)
T1-P4: Hydro-tremors and incidence of ground rupturing in the northern parts of India: A plausible model (Daya Shanker, M. Banerjee, H. N. Singh, Sanjay , U. S. Singh)
T1-P5: Shallow structure study using gravity data (Agustya Adi Martha)
T1-P6: Analysis spatial and temporal b-value variability seismicity north of Sulawesi (Jimmi Nugraha)
T1-P7: Seismic anisotropy from IDC data (Goetz Bokelmann)
T1-P8: The RN50 station of the International Monitoring System (IMS) as a reference station to the airborne particles pollution in Panama City (Omayra Perez Castro)
T1-P9: Observations of acoustic-gravity waves in the Czech Republic (Tereza Sindelarova, Jaroslav Chum, Jan Lastovicka, Dalia Buresova, Frantisek Hruska, Jiri Base)
T1-P10: Detection and identification of low-magnitude seismic events near Bala, central Turkey (Korhan Umut Semin, Nurcan Meral Ozel, Ocal Necmioglu)
T1-P12: Geophysical investigation for lake level rise (Berihun Asfaw Aregga)
T1-P13: Atmospheric transport processes over the Kathmandu valley, Nepal (Ram Prasad Regmi, Lok Narayan Jha)
T1-P14: 1-D Velocity model for use by the SANSN in earthquake location (Vunganai Midzi, Ian Saunders, Martin Brandt, Timothy Molea)
T1-P15: Determining of the contrast zones based on the analysis of microseismic noise (Svetlana Kishkina, Alexander Spivak)
T1-P16: Tectonic stress field and recent movements of the earth's crust in the Manila subduction zone and adjacent faults (Van Dinh Quoc, Duong Nguyen Van, Luong Nguyen Van)
T1-P17: Sensitivity analysis of infrasound based source verification: influences of atmospheric conditions and

surface orography (Christoph Pilger, Florian Streicher, Michael Bittner)

T1-P18: Detection, location and screening of seismic, hy droacoustic, infrasound and tsunami waveforms associated with May 29, 2010 S-Sarigan submarine volcano eruption, Marianas islands (Jacques Talandier, Olivier Hyvernaud, Dominique Reymond, Helene Hebert, Alexis Le Pichon)

T1-P19: Dissipated energy by S-Sarigan paroxysmic eruption and explosive discrimination on hydroacoustic wave forms (Jacques Talandier, Jean Marc Guerin, Olivier Hyvernaud)

T1-P20: Infrasound studies of some local and regional events detected by I33MG (Fanomezana Randrianarinosy, Gerard Rambolamanana)

T1-P21: Acoustic observations of stratospheric solar tides: Examples from the eruption of Eyjafjallajökull, Iceland, April-May 2010 (David Green, Julien Vergoz, Robin Matoza, Alexis Le Pichon)

T1-P22: Adaptively parameterized surface wave tomography: Methodology and a global model of the upper mantle (Lapo Boschi, Julia Schaefer, Eduard Kissling)

T1-P23: Unexpected high seismic activity observing near the Ulaanbaatar area, capital city of Mongolia: Improved relocation by using array-based earthquake location technique (Ulziibat Munkhuu)

T1-P24: Vp/Vs ratio and seismic activity at active structure of Ulaanbaatar area, the capital city of Mongolia (Demberel Sodnomsambuu)

T1-P25: Investigating body wave energy in ambient seismic noise (Moira Pyle, Keith Koper)

T1-P26: Characterization of the Carancas meteor fall from infrasound signals (C. Millet, C. P. Haynes Millet)

T1-P27: The OGS local virtual seismic network in South-Central Europe as an array: exploiting depth phases to locate upper mantle discontinuities (George Helffrich, Damiano Pesaresi, Takashi Tonegawa)

T1-P28: Observations of atmospheric radionuclide cycles: The benefit for global paleoclimate studies (Christoph Elsasser, Dietmar Wagenbach, Ingeborg Levin, Rebecca Bremen, Rolf Weller, Clemens Schlosser, Matthias Auer)

T1-P29: Effect of anisotropic inhomogeneities in the atmosphere on long-range sound propagation from explosions (Elena Golikova, Igor Chunchuzov, Sergey Kulichkov, Oleg Popov)

T1-P30: Comparison of recurrence curves from the IDC and ISC catalogs (Ivan Kitov, Dmitry Bobrov, John Coyne, Robert Pearce)

T1-P31: Inverse modelling of the 2010 Eyjafjallajökull eruption and comparison with infrasound signals (Petra Seibert, Lars Ceranna, Andreas Stohl, Adam Durant, Stephan Henne, Kjethil Torseth, Robin Matoza, Alexis Le Pichon)

T1-P32: Using the International Monitoring System infrasound network to study large-scale atmospheric waves (Julien Marty, Francis Dalaudier)

T1-P33: Remote monitoring of volcanic eruptions using the International Monitoring System infrasound network (Amy Dabrowa, David Green, Jeremy Phillips, Alison Rust)

T1-P35: Explosion of crater lake in the "Cameroon line" area: seismic contribution (Parfait Noel Eloumala Onana)

T1-P36: Computation of pressure change in the sea from acous-tic and tsunami waves excited by a suboceanic earthquake with a finite-difference scheme for seismic waves (Hiroshi Takenaka, Toshihiro Kuramoto, Takeshi Nakamura, Taro Okamoto, Genti Toyokuni)

T1-P37: Environmental impact of the nuclear tests in Argentina (Eduardo Quintana)

T1-P38: Evaluating 238U/235U in U-bearing accessory minerals (Joe Hiess, Daniel J. Condon, Stephen R. Noble, Noah McLean, Samuel A. Bowring, James M. Mattinson)

T1-P39: Time series analysis of the seismic events worldwide (Jun-Hee Lee, John Coyne)

T1-P40: Phase velocity and attenuation parameters in the Iranian Plateau (Reza Rezaei, Ali Safepour)

T1-P41: Do triggered earthquake patterns depend on trigger faulting style? (Mohammad Tahir, Jean Robert Grasso)

T1-P42: The physics of tsunami: basics understanding and its disastrous effects (D. Shanker)

T1-P43: Assessment of tsunami damage using remote sensing and GIS and expected benefits of disaster early warning systems to tsunami vulnerable areas (Oscar Kithsiri Dissanayake Dissanayake Mudiyanselage Don)

T1-P44: Seismic monitoring in Azerbaijan in aspects of seismic hazard assessment (Gulam Babayev, Fakhraddin Gadirov)

T1-P45: The ARISE project (Elisabeth Blanc, Michael Bittner, Alain Hauchecorne, Lars Ceranna, Andrew Charl ton-Perez, Maurizio Ripepe, Nicolas Brachet, Christoph Pilger, Alexis Le Pichon, Thomas Farges, Philippe Keckhut, Tormod Kvaerna, Jan Lastovicka, Ludvick Liszka, Norma Crosby, Philippe Blanc-Benon)

T1-P46: A report of natural background radiation hazard in southern Tamil Nadu, India and its effect on habitat and environment (Daya Shanker, H. N. Singh, V. N. Neelakandan, A. Kumar)

T1-P47: Forecast of the earthquakes' aftershocks in the common operations of seismic risk reduction (Farshed Karimov)

THEME 2. UNDERSTANDING THE NUCLEAR EXPLOSION SOURCE

ORAL PRESENTATIONS

T2-01: Understanding the radionuclide source term for underground nuclear explosions (Harry Miley)

T2-02: The global atmospheric noble gas background (Anders Ringbom)

T2-03: New and novel technologies for CTBT radionuclide measurement and analysis (Harri Toivonen)

T2-04: Numerical experiments on explosions triggering earthquakes (Luis Angel Dalguer, Florian Haslinger, Seok Goo Song, Tarje Nissen-Meyer, Domenico Giardini)

T2-08: The source time function of an explosive source (Anton Ziolkowski)

T2-09: Effects of non-isotropic explosion sources upon the utility of the Ms-mb discriminant (Paul G. Richards)

T2-010: Temporal evolution of the radioxenon signature from underground nuclear explosions (Martin Kalinowski)

T2-011: Seismo-acoustic energy partitioning from shallow and surface explosions (Jessie Bonner, Mark Leidig, Yefim

Gitterman, Todd Ewy, Phillip Cole, Aaron Ferris, Robert Reinke, Roger Waxler)

T2-O12: Medical isotopes studies (Judah Friese, Rosara Payne)

T2-O13: The IAEA Department of Safeguards: Crossover novel technologies (Andrew Monteith, Julian Whichello)

POSTER PRESENTATIONS

T2-P2: A near-regional verification analysis of North Korean nuclear tests (Kin-Yip Chun)

T2-P3: Contribution of isotopes production facilities and nuclear power plants to Xe-133 worldwide atmospheric background (Pascal Achim, Gilbert Le Petit)

T2-P4: Study on underground vacancy detection based on vertical gravity gradient measurements (Qingbin Wang, Dong Jiang, Yin Chen, Dongming Zhao)

T2-P5: Spectral ratios of regional phases recorded at the Dongbei Seismic Network for the North Korean explosions in 2006 and 2009 (Hans Israelsson, Kin-Yip Chun)

T2-P6: CTBT related activities of Turkish National Data Center (Nurcan Meral Ozel, Ocal Necmioglu, Korhan Umut Semin, Serdar Kocak, Tahir Cem Destici, Ugur Teoman)

T2-P7: Features of geomagnetic anomalies (Dmitry A. Sagaradze, Natalia V. Rachkova)

T2-P8: Discrimination of natural earthquakes and artificial explosions in 2010, North Korea (Yun Kyung Park, Sung Tae Nam, Young Woong Kim)

T2-P9: Tritium in the air as an indicator of nuclear testing venues (Sergey Lukashenko, Oxana Lyakhova)

T2-P10: Design based approach to OSI sampling strategy (Antonietta Rizzo, Paolo Bartolomei)

T2-P11: Nuclear test fall-out determination by plutonium isotopic composition (Dalis Baltrunas, Andrius Puzas, Ruta Druteikiene, Vidmantas Remeikis)

T2-P12: Finding and identifying radioactive material by carborne search for OSI deployment (Theo Koble, Wolfram Berky, Sebastian Chmel, Hermann Friedrich, Monika Risse, Wolfgang Rosenstock, Olaf Schumann)

T2-P13: The use of explosion aftershock probabilities for on-site inspection planning, deployment, and reporting (Sean Ford, Peter Labak, Gideon Leonard, Albert Smith, Jerry Sweeney)

T2-P14: Analysis and modeling of shear waves generated by explosions at the San Andreas Fault Observatory at depth (Justin L. Rubinstein, Fred Pollitz, William L. Ellsworth)

T2-P15: Emerging science for nuclear test monitoring (Joanna Ingraham, Justin McIntyre)

T2-P16: On-site inspection strategy for subsurface detection of noble gases from an underground nuclear test (Charles R. Carrigan, Yunwei Sun, Gardar Johannesson)

T2-P17: Analysis into the evolution of radionuclide inventory with time for some scenarios of nuclide migration into the atmosphere after a nuclear test (Andrey Ustselemov)

T2-P18: Proficiency test program for CTBT radionuclide laboratories: An update (Emerenciana Duran, Kirill Khrustalev, Matthias Auer)

T2-P19: Proposal for an information-led search logic during an on-site inspection (George W. Tuckwell, Luis R. Gaya-Pique)

T2-P20: Barkhan (Baluchistan) earthquakes of June 26 and July 12, 1999: Source process from teleseismic body waves (Mohammad Tahir, Tariq Mahmood Taiq)

T2-P21: Exploitation of the IMS and other data for a comprehensive, advanced analysis of the North Korean nuclear tests (Benjamin Kohl, John R. Murphy, Jeffry Stevens, Theron J. Bennett)

T2-P22: Stable coda estimates from P and S codas at regional and near-teleseismic distances (Kevin Mayeda)

THEME 3. ADVANCES IN SENSORS, NETWORKS AND OBSERVATIONAL TECHNOLOGIES

ORAL PRESENTATIONS

T3-O1: Integrated solutions for a sustainable development of the offshore industry: live monitoring of noise and acoustics events (Michel André, Mike van der Schaar, Serge Zaugg, Ludwig Houegnigan, Antonio M. Sanchez, Alex Mas)

T3-O2: Open data resources and shared instrumentation facilities to support research in seismology (David Simpson)

T3-O3: Challenges and growth for NEPTUNE Canada (Lucie Pautet, Christopher R. Barnes, Fern Johnson, Mairi M. R. Best, Benoit Pirenne)

T3-O4: The effectiveness of radionuclide monitoring: assessed with a natural airborne tracer (Murray Matthews)

T3-O5: The Optical Seismometer—a new technology for seismographic observations (Jonathan Berger, Mark Zumberge)

T3-O6: Data for OSI multi-spectral and infrared instrument development (John Henderson, Milton Smith, Michael Zelinski)

T3-O7: The Optical Fiber Infrasound Sensor—improved wind noise reduction (Mark Zumberge, Kris Walker, Jonathan Berger)

T3-O8: A new underground radionuclide laboratory - RL16 (Joel Forrester, Craig Aalseth, Larry Greenwood, Harry Miley, Cory Overman)

T3-O9: Figure of merit for choosing Xe background study locations (Paul Eslinger, Derek Haas, Harry Miley)

T3-O10: Production of Xe standards for the calibration of noble gas sampler stations and laboratory equipment (Kari Perajarvi, Tommi Eronen, Dimitry Gorelov, Jani Hakala, Ari Jokinen, Anu Kankainen, Heikki Kettunen, Veli Kolhinen, Mikko Laitinen, Iain Moore, Heikki Penttila, Juho Rissanen, Antti Saastamoinen, Harri Toivonen, Jani Turunen, Juha Aysto)

T3-O11: Xenon diffusion reduction using surface coatings on plastic scintillators in beta-gamma coincidence detection systems (Lisa Bläckberg, Alexander Fay, Anders Ringbom, Lars Martensson, Klas Elmgren, Fredrik Nielsen, Tomas Fritioff, Steven Biegalski, Henrik Sjostrand, Mattias Klintenberg)

T3-O12: The EarthScope USArray Transportable Array: Results from large-scale network operations (Robert Woodward, Robert Busby, Katrin Hafner, David Simpson)

T3-O13: Measuring mesopause temperature perturbations caused by infrasonic waves - An innovative sensor approach (Michael Bittner, Kathrin Hoppner, Christoph Pilger, Carsten Schmidt)

T3-O14: Optimal design of a noble gas monitoring network (Ian Hoffman, Jing Yi, Kurt Ungar, Dov Bensimon, Real D'Amours, Richard Hogue, Jean-Phillippe Gauthier, Paul Eslinger, Derek Haas, Harry Miley, Brian Schrom, Paul Saey)

T3-O15: Potential of the International Monitoring System (IMS) radionuclide network for inverse modeling (Mohammad Reza Koohkan, Lin Wu, Marc Bocquet, Monika Krysta)

POSTER PRESENTATIONS

T3-P1: Characterization of 2010 Mentawai earthquake based on source mechanism analysis by using regional and CTBT monitoring station (Sugeng Pribadi, Nanang T. Puspito, Hendar Gunawan)

T3-P2: Analysis of the first arrival of P-wave of Ina-TEWS and CTBT stations to support earthquake early warning (Hendar Gunawan, Gunawan Ibrahim, Sugeng Pribadi)

T3-P3: Detection of tsunami and T-phase by the Dense Oceanfloor Network System for Earthquakes and Tsunamis (DONET) (Seiji Tsuboi, Takeshi Nakamura, Masaru Nakano, Tomoki Watanabe, Akiko To, Yoshiyuki Kaneda)

T3-P4: A technique to determine the self-noise of seismic sensors for performance screening (Horst Rademacher, Darren Hart, Cansun Guralp)

T3-P5: Seismic noise analysis at some broadband stations of Egyptian National Seismological Network (Abd El-Aziz Khairy Abd El-Aal)

T3-P6: Improvement of the equipment for measurements of atmospheric xenon radionuclides (Sergei Pakhomov, Yuri Dubasov)

T3-P7: Using the Garni IMS auxiliary station records in operation of the next-generation real-time seismic intensity display system in Armenia (Valery Arzumanyan)

T3-P8: Seismic networking in the south Pacific region (Faatali Malaefatu Leavasa, Lameko Talia)

T3-P9: Developing a block diagram for the earthquake warning device (Konstantin Kislov, Valentin Gravirov)

T3-P10: New tiltmeter developed in Institute of Physics of the Earth of the Russian Academy of Sciences (Sergey Matcievsky, Igor Vasilev, Valentin Gravirov)

T3-P11: Superbroadband seismometer for seismomonitoring networks and a tsunami notification service (Sergey Matcievsky, Valentin Gravirov, Konstantin Kislov)

T3-P12: Modelling global seismic network detection threshold (Mark Prior, David Brown)

T3-P13: Equipment testing for IMS waveform technologies (Yuri Starovoit, Patrick Grenard, Georgios Haralabus, Darren Hart, Peter Melichar)

T3-P14: The IDC seismic, hydroacoustic and infrasound global low and high noise models (David Brown, Lars Ceranna, Pierrick Mialle, Mark Prior, Ronan Le Bras)

T3-P15: Long term - real time background noise monitoring around BR235 (Nurcan Meral Ozel, Serdar Kocak, Ocal Necmioglu, Korhan Umut Semin, Tahir Cem Destici, Ugur Teoman)

T3-P16: Bayesian waveform inversion for moment tensors of local earthquakes in the Pannonian basin (Zoltan Weber)

T3-P17: Romanian infrasound structure: design and data processing (Constantin Ionescu, Daniela Ghica)

T3-P18: Analysis of the background noise at the auxiliary seismic station Muntele Rosu (Daniela Ghica, Bogdan Grecu, Constantin Ionescu, Mihaela Popa)

T3-P19: The GSN data quality initiative (Kent Anderson)

T3-P20: Transportable Xenon Laboratory (Timothy Stewart, Robert Thompson, Harry Miley)

T3-P21: Towards an effective on-site inspection—A geophysical view (Kristof L. Kakas, Tibor Guthy, Endre Hegedös)

T3-P22: Ionospheric detection of the recent North Korean underground nuclear test (Jihye Park, Dorota A. Grejner-Brzezinska, Yu (Jade) Morton, Ralph R.B. von Frese, Luis R. Gaya-Pique)

T3-P23: Infrasound monitoring of explosive eruptions at Shinmoe volcano in Japan (Hee-Il Lee, Il-Young Che)

T3-P24: Development of the IMS facilities, experimental seismic and infrasound observation in Ukraine (Igor Kachalin, Aleksander Liashchuk)

T3-P25: Real time seismic monitoring in South-Central Europe: data sharing, cooperation and improvements of the OGS NI Seismic Network (Damiano Pesaresi, Nikolaus Horn, Pier Luigi Bragato, Giorgio Duri)

T3-P26: The "Hellenic Unified Seismological Network-HUSN": its implication in the accurate monitoring of the seismicity in the broader area of Aegean Sea (Dimitrios Papanastassiou, Christos Evangelidis, Kostantinos Makropoulos)

T3-P27: Studies of vibrations from wind turbines in the vicinity of the Eskdalemuir (AS104) IMS station (Sam Toon, Rachel Westwood, Peter Styles)

T3-P28: Re-analysis of noble gas samples from IMS stations at laboratories—a review of the results since 2007 (Herbert Gohla)

T3-P29: Development of a cosmic veto device to improve detection limits of CTBT detectors (Jonathan Burnett, Ashley Davies)

T3-P30: SAUNA - Equipment for low level measurement of radioactive xenon (Helena Berglund)

T3-P31: Integrating infrasonic arrays into the Utah Regional Seismic Network (Relu Burlacu, Kristine L. Pankow, Keith Koper, Brian W. Stump, Chris Hayward)

T3-P33: Analysis of network QA/QC and Level 5 samples at certified laboratories (Dongmei Han)

T3-P34: Mobile radiation measurements for on-site inspections (Mika Nikkinen, Markku Kettunen)

T3-P36: Possible improvements of the detection capability of the CTBT monitoring system using active Compton suppression techniques (Mika Nikkinen, Tetsuzo Oda, Harry Miley, Ulrich Stoehlker, Kirill Khrustalev, Matthias Auer)

T3-P37: Operation of the International Monitoring System network (Timothy Daly, Staff IDC/Operations Section)

T3-P39: A new vision on data acquisition and processing (Ali Safepour, Reza Rezaei)

T3-P40: Soccoro Island's IMS T-stations record the modification of the strain field due to the passage of tsunamis (Alexander Poplavskiy, Ronan Le Bras)

T3-P41: Can OSI use off the shelf techniques? (Mordechai Melamud, Luis R. Gaya-Pique)

T3-P42: Miniature optical seismic sensors for monitoring applications (Caesar Garcia)

T3-P43: Technology foresight for the Provisional Technical Secretariat of the CTBTO (Patrick Grenard, Philippe Steeghs)
T3-P44: GCI-II: How CTBT data is transmitted around the globe (James Crichton)
T3-P45: Coseismic tectonomagnetic signals as a tool for seismic risk reduction (Farshed Karimov)
T3-P47: Earthworm: A powerful and open-source real-time earthquake and infrasound monitoring software tool (Sidney Hellman, Paul Friberg, Ilya Dricker, Stefan Lisowski)
T3-P48: Exploring the potential of satellite imagery for CTBT verification (Bharath Gopalaswamy, Irmgard Niemeyer)
T3-P49: IS42: A new IMS certified infrasound station in the Graciosa Island, Azores, Portugal (Nicolau Wallenstein, Joao Luis Gaspar, Alfred Kramer, Juraci Carvalho, Paola Campus, Georgios Haralabus, Joao Gregorio, Pierrick Mialle, Soares Flavio)

THEME 4. ADVANCES IN COMPUTING, PROCESSING AND VISUALIZATION FOR VERIFICATION APPLICATIONS

ORAL PRESENTATIONS

T4-01: Distributed e-infrastructures for data intensive science (Robert Jones)
T4-02: Improved signal detection at seismometer arrays (Neil Selby)
T4-03: Improving regional seismic travel times (RSTTs) for more accurate seismic location (Stephen Myers, Michael Begnaud, Sanford Ballard, Abelardo Ramirez, Scott Phillips, Michael Pasyanos, Harley Benz, Raymond Buland)
T4-04: Bayesian inference for the study of low-level radioactivity in the environment: Application to the detection of xenon isotopes of interest for the CTBTO (Isabelle Rivals, Xavier Blanchard)
T4-05: Improvements to seismic monitoring of the European Arctic using three-component array processing at SPITS (Steven J. Gibbons, Johannes Schweitzer, Frode Ringdal, Tormod Kvaerna, Svein Mykkeltveit)
T4-06: NET-VISA model and inference improvements (Nimar Arora, Stuart Russell, Paul Kidwell, Erik Sudderth)
T4-07: Real-time global seismic wave propagation and non-linear inversion for source and structure (Tarje Nissen-Meyer, Alexandre Fournier, P. Martin Mai, Florian Haslinger, Domenico Giardini)
T4-08: Anomalous infrasound propagation through the dynamic stratosphere (Laslo Evers, Anton Van Geyt, Pieter Smets, Julius Fricke)
T4-09: On the potential of public available gridded precipitation re-analysis and monitoring products to access the wet-deposition impact on PTS radionuclide monitoring capability (Andreas Becker, Ole Ross, Lars Ceranna)
T4-010: A statistical framework for operational infrasound monitoring (Stephen Arrowsmith, Rod Whitaker)
T4-011: Reliable Lg arrival time picks and potential for enhanced epicenter (Eystein S. Husebye, Tatiana Matveeva)
T4-012: Analysis of classification possibility infrasound signals from different sources based on correlation ability (Sergey Kulichkov, Alexei Chulichkov, Nadezhda Tsybulskaya)
T4-013: High resolution array processing for earthquake source studies at regional distance (Lingsen Meng, Jean-Paul Ampuero)

POSTER PRESENTATIONS

T4-P1: Network performance of the CTBT monitoring regime (Jerry A. Carter, Monika Krysta, Ronan Le Bras, Pierrick Mialle, Mika Nikkinen, Mark Prior)
T4-P2: A system for automatic detection of seismic phases in high noise conditions (Valentin Gravirov, Konstantin Kislov)
T4-P3: Comparison of regional seismic phases interpretation in REB and KazNDC bulletins (Zlata Sinyova, Natalya Mikhailova)
T4-P4: Focal depth estimation through polarization analysis of the Pn coda (Eystein S. Husebye, Tatiana Matveeva)
T4-P5: Evaluating OSI aftershock monitoring efficiency (Mikhail Rozhkov, Alexander Kushnir, Alexander Varypaev)
T4-P6: Automatic clustering of seismic events in an on-site inspection scenario (Benjamin Sick, Manfred Joswig)
T4-P7: Large earthquakes' secondary phenomena and their space-ground geodata assessment (Farshed Karimov, Mirzo Saidov)
T4-P8: Fuzzy ARTMAP: A neural network for fast stable incremental learning and seismic event discrimination (El Hassan Ait Laasri, Es-Said Akhouayri, Dris Agliz, Abderrahman Atmani)
T4-P9: Application of detection probabilities in the IDC Global Phase Association Process (Tormod Kvaerna, Frode Ringdal, Jeffrey Given)
T4-P10: Radioxenon analysis methods and atmospheric transport modelling to distinguish civilian from nuclear explosion signals (Michael Schöppner)
T4-P11. Listening to the SEL: is the ear easier to train than the eye? (Heidi Anderson Kuzma, Emerson Arehart)
T4-P12: Explanation of the nature of coherent low-frequency signal sources recorded by the monitoring station network of the NNC RK (Alexandr Smirnov, Vitaliy Dubrovin, Laslo G. Evers, Steven J. Gibbons)
T4-P13: Assessing the improvement capabilities of a generative model 3C-station detector algorithm forthe IMS (Carsten Riggelsen)
T4-P14: Real time cross correlation estimated program and its application to processing seismic data (Es-Said Akhouayri, El Hassan Ait Laasri, Dris Agliz, Abderrah man Atmani)
T4-P15: Advances in kernel-based classification of IMS hydroacoustic signals (Matthias Tuma, Christian Igel, Mark Prior)
T4-P16: Stockwell transform fingerprints of earthquake waveforms (Matthew J. Yedlin, Yochai Ben Horin)
T4-P17: Travel time corrections via local regression (Christopher Lin, Stuart Russell)
T4-P18: Challenges of infrasound analysis in IDC operations (Paulina Bittner, Pierrick Mialle, Paul Polich, Ali Kasmi, Sherif Mohamed Ali, Urtnasan Khukhuudei)
T4-P19: Signal-based Bayesian monitoring (Stuart Russell,

Nimar Arora, Stephen Myers, Erik Sudderth)

T4-P20: Threshold based algorithms for iron buried objects detection using magnetic field mapping (Abdelhalim Zaoui, Said Mitt, Amar Mesloub)

T4-P21: Categorization of infrasound detections (Pierre Gaillard, Julien Vergoz, Alexis Le Pichon)

T4-P22: Metrics to determine the effectiveness of computer learning and data mining algorithms developed to aid automatic processing at the International Data Centre (IDC) (Heidi Anderson Kuzma, Ronan J. Le Bras)

T4-P23: Case study of adding an F-trace algorithm to Geotool (Vera Miljanovic, Jeffrey Given, David Bowers)

T4-P24: Analysis of the representativeness of backward atmospheric transport modelling at different resolutions at the Takasaki RN38 IMS station (Delia Arnold, David Pino, Arturo Vargas, Petra Seibert)

T4-P25: Contribution to the study of seismic background noise application to the region of Agadir (Abderrahman Atmani, Es-said Akhouayri, Driss Agliz, El Hassan Ait Laasri)

T4-P26: Performance of an atmospheric source location algorithm at CTBTO (Monika Krysta, John Coyne)

T4-P27: Investigating coupled wave interaction between the atmosphere and near-surface (Wayne N. Edwards, Peter G. Brown, Phil A. Bland, David McCormack Philippe Heinrich, Romain Pilon)

T4-P29: Removing periodic noise: Improved procedures (Felix Gorschluter, Jurgen Altmann)

T4-P30: An alternative approach to waveform event definition criteria (Robert Pearce, Ivan Kitov, John Coyne)

T4-P31: REB events recorded with all waveform technologies (Peder Johansson, Pierrick Mialle)

T4-P32: A novel technique for phase classification and association based on integral and local features of seismograms (Chengliu Zhang, Ping Jin, Hongchun Wang, Xufeng Shen, Chaohui Feng, Na Lu)

T4-P34: The study of seismic event screening methods of IDC SEL3 (Wei Tang, Junmin Liu, Haijun Wang, Xiaoming Wang)

T4-P35: Introducing noble gas data into IDC operations (Mika Nikkinen, Ulrich Stoehlker, Abdelhakim Gheddou, Xuhui Wang, Carla Pires, J. S. Elisabeth Wieslander, Dongmei Han)

T4-P37: A regional investigation into the event location threshold using stations of the IMS (Spiro Spiliopoulos, Robert G. Pearce, MDA Analysts)

T4-P38: Mitigation of IDC waveform analysts' increasing workload (Robert Pearce, Ivan Kitov)

T4-P39: Testing and integration of infrasound threshold monitoring software in the CTBTO operational environment (Alexis Le Pichon, Julien Vergoz, Lars Ceranna, Pierrick Mialle, David Brown, Nicolas Brachet)

T4-P40: Validation process of the detector response for noble gas systems (Abdelhakim Gheddou, Kirill Khrustalev, Elisabeth Wieslander)

T4-P41: Xe release calculation from BNPP (Mohammad Javad Safari, Mohammad Sabzian)

T4-P42: Towards an automatic waveform correlation detector system (Megan Slinkard)

THEME 5. CREATING KNOWLEDGE THROUGH PARTNERSHIPS, TRAINING AND INFORMATION/ COMMUNICATIONS TECHNOLOGY

ORAL PRESENTATIONS

T5-01: The global earth observation system of systems (José Achaché, Francesco Gaetani)

T5-03: Transnational cooperation: What and why? (Christine Wing)

T5-04: Capacity building in the context of the Comprehensive Nuclear-Test-Ban Treaty (Lassina Zerbo, John Coyne, Belkacem Djermouni)

T5-05: Educational outreach as a capacity development strategy, using the Irish example, seismology in schools, Dublin Institute for Advanced Studies (DIAS) Outreach Programme (Thomas Blake, Grace Campbell)

T5-06: CTBTO contribution to the global earthquake data collection: a view from the International Seismological Centre (ISC) (Dmitry A. Storchak, Istvan Bondar, James Harris, Ben Dando)

T5-07: The IMS network and the International Federation of Digital Seismograph Networks FDSN—a long and winding road (Gerardo Suarez, Florian Haslinger)

T5-08: Contributions of the scientific community to CTBT monitoring and verification (Martin Kalinowski)

T5-09: Infrasound calibration in the Eastern Mediterranean (John Coyne, Jeffrey Given, Patrick Grenard, Georgios Haralabus, Julien Marty, Pierrick Mialle, David Brown, Lassina Zerbo)

T5-010: Ghana's experience in the establishment of a National Data Centre (Paulina Ekua Amponsah, Yaw Serfor-Armah)

T5-011: Creating knowledge and building capacity in Uganda (Cynthia Ayero)

T5-012: A CTBT implementation process in Panama to forge broader partnerships (Miguel Gonzalez Marcos, Omayra Perez Castro, Bernardo Fernandez Garcia)

T5-013: Methodology for on-site inspections and lessons learned from different verification regimes (Yousry Abushady)

POSTER PRESENTATIONS

T5-P1: More and more data formats, is it a plus? (Walid Mohammad)

T5-P2: The construction and development of the radionuclide station (RN42) at Tanah Rata (Alawiah Musa, Faizal Azrin Mohd Razalim, Mohd Azmi Sidid Omar, Muhammed Zulfakar Mohd Zolkaffly, Mohd Jamil Hashim, Pasupathi Ellapakavendan)

T5-P3: The recently acquired broadband and strong motion sensors network in Ghana and the access to CTBTO's data and products will help Ghana to update its Nation al Seismic Hazard Assessment for a sustainable infrastructural development (Nicholas Opoku)

T5-P4: The CTBTO link to the International Seismological Centre (Istvan Bondar, Dmitry Storchak, Ben Dando, James Harris)

T5-P5: Datasets for monitoring research at the International Seismological Centre (Istvan Bondar, Dmitry Storchak, James Harris, Ben Dando)

T5-P6: New ground truth events in Central Asia. (Natalya Mikhailova, Zlata Sinyova)

T5-P7: International Training Center in support of the CTBTO (Natalya Mikhailova, Nadezhda Belyashova, Johannes Schweitzer, Svein Mykkeltveit)

T5-P8: Building capacity to sustain disaster management and preparedness through civil applications of CTBTO's global verification regime (Simon Leonard Clement Mdoe, Alex Muhulo, Mlwilo Nolasco)

T5-P9: Experiences gained by NDC Austria during the NDC Preparedness Exercise 2010 (Ulrike Mitterbauer, Gerhard Wotawa)

T5-P10: Knowledge exchange and cooperation between National Data Centers (NDC) (Lotfi Khemiri, Mohamed Kallel, Atef Blel, Ulrike Mitterbauer, Gerhard Wotawa)

T5-P11: The new digital seismic network KRNET: Perspectives and capacity development (Anna Berezina, Jan Fyen, Kanatbek Abdrakhmatov, Johannes Schweitzer)

T5-P12: The Republic of Mali's participation in the CTBT verification regime (Emmanuel Thera)

T5-P13: CTBTO capacity building follow-up visits in Africa (Misrak Fisseha, John Coyne, Belkacem Djermouni, Gadi Turyomurugyendo, Lassina Zerbo)

T5-P14: The "Global Seismological Observation" training course (Tatsuhiko Hara)

T5-P15: Advances in data distribution systems, high-level product generation, and the measurement of data quality metrics at the IRIS Data Management Center (Timothy Keith Ahern)

T5-P16: Database of digitized historical seismograms for nuclear tests monitoring tasks (Inna Sokolova, Iraida Aleschenko, Abylay Uzbekov)

T5-P17: Identification of industrial blasts in seismic bulletins for Kazakhstan Territory (Inna Sokolova, Natalya Mikhailova, Alexander Velikanov, Irina Aristova)

T5-P18: Creating a seismic network and knowledge through collaborations, training in Zimbabwe (Kwangwari Marimira)

T5-P19: IMS sustainment for an operational, reliable and credible IMS - a close coordinated and joint effort achievable goal (Natalie Brely, MFS Section Staff)

T5-P20: IMS sustainment—Modeling and logistic support analysis—from theory to reality sustainment (Natalie Brely, Jean-Pierre Gautier, MFS/LS Unit Staff)

T5-P21: ORFEUS: Facilitating seismological observatory cooperation and open data access (Torild van Eck, Reinoud Sleeman, Gert-Jan van den Hazel, Alessandro Spinuso, Luca Trani)

T5-P22: Cooperative seismology between Michigan State University in the USA, and Russia (Kevin Mackey, Kazuya Fujita, Larissa Gounbina, Sergei Shibaev)

T5-P23: Processing results from the infrasound campaign in the Eastern Mediterranean (Pierrick Mialle, David Brown, Jeffrey Given, Paulina Bittner, John Coyne)

T5-P24: Regional infrasound observations from the Sayarim 2011 experiment (Jelle Assink, Roger Waxler, Dan Kleinert, Carrick Talmadge, Claus Hetzer, Hank Buchanan, Phil Blom, Laslo Evers, Rami Hofstetter, B. Yochai)

T5-P25: Potentials of using radionuclide monitoring derived-data for scientific research (Fe dela Cruz, Teofilo Y. Garcia, Ana Elena L. Conjares, Adelina Bulos)

T5-P27: Using infrasound data of Nairobi Station (IS32) to study Bubuda landslide in eastern Uganda (Isaiah Tumwikirize Tumwikirize)

T5-P28: Government initiatives and international cooperation in seismology providing knowledge and training in Namibia (Bufelo Lushetile, Dave Hutchins)

T5-P29: National earthquake monitoring and tsunami early warning system in Thailand (Sumalee Prachuab)

T5-P30: Science, technology and values in the context of global threats (Graham Parkes)

T5-P31: Large-scale explosion sources at Sayarim, Israel, for infrasound calibration of the International Monitoring System (Yefim Gitterman, Jeffrey Given, John Coyne, Lassina Zerbo, Rami Hofstetter)

T5-P33: Partnership in multidisciplinary research in earth and polar sciences: the contribution of the European Science Foundation (Paola Campus, Roberto Azzolini)

SESSION ON THE 11 MARCH 2011 TOHOKU EARTHQUAKE AND ITS AFTERMATH

ORAL PRESENTATIONS

JS-01: Source process and broadband waveform modeling of 2011 Tohoku earthquake using Spectral-Element Method (Seiji Tsuboi, Takeshi Nakamura, Akiko To)

JS-02: Magnitude determination using duration of high frequency energy radiation for the 2011 Off the Pacific Coast of Tohoku Earthquake (Tatsuhiko Hara)

JS-03: Analysis of the Fukushima accident by the French National Data Centre (Gilbert Le Petit, Pascal Achim, Guilhem Douysset, Philippe Gross, Marguerite Monfort, Christophe Jutier)

JS-04: Tsunami infrasound: 2004 Sumatra and 2011 Tohoku case studies (Milton Garces, Nickles Badger, Yoshiki Yamazaki, Fai Cheung, Alexis Le Pichon, Kris Walker)

JS-05: Canadian monitoring of Fukushima incident (Ian Hoffman, Kurt Ungar, Weihua Zhang, Ed Korpach, Marc Bean, Brian White, Laurel Sinclair, Henry Seywerd, David McCormack, Real D'Amours, Richard Fortin, John Carson, Patrick Saull, Maurice Coyle, Reid Van Brabant, John Buckle)

JS-06: A window into the complexity of the dynamic rupture of the 2011 Mw 9 Tohoku-Oki earthquake (Lingsen Meng, Asaf Inbal, Jean-Paul Ampuero)

JS-07: Detection of elevated Xe-133 following the Fukushima nuclear accident (Ted Bowyer, Steven Biegalski, Matthew Cooper, Paul Eslinger, Derek Haas, James Hayes, Harry Miley, Daniel Strom, Vincent Woods)

JS-08: Response of the Austrian Meteorological and Geophysical Service and the National Data Centre Austria to the nuclear accident in Fukushima: Atmospheric transport modelling and situation assessment based on CTBTO radionuclide data (Gerhard Wotawa, Ulrike Mitterbauer)

JS-09: Operational experience of CTBTO related to the Fukushima nuclear accident and long term perspectives (Mika Nikkinen, Xuhui Wang, John Coyne, Denys Rousseau, Monika Krysta, Matthias Auer, Robert Werzi, Ulrich Stoehlker, Abdelhakim Gheddou, Dongmei Han)

POSTER PRESENTATIONS

JS-P1: Pressure signals on IMS hydrophones at Wake Island due to the M9.0 event on March 11th 2011 off the coast of Japan (Mark Prior, David Salzberg)

JS-P2: Assessment of release scenarios for the Fukushima Dai-ichi Nuclear Power Plant accident (Rick Tinker, Blake Orr, Marcus Grzechnik, Stephen Solomon, David Jepsen)

JS-P3: Source modeling earthquake as tsunami generation in Japan (East of Pacific Plate) (Wiko Setyonegoro)

JS-P4: Experimental check of work on an adaptive algorithm for detection of onset times of low amplitude seismic phases based on time series analysis with use of Japan earthquakes data records in March 2011 (Valentin Gravirov, Konstantin Kislov, Tatiana Ovchinnikova)

JS-P5: The International Data Centre analysis of the aftershock sequence following the March 11, 2011 earthquake off the coast of Japan (Spiro Spiliopoulos, IDC Waveform Analysts)

JS-P6: Bulgarian experience with Fukushima event in March 2011 (Rositza Kamenova-Totzeva, Victor Badulin)

JS-P7: Infrasound signals excited by upheaval and subsidence of ocean surface during the tsunami genesis related to 11 March event (Nobuo Arai, Takahiko Murayama, Makiko Iwakuni, Mami Nogami)

JS-P8: Detection of aerosol radionuclides in the United States following the Fukushima nuclear accident (Harry Miley, Ted Bowyer, Steven Biegalski, Paul Eslinger, Joel Forrester, Judah Friese, Larry Greenwood, Derek Haas, James Hayes, Martin Keillor, Elwood Lepel, Khris Olsen, Daniel Strom, Vincent Woods)

JS-P9: Some measures to face potential impacts of Fukushima nuclear accident in Burkina Faso (Desire Marie Alexis Belemsaga)

CLOSING

Perspective of the Scientific Community (Paul G Richards)
Perspective of the CTBTO (Lassina Zerbo)
Perspective of the States Signatories (Jay Zucca)

Index of Contributing Authors

Only the first author (who is not necessarily the presenter) of each cited contribution is included. For other authors, reference can be made to the Book of Abstracts. Authorship follows that submitted with the abstract and printed in the Book of Abstracts.

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Many CTBTO staff discussed and reviewed material for this publication, including Matthias Auer, Jerry Carter, John Coyne, Jeffrey Given, Patrick Grenard, Georgios Haralabus, Peder Johansson, Martin Kalinowski, Monika Krysta, Pierrick Mialle, Mika Nikkinen, Matjaz Prah, Mark Prior and Yuri Starovoit.

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