CTBT: SCIENCE AND TECHNOLOGY SERIES

In order to build and strengthen its relationship with the broader science community in support of the Comprehensive Nuclear-Test-Ban Treaty, the CTBTO PrepCom invites the international scientific community to conferences on a regular basis; SnT2015 was the fifth such conference since 2006.

These conferences contribute to a process whose aim is to ensure that the CTBTO’s verification regime can benefit from current scientific and technological developments in relevant fields. The Conference Goals define in more detail the scope of topics covered.

These multidisciplinary scientific conferences attract scientists and other experts from the broad range of the CTBTO’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.

SnT2015 was held in Vienna’s Hofburg Palace on 22-26 June 2015, in cooperation with the Austrian Federal Ministry for Europe, Integration and Foreign Affairs. This report summarizes the scientific contributions presented at the conference and identifies some highlights and potential focus areas for the future. The text of this report was presented to Working Group B of the Preparatory Commission in August-September 2016.
THE PREPARATORY COMMISSION AND THE CTBTO

The Preparatory Commission for the Comprehensive Nuclear-Test-Ban Organization was set up by Resolution CTBT/RES/1, adopted by the States Signatories 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 PrepCom will be replaced by the Comprehensive Nuclear-Test-Ban Treaty 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 regions is important to the context.

DISCLAIMER

The views expressed are those of the authors and do not reflect the positions and policies of the CTBTO PrepCom.

The boundaries and presentation of material on maps do not imply the expression of any opinion on the part of the Provisional Technical Secretariat concerning the legal status of any country, territory, city or area or its authorities, or concerning the delimitation of its frontiers or boundaries.
Scientific Advances in CTBT Monitoring and Verification 2015

REVIEW OF PRESENTATIONS AND OUTCOMES OF THE COMPREHENSIVE NUCLEAR-TEST-BAN TREATY: SCIENCE AND TECHNOLOGY 2015 CONFERENCE
22–26 June 2015, Hofburg Palace, Vienna

with the generous support of the Republic of Austria, Federal Ministry for Europe, Integration and Foreign Affairs
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<td>Atmospheric dynamics Research InfraStructure in Europe</td>
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<td>AU</td>
<td>African Union</td>
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<td>AutoDRM</td>
<td>Automated data request manager</td>
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<td>ATM</td>
<td>atmospheric transport modelling</td>
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<td>CNS</td>
<td>James Martin Center for Nonproliferation Studies</td>
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<td>CSS</td>
<td>Center for Seismic Studies</td>
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<td>CTBT</td>
<td>Comprehensive Nuclear-Test-Ban Treaty</td>
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<td>CTBTO</td>
<td>Comprehensive Nuclear-Test-Ban Treaty Organization</td>
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<tr>
<td>CWC</td>
<td>Chemical Weapons Convention</td>
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<td>DACS</td>
<td>distributed access control system</td>
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<td>DONET</td>
<td>Dense Ocean-floor Network System for Earthquakes and Tsunamis</td>
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<td>DPRK</td>
<td>Democratic People's Republic of Korea</td>
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<td>EARNW</td>
<td>East Asia Regional NDC Workshop</td>
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<td>EMP</td>
<td>electromagnetic pulse</td>
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<td>GCI</td>
<td>Global Communications Infrastructure</td>
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<td>GIS</td>
<td>geographic information system</td>
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<td>GNSS</td>
<td>global navigation satellite system</td>
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<td>GPRS</td>
<td>General Packet Radio Service</td>
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<td>GPS</td>
<td>Global Positioning System</td>
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<td>GSN</td>
<td>Global Seismographic Network</td>
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<td>GT</td>
<td>ground truth</td>
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<td>HPGe</td>
<td>high-purity germanium</td>
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<td>IAEA</td>
<td>International Atomic Energy Agency</td>
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<td>IDC</td>
<td>International Data Centre</td>
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<td>IFE14</td>
<td>Integrated Field Exercise 2014</td>
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<td>IMS</td>
<td>International Monitoring System</td>
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<td>IRE</td>
<td>Institute for Radioelements</td>
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<td>IRIS</td>
<td>Incorporated Research Institutions for Seismology</td>
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<td>ISC</td>
<td>International Seismological Centre</td>
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<tr>
<td>KLSH</td>
<td>kernalized locality-sensitive hashing</td>
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<tr>
<td>LTA</td>
<td>long-term average</td>
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<td>MARDS</td>
<td>Movable Argon-37 Rapid Detection System</td>
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<td>MDC</td>
<td>minimum detectable concentration</td>
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<tr>
<td>MSIR</td>
<td>multispectral including infrared</td>
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<tr>
<td>NCPA</td>
<td>National Center for Physical Acoustics</td>
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<td>NDC</td>
<td>National Data Centre</td>
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<td>NEIC</td>
<td>National Earthquake Information Center</td>
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<td>NET-VISA</td>
<td>Network Vertically Integrated Seismic Analysis</td>
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<td>NNSS</td>
<td>Nevada National Security Site</td>
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<td>NPE</td>
<td>NDC Preparedness Exercise</td>
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<td>NPT</td>
<td>Nuclear Non-Proliferation Treaty</td>
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<td>NTI</td>
<td>Nuclear Threat Initiative</td>
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<td>NTM</td>
<td>national technical means</td>
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<td>OPCW</td>
<td>Organisation for the Prohibition of Chemical Weapons</td>
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<td>OSI</td>
<td>On-Site Inspection</td>
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<tr>
<td>OSIRS</td>
<td>OSI Radiosotopic Spectroscopy</td>
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<tr>
<td>PMCC</td>
<td>progressive multichannel correlation</td>
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<td>REB</td>
<td>Reviewed Event Bulletin</td>
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<tr>
<td>RSTT</td>
<td>regional seismic travel time</td>
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<td>SAMS</td>
<td>Seismic Aftershock Monitoring System</td>
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<td>SAUNA</td>
<td>Swedish Automatic System for Noble Gas Acquisition</td>
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<td>SEED</td>
<td>Standard for the Exchange of Earthquake Data</td>
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<td>SEL</td>
<td>Standard Event List</td>
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<tr>
<td>SIG-VISA</td>
<td>Signal Vertically Integrated Seismic Analysis</td>
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<tr>
<td>Si-PIN</td>
<td>silicon positive intrinsic negative</td>
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<tr>
<td>SKA</td>
<td>Square Kilometre Array Radio Telescope</td>
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<tr>
<td>SMS</td>
<td>Short Message Service</td>
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<tr>
<td>S-Net</td>
<td>sea-floor observation network for earthquakes and tsunamis along the Japan trench</td>
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<tr>
<td>SnT</td>
<td>CTBT: Science and Technology</td>
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<td>SnT2011</td>
<td>CTBT: Science and Technology 2011 conference</td>
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<td>SnT2013</td>
<td>CTBT: Science and Technology 2013 conference</td>
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<tr>
<td>SnT2015</td>
<td>CTBT: Science and Technology 2015 conference</td>
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<tr>
<td>SOFAR</td>
<td>sound fixing and ranging</td>
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<tr>
<td>SSCS</td>
<td>source-specific station correction</td>
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<tr>
<td>STA</td>
<td>short-term average</td>
</tr>
<tr>
<td>UAV</td>
<td>unmanned aerial vehicle</td>
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<tr>
<td>UPS</td>
<td>uninterruptable power supply</td>
</tr>
<tr>
<td>USGS</td>
<td>United States Geological Survey</td>
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<td>vDEC</td>
<td>virtual Data Exploitation Centre</td>
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<tr>
<td>WGB</td>
<td>Working Group B</td>
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<tr>
<td>WOSMIP</td>
<td>Workshops on Signatures of Medical and Industrial Isotope Production</td>
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<tr>
<td>XESPM</td>
<td>Radioxenon Sampling, Purification and Measurement System</td>
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Opening Remarks
from the Executive Secretary of the CTBTO PrepCom

Minister Pandor, Secretary-General Linhart,
Director-General Amano, Director-General Üzümcü,
Director-General Li, excellencies, distinguished scientists,
ladies and gentlemen,

It gives me great pleasure to welcome you to the CTBT:
Science and Technology 2015 conference. This is now
the fifth such conference. And, having served as Project
Executive for the conferences in 2011 and 2013, this is my
first as Executive Secretary. I am delighted to see so many
familiar faces here from previous conferences, going right
back to “Synergies with Science” in 2006.

Many of you have heard me say again and again that I
am passionate about this organization and its role. Looking
around the room, I feel that I am in the company of many
who share this passion: a passion for science in the service
of peace. It gives me hope for the future of our children
that the best and brightest scientists of our time have come
together to perfect the detection of the bomb, instead of
working to perfect the bomb itself.

SnT2015 is poised to break all records. With nearly 1110
registered participants and over 550 abstracts, it is the largest
such conference to date. But the SnT process is not about
quantity—it’s all about adding quality to our work.

And the track record in this respect is impressive. To
name just a few of the important developments that have
originated from these conferences and are being integrated
into our procedures: machine learning methods to improve
automatic data processing, Network Processing Vertically
Integrated Seismic Analysis (NET-VISA), self-calibrating
infrasound sensors and infrasound network performance
monitoring tools, high-resolution beta–gamma coincidence
spectrometry—the list continues.

The issue of mitigating the effects of radioxenon
emissions from medical isotope production was a hot topic
at past SnT conferences, and I am pleased to report that
following the Workshop on Signatures of Medical and
Industrial Isotope Production (WOSMIP) in Brussels last
month, we now have 10 companies that have signed a
pledge to cooperate with us on this important issue.

This conference will also profit from the recent
conclusion of the 2014 Integrated Field Exercise (IFE14) in
Jordan. IFE14 was the most ambitious and comprehensive
on-site inspection exercise to date, with 15 of the 17 on-site
inspection techniques deployed under challenging conditions
and in a scientifically credible and realistic scenario.

For the first time at a SnT conference, we are also offering
an event for academics interested in CTBT education to identify
ways to integrate Treaty-related topics into existing policy- or
science-based academic curricula and to develop educational
resources to further this objective. The 2015 Academic Forum
on “Strengthening the CTBT Through Academic Engagement”
will take place on Friday, 26 June, and I look forward to
hearing all about the ensuing discussions.
I used to be a scientist. These days I am more of a diplomat or a politician. The longer I carry out my role as Executive Secretary, the more obvious it becomes to me how closely interconnected both realms are—even if scientists and diplomats don’t always speak the same language.

Last month I addressed the Nuclear Non-Proliferation Treaty (NPT) Review Conference in New York. As you know, the conference failed to agree on a final document. However, the support for the CTBT and its verification regime came across loud and clear, being voiced strongly over 100 times by different delegations. In my statement to the Review Conference, I stressed that a legally binding test ban represents one key area where all NPT States Parties were already in agreement. At the same time, I reminded delegates that mere words of support without real action would not suffice to bring the CTBT into force.

In this context, I am encouraged to see scientists from most of the remaining Annex 2 States here today. It is encouraging to see that where diplomacy seems stalled, science perseveres and moves forward regardless of political or diplomatic differences. Every opportunity to create conditions for increased trust and mutual understanding must be seized if we are to free the world of the nuclear threat. We are sure that you can bring the message to decision makers in your home countries that the CTBT is verifiable and that its entry into force would significantly strengthen the disarmament and non-proliferation regime and reduce the risk of the unthinkable becoming a reality.

I am also immensely grateful for the support we enjoy from CTBT States Signatories. To me, this is yet more proof of our success. Many of our gains are due to the technical and financial support of our members. In recent years, we have benefitted from the generous voluntary contributions of Austria, Japan, Sweden, Norway, the United States and the European Union.

The resources that States Signatories continue to invest in our system secure an immense return on investment since the CTBT’s monitoring facilities, at 90% completion, are already at the service of the international community to support national security needs, foster regional stability and reinforce non-discriminatory and participatory verification.

And an even more tangible return on our States Signatories’ investment: the daily monitoring of an active and evolving earth, and making the data collected freely available to science to improve understanding on climate change, tsunami warning, disaster mitigation, as well as a wide range of different civil applications. I very much look forward to hearing presentations and seeing posters on the newest developments in this field over the coming days.

Recent disasters such as the devastating earthquake in Nepal in April remind us again and again of the importance of advancing and improving our understanding of the earth’s processes in the service of humanity.

Among the many elements of this year’s conference that I look forward to, I wish to highlight in particular our keynote speakers this morning: Naledi Pandor, Minister of Science and Technology of South Africa, Ahmet Üzümcü, Director-General of the Organisation for the Prohibition of Chemical Weapons (and Nobel Peace Prize laureate in 2013) and Lord Browne, former Secretary of State for Defence of the United Kingdom, Vice Chairman of the Nuclear Threat Initiative and member of the Group of Eminent Persons for the CTBT.

The afternoon will continue with eminent speakers who will kindly share with us their breadth of experience and expertise. Frank Klotz, Under Secretary for Nuclear Security and Administrator of the National Nuclear Security Administration, USA, and Robin Grimes, Chief Scientific Adviser to the Foreign and Commonwealth Office, UK, will discuss collaboration on nuclear test monitoring science.

The need for a collaborative approach to global security issues will be further explored by representatives of the World Economic Forum Global Agenda Council on Nuclear Security and key figures of world affairs in a discussion on how to enhance governmental, industry and scientific engagement on nuclear non-proliferation and disarmament.

Finally, allow me to thank Secretary-General Michael Linhart, who is representing our host country here today. Secretary-General, please accept my heartfelt appreciation for the generous financial support offered by the Federal Ministry for Europe, Integration and Foreign Affairs of Austria to this conference.

I look forward to fruitful and successful deliberations and declare SnT2015 open.
Mr Lassina Zerbo, Executive Secretary of the Comprehensive Nuclear-Test-Ban Treaty Organization, excellencies, distinguished delegates, ladies and gentlemen,

It is my pleasure to send this message as you come together to forge stronger ties between the scientific, technical and policy-making communities. This contributes to a more secure world, just as the Comprehensive Nuclear-Test-Ban Treaty can usher in a world free of the lethal effects of the testing of nuclear weapons. The CTBT’s global monitoring system is an indispensable tool in this process. Verification builds trust that all states are complying with their obligations.

I also congratulate you on the Integrated Field Exercise conducted in Jordan in 2014, the largest ever undertaken. This has brought the Treaty even closer to full operational capability.

Ensuring that the monitoring system remains reliable and sustainable is vital, since it also contributes to scientific research on other global challenges, such as climate change. With such a strong verification system, backed by cutting-edge technology, there is no excuse for the CTBT not to enter into force.

Let us demand an end to all nuclear tests and get on with the unfinished business of achieving a world free of nuclear weapons.
Welcome from the Host Country

Dear Executive Secretary Zerbo;
Madam Minister Pandor; distinguished delegates,
excellencies, ladies and gentlemen,

It is now my turn to welcome you here to Vienna, to welcome you to this beautiful conference hall, which I think it is a very nice example of Austrian history and Austrian modern art. Both ancient times history; but also modern times—the future.

Thank you also Executive Secretary Zerbo for your kind words of welcome; be sure that the Austrian Foreign Ministry will always be with you and supporting you in your important task. So, I welcome you to this conference, this is the fifth such event in the CTBT: Science and Technology conference series.

And I think it has become by now a regular feature, a tradition, in the calendar of international conferences in Vienna. I am delighted to see that over the years, each Science and Technology conference has become bigger and attended by more and more experts from different scientific backgrounds.

I think it is encouraging that yet again the importance of this conference has further increased with an even higher number of research papers and posters than before. This evidence not only of the cutting edge monitoring and verification capabilities that the CTBTO has developed in the past 19 years, but also of the very fruitful and intense dialogue and cooperation between the CTBTO and the scientific and technical communities in many different fields.

The unique global monitoring system and the verification capacities of the CTBTO are of considerable value and interest to the scientific community. At the same time, the organization needs this constant exchange and peer review to remain at the cutting edge in order to be able to fulfil the verification mandate that the Treaty foresees. These verification capabilities have been expressively validated in the past, for example, in the context of the North Korean nuclear test and most recently for the on-site inspection exercise in Jordan.

The verification regime is ready, the organization is ready, and the CTBT should by now be the most unequivocal success of our multilateral disarmament and non-proliferation efforts. What is of course not ready, however, and I have to say that openly, is the political will in the remaining States whose ratification is required for the entry into force. The fact that the CTBT has still not been brought into legal effect is disappointing and harming the global disarmament on non-proliferation efforts.

Michael Linhart
Secretary-General for Foreign Affairs
of the Federal Ministry for Europe,
Integration and Foreign Affairs
We call on all Annex 2 States to take the necessary steps as soon as possible. The CTBTO enters into force only when all Annex 2 States have done so. Consequently, all Annex 2 States can and should show leadership on this important task.

We have recently concluded a very difficult four week long Nuclear Non-Proliferation Treaty Review Conference. It was to a large extent a polarized and divisive conference that ended without an agreed outcome. Against this backdrop it is even more urgent I think to make the necessary progress on the one treaty that is ready and whose legally binding effect would make a vital contribution to both nuclear disarmament and non-proliferation.

Last December, Austria hosted an international conference on the humanitarian impact of nuclear weapons. The consequences of nuclear testing were given significant prominence at this event. We heard heroic testimonies of victims of nuclear testing speaking about the impact on the health, the environment, and the social and cultural fabric of their families and communities. We heard experts speak about the wide range of consequences and highlight that, “nuclear testing in several parts of the world has left a legacy of serious health and environment consequences. Radioactive contamination from these tests disproportionately affects women and children, it contaminated food supplies and continues to be measureable in the atmosphere to this day.”

The world must never get back to this stage; it must close the door on nuclear testing once and for all and bring this treaty into force.

Ladies and gentlemen,

Earlier this year, the Bulletin of the Atomic Scientist moved the famous doomsday clock to 3 minutes to midnight. It said, “a nuclear arms race resulting from modernization of huge arsenals poses extraordinary and undeniable threats to the continued existence of humanity. World leaders have failed to act with the speed or on the scale required to protect citizens from potential catastrophe. These failures endanger every person on earth.”

Scientists and experts I think have a great responsibility today to generate the political will that is needed to urgently move away from nuclear weapons. At this SnT conference it will be you, the scientific community, who will take the work forward. You represent those that promote science for security or rather science for human security. We need many more scientists and experts to commit themselves to overcoming the legacy of nuclear weapons. Together with the experts and the CTBTO, you are all devising and improving ways and means to control and overcome nuclear weapons through science and global cooperation.

Austria is proud to host the CTBTO in Vienna and to welcome you here, scientists assembled to further a crucial goal. I wish you at this conference great success for your future work but as well a pleasant stay in Vienna. I hope you will find some moments to see that town, that beautiful town as well.
1 Introduction

1.1 Purpose of This Report

As the series of CTBT: Science and Technology conferences evolves, the need to maintain a full and accessible record of its achievements is clear. This is necessary not only as a report of activity to the PrepCom and as a record for later reference, but also as a means to facilitate the measurement of progress in implementing ideas presented at the conferences and to foster new work among the concerned community of scientists. The aim is to provide a concise and comprehensive record of oral and poster presentations that is cross-referenced and useful for policy makers as well as scientists, and for conference non-participants as well as participants.

1.2 SnT as a Continuous Process

The SnT conferences are part of a continuous process of engaging the global scientific community. Presentations on specific scientific developments from SnT at meetings of the CTBTO’s verification working group, Working Group B (WGB), is one facet of this process. WGB expert groups on verification-related topics, the progressive enhancement of the CTBTO’s technical capabilities in its verification mandate, and the CTBTO’s programme of workshops and training all interact with the SnT process in various ways.

The SnT process takes into account the Treaty’s recognition of the need to progressively enhance the efficiency and cost-effectiveness of its verification regime. It also takes into account the Treaty’s recognition that, after its entry into force, it may be appropriate to have a formal mechanism to solicit external scientific advice on the enhancement of the verification regime’s technical capabilities.

Many of the same scientific instruments, methods and ideas feature in contributions of successive SnT conferences, often in presentations by the same authors or from the same research institutes. Where appropriate, the ideas may make their way through development and testing, with a view to incorporation into Provisional Operations at the CTBTO. In other cases, taking note of Treaty provisions, the ideas may be more appropriate for development by States Signatories in support of their own verification efforts. In either case, a continuous record of the proceedings and outcomes of the SnT conferences can play a valuable role in the monitoring of progress in the enhancement of CTBT verification science and technology.

1.3 Conference Goals and Themes

SnT2015 had the following three goals:

- Enlarge the scientific community engaged in test-ban monitoring
- Promote the wider scientific application of data that are used for test-ban verification
- Enhance the exchange of knowledge and ideas between the CTBTO and the broader scientific community

The content of the conference was divided into four scientific Themes, under each of which several Topics were identified:

**Theme 1** The Earth as a Complex System

T1.1 Infrasound and Atmospheric Dynamics
T1.2 Solid Earth Structure
T1.3 Atmospheric and Subsurface Radionuclide Dispersion and Depletion
T1.4 Exploratory Drilling Techniques for On-Site Inspection
T1.5 Civil and Scientific Applications of IMS Data and IDC Products

**Theme 2** Events and Their Characterization

T2.1 On-Site Inspection: Integrated Field Exercise 2014 (IF Ej14)
T2.2 Treaty-Relevant Events
T2.3 Seismoacoustic Sources in Theory and Practice
T2.4 Atmospheric Background of Radioxenon

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1 CTBT, Article IV, paragraph 11.
2 CTBT, Article II, paragraph 26(f).
THEME 3  Advances in Sensors, Networks and Processing
   T3.1 Design of Sensor Systems
   T3.2 Advanced Sensor Technologies
   T3.3 Data Processing and Interpretation
   T3.4 Developments in Seismology for On-Site Inspection

THEME 4  Performance Optimization
   T4.1 System Network Performance
   T4.2 Information Technology Trends and Future Developments
   T4.3 Logistics and Lifecycle Management

Authors submitted each of their abstracts under one of these Topics, which formed the basis of the scientific sessions and the reference number assigned to each accepted abstract. Under each Topic both oral and poster presentations were invited. Since few abstracts were submitted under Topic T4.2, it was eliminated, with submitted abstracts reassigned to other Topics.

1.4 REPORT STRUCTURE

The structure of this report follows closely that of the SnT2011 report. The scientific part of the conference programme was, by convention, divided according to the conference Themes and the Topics within those Themes, as listed above. The account of scientific contributions in this report (sections 3–9) is organized according to the flow of data, from acquisition through transmission, processing and analysis, to interpretation. Additional sections cover properties of the earth that are necessary to support the verification science, as well as performance monitoring, and capacity building and training. Each section includes relevant material on global monitoring using the International Monitoring System (IMS), as well as local scale activities for on-site inspection (OSI) and non-CTBTO or novel methodologies as appropriate. These sections are followed by a section on conference highlights and potential focus areas for the future. The opening speeches and keynote addresses are also included to provide a context.

Each of sections 3–9 begins with an introduction that defines its scope and explains the demarcation of topics among related sections. In this way it is intended that all topics covered under the SnT umbrella are represented in exactly one of these sections. Only a few minor adjustments have been made to this structure compared with that of the 2011 report. Many contributions present material relevant to more than one section, so many contributions are cited multiple times in the report.

Lists of the presentations (Appendix 1) and of authors (Appendix 2) provide for cross-referencing.

It will be seen that sections 3–9 and their subsections vary greatly in length. This reflects the spread of topics covered by submitted abstracts and may itself suggest areas where efforts should be focused to encourage more active interest within the external scientific community.

1.5 RELATED MATERIAL

The SnT2015 Conference Programme and Book of Abstracts complement this report and can be referred to for additional material. For example, the Conference Programme includes the membership of scientific panel discussions. Details of the membership of the Scientific Programme Committee, slides of oral presentations, images of poster presentations and a video record of all the sessions are also available at http://www.ctbto.org/snt2015.

This complementary information is also available for the four previous conferences in the series along with the reports of previous conferences. As well as containing a summary of contributions and outcomes, these reports contain ‘focus boxes’ with background information, explanations and graphical material on selected verification-related subjects covered in the scientific contributions.


Keynotes

2.1 NALEDI PANDOR

Naledi Pandor
Minister of Science and Technology, South Africa

Dr Lassina Zerbo, CTBTO Executive Secretary; Dr Michael Linhart, Secretary-General for Foreign Affairs of the Austrian Federal Ministry for Europe, Integration and Foreign Affairs; Mr Ahmet Üzümcü, Director-General of the Organisation for the Prohibition of Chemical Weapons; Lord Browne of Ladyton, Vice Chairman of the Nuclear Threat Initiative; excellencies, delegates to the CTBT; Science and Technology 2015 conference; ladies and gentlemen,

It’s a rare privilege to be here today. South Africa is a committed and consistent supporter of the work of the CTBTO. I had no hesitation in accepting the invitation, which I was honoured to receive from Dr Zerbo. I hope that my intervention this morning will assist our efforts to harness science and technology partnerships to build research and innovation capacity on the African continent.

South Africa is currently the only African country to operate nuclear power plants for electricity generation; Namibia, Niger and South Africa are major uranium producers, accounting for about 15% of world output; and South Africa hosts the African Commission on Nuclear Energy (AFCONE) established under the mandate of the Pelindaba Treaty. South Africa has been at the forefront of nuclear non-proliferation in Africa for over 20 years. We gave up our nuclear arsenal and in 1996 signed the Pelindaba Treaty, which establishes Africa as a nuclear-weapons-free zone, a zone that only came into force in July 2009.

Our continent’s policy makers and institutions are increasingly focusing their attention on developing science, technology and innovation capacity in Africa. South Africa is one of the champions for the new Science, Technology and Innovation Strategy for Africa (STISA) adopted by African leaders at the July 2014 African Union (AU) Assembly. STISA will focus Africa’s science, technology and innovation investment in six socio-economic benefit areas: (1) eradicating hunger and ensuring food security in Africa; (2) preventing and controlling disease and ensuring human welfare in Africa; (3) improving intra-African communication through investing in physical and digital infrastructure; (4) protecting Africa’s natural resources; (5) building African communities, addressing aspects such as democratization, urbanization and conflict resolution; and (6) creating wealth for Africa. Science is indeed at the heart of the AU’s Agenda 2063.

Two trends are placing Africa under ever-increasing pressure: rapid urbanization and fast growth (Africa has no fewer than 6 of the world’s 10 fastest growing economies). Cities built for small numbers are experiencing the in-migration of large numbers of people seeking new opportunities, modern infrastructure and public services. Economic growth has come mainly from commodity exports and not from developing manufacturing capacity or innovative products.

To cope with this twin pressure on the continent, Africans have to embrace the complex issue of sustainable development and design and act on innovative responses to energy, health and education challenges. While the challenges are not new, the solutions cannot be replicas of the past. The future for Africa depends on our development of talented scientists who can serve as professionals in scarce-skills fields and take up the opportunity to develop new technologies and innovative solutions for intriguing scientific challenges in the water, sanitation and health fields.

One of the strategies we have developed with strong support from global partners is to utilize big science
It is imperative for Africa’s scientists also to work in Africa if they are to support development on the continent, if they are to play a role in smooth technology transfer, and if they are to drive innovation. A global project such as the SKA is giving effect to all these objectives. This astronomy infrastructure presents a massive leap forward in terms of IT infrastructure, bringing enhanced high-speed connectivity and computing capability to Africa. These are capabilities which would be valuable assets also for the work of the CTBTO.

It is our belief that prosperous African nations will be those with governments that create the right enabling environment for science and technology to flourish. Determining the best technology policy is relatively straightforward, but having the people ready to take advantage of resource-rich opportunities is the real challenge.

South Africa and several African countries have begun to invest in young scientists in an effort to expand our human capital base. We need larger numbers of Masters and PhDs to support our ambitions.

Young people trained in strategic science priorities such as renewable energy, bio-economy, information and communications technology, health sciences, geology and all the engineering sciences are an urgent necessity for Africa. South Africa has acted in response to these needs by creating science institution-based mechanisms. We have a bold well-funded research chairs programme that has created 150 research chairs in a wide range of fields. These chairs have assisted us in attracting senior researchers to train our next generation of researchers and innovators.

The complex challenges confronting African countries have created an opportunity to be at the forefront of global scientific discovery. One example is global change. Africa is affected by climate change in devastating ways. South African scientists are renowned for their contributions to earth-system science and understanding socio-ecological systems through their involvement in international research programmes. South Africa’s unique geographic position at the bottom tip of Africa and surrounded by the southern oceans as well as our long-standing research efforts in Antarctica and Marion Island have allowed us to make an important contribution to the scientific understanding of the science of climate change and its biological effects.

The climate system, as part of a broader earth system, is complex and there are many areas where it is imperative for fundamental understanding to be substantially improved. South Africa has identified the importance of adopting a broader earth systems approach in order to better understand the likely impacts of human and natural changes and include areas of research that go beyond climate change. The principal questions remaining for the majority of scientists concern, not whether greenhouse gases will result in climate change, but the magnitude, speed, geographic details and likelihood of surprises in the process of climate change. Enhancing our ability to effectively mitigate and adapt to climate change is an excellent example where international scientific partnership was a critical prerequisite. The same will apply to non-proliferation.

Another global science opportunity is that of responding to energy insecurity in Africa. Many countries on the continent face an energy shortage for domestic and economic needs. South Africa has in the past seven years grappled with the significant problem of energy insecurity despite having the largest stock of energy on the continent. This has led to us developing an energy plan that exploits solar technology and enhances solar technology innovation for energy security and economic development in poor communities. Our Renewable Energy Independent Power Producers Procurement Programme is a progressive alternative energy plan that has drawn approval from many countries around the world. In addition to solar, biomass and wind technology, we are planning to undertake a nuclear-based energy build programme. As you know, we already have a power station at Koeberg in South Africa. We have begun...
receiving support from the International Atomic Energy Agency (IAEA) and the CTBTO.

World-class research infrastructure is one of the pillars for building competitive knowledge-based activities. Such research infrastructure attracts the best human capital resources. Sharing infrastructure means sharing resources and skills. We have begun to create such opportunities through the regional centre for climate change research, the Southern Africa Science Service Centre for Climate Change and Adaptive Land-use, which is located in Namibia and serves as a research hub for the entire Southern African Development Community (SADC) region.

Joint investments and exploitation of research infrastructures is essential. We believe such institutions create a platform for the regional and global collaboration support of work done by global bodies such as the CTBTO. Our science system is still relatively small compared to systems in the developed world.

This is one of the reasons we have focused on local and global partnerships. We have created 15 centres of excellence as hubs that draw together a whole range of universities and science councils into partnerships in tackling challenges such as HIV/AIDS, tuberculosis, food security and malaria. We are hoping some of these centres will benefit from one of our biggest international science and innovation partnerships: the European and Developing Countries Clinical Trials Partnership (EDCTP). The partnership has contributed to accelerating the development of new interventions to fight HIV/AIDS, malaria and tuberculosis. The EDCTP is a public-private partnership between 13 European and 13 Sub-Saharan African countries. The 10-year budget is €1.9 billion and it harnesses health innovation and technology investment. Similar partnership methodologies could serve the work of the CTBTO well.

During the past 20 years science cooperation with European, American and Asian countries has played a valuable part in facilitating South African scientists’ integration into the global community following the isolation of apartheid. Through multiple training, mobility and networking programmes, international partnerships actively contributed to human capital development for science and technology in South Africa. These are partnerships we greatly appreciate. If South Africa today has a vibrant national system of innovation, with knowledge production consistently on the increase, this is in no small part due to international cooperation.

I would like to thank all our international partners for their support in this regard. We will continue to join forces in support of the work of the CTBTO.

In closing, Africa’s drive for innovation will change the world beyond Africa because out of it will come a new way of thinking about the world, about health, and about technology. This will also impact on the work of the CTBTO. Africa’s socio-economic evolution will change conventional assumptions about every compartment of human activity. In other words, it is my belief that Africa’s capacity for innovation will shape the future of not only Africans but everyone on this planet. In South Africa we tried “to pick winners” with an electric car and a small-scale nuclear reactor project. We then turned to astronomy and “picked a winner” in radio astronomy, where we had a comparative advantage in knowledge and geography.

The most important new technology driver is highly skilled human capital. We all compete in a global market for scientists and entrepreneurs. It’s remarkable that of the five South African Nobel laureates who have received their prize for chemistry or medicine, all now live in other countries. South Africa is the only major Nobel country (with more laureates than any other developing country, and indeed more than many developed ones) that has seen a net emigration of prize winners. And the same is true of entrepreneurs, including the 2013 laureate Michael Levitt and the USA-based space entrepreneur Elon Musk.

We are determined to reverse this trend. The SKA has resulted in important gains but we will step up our efforts. Reversing the brain drain and achieving brain circulation will also be critical if we are to achieve our objective of making science and technology work for the CTBTO. We are committed to this objective and would like to work with all delegates and members in developing a new science and technology compact, to underpin the work of this critical multilateral agreement. You can count on South Africa’s full support.

I thank you.
It is an honour to address this year’s CTBT: Science and Technology conference organized by the CTBTO. At the outset, I wish to note my appreciation to Executive Secretary Zerbo for his friendship and kind invitation to this important event. There is much that the CTBTO and the Organisation for the Prohibition of Chemical Weapons (OPCW) have in common—both in their origins and their missions. Both organizations were born of science-based treaties, and are based on verification and monitoring provisions of unprecedented rigour. Nearly 20 years later, both treaties continue to attract a high degree of consensus on their strategic goals and working methods. And the tangible results we have been able to achieve depend first and foremost on our highly credible verification regimes. Indeed, it is these regimes that make us role models in disarmament and non-proliferation—they are the foundation of our efforts to build trust and confidence among our Member States.

Intense international scrutiny of our work tests every aspect of these regimes and requires us to maintain the highest possible operational standards. To this end, the credibility of our verification regimes relies on closely informed partnerships with science. These partnerships were vital in establishing verification techniques and methodologies during the negotiations for these treaties. And they will be ever more important in preventing future misuses of science and technology. For this, we need to be at the vanguard of the latest advances in science and technology—not only to anticipate challenges, but also to convert them into opportunities to strengthen our regimes. And we must do so amid rapid developments in information technology—and in an increasingly tight fiscal environment. We have no choice, in this regard, but to pursue new avenues of cooperation between organizations like our own, and the scientific and research community. We need this to be at the heart of our game plan in preventing new weapons of mass destruction from emerging, and ensuring that old ones are destroyed.

Let me expand on our experience at the OPCW. Science is at the very core of our work at the OPCW, for it is the use of chemistry for hostile purposes that gives rise to our existence. Misuse of chemistry is made all the more complex by its dual-use nature. Take the widely traded industrial chemical chlorine, for instance. The same chemical used to purify municipal water supplies can be used as a poison gas to suffocate and kill, as we have recently seen in Syria.

George Bernard Shaw once said, “Science is always wrong. It never solves a problem without creating ten more”. The fact of the matter is that it is people, not science, who create problems. This speaks to the importance of our work in promoting the peaceful uses of chemistry, while building on our verification regime to hinder malevolent uses. And at a time when we are witnessing leaps and bounds in science and technology, in our case, we are seeing increasing convergence in the fields of biology with chemistry—a development not foreseen when the Chemical Weapons Convention (CWC) was being drafted.

Application of new production technologies could also present challenges for inspection methodology. The global expansion of the chemical industry likewise stretches the scope of our inspection regime. While these are developments that augur well for increasing prosperity and innovation, they can also potentially test the resilience of our efforts to prevent the re-emergence of chemical weapons.

Carrying out industry inspections, collecting relevant data and tracking transfers of sensitive chemicals is only half the task. We cannot hope to control and track every development, when no fewer than 15 000 new chemical substances are listed on the chemical abstracts database every day—nor should we try to. This is where the promotion of responsible science comes in. This is where outreach to universities, research institutes and schools...
And this is where encouragement of ethical applications of science comes in. At the OPCW, we are enhancing our efforts across all these areas. We have invested major effort to increase our engagement with universities and schools with a new suite of interactive tools and materials. And we are benchmarking these efforts with those of other international organizations to arrive at, and maintain, best practice.

The OPCW has greatly benefitted from the experience of the CTBTO in this area. An international conference was hosted by the OPCW last September on “Education for Peace: New Pathways for Securing Chemical Disarmament”. The OPCW is now considering establishing an Independent Advisory Board on Education and Outreach to better inform and coordinate our efforts in this area. We have also facilitated efforts by the scientific and industry community to prepare a code of ethics for professionals engaged in the chemistry field, following an initiative taken by Germany at our last Conference of the States Parties. Further afield, we actively promote research initiatives in chemistry, fostering new projects that can demonstrate the benefits of chemical sciences—in agriculture, in medicine and in environmental management.

We are deepening engagement with our network of laboratories, especially with a view to expanding the number and geographical reach of the current 21 OPCW designated laboratories. To join, and remain, in this network, aspiring laboratories must pass a rigorous accreditation process before being designated by the OPCW as competent to analyse on-site samples. Following initial accreditation, these laboratories must undergo stringent proficiency tests on an annual basis, ensuring the very highest of scientific standards in our verification work. Recently I unveiled a new training facility at our laboratory in Rijswijk near The Hague that will help increase the proficiency ratings of some of our members’ laboratories in chemical analysis.

To further extend our technical capabilities, we are also considering purchase of nuclear magnetic resonance equipment. At the same time, we are running training courses around the world, aimed at enhancing chemical analytical capacity, as well as measures for effective response to chemical attacks or incidents.

In all of this, we are striving to emphasize the proactive role that science and technology can play in security—a role we want more scientists around the globe to engage in.

The OPCW is engaged in verifying disarmament, as well as guarding against proliferation. Allow me to update you on our progress to this end:

• Since the CWC entered into force in 1997, 190 States Parties have signed on to the treaty. Of these, eight States Parties have declared possession of chemical weapons, six of which have now completed full destruction of their stocks of Category 1 weapons.
• Amid challenging circumstances, Libya and Iraq have finalized plans for destroying some Category 2 component chemicals and remnants of chemical weapons, respectively.
• Russia and the United States, both of which amassed enormous chemical arsenals, have committed to complete destruction of their stockpiles early next decade.
• In less than a year after the OPCW Executive Council’s decision on a destruction plan, all of Syria’s declared Category 1 chemical weapons were destroyed, and only a small amount of hydrogen fluoride remains to be destroyed at a facility in the United States.
• To date, 90% of all declared chemical weapons worldwide have been eliminated. And by 2023, all declared stocks of chemical weapons will have been eradicated. This will represent a historic achievement for multilateral disarmament. It should infuse the international treaty regime with renewed confidence in the power of diplomacy. And its tangible outcomes should motivate new efforts to achieve comparable results in other areas of disarmament.

As partners in the pursuit of global security, we all have a stake in this accomplishment. This entails obligations that are sensitive to the need for continuity and change in a shifting strategic environment—obligations that will continue to be informed by a collaborative international approach underpinned by best practices in science and technology.

Our recent efforts in Syria were highly instructive in this regard. They benefitted from technical innovation in response to unforeseen challenges, and from political will in response to a broader situation strewn with obstacles. Let me explain what I mean by this. In the absence of a land-based option for getting chemical weapons removed from Syria, stores of sulphur mustard and a sarin precursor were loaded onto the Cape Ray, a US maritime vessel. Two mobile systems aboard the Cape Ray neutralized these materials using a process
of hydrolysis to break down the agents with hot water and a caustic compound—the first such operation ever conducted at sea. This operation was verified by specially trained OPCW inspectors on board the vessel. The effluents that resulted from this process were then stored aboard the ship and later transported to other industrial facilities for safe disposal that has just been completed in Germany and Finland. Additional facilities in the United Kingdom and United States have worked to destroy other components of the Syrian stockpile.

Another technical innovation is related to monitoring sites in a conflict situation. To reach sites inaccessible due to the conflict, we deployed Global Positioning System (GPS) mounted cameras to monitor remotely some sites in Syria.

The CTBTO’s International Monitoring System is widely recognized as a marvel of modern science. Apart from serving as a bulwark of the CTBTO’s global verification regime, the scientific data generated by the IMS is impressively wide-ranging in its potential applications, from tsunami warnings to radionuclide detection. For our part, the OPCW employs a wide range of scientific tools in support of our verification regime. Sharing information on the various technologies and methods that we employ for our verification activities may open new horizons for partnership.

Finally, our analytical chemistry capability has played a crucial role in investigating alleged use of chemical weapons in Syria.

I mentioned also political will, without which this mission would not have been possible. The Russian Federation and the United States played an instrumental role in this regard by laying the foundations for the OPCW Executive Council’s decision on a programme for eliminating Syria’s chemical weapons. The resolve demonstrated by these two States and the generous in-kind and financial contributions of other countries to the mission not only affirmed the well-established legal norm of the CWC—it also significantly extended our capability in chemical demilitarization through innovative applications of science and technology.

The Syrian disarmament mission represents one of the few bright spots in what continues to be an otherwise brutal conflict. With no fewer than 30 countries involved in the operation to destroy Syria’s chemical weapons programme, this experience speaks to the importance of partnerships to achieve practical gains in disarmament and non-proliferation. The fact that we were able to achieve a mandate from the United Nations Security Council to remove chemical weapons from Syria lays clear testimony to the strength and effectiveness of such partnerships.

Our organizations traverse a common path. As we stand today, the verification regimes of the OPCW and CTBTO have accumulated nearly two decades of experience—with proven results. With this specialized experience and knowledge, we see value in reaching out and collaborating in key areas. In the past, our organizations have exchanged best practices particularly in relation to inspection activities. In recent years, the CTBTO and the OPCW have participated in one another’s field exercises. At the OPCW, we took particular note of the success of IFE14 in Jordan as a significant milestone for the CTBT’s on-site inspection regime.

Whether through joint participation in OPCW challenge inspection exercises or field exercises such as that in Jordan, these occasions represent valuable moments where our operational readiness is tested and verification practices are shared. Our mutual involvement in such activities provides a window into best practices for inspections, including in logistics and planning.

We must now look to build greater cooperation in these efforts and expand them to new areas. Our Scientific Advisory Board and associated Technical Working Groups, which provide specialized advice in science, technology and related issues to our Member States, provide excellent forums for cross-fertilizing innovation. Given the highly sensitive nature of the data we manage, ensuring the secure exchange of information in real time has always been a priority for our organization. This applies to communication from our Member States to the OPCW, and from our inspectors in the field back to headquarters. For its part, the CTBTO maintains an impressive global communication system that requires a similarly high level of security and data authentication.

And as our Syria mission has shown, the OPCW has had to make a special effort not to compromise the outcomes of our verification activities undertaken in the field. The security of information exchange and employment of remote monitoring techniques are clearly
areas where we could usefully pursue exchange of best practices.

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Training of our inspectors is another area where we could expand our collaboration. Though our technologies and operational parameters for inspections differ, there are a number of common issues facing our inspectors in the field that warrant further discussion. Capturing the know-how of our inspectors and experts is critical to retaining the effectiveness of our verification efforts over generational change. Whether we talk of a possible nuclear detonation or an OPCW challenge inspection, knowledge management is essential if we are to ensure readiness for the next moment of crisis.

A final yet critical common challenge confronting our organizations is achieving universality. Six states currently sit outside the CWC, three of which we expect to soon join the treaty—namely Angola, Myanmar and South Sudan. The three other states remaining outside the Convention—Egypt, Israel and North Korea—represent more daunting challenges for their joining the global chemical weapons ban. For its part, the CTBTO is extending every effort to facilitate entry-into-force of the CTBT. As stewards of these efforts within the international disarmament and non-proliferation regime, we should seek to partner in efforts to impress the urgency of reaching universality to these treaties at every occasion—in front of every audience.

Ladies and gentlemen, within eight years we will have eliminated all declared stocks of an entire category of weapons of mass destruction. Reaching this milestone, however, will not be the sole determinant of our success. As Winston Churchill once said, “Success is not final, failure is not fatal: it is the courage to continue that counts”. This must be the basis of how we approach post-destruction challenges—for, preventing the re-emergence of chemical weapons is a much harder and less visible task. Yet, we do not stand alone in this effort, and we count on the endeavours of scientists and innovations in technology in this regard.

The CTBT and the Chemical Weapons Convention stand among the most tangible, most scientifically informed human undertakings towards ensuring a world free of weapons of mass destruction. Through partnership and collaboration, we can strengthen these undertakings—and further strengthen the norm against weapons that threaten our collective future. Let us build on the scope of what we have already achieved to realize a world at peace, a more peaceful world for future generations.

Thank you for your attention.
It is a pleasure to be back in Vienna, and I am delighted to be in the company of Secretary-General Linhart, Minister Pandor and Director-General Üzümcü in opening this important conference. I am always pleased to share a stage with my good friend, the extraordinarily capable leader of the CTBTO, Lassina Zerbo. Dr Zerbo and I have worked together on security issues for a number of years, and I can say from experience that he is a true visionary and creative thinker—and I know we are all grateful to have him at the helm of the CTBTO.

I look forward, as well, to hearing from this afternoon’s speakers on the topics of Collaboration on Nuclear Test Monitoring Science and Enhancing Governmental, Industry and Scientific Engagement on Nuclear Non-Proliferation and Disarmament.

This year’s conference comes at an important time. On the eve of the 70th anniversary of the bombings of Hiroshima and Nagasaki, we have recently concluded a 2015 NPT Review Conference which was marked by discord and dysfunction, raising troubling questions about the very future of the regime. Twenty-five years after the end of the Cold War, the Euro-Atlantic region is in turmoil and President Putin is sending troubling messages about his nuclear intentions. Meanwhile, President Obama’s once-robust nuclear agenda appears to be on ice, and regional tensions between nuclear powers, arsenal modernization plans, lurking cyber threats and terrorist organizations bent on mass destruction all are serving to undermine stability and threaten global security.

It is most certainly a time to reflect and re-evaluate how best to proceed across a range of challenges to long-term nuclear security, non-proliferation and disarmament. Amid all this trouble, however, there are hopeful signs—including that important groundwork has been laid for a deal with Iran. Of course, there are many hurdles ahead on that front—but I raise it to offer encouragement. The very fact that negotiations have been possible in the current environment shows that progress is always possible. Nowhere has that been made more clear than here at the CTBTO.

Yes, we are approaching the 20th anniversary since the CTBT was opened for signature—and I know we are all frustrated that it is not yet in force. But the CTBTO has a remarkable story to share, and I’d like to talk today about why it’s so important that you—the scientists and the technical experts who have written much of that story of success—work just as diligently outside of your labs and workshops as you do inside of them in order to share that story.

As Dr Zerbo has so aptly said, “Science should support diplomacy”. In this case, there’s no question that it can because yours is not a difficult story to tell.

You could begin back in 1997, when France and the United Kingdom, among other early adopters, were taking the necessary steps to ratify the Treaty. In introducing the ratification measure in the British House of Lords, Baroness Symons of Vernham Dean, then serving as the minister for the government, made clear the level of commitment the British Government had to the CTBT. She went into some detail to explain the central importance of an international monitoring system. Indeed, this dominated her short speech. Clearly, this was the most important factor in the UK’s consideration of the Treaty, and in a few carefully chosen words, the minister described what the CTBTO would have to put together to satisfy the monitoring and verification challenges.

So the UK—and other ratifying States as well—set out a significant challenge: to build a regime that would allow for monitoring and verification of compliance with the Treaty, while at the same time governments developed the complimentary science and technology to ensure the reliability of their existing nuclear stockpiles. Let’s just say there were sceptics galore—and to be fair, no matter how confident some were that a workable verification system could be built, governments were at the time taking a leap of faith in signing and ratifying the Treaty—a necessary leap of faith for some, as part of holding up their end of the bargain on the NPT, but a leap of faith nonetheless.
Now, let’s examine what has happened since that time. The bottom line is that we have 183 signatories and 163 ratifications of what is now one of the world’s most broadly supported arms-control treaties. How has this come to pass? How has this Treaty won such broad support—and now what must we do to bring it into force?

The fact is that the scientists and technical experts behind the Treaty—you—have delivered, and the organization established to prepare it for entry into force has executed. The CTBTO quite simply has passed every test it has ever been given and delivered a working global verification system with more than 300 stations in 89 countries that monitor for signs of nuclear tests every minute of every day. It is a robust system, supported by a global communications infrastructure, and it has exceeded every expectation—with important life-saving applications for humanitarian purposes, such as tsunami warning and scientific research. The system also contributes to nuclear safety. Following the Fukushima accident in 2011, the CTBTO’s systems provided information on emissions from the damaged plant. You have every reason to be enormously proud of your work.

So I think we can all agree that governments set out a challenge and you have more than met it. Today, because of the confidence that you have built, with limited exceptions, we have a verifiable de facto global moratorium on testing; we have a robust, well-led organization in the CTBTO; and we have effective cutting-edge technology in play. In fact, those at work to build the underpinnings of the CTBT have delivered a far better verification and monitoring system than anyone expected. And, in addition, your professional and expert colleagues, where necessary, have developed the technology to ensure the safety and efficacy of reduced nuclear arsenals, where that confidence was also demanded.

So why, with all that support and no states but North Korea having tested now for 17 years, do we need final entry into force? Why is it necessary to take that last legal step? What is the sense of expending a huge amount of time and effort and political capital to take the final step?

Because I believe that final step is crucial—and here’s why: without it, all that we have worked so hard to accomplish—a system around the Treaty that is integral to the global non-proliferation and disarmament regime—remains at risk every day that passes without entry into force.

As I see it, the danger is that those who have made the tough decision to ratify will run out of patience as they watch the countries that have failed to act continue to drag their feet and make promises that go unfilled year after year. In Russia, in particular, I would think it would come as no surprise if some begin to ask: “Why are we in this treaty if other nuclear-armed states are not? Why should we be hemmed in? Where is the collective good faith?”

Adoption of the CTBT in 1996 represented a high-water mark for multilateralism. It led to the creation of this world-class organization in Vienna and to the development of powerful and promising new technologies. It established the de facto global moratorium on testing. Do we want to risk losing the progress we’ve made? I know we don’t.

The CTBTO quite simply has passed every test it has ever been given and delivered a working global verification system with more than 300 stations in 89 countries that monitor for signs of nuclear tests every minute of every day. It is a robust system, supported by a global communications infrastructure, and it has exceeded every expectation—with important life-saving applications for humanitarian purposes, such as tsunami warning and scientific research. The system also contributes to nuclear safety. Following the Fukushima accident in 2011, the CTBTO’s systems provided information on emissions from the damaged plant.

So how do we get the job done? We must act together. We do it with a concerted, coordinated effort by political leaders, governments, civil society and the international scientific community. At the political and government level, we do it with the delivery of a clear and compelling message that can convince those who are hesitant and those who oppose the Treaty outright that it is in their best security interests—and in the best security interests of the world—if the Treaty is legally binding. At the scientific and technical level, we turn to you to tell the CTBTO’s story of success.

What does that mean? It means that scientists from India and other countries that have not signed the Treaty should engage with the CTBTO and work with scientists from countries that have. It means that those of you who have built this amazing structure must share the story of how it was built and what it can do. It means that when you return home from Vienna, you should...
consider briefing your peers in the scientific community so that they can help the cause. Collectively, you must then brief politicians, who in turn can talk to your foreign ministries. You can all, politicians and scientists together, inform government officials. Let them know about last year’s successful five-week field exercise in Jordan, the most sophisticated exercise of its kind ever undertaken. Make the case that the Treaty must enter into force, because as long as it isn’t in force, it will remain vulnerable.

Those of us from countries that have signed and ratified have a special obligation and responsibility to work to bring the Treaty into force. If we don’t, what does it say about our ability in the future to enter into negotiations of any kind in good faith? As scientists, you can help us make the arguments to move forward.

So I hope you will work with us—both to prepare to face the perennial arguments against progress and to engage with political leaders around the globe by making a convincing case that joining the test-ban treaty doesn’t leave their countries more vulnerable—it enhances their security.

The United States should be a particular focus of all of our efforts as it can serve as a trigger for others to sign and ratify. In my new role as Vice Chairman of the Nuclear Threat Initiative (NTI) in Washington, D.C., I am of late getting a closer view of US politics—and the level and quality of the partisanship in the capital city is simply debilitating. It’s difficult to know how and when that situation will change—but I am confident it will.

The CTBTO has proven the concept that a system of verification could be built and that it could work—which was the basis many countries signed onto the Treaty in the first place. Those who haven’t ratified should not be granted the political cover offered by any suggestion that the system isn’t ready. So at the very minimum, I believe we need to create a coalition of governments and political leaders—backed by scientists—to deny those who oppose the Treaty. We mustn’t let those voices go unanswered; we must push back every time.

I urge you to use this amazing technical creation of the 20th Century—the Internet—to issue rebuttals that are instantaneous, comprehensive and effective.

In 1999, when ratification of the CTBT came before the United States Senate, then-senator Richard Lugar—a partner to the NTI on so much of our work—issued a statement opposing ratification. Here’s what he said: “The goal of the CTBT is to ban all nuclear explosions worldwide: I do not believe it can succeed. I have little confidence that the verification and enforcement provisions will dissuade other nations from nuclear testing. Furthermore, I am concerned about our country’s ability to maintain the integrity and safety of our own nuclear arsenal under the conditions of the treaty.”

Last month, former Senator Lugar signed a statement by NTI and a set of global leadership networks that called for, among many other things, prompt ratification of the Treaty. Minds can be changed—particularly with proof now that the science is solid and a system exists that, as Lassina recently wrote, “monitors the earth’s crust, listens in the atmosphere and in the oceans, and sniffs the air for traces of radioactivity”.

Today, US Secretary of State John Kerry understands what you know as well. Last fall, in a speech at the United Nations, he called the verification regime you have built “one of the great accomplishments of the modern world”.

So help him out. Help supporters in other countries take action as well. I admire you for what you have accomplished and I implore you: don’t lose heart, don’t relax, and don’t allow the politicians and diplomats to get away with letting the de facto moratorium stand. We all have an obligation to work for ratification—and entry into force—for the victims of Hiroshima, Nagasaki and the legacy of 2000 nuclear tests; for the safety and security of our individual countries; for the future of the planet.

Thank you.
This Section is concerned with the equipment used to acquire data, its method of installation; methodologies for making, recording and if necessary digitizing the measurements; and methods of calibrating instruments. It also includes the design and configuration of sensor arrays and networks intended for both portable and permanent deployment. Measurement of data not directly related, such as meteorological or environmental data, which may or may not be relevant to the primary data, are also included, as is ancillary equipment in support of data acquisition, such as power supplies, timing systems, and cooling and vacuum systems.

Data processing is included in this Section only when it is integral to the process of measurement or recording of the data; methods to combine and process data recorded by different sensors of an array are included under SECTION 5.

Instrumental self-noise and other instrument characteristics are included in this Section, as well as methods to reduce noise during the recording process. However, studies of background signals and noise originating externally to the recording system, and their effect on instrument performance and detection thresholds, are considered in SECTION 8. While studies of instrument capability are included here, studies of instrument performance are included along with other performance-related topics in SECTION 8.

This Section includes measurement platforms such as satellites, aircraft and unmanned aerial vehicles (UAVs or drones). Matters related to the authentication, encryption and security of data are included in SECTION 4. Data storage is only included in this Section if it is integral to recording equipment; other data storage issues are considered in SECTION 4 or, in the case of shared data platforms, SECTION 9.4.

This Section also includes equipment used in IMS facilities (conventionally taken to refer to IMS stations plus IMS radionuclide laboratories), as well as equipment used for OSI, and equipment of any other verification technology that is used, or might be usable, in the CTBTO verification regime or as national technical means (NTM) by entities outside the CTBTO.

Finally, this Section includes strategies for OSI because such strategies are intimately related to the technological possibilities and limitations of data acquisition; many IFE14 presentations are included here and appear also under other Sections depending on their relevance.


3.1

SENSORS AND MEASUREMENTS

3.1.1

SEISMIC

Seismic arrays in the IMS have a wide range of shapes and sizes, reflecting the legacy of stations that existed before the IMS seismic network was designed and installed. These arrays range from a station with multiple sub-arrays providing an aperture of 60 km, via linear cross arrays with an aperture of 20 km and seismometer spacing of 2 km, to smaller regional arrays with apertures down to 1 km. Kemerait (T3.1-02) considers factors that should be borne in mind in the design of an IMS array as existing stations become due for upgrading or replacement. Noting the need for IMS seismic arrays to perform well at both teleseismic and regional distances, the author discusses increased sampling rate, more elements to improve detection threshold, hybrid short period and broadband seismometers, and full three-component instrumentation.

Several other contributions also focus on array and network design. Kaneda et al. (T3.1-03) describe the Dense Ocean-floor Network System for Earthquakes and Tsunamis (DONET1 and DONET2) off the coast of Japan, which are primarily designed as a real-time monitoring system for earthquake and tsunami hazard mitigation. These networks include broadband seismometers, strong motion seismometers, hydrophones and ocean-bottom pressure gauges. Another sea-floor earthquake and tsunami monitoring system being deployed in multiple off-shore locations around Japan is described by Shinohara et al. (T3.1-01).

Kadiri Afegbua et al. (T3.1-P1) describe enhancements to the national seismic network of Nigeria, including improvements in calibration and signal-to-noise ratio. For the recording of strong motion data, Zimakov et al. (T3.1-P10) describe a system that combines a seismic accelerometer with geodetic measurements using GPS; this offers real-time acceleration and displacement monitoring for the characterization of strong earthquakes. An integrated three-component short period seismometer and three-component accelerometer with digitizer for rapid deployment in aftershock monitoring is described by Zimakov et al. (T3.4-P2).

The calibration of seismic sensors and their electronics remains crucial to the monitoring effort, especially since event screening depends on the correct determination of seismic magnitude. Burk et al. (T3.1-P2) describe a field calibration method for non-feedback seismometers that employs a laser to measure mass position and displacement. A 13-tonne hammer source described by Jones et al. (T3.3-03) is characterized seismically using nearby seismometers but is also investigated as an infrasound source (see section 3.1.3).

3.1.2

HYDROACOUSTIC

The IMS hydroacoustic network comprises five T-phase stations and six hydrophone stations. The T-phase stations are similar to three-component seismic stations and are located in coastal areas with steep bathymetry to facilitate coupling of waterborne acoustic energy into the earth’s crust. All except one of the hydrophone stations are based on remote oceanic islands and comprise two hydrophone triads that are located up to 200 km away from opposite sides of the island and are linked to a shore-based central recording and satellite communications facility by sea-floor cable. Each triad is suspended in the water column in a horizontal triangular configuration with a 2 km hydrophone separation. The hydrophones are suspended in the sound fixing and ranging (SOFAR) channel (at depths of down to about 1 km depending on the station) to optimize the propagation of acoustic waves.

Due to the great efficiency with which acoustic waves travel in the SOFAR channel, only a small number of hydroacoustic stations is needed to monitor the world’s oceans. However, it follows that every hydroacoustic station in the IMS network is crucial to maintain global coverage; this places additional importance on the need for high reliability and long mean time between failures.

The design, manufacturing and installation of cabled hydrophone stations constitute a major engineering undertaking (FIGURE 3.1). One example is the installation of HA03 at Juan Fernández Island, Chile. This station was functioning normally before being destroyed by the tsunami associated with an earthquake in Chile on 27 February 2010. Haralabas et al. (T3.1-P24) report on the re-establishment of this station, with the shore facility at a new location better protected from any future tsunami. The authors report that this installation was one of the most complex projects in the history of the CTBTO.

The next planned installation is HA04 (Crozet Islands, France). At the time of SnT2015 this remains the only uncertified hydroacoustic station in the IMS network. The installation challenges for HA04 are attributed to the remoteness of the site, the morphology of the bay and local weather conditions. Zampolli et al. (T3.1-P9) describe
the preparatory environmental studies performed to optimize the location and depth of hydrophones, the pathways for the sea-floor cables, and in general all the a priori knowledge necessary to ensure survivability of the hardware and optimum data quality. The authors describe the role of high-resolution bathymetry and year-long three-dimensional sea-current modelling.

3.1.3 INFRASOUND

In a presentation entitled “Ubiquitous Infrasound” Garces (T3.1−O5) points out the omnipresence of infrasound, and the existence of smartphone applications to record and locate infrasound sources. Advances in the development of infrasound sensors and associated noise suppression systems for the IMS and other infrasound networks continues, and this is reflected in several contributions. Talmadge (T3.1−P28) reports on the status of analogue and digital infrasound sensors developed by the National Center for Physical Acoustics (NCPA) in Oxford, Mississippi, USA, using piezoceramic transducers. A project designed with a view to developing international standards for infrasound sensors, beyond IMS minimum requirements, is presented by Doury et al. (T3.1−P22) and described in section 8.3. The authors report on laboratory comparison of different existing infrasound sensor systems.

Previous SnT conferences have heard about the use of optical interferometers to record infrasound. Olivier et al. (T3.1−P33) report on a range of new microbarometers currently under test. Kramer and Marty (T3.1−P33) describe developments in the wind noise reduction systems used at IMS infrasound arrays. In particular, they report on the move towards stainless steel pipe arrays, including the modelling of all parts of the noise reduction system to find the optimum size of manifolds and pipe lengths, and to ensure a standard system response.

The geometry of sensors within an infrasound array has a major influence on its performance under different temperature and wind conditions. Randrianarinosy et al. (T1.1−P8) consider the performance of three array designs implemented at three infrasound stations in East Africa: IS33 (I33MG) in Madagascar, IS35 (I35NA) in Namibia and IS47 (I47ZA) in South Africa.

 Calibration of infrasound stations is addressed by Zeiler (T3.1−P23). The author describes a facility being established at Pinedale, USA, to compare, test and optimize infrasound recording systems, with facilities to bench test up to three sensors against a control sensor and a field test bed configurable as a small or large aperture array.

 Hammer sources are normally associated with seismic surveys, but Jones et al. (T2.3−O3) investigate infrasound signals from a large hammer source used for a survey in the Nevada National Security Site (NNSS), USA. They employ drones to allow the three-dimensional infrasound radiation from the source to be measured.

 The recording of meteorological data as ancillary data at IMS infrasound stations is important in view of the sensitivity of infrasound station performance to meteorological parameters, especially wind direction, wind speed and temperature. An account of efforts made by the CTBTO to improve the quality of such data is presented by Martysevich et al. (T3.1−P11). For the future, it is reported that tests on a new generation of digital meteorological stations have been performed with a view to installing them at IMS stations.

 Infrasound signals from atmospheric nuclear explosions recorded in Kazakhstan are presented by

FIGURE 3.1
Hydroacoustic node being deployed from a cable ship. From Haralabus et al. (T3.1−P24).
Sokolova (T2.3−P3), illustrating the creation of a database of digitized seismic and infrasound recordings. They include unique records from a microbarograph installed in 1960 at the Talgar Observatory near Almaty, Kazakhstan.

3.1.4 SEISMIC, HYDROACOUSTIC AND INFRASOUND AS A GROUP

A common requirement for seismic, hydroacoustic and infrasound stations is the accurate calibration (and recalibration) of sensors and associated electronics and digitizers. Requirements are detailed in the draft IMS Operational Manuals and are actively being pursued at the CTBTO, in some cases with collaborating partners. These activities are described by Doury et al. (T3.1−P27). As well as annual calibration of seismic and T-phase stations, methods for calibrating the in-water electronics of hydrophone stations and the use of self-calibrating infrasound sensors is covered. In view of the fact that methodologies for calibrating seismic systems are much longer established than those of hydrophone and infrasound, emphasis is being placed on bringing calibration procedures in all three of these technologies to the same level of maturity.

The Treaty has specified many cases where IMS stations of more than one technology are co-located. Gibbons et al. (T3.3−P6) point out that whereas the design of the IMS primary seismic network was influenced by the location of pre-existing seismic stations, the design of the IMS infrasound network suffered no such constraint because very few infrasound stations pre-existed. These authors consider whether the co-location of additional seismic arrays with IMS infrasound stations (Figure 3.2) could in future improve seismic monitoring while exploiting the infrastructure of the IMS and the Global Communications Infrastructure (GCI) that is already in place. They conclude that small seismic arrays of similar aperture to existing infrasound stations could provide significant improvement in certain locations, particularly in the southern hemisphere. They note that such enhancement could greatly enhance the host State’s ability to monitor natural and induced seismicity on a regional scale and could enhance the value of the associated infrasound data. Accordingly the authors recommend experimenting.

3.1.5 RADIONUCLIDE

One option available for the sampling of atmospheric radioactive xenon is the Swedish Automatic System for Noble Gas Acquisition (SAUNA). A major upgrade, referred to as SAUNA III, is described by Ringbom et al. (T3.1−O4 and Figure 3.3). The issues identified by these authors, as the focus of this initiative, include increased sensitivity as well as more precise isotope ratio estimates through reduction of measurement uncertainty, increased temporal resolution through reduced acquisition time, and improved maintainability. In pursuit of these targets the design goals presented include increased volume per sample, active energy drift control of the detectors, and a change of carrier gas from helium to nitrogen. In addition, the authors describe planned improvements to the beta detector in order to improve energy resolution. Developments in the detector are further discussed by Axelsson et al. (T3.1−P25), who make a number of proposals for new cell design. One challenge identified is the need to minimize the reduction in the energy resolution, which results from scintillator coatings being applied to...
mitigate the memory effect of beta detectors. The goal of increasing the time resolution along with doubling the sample size, while using the pressure swing absorption (PSA) method for a new pre-enrichment step of xenon prior to the inlet sampling, is discussed by Aldener et al. (T3.1-P29). They also discuss the switch to nitrogen as a carrier gas.

Berglund and Sundstrom (T3.1-P26) describe the SAUNA mobile sampling unit and portable xenon laboratory. The OSI SAUNA, based on the concepts of the SAUNA II system, is described by Aldener et al. (T2.1-P15); this provides higher throughput of smaller samples and the ability to cope with field deployments as well as a wide range of sample gas compositions, in particular by separating out carbon dioxide, water vapour, methane and radon in order to accommodate both atmospheric and subsoil gas samples.

The Swedish noble gas laboratory operates a SAUNA laboratory system modified with a higher performance detector shielding to reduce natural radiation background. Fritioff et al. (T3.1-P32) describe upgrades to this system with new control software and state-of-health monitoring, new software to support fully automatic processing, and capability to measure two samples.

The high-purity germanium (HPGe) detectors typically used in CTBT radionuclide applications are used for OSI as well as at IMS stations. OSI involves laboratory and field-based measurements in unpredictable terrain and climatic conditions, where reliability and robustness are especially important. Flamanc et al. (T3.2-O3) report new developments in ruggedized HPGe detectors designed for outdoor use, and Tayyebi et al. (T3.1-P5) describe the use of a radon-222 source combined with simulations using the Monte Carlo N-Particle Extended (MCNPX) code to perform full detector calibration of an HPGe detector. Hennig et al. (T3.1-P7) describe the further development of the detector system using a combination of caesium and iodine and a plastic scintillator, for example the phoswich detector for radioactive xenon field measurements. They report a number of improvements and tests with radon and xenon sources.

As with many experimental measurements, the ability to detect a radionuclide signal of interest is compromised by the existence of many interfering signals with multiple unrelated origins. Generally referred to as ‘background’, these other signals receive much attention from designers of detectors and measurement systems, with the aim of finding methods to reduce the background, and thereby reveal signals of interest at a lower concentration; this is referred to as reducing the minimum detectable concentration (MDC). The simplest way of reducing background is by shielding. Typical measurement systems for CTBT-relevant applications normally comprise an HPGe detector both for radionuclide particulate samples and in one type of noble gas system set-up, while for xenon detection systems beta–gamma coincidence detectors are widely used to limit background and achieve the current MDCs. The beta–gamma detector systems make use of a combination of a gamma-ray detector (e.g. sodium iodide detectors) with a beta cell for detection of electrons (either a plastic scintillator or a silicon positive intrinsic negative (Si-PIN) diode detector). By surrounding the detector with a shield, the flux of gamma rays reaching the detector from decay events outside the system is reduced (passive shielding). Other methods of background reduction exploit differences between the products of irrelevant decays from those of interest (active shielding). Such methods can use ‘coincidence’, ‘anti-coincidence’ or ‘veto’ logic to exclude signals that are not of interest.

One such system is the cosmic muon veto system (CMVS) developed at the CTBTO to reduce the background arising from muons passing through the detector system. Khrustalev and Nadalut (T3.2-P9) describe the system (figure 3.4), present results and give future plans.

Britton and Davies (T3.2-P1) describe a gamma–gamma coincidence system developed at the British IMS radionuclide laboratory for the improved identification of multiple gamma emissions from coincident events.
from CTBT-relevant nuclides. In anti-coincidence mode the system can be used to improve detection of nuclides which decay via single emission. A list of demonstrated benefits is presented together with the results of testing.

A new beta–gamma coincidence system for the measurement of radioactive xenon isotopes is described by Afarideh and Doost Mohammadi (T3.1-P18). The system consists of a well-type sodium iodide gamma detector and a cylindrical plastic scintillator for beta detection. Using only one photomultiplier for the beta detection, this system does not require gain matching in the set-up procedure.

Foxe et al. (T3.2-P7) consider the benefits of using a Si-PIN beta detector in place of the plastic scintillator in a beta–gamma coincidence measurement system. These detectors have significantly improved electron energy resolution, which facilitates isotope discrimination and consequently increases the ability to identify the source of xenon using the ratio of isotope concentrations. Different designs of the detector cell are compared, each having a different potential to decrease the MDC.

Another beta–gamma coincidence system is reported by Le Petit et al. (T3.2-P13). This combines a high-resolution HPGe detector for detection of the gamma radiation with a Si-PIN detector. Several advantages are outlined, notably better discrimination of isotopes and less interference of xenon-133 with the detection of xenon-133m and xenon-131m, and improved performance is presented.

Davies et al. (T3.1-P4) tests a small anode germanium (SAGE) well detector and concludes that it offers benefits in measuring OSI-relevant radionuclide particulates with improved MDC, while maintaining excellent energy resolution.

Good calibration of detectors is essential for correct identification of spectral peaks and accurate quantification of nuclides. Calibration of beta–gamma coincidence detectors is considered by Khrustalev and Wieslander (T3.2-P19), and further developments to simplify what is a multistep process are described with test results from measurements and Monte Carlo simulations. Beta energy calibration of a beta–gamma coincidence system using a caesium-137 point source is considered by Sabzian et al. (T3.1-P21), and in particular the effect of source position on the energy calibration of the beta detector. Observations and Monte Carlo simulations are used to determine the effect of the source position, and at which point the source best resembles a xenon gas source.

Topin et al. (T3.2-P16) describe developments in the use of a silver-doped zeolite for adsorption of xenon in the context of the French Système de prélèvement d’air automatique en ligne avec l’analyse des radio-xénons (SPALAX) noble gas measurement system. This is seen as a major breakthrough in separation methods, as the material is highly efficient in separating xenon in traps which are significantly smaller than the currently used traps based on active charcoal.

Gohla et al. (T3.2-P22) describe xenon laboratory intercomparison exercises using reference standards for radioactive noble gas concentration measurements. Since radioactive xenon reference standards have not been available until recently, this is seen as a major step forward in carrying out such intercomparison exercises.

The OSI Radioisotopic Spectroscopy (OSIRIS) instrument is described by Coffrey et al. (T3.2-P4). This is a field-based gamma-ray spectrometer that has a built-in filter (i.e. blinding) capable of removing non-CTBT-
relevant gamma-ray peaks from the displayed output. So-called ‘blinded’ spectrometers could potentially be relevant for the development of equipment for OSIs in support of the CTBT. OSIRIS is designed for remote field use, with mechanical cooling (no liquid nitrogen) and battery operation, while raw spectra are not displayed to operators. It is reported that the technology is being transferred to a commercial manufacturer.

The collection of particulate radionuclide samples by blowing air onto a filter for 24 hours results in a concentration of atmospheric radionuclide particulates on the filter. In routine operation, first measurement results are available not sooner than 50 hours after measurement starts. In the case of a nuclear accident, where atmospheric radionuclide levels are elevated, the filter could accumulate a level of radioactivity above the normal amount. Concerns were raised regarding this filter could accumulate a level of radioactivity above the normal amount. Concerns were raised regarding this after the Fukushima Daiichi nuclear power plant accident in March 2011. Khrustalev and Wieslander (T3.2-P14) describe a small detector system to provide early warning of elevated concentration using a lanthanum bromide detector system, which has the advantage of high efficiency combined with reasonably good resolution in order to discriminate between radionuclide isotopes. The system design, full calibration validation and results from long-term testing at a station are presented.

A system for the continuous measurement of atmospheric gamma radiation using germanium and scintillation detectors is described by Saez Vergara et al. (T3.2-P4). It is reported that this system is installed in Spain as part of the national radiological hazard monitoring network. Bell et al. (T3.2-P5) compare gamma spectrometers for the monitoring of atmospheric radiation.

Klingberg and Biegalski (T2.4-P8) investigate additional xenon isotopes to those used in IMS noble gas analysis. They produce xenon-125, xenon-127, xenon-129m and xenon-137 in isotopically pure form by neutron activation, and measured using a beta–gamma coincidence detector. Even though not produced in significant quantities in a nuclear explosion, these isotopes could interfere with the detection at IMS systems, as well as during an OSI, if released from an anthropogenic source.

Carrigan et al. (T2.2-P22) describe tracer gas experiments in the subsoil at a former underground nuclear test site, combining measurements with computer simulations. These experiments contribute to the expansion of scientific knowledge related to subsoil noble gas migration processes, which supports further development of OSI noble gas field sampling strategies. The authors show that barometric pressure and natural radon concentrations are environmental variables that are useful in triggering noble gas field sampling.

The administrative process of commissioning a mobile noble gas system for OSI with the financial support of the European Union’s Joint Action Programme is described by Wieslander and Khrustalev (T3.1-P20). From planning through development to testing, and finally successful deployment during IFE14.

An overview of the main components of the OSI noble gas programme is provided by Wieslander and Khrustalev (T3.1-P20). The noble gas field sampling equipment, process and general methodology are described as well as the noble gas field laboratory and its associated equipment. The two types of sample collection method are described: ‘shallow’ methods using sampling under a tarpaulin and ‘deep’ methods, which require drilled boreholes down to 10 metres depth. The field laboratory uses primarily three types of noble gas processing system: OSIS-SAUNA from Sweden together with the Radioxenon Sampling, Purification and Measurement System (XESPM) and the Movable Argon-37 Rapid Detection System (MARDS), both from China. A number of challenges with the current field sampling methodology and equipment are mentioned, as well as future developments needed in the field laboratory equipment and associated processes.

Gas chromatography is used to analyse the concentration of a stable gas by means of separation. It also finds uses in the preparatory phase of sample measurement, in particular to remove unwanted gases such as carbon dioxide, water vapour and radon. Zhou and Zhou (T3.2-P8) describe a proposal to implement a gas chromatograph for impurity removal in the preparatory phase of the gas sample measurement, while removing the last gas impurity traps of the gas processing system, thus simplifying the whole system and making it lighter. This work is part of the development of the Chinese noble gas system XESPM-III, which was used in IFE14.

In the OSI context, noble gas monitoring may include argon as well as xenon. Li et al. (T2.1-04) describe the latest improvements to the Chinese system MARDS (FIGURE 3.5), the world’s only mobile argon-37 detection system, including a decrease in the MDC to 26 mBq/m³ for a counting time of 10 hours, increased sample throughput, and enhancement of suitability for field use. Based on its deployment in IFE14 and the technical activities leading up to this, plans for future improvement are also outlined.
Equipment for measuring plutonium isotopes, including an alpha spectrometer and an inductively coupled plasma mass spectrometer, together with a gamma spectrometer system for measuring caesium-137 and a beta counter for strontium-90, are described by Puzas et al. (T2.2−P16).

3.1.6 SATELLITE-BASED AND OTHER

The Treaty foresees that additional monitoring technologies may be added to the CTBTO verification regime in the future, and satellite monitoring is specifically mentioned in this context. The trend towards large constellations of relatively inexpensive small earth observation satellites described by Patton (T3.2−O1) is especially relevant. She suggests that the economics of such systems, combined with the technological flexibility that they offer, may make it feasible for such systems to be incorporated into the CTBTO verification regime sometime in the future.

An introduction to spectral imaging, and in particular the airborne data acquisition methods used for OSI, is presented by Jones et al. (T3.2−O5), who then consider the advantages of the snapshot spectral image in the OSI context, including the ease and flexibility of data acquisition and the simplification of data analysis. It is pointed out that this may offer particular benefits in an OSI, since OSIs will be constrained by limitations on time and other resources.

Infrared imagery is permitted during an OSI and is of potential importance in locating a possible underground test. Szalay et al. (T3.2-P16) describe an experiment to test the capability of a ground-based handheld thermal camera to detect a thermal anomaly created by passing warm water through a submerged pipe. The viability of this for deployment in an OSI is demonstrated. The potential use of Landsat imagery for OSI is considered by Bedini (T3.2-P21) with reference to imagery from several known nuclear test sites. Vásconez Albán et al. (T3.1-P31) report on the use of thermal imaging for volcano monitoring and highlight its advantages especially for detecting activity at night or in cloudy conditions. The use of multispectral imaging in OSI is also discussed in section 3.3.4 in the context of strategies for OSI.

A range of investigation methods are permitted under OSI, and these are listed in the Treaty. Magnetic and geoelectric measurements and measurements of radon in conjunction with seismic recording for earthquake hazard in Colombia, which are described by Solano Fino et al. (T3.1-P16), may be potentially relevant.

3.2 MONITORING FACILITIES

3.2.1 IMS STATIONS AND LABORATORIES

Data from one or more of the IMS station networks are used in many SnT2015 contributions. Other contributions focus on data from one station or group of stations. In this Section a selection of these is mentioned in order to provide an impression of the broad range of topics relevant to the design of IMS stations and the use of their data.

Roth et al. (T4.1-P26) refer to the recapitalization (i.e. replacement) of the PS28 (ARCES) array in Norway, just completed, which unusually has 25 full three-component broadband sites. Gibbons et al. (T3.3-P17) describe the improved detection and parameter estimation for regional S phases achieved utilizing its three-component data.

5 CTBT, Article IV, paragraph 11.
6 CTBT Protocol, Part II, paragraph 69.
Edwards (T3.1-P15) describes the recapitalization of the seismic array PS09 (YKA) at Yellowknife, Canada, whose new installation was operated in addition to the old for six months for comparison. In view of their reliability and robustness, it is reported that the existing Teledyne Geotech S13 short period seismometers have been retained in the new installation. The PS19 (GERES) array in Germany is utilized by Apoloner and Bokelmann (T3.3-P22) for the detection and modeling of regional depth phases.

Seismic noise from wind turbines with the potential to degrade the detection capability of the AS104 (EKA) seismic array, UK, is discussed by Bowers et al. (T2.3-05). The aim is to develop a physical understanding of the seismic noise generated by wind turbines, and hence to develop a model to predict the noise produced by different types of turbine. A description of how this approach was used to specify appropriate restrictions on wind turbine deployment is given. Another contribution that focuses on specific auxiliary seismic stations is that of Bregman et al. (T3.3-P33), who use data from two stations in Israel: AS049 (MMAI), Mount Meron, and AS048 (EIL), Eilat.

Turning to infrasound, Nasholm et al. (T1.1-P17) describe signals recorded at the newly installed station IS37 (I37NO) in Norway from a series of chemical explosions in Finland, and Opiyo (T3.1-P1) reports the benefits accrued to IS32 (I32KE) in Kenya in terms of data availability from a major upgrade. The potential benefits of co-locating additional seismic arrays with a number of IMS infrasound stations is explored by Gibbons et al. (T3.3-P6).

On hydroacoustic stations, two contributions describe the reinstallation of hydrophone stations. Zampoli et al. (T3.1-P9) describe that of HA04 (Crozet Islands, France) and Haralabus et al. (T3.1-P24) that of HA03 (Juan Fernández Island, Chile).

One example of the use of an IMS radionuclide station to monitor radioactive xenon in the Canadian Arctic is presented by Hoffman et al. (T2.4-P16) using stations RN15 (CAX15), Resolute, and RN16 (CAX16), Yellowknife (see also section 8.1.2). Another example is the use of observations made at RN38 (JPIX38), Takasaki, Japan, and RN58 (RUX58), Ussuriysk, Russian Federation, by Hofman and Seibert (T2.2-P11) and others to explore their possible association with the 2013 announced nuclear test in the Democratic People’s Republic of Korea (DPRK). Yet another is the use of xenon-133 observations at station RN33 (DEX33), Freiburg, Germany, by de Meuter et al. (T1.3-07), as possibly arising from the medical isotope production plant in Belgium. These last two examples are also considered in section 6.3.3.

### 3.2.2 NON-IMS STATIONS AND NETWORKS

Although the IMS hydroacoustic, infrasound and radionuclide networks had no previous analogues as global networks, there are many seismic networks around the world, many of which pre-dated the IMS. Indeed, many IMS stations began life as part of another network to which they still also belong. In the context of CTBT verification, non-IMS stations and networks are valuable in offering additional evidence of potentially suspicious events, in the form of NTM, as pointed out by Ghelami and Safepour (T1.1-P27) in the context of Iran. Accordingly, there are many references to non-IMS seismic networks, some national and some international, in SnT2015 presentations. A selective summary of the non-IMS stations and networks appearing in SnT2015 presentations is given here. Most of the cited contributions are also referred to in appropriate Sections elsewhere in this report.

The Global Seismographic Network (GSN) is a US global network that is not part of the IMS; its current status is described by Hafner et al. (T4.1-P26). Jonsdottir et al. (T1.5-05) use national stations in Iceland, while Georgieva (T1.2-P3) uses 11 stations of the Bulgaria national seismic network. Kitov et al. (T3.3-05) use observations from the Mikhnevo seismic array in the Russian Federation. Aronov et al. (T4.1-P26) describe the national seismic network of Belarus, and Karyagin and Alexander (T2.3-P10) use data from the national station network of Ukraine.

In the Middle East, Gok et al. (T3.3-P32) refer to the broadband station Mutribah (MIB) in Kuwait, the station Minazif (UOSS) in the United Arab Emirates, and a temporary nine-element seismic array (QWAR) in Saudi Arabia. The Egypt National Seismograph Network (ENSN) is used by Shater and Mahmoude (T1.2-P5).

In Africa, the national seismic network of Namibia is described by Sitali et al. (T1.5-P17) and is referred to by Titus et al. (T4.1-07), while Kadri Afogbua et al. (T4.1-P21) describe the national seismic network of Nigeria. In Latin America, the seismic and volcano monitoring network of Costa Rica is used by Villalobos Villalobos (T3.1-P27), several seismic networks in Brazil are described by Carvalho et al. (T4.1-04), and Vieira Barros et al. (T1.2-P9) also use stations in Brazil. The Naqu and Hetian seismic arrays in China are referred to by Hao and Zheng (T1.2-06), and stations Mudaniang (MDJ), China, and Hanoiara...
(HNR), Solomon Islands, are used by Fergany (T3.4-01). The Pilbara three-component seismic array (PSAR) being operated in the north of Western Australia is described by de Kool (T3.3-P26).

Offshore Japan is the home of some sea-floor observatories that include seabed seismometers and other sensors. The sea-floor observation network for earthquakes and tsunamis along the Japan trench (S-Net) project is described by Kanazawa et al. (T3.1-P30), and the DONET1 and DONET2 networks of sea-floor observatories are described by Kaneda et al. (T3.1-03) and referred to by Kaneda (T2.3-P6). Additional networks are described by Shinohara et al. (T3.1-01).

In infrasound, the infrasound network of Kazakhstan is described by Dubrovin (T1.1-P14). Developments in the infrasound capability of the Pinedale station (USA) is described by Zeiler (T3.1-P23), and Park et al. (T1.1-P1) use data from the Republic of Korea infrasound array.

**Focus**

**Evolution of the IMS**

The number and location of IMS stations and radionuclide laboratories (together referred to as ‘IMS facilities’) are specified in the Treaty. The first IMS stations were certified in 2000, and the largest number of facilities was certified in 2004. By 2015 nearly 85% of IMS stations and radionuclide laboratories were certified.

FIGURE 3.6(a) shows the number of IMS stations and radionuclide laboratories certified during each year; numbers are given separately for primary and auxiliary seismic, hydroacoustic, infrasound and radionuclide stations. In FIGURE 3.6(b) these numbers are shown cumulatively, with the full number of planned facilities in each category shown in an additional column to the right.

Radionuclide facilities are first certified as radionuclide particulate stations or laboratories. Where noble gas monitoring is also planned, the installation of equipment and certification are performed separately.

The installation and maintenance of IMS facilities require an appropriate formal arrangement to be made between the CTBTO PrepCom and the host State; this is achieved through a ‘facility agreement’. Such an agreement is foreseen in respect of all the 89 States that host IMS facilities under the Treaty. FIGURE 3.6(c) shows the number of facility agreements that have been concluded during each year, and FIGURE 3.6(d) shows these numbers cumulatively.

To minimize delays that may be caused to station installation by the formalities associated with concluding a facility agreement, work often begins under an ‘exchange of letters’. FIGURE 3.6(e) shows the number of exchanges of letters relevant to IMS facility installation.
CHNAR as well as infrasound data from the USArray transportable array. *Appibaum and Price* (T1.1-P6) focus on Mount Etna, Italy, and report on signals concluded to be from Mount Etna in data recorded over four years at the Meron experimental infrasound array in Israel.

The monitoring of volcanoes in Ecuador using infrasound is reported by *Ruiz Romero and Steele* (T1.1-P28). The authors describe a project of the Instituto Geofisico with six microbarometers for monitoring active and potentially active volcanoes in Ecuador. Non-IMS radionuclide monitoring networks are used by *Chai et al.* (T1.5-02).

The Treaty provides for States Parties after entry into force of the Treaty to offer non-IMS stations as ‘cooperating national facilities’ (CNFs) which could be accepted provided that they meet the IMS station specifications and are certified accordingly*. *Pesaresi* (T1.1-P31) describes a proposal for such a facility based in Italy.

### 3.3 STRATEGIES FOR ON-SITE INSPECTION

#### 3.3.1 GENERAL

Many strategic questions arise in the development of OSI capabilities. There are questions concerning the optimization of the on-site inspection itself, but during the build-up phase there are many more questions concerning the conduct of field exercises and table top exercises, and the development and testing of realistic scenarios in ways that will maximize the benefits for the conduct of an OSI after entry into force. These questions are not only scientific and logistical but also concern the conduct of meetings of the Executive Council that will be the focus of decisions leading up to an OSI. The conduct of an OSI exercise is not only scientific and logistical but also concerns external data (maps etc.) provided to the inspection team, a flow diagram of the relationship between the involved parties, and lessons learned as well as suggestions for future development and refinement.

The example of IFE14 is used by *Sussman et al.* (T2.1-05) to demonstrate that visual observation at the surface represents not only the foundation of an OSI exercise, but also of an actual OSI. The methods of finding and characterizing such observables are accordingly seen as an important component of both inspector training activities and of scenario development in the preparation of OSI exercises. The authors conclude that there needs to be a focus on the understanding of potential surface, subsurface and radionuclide observables from a nuclear weapon test explosion.

*Malik et al.* (T2.1-03) consider the practical aspects of information-led search, beginning with the planning of such a search, the identification of areas of special interest within the inspection area, the gathering and assimilation of observable data, and the use of a five-step logic loop to control the evolution of the data gathering exercise. The design complexities of a realistic observational environment for a scenario-based OSI exercise are then discussed in the context of IFE14. The methods and protocols for handling different types of observed data are described by *Labak et al.* (T2.1-P10), again in the context of IFE14; this includes the transmission of data from the point of collection to field office premises or field laboratory, the storage of data, security controls and other matters.

External to OSI field operations is the Operational Support Centre in Vienna, which coordinates support to the OSI inspection team from the Future Technical Secretariat, including the International Data Centre (IDC), in accordance with the requirements of the Treaty and the draft OSI Operational Manual. In the context of IFE14 this arrangement is described by *Sussman et al.* (T2.1-P11), with the inclusion of examples of the type of external data (maps etc.) provided to the inspection team, a flow diagram of the relationship between the involved parties, and lessons learned as well as suggestions for future development and refinement.

In the planning of an OSI, all relevant information on the location of the potential violation needs to be integrated. *Pabian* (T2.2-01) uses the DPRK example to combine absolute and relative locations of past announced tests with topographic images and geological data in order to provide the best estimate of emplacement locations ([Figure 3.7](#)). This is an example of data fusion and is considered further in section 5.3. *Zasimov et al.* (T3.4-01) describe scientific and methodological support given to OSI by the All-Russia Research Institute of Automatics (VNIIA).
Precise location is essential at all stages of an OSI, from the definition of the OSI inspection area itself, via logistics planning and the design and deployment of accommodation and equipment, to location-tagging of every field measurement and the overlaying of geospatial data and externally acquired imagery. The use of a geographic information system (GIS) combined with a global navigation satellite system (GNSS) (of which the GPS is one of several systems) is the established relevant technology. Abushady and Prah (T3.3−P9) review the use of this technology during IFE14 and consider future developments for OSI use.

Planning and data acquisition during an OSI have the potential to be greatly influenced in the future by UAVs, and Palmer (T3.2−O6) considers how UAVs might be used (FIGURE 3.8). A review of options is given, and various potential applications are explored. Although a number of questions are posed, the author’s overall conclusion is that there is huge potential for applications to OSI.

Finally, the political framework of challenge-type OSIs, as exemplified by the CWC as well as the CTBT, is considered by Lampalzer (T2.1−P4) with reference to the author’s doctoral dissertation. Several research methods are used to shed light on the political origin of challenge inspections, the attitude of different Member States towards challenge-type inspections, the effect of international relations on the challenge-inspection regime, and policy implications for States Parties. A number of conclusions are drawn on the status of challenge-type inspections and Member States’ attitudes to them, and the author concludes that challenge-type inspections are widely accepted as integral tools of the verification toolbox.

### 3.3.2 Seismic

Deployment of the Seismic Aftershock Monitoring System (SAMS) during the IFE14 is reported by Gestermann et al. (T2.1−P18). They describe the successful recording of three unannounced small explosions detonated as part of the OSI scenario to test the SAMS capability, and they note that one of the explosions generated an acoustic signal that was detected on seismometers. However, they report that there was insufficient time to deploy all SAMS mini-arrays (FIGURE 3.9), and that much of the inspection area was inaccessible to vehicles and hence to SAMS deployment. The methods used to detect and locate the IFE14 events are described by Sick et al. (T3.4−O2). Gestermann et al. (T2.1−O2) also describe processing of IFE14 SAMS data and consider the network event detection threshold (see also SECTION 8.2.1).

Liebsch and Altmann (T3.2−P9) consider the problem of aircraft acoustic noise being coupled to the ground and recorded on seismometers. This is of importance in an OSI context because of helicopter and aircraft operations above a SAMS or other seismic network deployment. The authors anticipate that a better understanding of the seismoacoustic coupling mechanisms will allow some mitigation to be designed.
Active seismic surveys, in which a controlled source is used to generate seismic waves to investigate the subsurface, often use explosives but can use a hammer source. Jones et al. (T2.3-03) describe a large hammer source that could potentially be used as an active seismic source in OSIs.

Esterhazy et al. (T3.4-03) present numerical results for the scattering of acoustic plane waves around a subsurface cavity. The possibility of using resonance seismometry to detect an underground cavity is considered by Mellors et al. (T3.4-04). Finite difference modelling is used to compare synthetic signals predicted with and without a cavity. Stacked cross-correlations of continuously recorded noise are used in a process of seismic interferometry. Experimental results are shown using a small network of stations above a known cavity.

3.3.3 RADIONUCLIDE

The gathering of evidence for subsurface or airborne radionuclide anomalies during an OSI requires, first, a strategy for narrowing down the search areas and selecting sampling sites. It subsequently requires methodology and procedures for gathering samples, and then for processing and measuring of those samples in a mobile radionuclide particulate and noble gas laboratory located in the field.

Aldener et al. (T2.1-P15) report that about 25 subsoil samples plus several atmospheric gas samples were taken, processed and analysed during IFE14 using the SAUNA OSI noble gas equipment, with two minor equipment malfunctions that were rectified in the field. In IFE14 a transportable radionuclide laboratory was used for the analysis of samples, and Blanchard et al. (T2.1-P12) review its objectives and performance. The authors report that all 161 environmental samples and in situ spectra taken during the field missions were analysed and the results reported. They report that all sources prepared by the control team were detected, and false detections eliminated. They also report that lessons have been learned and will assist in future development.

Areas in which improvements could be made are also considered by Friese et al. (T2.1-P2). One is the desirability of standardizing software used for the analysis of spectra, using commercial packages with which inspectors are likely to be familiar from their home institutions. Another example is the use of robust, portable gamma detectors that are more suited to the rigours of field use, not only for use by field teams but also in the field-based laboratory.

Radionuclide measurements during an OSI can be performed either as in situ gamma spectroscopy or by laboratory analysis of environmental samples taken in the field. In a comparative study, Kreek et al. (T2.1-P5) suggest that, despite its lower sensitivity, improvements in equipment for in situ measurements will favour its increased use for guiding sampling decisions in the future, especially when considered alongside the logistical limitations and delays inherent in sample collection and laboratory measurements and analysis.

Köble et al. (T3.2-P12) describe a car-mounted gamma radiation and neutron detection system for potential use in OSI. They report an experiment to test the consistency of independent measurements made by a large number of different field teams with different experience levels, using the same equipment at the same field site. It is concluded that all users performed well after briefing, but those with more experience were at an advantage for weaker sources. Training with real radioactive sources is seen as essential to gain experience.
In an OSI, airborne radiometric surveys may offer strong advantages. Sinclair et al. (T3.1-P20) describe simulations and experimental results for aerial radiometric surveys conducted in the context of preparation for response to radiological accidents. An airborne system for performing gamma radiation surveys for an OSI is described by Buckle et al. (T2.1-P7), together with an account of operational experience during IFE14 using a helicopter as a data acquisition platform. Despite the obvious advantages of ease-of-access and speed of data acquisition, significant operational difficulties are reported, including flight planning, negotiation with the pilot, harsh topography and strong winds.

The Treaty requires that OSI activities are limited to the specific task of investigating whether a Treaty violation may have occurred. This raises the question of whether information on radioisotopes not relevant to CTBT verification should be made invisible to OSI inspectors (‘blinded’). A spectrometer designed for this purpose, reported by Coffrey et al. (T3.2-04) and described in Section 3.1.5, is relevant to the conduct of OSIs, especially with the knowledge that, if required, such equipment is in principle available.

Three other presentations reported in Section 3.1.5 are potentially relevant to strategies for OSI. These are the mobile noble gas system for OSI described by Wieslander and Khrustalev (T3.1-P8); methods for retrieving soil gas samples for radionuclide detection described by Wieslander and Khrustalev (T3.1-P20); and the use of gas chromatography for impurity removal described by Zhou and Zhou (T3.2-P8). The use of carbon-13 as a monitoring tool for subsurface gas sampling methodology as described by Rizzo et al. (T3.1-P1), reported in Section 6.1.5, is also potentially relevant.

With reference to IFE14, Miles and Haas (T2.1-P9) estimate the realistic technical capabilities of a 10-person radionuclide team operating a mobile laboratory and portable equipment investigating a nuclear anomaly that could be an underground nuclear explosion. The authors conclude that, despite the need to further develop OSI capabilities in the radionuclide field, the capability demonstrated during IFE14 in respect of surveying, sampling, measurement sensitivity (both in situ and in a field laboratory) and throughput would already be formidable to Treaty violation.

Given that the IFE14 scenario included a short, prompt release of radioactive xenon and radioactive iodine, which the inspected State Party had attempted to conceal by bulldozing and covering the soil with new material, there was a need to simulate this part of the scenario. Milbrath et al. (T2.1-P6) describe the steps taken to implement the scenario using buried cobalt-60 sources. The development and implementation of simulated radionuclide debris for IFE14 is described by Bowyer (T2.1-P8). This included simulations of remote detections at IMS noble gas stations. In the inspection area it included the use of silver-110m as a surrogate source for environmental samples, and cobalt-60 in buried sources as a surrogate for iodine-131.

The radionuclide element of any OSI exercise poses major challenges in the quest for a realistic scenario because it is very difficult to simulate a realistic scenario with substitute radionuclide sources and without a real underground test environment. Kreek et al. (T2.1-P9) review IFE14 in this respect, pointing out especially the inability to realistically produce and distribute short-lived fission products on the surface surrounding the supposed nuclear test. The authors describe a system to produce realistic radionuclide outputs in real time from real detectors. This is achieved by injecting pulses into detector circuitry, to mimic an actual radiation field without the need to use real radioactive sources.

Knowledge of subsurface gas transport mechanisms can be of importance in developing OSI radionuclide sampling strategies. For example, Guillen et al. (T1.3-P8) present numerical modelling and discussion of a variety of environments in regard to the subsurface migration of noble gases, and Guillen et al. (T1.3-P15) consider the effects of topography on subsurface gases. Guillen et al. (T1.3-P8) study the variation in argon-37 background in fractured porous media. More details on these contributions are given in Section 6.1.5. The use of tracer experiments to improve OSI radionuclide sampling strategy, described by Carrigan et al. (T2.2-P22), is covered in Section 3.1.5.

The observation and measurement of subsurface radioactive noble gas can provide strong evidence of an underground nuclear test, but subsurface measurement must not be contaminated by atmospheric radionuclide background. Rizzo et al. (T3.1-P3) propose to use carbon-13 content as an indicator of such mixing; this is discussed in Section 6.1.5.

Strategies for gamma-ray sampling of a ground plume resulting from small-scale venting of an underground test are considered by Milbrath et al. (T2.2-P9) while reporting on an experiment conducted at the NNSS, USA. Among

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9 CTBT, Article IV, paragraph 35.
their observations they note that they were able to achieve much higher throughput of soil sample analysis in their field laboratory than in IFE14.

3.3.4 REMOTE IMAGERY

Airborne multispectral including infrared (MSIR) imaging is relevant for OSI, and measurements were made during IFE14 for proof-of-concept. Palmer (T3.2-P11) considers the design requirements for a system tailored to OSI applications, taking into account technical requirements as well as Treaty restrictions. The author argues that the development of a research system to investigate how OSI-relevant data can best be acquired is an essential prerequisite for the designing of a Treaty-compliant system, in order to avoid developing equipment that is not fit for its purpose. Palmer (T2.1-P19) reports on the use of airborne MSIR during IFE14 and makes suggestions for future development. Before a proposed OSI inspection area has been defined, lower resolution satellite imagery may be examined in order to gather relevant evidence. Bedini (T3.2-P21) explores the use of Landsat imagery at known nuclear test sites for this purpose.

Rowlands et al. (T2.1-01) list the airborne methods permissible during an OSI and provide an account of the airborne deployments carried out during IFE14 (FIGURE 3.10). Many activities within an OSI require the acquisition of data on an airborne platform, and this requires planning and coordination in order to make maximum use of resources and to avoid conflicts between different requirements. These issues are explored by Rowlands and Malich (T3.2-P18), who list the aspects of coordination to be taken into account and suggest developments in this area for future OSI exercises. They also point out that flexibility can be enhanced, and space saved, by the use of certified external pods to house airborne sensors.

The trend towards large constellations of relatively inexpensive small earth observation satellites may bring major changes to the imagery available for OSI planning in the future. Patton (T3.2-01) describes the emergence of this trend and presents a case study of imagery for the DPRK test site. The author concludes that the greater flexibility offered by these systems will in the future provide advantages such as the ability to detect surface changes at greater temporal resolution, with benefits for CTBT verification in general.

3.3.5 DRILLING

Drilling for radioactive samples during an OSI could potentially provide irrefutable evidence on whether or not a nuclear explosion has taken place. At any time during an inspection, the inspection team may submit a
The proposal to conduct drilling to the CTBTO Executive Council through the Director-General; this is provided for under the Treaty. Hawkins (T1.4-O1) considers the concept of operations for the drilling and sampling process. The presentation includes consideration of site selection, regulations and permits, choice of equipment (FIGURE 3.11) and personnel for rapid deployment, mobilization issues and environmental protection. The relevance of the emplacement configuration (vertical or horizontal) and of information on geology, terrain, material properties, etc. for the design of the drilling plan is highlighted as is the importance of health and safety.

The challenges posed by OSI drilling to safely recover relevant radiological samples from an underground nuclear explosion (FIGURE 3.12) are considered further by Dekin (T1.4-O4). Pointing to the nature of a radiological target and the challenging work environment, the author points out that significant effort is required to plan and successfully execute drilling operations. Aspects considered include the drilling plan, down-hole guidance and detection systems, radiation safety systems, and sample handling. It is noted that such drilling was not performed as part of IFE14 but that enhanced understanding of the challenges to be addressed and implemented for drilling will prompt the discussion necessary to develop a prioritized approach to OSI drilling capability.

The problem of selecting a target for OSI drilling is considered by Hawkins (T1.4-O3), who points out that there are similarities with post-shot drilling activities that have been conducted after past underground nuclear tests. Noting that knowledge of the potential post-test location of relevant radionuclides should guide the selection of drilling and sampling targets for OSI, the author considers design aspects and sampling methods under the overall premise that there would need to be a reasonable chance of success before proceeding.

The findings of seismic modelling performed for a naturally fractured tight carbonate oilfield are presented by Osinowo (T1.4-O2). This approach may be helpful to identify drilling targets for OSI sampling as the derived information aids the design of horizontal well paths that intercept open fractures to guide placement of wells for production optimization and sweep efficiency.

MacLeod (T1.4-P1) presents an overview of the needs and challenges of any attempt to drill into the supposed site of an underground nuclear explosion to retrieve radionuclide samples. Noting that this is not a routine industrial practice, and that it will have additional health and safety issues compared with oilfield drilling, the author lists additional equipment that would need to be purchased or developed to supplement a conventional oilfield directional drill rig operation in the OSI context.
This Section focuses on the handling of verification data from the time it is recorded, through data transmission, to data archiving and data access. This includes issues relating to data format, data authentication, encryption (which is not envisaged for IMS data), data surety and security.

One indication of the importance of data transmission in the CTBT verification regime is its GCI, whose role in providing secure near-real-time data transmission from IMS stations or National Data Centres (NDCs) to the IDC in Vienna is enshrined in the Treaty. Since the Treaty was negotiated, fundamental changes in the technologies and costs of data transmission have been accompanied by conceptual changes in the options for mass data storage and retrieval, with a tendency towards having massive volumes of data available in the data processing environment. It may therefore seem surprising that there have been few contributions on these topics either in SnT2015 or previous conferences in the series.

The transmission and storage of OSI data is another aspect of this field. Although there has been a tendency towards the central processing of field data over the last decade, limitations on how and where OSI data are processed are imposed by the Treaty.11

As more extensive ocean-bottom sensor networks are installed, issues of data transfer, command and control, and power become an essential part of network design. Shinohara et al. (T3.1-01) describe the information and communications technology used in systems that have been deployed or are planned in offshore Japan, with 10 megabit per second ethernet and power over ethernet for seismometers and other sensors.

Gholami and Safepour (T4.1-P7) describe a system for transmitting triggered seismic data for a network of stations using mobile phone networks. The system utilizes the Standard for the Exchange of Earthquake Data (SEED) format miniSEED, and includes command and control functionality using Short Message Service (SMS) messages over the General Packet Radio Service (GPRS). The system allows communication with the recording system, for example for administrative purposes, with SMS messages. For OSI applications, the use of custom GIS solutions is described by Abushady and Prah (T3.3-P9). Enhancement of the system to include applications for mission planning, field team planning and viewing, as used during IFE14, is described.

4
Data Transmission, Storage and Format

4.1
DATA TRANSMISSION

11 E.g. CTBT Protocol, Part II, paragraph 102.
4.2 DATA FORMATS

The need to accommodate different formats for the transmission and storage of continuous and segmented waveform data has long been known. In particular, the widespread use of SEED and miniSEED formats in the academic and natural hazard community, rather than the Center for Seismic Studies (CSS) format CD1.1 and the IMS formats and protocols for segmented data, became a focus of attention in the context of the transmission of IMS data to tsunami warning centres 10 years ago. The extended NDC-in-a-box software made available to NDCs and described by Becker et al. (T3.3-02) supports these international standards for the exchange of seismological data through its use of the open source SeisComP software. These developments in support of format compatibility are also described by Becker et al. (T3.3-P11).

FOCUS

Data Transmission and Data Storage

The report on the 2009 CTBT International Scientific Studies Conference¹² presented historical costs of data transmission and data storage, highlighting the dramatic changes since the Treaty was opened for signature. Updated graphs are presented in FIGURE 4.1 using the same or similar data overlain with the same trend lines; data for the new time period are shown in blue. It can be seen that the cost of both data transmission and data storage have decreased by a factor of about 100 since the Treaty was negotiated. Such dramatic changes in simple technical parameters remind us that Treaty text that was itself based on technical factors could easily create constraints in the context of new technologies.

FIGURE 4.1

The Treaty provides that data acquired at IMS stations be ‘authentic’. Additionally, IDC products, command and control messages that may be used to modify the behaviour of IMS stations, requests from States Parties, and other important information exchanges are also to be authenticated; these additional provisions are outlined in the draft Operational Manuals of the CTBTO.

Data authentication is distinct from data ‘encryption’. Encrypted data is unintelligible to the eavesdropper in the absence of means to decrypt the data. In contrast, authenticated data can be read and copied by an eavesdropper leaving no trace. The purpose of authentication is rather to ensure the capability to discover whether the data have been changed, and whether the data originate from the correct IMS sensor or from another source.

The implementation of data authentication requires that a digital signature be appended to each data element at or near its source (e.g., in the digitizer attached to an IMS sensor), using a digital ‘private key’; such data is said to be ‘signed’. Thereafter, anyone with access to an associated ‘public key’ can check the signature and ‘verify’ (or ‘authenticate’) the data. If the data have been changed, or they were not signed using the correct private key, authentication will fail and the user is alerted to the fact that the data have been tampered with or replaced.

The issuance of digital keys for the purpose of signing and verifying data, together with associated requirements to ensure a chain of trust, are together referred to as a ‘public key infrastructure’ (PKI); CTBTO has implemented such an infrastructure for the purpose of data authentication.

Data encryption imposes a much higher load on digital processing resources than data authentication, meaning that more computer resources are required for encrypting/decrypting data than are required for signing and verifying under authentication. Since most IMS waveform data are continuous, such an additional processing load is itself continuous and must be satisfied in near-real-time; encryption would require a major increase in resources. Another advantage of data authentication that is not available with data encryption is that a user can choose not to verify the data signatures, thereby retaining full access without any additional demands on processing.

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13 CTBT Article IV, paragraph 19(b).
5

Data Processing and Synthesis

This Section is concerned with the processing of acquired data and measurements in order to retrieve the maximum amount of information and to present that information in a form suitable for interpretation. Such processing includes methods specific to one type of data, whether or not it is used in the CTBTO verification regime, as well as methods used to combine data from different ‘technologies’ (e.g. seismic and infrasound). Such combining of different types of data, at either the processing or interpretation stage, is called ‘data fusion’ in the CTBT verification community. Also included is the processing of the many types of data that may be acquired during an OSI.

‘Event screening’, which is defined in the Treaty as the use of approved methods to identify events of natural or non-nuclear man-made (anthropogenic) origin, is part of interpretation, and so is considered in SECTION 7. This applies both to event screening used for events located using seismic, hydroacoustic and infrasound data and to the methods used to categorize radionuclide spectra according to the presence or absence of CTBT-relevant radionuclides.

Most data processing is computer-based and performed automatically. A crucial component of the preparation of seismoacoustic event lists and the processing of radionuclide spectra at the CTBTO is interactive analysis by expert analysts. This is conventionally referred to as ‘data analysis’ and is included in this Section.

The processing of verification data, as well as its interpretation, relies in many ways on knowledge of the structure of the earth, its oceans and its atmosphere. For example, the location of events within the earth relies on the seismic wave-speed field; the location of events in the atmosphere relies on the acoustic wave-speed field in the atmosphere; and mapping the source of an atmospheric radionuclide observation requires knowledge of atmospheric transport. These requirements apply equally at the global scale, applicable to IMS data, and at the local scale for OSI data. Studies that investigate properties of the earth are considered in SECTION 6.

CTBT Protocol, Part I, paragraph 18(b).
5.1 CREATING SEISMOACOUSTIC EVENT LISTS

5.1.1 SCOPE

Automatic processing of IMS waveform data at the IDC comprises a large number of asynchronous processes with multiple transactions. Formerly, this was controlled using the Transactions for Unix, Extended for Distributed Operations (Tuxedo) commercial software product. This function, referred to as the IDC Distributed Access Control System (IDC-DACS) has now been ported to open source software as described by Ertl et al. ([T3.3−P14]).

The extended NDC-in-a-box software is offered by the CTBTO to NDCs as an option to allow processing of IMS data from both waveform and radionuclide stations; it also provides functionality to apply ATM to constrain the source of radionuclide observations, and to fuse waveform and radionuclide data into the event location process. The current version also includes data acquisition support for widely used waveform data formats outside the CTBTO. The extended NDC-in-a-box is described by Becker et al. ([T3.3−O2]) and Becker et al. ([T3.3−P11]).

Sections 5.1.2-5.1.4 cover contributions on the processing of seismic, hydroacoustic and infrasound data, respectively. Methods that are applicable to seismic data plus hydroacoustic or infrasound data or both are described in Section 5.1.2 on seismic data.

5.1.2 EVENTS FROM SEISMIC DATA

The conventional steps in seismoacoustic event building comprise signal detection, signal feature measurement, association of signals at multiple stations, then location. This conventional sequence does not apply to some novel methods that may use waveform cross-correlation applied to massive waveform data sets in order to define event hypotheses directly. This challenge to the conventional sequence of steps implies a need for major changes in the way that data are organized and stored in the future and in the way that data processing is managed.

The IMS primary seismic network consists mostly of seismic arrays. The directional and noise-reducing properties of arrays offer special advantages in the field of signal detection. One conventional signal detection method, which is used in the IDC, triggers on a predefined ratio of short-term average to long-term average (STA/LTA) signal level within a certain frequency range. An alternative approach is to cross-correlate the waveform with waveform ‘templates’ that correspond either to past signals or to synthetic signals representing a target signal type. There has been some success over many years in using past signals when looking for new signals from high seismicity regions, but the CTBT mission requires detection of explosion signals that may occur anywhere. One question is whether signal templates built by synthetic signals computed using inferred seismic wave-speed fields would be useful for detecting signals from source regions with no previous events. Even if they are found to be useful for detecting earthquake signals, there may still be a question as to whether they would detect small explosion signals. Harris ([T3.3−P3]) points out that for short-period signals recorded from smaller events, the required high spatial resolution of the wave-speed model is not currently available. Instead, the author explores the possibility of characterizing the high spatial resolution of the wave-speed model via a stochastic extension of an earth model. He also experiments with subspace detectors, a class of inverse modelling. Using synthetic modelling involving multiple realizations of the stochastic part of the model he shows that subspace detectors may provide better resolution than cross-correlation methods at low signal-to-noise ratios.

Atmospheric transport is an example of a property that varies widely, with timescales that range from hours to seasons. Although studies of atmospheric dynamics are included in Section 6 as an earth characterization property, the use of atmospheric transport modelling (ATM) to investigate a particular source of radionuclide observations is classed as interpretation and is included in Section 7.
Event Definition Criteria

In the IMS waveform technologies—seismic, hydroacoustic and infrasound—data processing aims to detect and locate events that occur in the earth, the ocean or the atmosphere. The quality, number and geographic distribution of signals used in the detection and location of an event have a crucial impact on the uncertainty in the event’s location. Uncertainties in the speed of the seismic or acoustic waves as they propagate also have an impact.

In order to eliminate events that are poorly recorded, or which have large uncertainties in their locations, or whose sets of associated signals are improbable, it is often desirable to specify criteria to be satisfied for including an event in the final list. These criteria might be based on location uncertainties directly, or on the number, quality and distribution of signals used. They might also be based on the likelihood of a set of signals that have been associated to a supposed event, using a probabilistic model that might be static or dynamic.

In IDC products, explicit criteria for including an event in the final list are referred to as ‘event definition criteria’. IDC event definition criteria are not based on the quality of the location directly. Rather, they are based on the number of stations that contribute to the location, and on the number and type of signal attributes (signal onset time, back-azimuth and slowness) that contribute for each station. A scoring system is used to sum the various attributes used at each station, with different attributes assigned different numerical ‘weights’; if the required sum of numerical weights is reached, the event is included in the event list.

Such explicit event definition criteria are only part of the picture, because separate criteria have to be met before each signal can be used in a location estimate. Some of these criteria relate explicitly or implicitly to the signal quality, as defined by the measurement error on each observation. Other criteria relate to consistency: if one observation is inconsistent with the others (e.g. because its measured onset time has too great a deviation from the onset time computed for that signal from the event hypothesis), then that observation has to be excluded (and the location recomputed). Such an observation is commonly referred to as an ‘outlier’.

In the processing of waveform data by the IDC, the event definition criteria are in general more relaxed for the earlier Standard Event Lists (SELs) that are produced entirely automatically, and become more restrictive for the Reviewed Event Bulletin (REB). The explicit event definition criteria for the REB are given below. It should be noted that IMS auxiliary seismic stations do not contribute to the event definition criteria, so that no event can be included using auxiliary seismic data alone.

It follows that IDC event definition criteria are not based on location uncertainty alone; indeed this uncertainty may be very high in some qualifying events. Accordingly, a potential topic for consideration in the future is the possible review of these criteria in order to improve the overall quality of the REB by selecting only those events which have a smaller location uncertainty.

Current REB Event Definition Criteria

There are two criteria, both of which must be met:
1. At least one phase from at least three primary seismic, hydroacoustic or infrasound stations must contribute to the location (auxiliary seismic stations do not count).
2. The total weight of the contributing attributes of the contributing phases, as defined in the table below, must be a minimum of 4.6.

REB Event Definition Criteria

Figures are the weights assigned to the attributes of signals (‘phases’) when they contribute to the location.

<table>
<thead>
<tr>
<th>Station Type</th>
<th>Phase Type</th>
<th>Phase Attribute</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Array</td>
<td>Time  Azimuth  Slowness</td>
</tr>
<tr>
<td>Seismic</td>
<td>P type primary 1</td>
<td>1.0  0.4  0.4</td>
</tr>
<tr>
<td></td>
<td>P type secondary 1</td>
<td>0.4  0  0</td>
</tr>
<tr>
<td></td>
<td>S type regional 1</td>
<td>0.7  0.4  0.4</td>
</tr>
<tr>
<td></td>
<td>S type teleseismic 1</td>
<td>0.7  0  0</td>
</tr>
<tr>
<td>3-Component</td>
<td>P type primary 1</td>
<td>1.0  0.2  0.2</td>
</tr>
<tr>
<td></td>
<td>P type secondary 1</td>
<td>0.4  0  0</td>
</tr>
<tr>
<td></td>
<td>S type regional 1</td>
<td>0.7  0  0</td>
</tr>
<tr>
<td></td>
<td>S type teleseismic 1</td>
<td>0.7  0  0</td>
</tr>
<tr>
<td>Hydroacoustic</td>
<td>Hydroacoustic</td>
<td>1.54  0  0</td>
</tr>
<tr>
<td>Infrasound</td>
<td>Infrasound I</td>
<td>0.8  1.0  0</td>
</tr>
</tbody>
</table>

Any attribute of any phase which does not contribute to the location: 0
Any attribute of any phase observed at an auxiliary seismic station: 0

*P type primary: P, PKP, Pn, Pg, PKPn, PKPnS, PKKP
*S type regional: S, Sn, Rp
*S type teleseismic: S, ScP, ScPK, ScPKP

Note: The term ‘primary’ as applied to a station type and to a phase type should not be confused.

Several other criteria are applied indirectly, by disallowing the contribution of certain otherwise allowable phases or phase attributes in certain circumstances. For example:
- Azimuth and slowness attributes must be non-defining if phases from more than six stations contribute to the location.
- An attribute cannot contribute if its residual exceeds a limit which depends on phase (e.g. ±2.0 s for P-time).
The use of synthetic waveform templates in correlation detectors in regions with no historical seismicity is also taken up by Kitov et al. (T3.3-P34). They define ‘master events’ as template waveforms specific to a source location for a number of IMS primary seismic stations and search for detections using an STA/LTA detector on the time-sequence of cross-correlation coefficients. They test the process against the Reviewed Event Bulletin (REB) and conclude that the method doubles the number of REB events and reduces the detection threshold by 0.4 magnitude units.

Gibbons et al. (T3.3-06) consider the issues involved in covering a source region using correlation detectors; the authors focus on the availability of data, accuracy of wave-speed models, signal-to-noise ratio and waveform dissimilarity. They conclude that correlation detectors can be used to scan source regions of the order of several kilometres wide using global and regional seismic networks, but that many factors can influence performance.

A question arises as to whether correlation detectors, or stochastic ‘subspace’ detectors as referred to by Harris (T3.3-P3) above, could be used to improve bulletin completeness by applying the detectors at individual stations at regional distances. Gok et al. (T3.3-P12) investigate this in the Middle East region using the broadband station Mutribah (MIB) in Kuwait, the station Minazif (UOSS) in the United Arab Emirates, and a temporary nine-element seismic array (QWAR) in Saudi Arabia. Such detectors essentially use pattern recognition to match waveforms with those from historical events at the same station and, as the authors point out, this implies not only a similar location and depth, but also similar source mechanisms and other source properties. A further question then arises as to whether such detectors would be as successful in the CTBTO context, where the target is explosive sources whose source mechanisms are different from those of earthquakes.

A further contribution on the use of a massive archive of past waveforms to improve current event building by cross-correlation is presented by Junek et al. (T3.3-P38). The motivation is to improve automatic processing so that analysts spend less time correcting errors in automatic processing, giving them more time to examine anomalous events. The same motivation is expressed by Slinkard (T3.3-P38), with particular focus on earthquake aftershock sequences, which can cause analyst workload to increase substantially. The author investigates the use of cross-correlation methods at stations at regional distances from aftershock sequences and applies this to aftershocks of the two large earthquakes off Chile on 1 and 3 April 2014. It is pointed out that even when additional detections lead to events being built that do not meet the REB event definition criteria, they can still improve the performance of signal association for events that do.

Ait Laasri et al. (T3.3-04) compare a new detector based on both amplitude and frequency with several other detection algorithms, with emphasis on accurate onset time determination. Their method uses the amplitude and time of each waveform maximum and minimum as input. The algorithm is tested on real data, and graphs are presented showing its performance as a function of signal-to-noise ratio, with comparative results shown against five other detector types including ones based on STA/LTA, skewness and kurtosis.

Selby (T3.3-P18) describes a generalized F-detector, which is proposed as a replacement detector for use in the IDC; he then draws some conclusions on the behaviour of the current IDC detector. He examines the process that defines the vector slowness of an IDC signal detection at a seismic array, and then investigates the station-dependent statistical relationship between all IDC signal detections and those IDC signal detections that are associated to an event in the REB. The author concludes that the vector slowness of the detection beam is not a reliable predictor of the refined beam that is computed subsequently using frequency–wavenumber (f-k) processing. He also observes that slowness residuals for associated detections are generally smaller than the differences between the detection-beam slowness and the refined f-k slowness. It is further shown that detections associated to REB events generally have a higher signal-to-noise ratio than the full detection population.

A different approach to improving the signal detection capability of seismic arrays is adopted by Gibbons et al. (T3.3-P27), who demonstrate improvement in detection and parameter estimation for regional S phases using three-component array processing applied to the fully three-component IMS primary seismic array PS28 (ARCES) in Norway. The benefits of a fully three-component array for signal detection are also investigated by de Kool (T3.3-P26) using data recorded at the Pilbara seismic array (PSAR) in the north of Western Australia with 20 km aperture. The author uses a detector that maximizes the similarity of the three-component surface motion vectors across the array as a function of vector slowness. It is found that...
that performance is limited for S waves because they are less coherent than P waves, but that correlation of the components can be useful in discriminating P waves from other wave types. A 0.5 km aperture three-component array is also used by Kitov et al. (T3.3-P30) to investigate mining explosions at regional distances. It is found that many S waves are missed if horizontal component sensors are not available. Correlation coefficients between different components are examined, and various options are compared for detection purposes.

Gordiyenko et al. (T3.3-P15) describe improvements to the NORSAR array processing system at the NDC of Kazakhstan, in particular to address processing of data from the IMS auxiliary station at Kurchatov, AS058 (KURK). Bui Quang et al. (T3.3-O3) consider the application of progressive multichannel correlation (PMCC), which is implemented for infrasound detection, to the detection of seismic signals and their classification into regional, teleseismic and noise detections.

Rozhkov and Kitov (T3.3-P28) consider the problem of separating closely spaced signals when trying to resolve multiple events in the context of a CTBT special event under expert technical analysis. The method of ‘blind source separation’ is described and tested using mixtures of real signals from chemical and nuclear explosions.

Once signal detections have been made and correctly associated, the event must be located using the measured arrival times, and perhaps azimuths and slownesses, together with information on the wave-speed model and station locations. This is a non-linear inverse problem that in principle uses well-established methods. But it is made more complicated when three-dimensional wave-speed models are used, especially in regard to the well-founded treatment of confidence limits on location parameters. Bondar (T3.3-P39) describes recent developments in the location algorithm used by the International Seismological Centre (ISC) for its global Bulletin. These developments include functionality to incorporate various three-dimensional wave-speed models. Comparisons of locations and their errors when using specific models including the regional seismic travel time (RSTT) model are presented.

Determination of the depth of a seismic source presents special difficulties because an accurate determination normally requires observations from above as well as below the source, and because computed depth is sensitive to the seismic wave-speed structure above the source, which may not be well known. Direct P wave observations from above require stations very close to the source, normally not available in a sparse global network. Surface reflected phases such as pP offer a means to observe the source from above, but their validity depends crucially on positive identification of the phase on the seismogram; this is often problematic. For nuclear explosion monitoring there is the added problem that if the calculated depth is greater than a few kilometres and has a confidence that excludes depths less than, say, 10 km, then this can be used as evidence that the source cannot be anthropogenic; this places added importance on the confidence of a depth phase identification.

Since the 1970s the strength of evidence in support of surface reflection identifications has utilized the mutual compatibility of arrival times and relative arrival times of direct P and surface reflections pP and sP. Letort (T2.3-O1) proposes to identify these reflections using a cepstral method by looking for surface reflections as echoes of the direct P wave. The author applies this to medium magnitude events (4.5<M<5.5) recorded at seismic arrays at teleseismic distances. The aim is to apply the method automatically, without the need for analysts to pick surface reflections manually. Apoloner and Bokelmann (T3.3-P22) consider surface reflections at regional distances. They use three-component synthetic seismograms to investigate the value of these phases in the determination of source depth and other source parameters.

Kitov et al. (T3.3-O5) investigate the improvement in the completeness of a catalogue of mining explosions within the Russian platform by combining observations from the Mikhnevo seismic array and IMS seismic array stations. They find that waveform cross-correlation detectors improve detection and association for repeat events and effectively reject invalid detections. Their combined use of a standard detector and a cross-correlation detector is seen as providing a prototype procedure for the recovery of aftershock sequences in IDC processing. Dupont (T3.3-P8) describes a project to apply cross-correlation to the entire record of IDC detections and events in an attempt to improve the quality of event bulletins.

Bayesian methods such as NET-VISA require prior information (‘the prior’) in order to establish valid statistics for any event hypothesis. This poses a special difficulty for CTBT monitoring because the event list is dominated by earthquakes with a global distribution characteristic of plate tectonics, while nuclear explosions
can occur anywhere. Thus, the prior has in the past been represented by the sum of a component driven by historical seismicity, and a uniform component to represent the possibility of a nuclear explosion anywhere. Arora et al. (T3.3-09) describe the use of ISC data to build a seismicity prior for NET-VISA. As depth is usually determined less accurately than location for shallow events, the depth is fixed a priori for many events because the observed data are unable to resolve it. The authors consider the treatment of depth in the prior, and consider the distribution of known mining explosions in the ISC Bulletin.

Visualization of the information on which NET-VISA is based, as well as information about the program structure, is provided through a web interface described by Kuzma and Arora (T3.3-P21). This acts as an information tool for users, and as a quality control mechanism especially when the system is retrained on new data. Visual representations of the priors for each IMS station and seismic phase are included.

NET-VISA and some other systems apply the Bayesian approach to a set of pre-defined detections in order to construct event hypotheses with calculated probabilities. The next logical development in this approach is to begin with the waveforms and attempt a construction of event hypotheses directly, given the history of all previous waveforms and associated event lists. Moore et al. (T3.3-07) describe Signal Vertically Integrated Seismic Analysis (SIG-VISA) as an implementation of this idea and present some initial results. For a single seismic phase (seismic signal) they describe an envelope template that depends on event location, event depth, magnitude and phase name, modulated by a fixed element related to the Green’s function (earth structure) that depends on event location, depth and phase name, plus a representation of seismic noise. The observed envelope is the sum of all arriving phases plus background noise. The authors describe a global beamforming with waveform correlation. Double differencing is used to optimize relative event locations. The method is held to remove the concept of a detection threshold because additional events can contribute energy to the solution even if the waveform would not be discernible. As an example, the authors report that the 2009 announced nuclear test in the DPRK was detected at 42 IMS stations, whereas SIG-VISA finds evidence of energy at 53 stations.

Improvements in automatic processing such as those presented in the foregoing presentations do not necessarily result in a reduced burden for interactive analysis. Improved automatic analysis of aftershock sequences, which is seen above as one priority of these efforts, is designed to reduce the maximum demand on the fixed analyst resource. However, any improvement that results in more events being built, even if they are real events, results in an increase in analyst workload because all events built automatically have to be reviewed (figure 5.1); this will continue until there are major improvements in the reliability of automatic processing. Pearce (T3.3-P36) explores this paradox, pointing out that
if the aim is to reduce the analyst resource required, then improvement priorities need to be carefully selected; the author reasons that a general improvement in the quality of automatic processing will increase analyst workload by creating more events that require review. To mitigate this, the author specifically highlights the improvement of detectors, the accurate determination of onset times, station-specific tuning of processing parameters and improvement in association algorithms as high-priority topics.

The ultimate aim has always been to approach an ideal in which seismic data processing is fully automatic, so that accurate, reliable and complete event lists can be compiled without the need for analyst intervention.

The motivation for this is partly financial, since staff are usually the most expensive resource, but speed can also be a motivation, especially for earthquake warning applications. Jin et al. (T3.3-08) consider the status of efforts towards that elusive goal. They describe the conventional steps from signal detection to event list, and they summarize the level of interactive review necessary to produce a REB. The authors describe an approach that is intended to incorporate the skills and actions of analysts into the automatic process. This uses ‘integral’ and ‘local’ features of seismograms. Detections are immediately classified as beginning (initial) detection or following (coda) detection. Events are built first using regional networks (Figure 5.2), then the data are extended to global networks. Some early results are presented using the method, which is intended to exploit the massive amount of open-access seismic data that is becoming openly available.

Ballard et al. (T3.3-P16) also present a project, the ‘iterative processing framework’, aimed at emulating the actions of the analyst to improve automatic processing. They incorporate a waveform correlation detector and an association algorithm based on a geographic grid that assigns conditional probabilities that each signal arises from an event at each grid node (Figure 5.3).

Seismic signal detection and event building for CTBTO verification is not limited to the global problem faced by the IMS network. Passive seismic monitoring during an OSI seeks to record collapses or aftershocks that may occur after an underground nuclear explosion, and the SAMS network has been developed for that purpose. Sick et al. (T3.4-O2) use spectral pattern recognition and a combination of array and network location methods to locate the smallest events that may be detected. Using IFE14 data as an example, they find that STA/LTA detectors create too many false detections, but they find that spectral patterns from previous deployments can be used to reduce these.

Also in the context of OSI, Esterhazy et al. (T3.4-O3) present a study in which synthetic seismograms are used to predict the detectability of an underground cavity by the passage of seismic waves. The presentation focuses on the acoustic case, with extension to the full elastic case in three dimensions planned. The intention is to utilize these detectability computations in the design of OSI data acquisition and processing.

Observations of the 2009 and 2013 announced nuclear tests in the DPRK at the Mikhnevo 1-km aperture seismic array in the Russian Federation are used by Kitov et al. (T2.2-P7) to demonstrate that cross-correlation
templates can be used to retrieve small signals. Using this method they retrieve a signal for the smaller 2006 announced nuclear test at the Mikhnevo array.

A suggestion in publications unrelated to SnT2015 that radioactive xenon and its daughter isotopes observed at IMS stations in Japan and the Russian Federation in May 2010 could have originated from a small nuclear test in the DPRK on or around 10 May provided an opportunity for seismologists to apply advanced processing methods to seismic waveforms recorded close to the DPRK in an attempt to find any potentially relevant seismic events. Richards et al. (T2.2−P9) report claims of other authors, and they apply cross-correlation methods to Lg waveforms of an event on 12 May recorded on the Dongbei network located in China near the border of the DPRK (FIGURE 5.4) to confirm the existence of one candidate event suggested by other authors. They conclude that there is no definitive evidence that this event, with an estimated magnitude of 1.4, is located at the known DPRK test site. Koch et al. (T2.2−P14) also discuss this event and describe the search for corroborating data at additional stations in China close to its border with the DPRK.

5.1.3 EVENTS FROM HYDROACOUSTIC DATA

Most signals recorded at IMS hydroacoustic stations that appear in IDC standard products are T phases recorded from earthquakes. A T phase travels along part of its path as a seismic phase and along part as an acoustic wave in the ocean. In-water acoustic sources resulting in an...
A comparative study of automatic infrasound detectors is presented by Park et al. (T1.1-P1). They use receiver operating characteristic (ROC) curves to estimate the trade-off between valid detection and false detection probabilities for PMCC and an adaptive F-detector, using data from the infrasound array CHNAR, Republic of Korea. They also examine the detection of infrasound signals at seismic stations of the USAArray transportable array and research infrasound arrays in Utah and Nevada, USA. An alternative and innovative infrasound detector, in which signals of interest are assumed to be random processes buried in white noise, is proposed by Nouvellet et al. (T1.1-P13). This method uses a Kalman filter and eliminates the concept of performing tests on successive windows of data, as well as allowing multiple simultaneous signals to be detected.

In IDC processing, the association of signals to events is performed jointly for seismic, hydroacoustic and infrasound detections. Mialle et al. (T1.3-P13) describe an infrasound-only pipeline in which the association of infrasound detections is performed separately. The main aim is to reduce the number of invalid associated detections that have to be removed by analysts. In pursuit of this, the authors point out the importance of using atmospheric wind field information to validate the association of infrasound detections to events. They also discuss the introduction of the NET-VISA approach to detection and association of infrasound signals.

The problem of false event solutions having an adverse impact on signal association is described by Dubrovin et al. (T1.1-P14) for events recorded in Kazakhstan. They point out that since two infrasound stations are the minimum required to locate an event, there is an expected improvement in the ability to exclude false event solutions when data from the IMS station IS31 (I31KZ) and the non-IMS Kurchatov infrasound array are processed together.

Infrasound detections from noise sources are often observed repeatedly, and this is used to reduce the number of invalid events. Figueres et al. (T1.1-P13) examine detections from the IDC SEL3 (used as the starting point for interactive analysis) for South American stations, and find a number of such repeated detections. Their absence from the IDC infrasound reference event database (IRED) is used to confirm that these are not sources of interest.

One difficulty in forming an infrasound event list is the measurement of source size. Seismic magnitude, although an empirical measure, has been used effectively for many years to provide an estimate of seismic source size; seismic magnitude scales normally anticipate that measurements be made at each recording station, with corrections for the type of instrument and epicentral distance, and these are then averaged to arrive at a network magnitude with an associated error. One difficulty with defining a magnitude scale for infrasound is that the propagation path is highly dynamic. Any distance correction needs to take into account multiple and changing propagation paths, as the atmospheric winds help to shape the infrasound propagation ducts and hence have a great impact on the detection of signals and their amplitudes. Rybin and Rogovoy (T1.1-P19) describe a method for jointly processing wind speed and pressure pulsation data at IMS infrasound stations.

Brown et al. (T1.1-P12) report on a project to introduce a magnitude for infrasound events. Three magnitude estimates are described, and the presentation compares results obtained using each. Two of the methods use an amplitude relation with epicentral distance to estimate a station magnitude; one of these includes additional corrections for geometrical spreading, absorption (due to wavefield energy loss to the medium by analogy with anelastic attenuation in seismology) and stratospheric ducting. The third approach is based on the period of the dominant acoustic signal at maximum amplitude. Although the authors find that the first of these three approaches yields the most consistent results, they note that this does not take into account stratospheric winds, and they conclude that more work is needed to incorporate atmospheric wind field information into individual station magnitude measurements.

With the several years of infrasound processing data accumulated since infrasound processing was introduced in to IDC Provisional Operations in 2010, Ceranna and Le Pichon (T1.1-01) present the results of an exercise to reprocess the global infrasound data. They conclude that this has permitted more accurate estimates of signal properties including frequency, azimuth and speed; identification of new types of infrasound source; better discrimination between interfering signals; better assessment of the quality of stations including detection capability and background noise; and the reduction of artifacts in the processed data.
5.1.5 FUSING OF WAVEFORM OBSERVATIONS

The large number of events in the REB that include both seismic and infrasound signals is emphasized by Bittner et al. (T2.3-P4), who examine the statistics since infrasound processing was reintroduced into IDC Provisional Operations in February 2010. A wide range of such events is reported, including volcanic events, meteorites, mining blasts and earthquakes. It is concluded that the fusion of seismic and infrasound observations may hold useful information on the nature of specific events, and that such events have diverse origins. For example, the authors find that larger earthquakes may give rise to infrasound detections even when the earthquake is deep, with a significant number deeper than 100 km.

The NET-VISA method of associating detections into events using Bayesian inference is described via several presentations in Section 5.1.2. The incorporation of infrasound data into this method, which offers direct fusing of seismic and infrasound data in the building of events, is described by Arora and Mialle (T1.1-P9).

Specific examples of events recorded at both seismic and infrasound stations in Romania, including quarry blasts, a meteorite, and an M 5.7 earthquake in Vrancea, are described by Ghica et al. (T2.3-P17). These last two events are also studied by Karyagin and Alexander (T2.3-P18) using infrasound data from the Ukraine national station network.

5.2 RADIONUCLIDE DATA PROCESSING AND ANALYSIS

The traditional methodologies for radionuclide particulate data analysis are not a major focus of SnT2015 presentations; the many contributions on calibration and quality assurance implementations for both radionuclide particulate and noble gas systems are considered in Section 3.1.5 and Section 8.3. However, there is a focus on the location of radionuclide sources using ATM results. Determining the location of a source of radionuclide observations relies on combining reliable radionuclide measurements with atmospheric transport information and a deeper understanding of the subsoil migration of especially noble gases, which is covered in Section 6.1.5. The ATM-related methods range from using highly selective radionuclide observations with a single validated transport model to using multiple ATM simulations combined with less selective radionuclide data. Ringbom and Axellson (T1.3-P1) compare four approaches, including a Bayesian approach in which a prior probability estimate of each hypothesis is compared with the likelihood of the data assuming that hypothesis. The authors report similar results when the methods are applied to the third announced nuclear test by the DPRK in 2013.

The use of ATM to constrain the source location and time of a release observed at one or more recording stations is not limited to CTBT verification applications, nor even to radionuclide observations; the methodology can be applied to any source of environmental monitoring data where observations of a pollutant or gas in the atmosphere need to be attributed to a source. Branda and Adam (T1.1-P12) compare different methods, including the handling of sparse data in the inversion process. They use as an example the European Tracer Experiment (ETEX), performed in 1994 in France, where the release parameters were well known and the recording network was dense, comprising 168 stations. Such experiments provide a valuable way to verify inverse modelling methods for estimating source terms, since the true source term was well known.

The categorization of processed radionuclide spectra is intended to distinguish those that may be Treaty-relevant from those that are not. This can be thought of as analogous to event screening applied to the waveform technologies, but the factors contributing to categorization are different in principle. For example, an observation may be assigned a higher category when it is anomalous by comparison with the past history of observations at that station (that are confidently known to be from non-CTBT-relevant sources). This poses special challenges for the calculation and assignment of categorization levels. Schoepner (T2.4-P11) takes a statistical approach to this problem to propose a categorization scheme for radioactive xenon, and proposes to include the potential exclusion of known sources through ATM calculations as input to the categorization process.

The process of constraining the location of a release by applying ATM to station observations is complex and highly non-linear. It may be affected by such factors as multipathing, multiple observations of the same source at the same or different stations, and the substantial three-dimensional nature of air movements, which often involves air rising to a high altitude and descending remotely. Generoso et al. (T1.3-P16) address some of these issues and note the importance of negative evidence (e.g. non-detecting stations) when constraining possible source locations. A statistical approach using Bayesian methods for the constraining of source location is used by Hofman et al. (T3.3-P12).
As with all non-linear inverse problems, estimation of the uncertainty is as important as estimating the solution. Robins (T1.3−O1) use data from the Fukushima Daiichi nuclear power plant accident of 11 March 2011 to investigate uncertainty and identify a modelling error that exceeds the expected confidence.

5.3 FUSING WAVEFORM WITH RADIONUCLIDE AND OTHER OBSERVATIONS

The three CTBTO waveform technologies—seismic, hydroacoustic and infrasound—have as their chief goal the location of an event of interest, whether underground, in the oceans or in the atmosphere. In all media an event may be recorded at more than one of these types of station, and fusion of such data is covered in SECTION 5.1.5. Relating an event to radionuclide or any other remote observations is also fusion, and tools to perform such fusion have been developed and tested. Krysta and Carter (T3.3−P23) discuss this topic and present ideas for an IDC ‘Fused Event Bulletin’ that would list events where a link is thought to be established between a waveform event and radionuclide observations. Such a bulletin was conceived in the 1990s but has not yet been implemented. The authors focus on the problem of attributing radionuclide observations to a specific event, which of course depends on adequate ATM, and the problem of quantifying the confidence of the association immediately arises. The authors point out that, paradoxically, the mixing resulting from the complexity of atmospheric air movement is beneficial in that, if instead the air exhibited streamlined flow, radionuclides from a specific source could easily miss all the radionuclide stations. However, such mixing poses difficulties for unequivocal attribution of transient radionuclide observations to a specific origin. One suggestion the authors make is to develop methods to fuse detected signals in the waveform and radionuclide technologies, as distinct from fusing events across these technologies.

Such a data fusion study using real observations is presented by Seibert et al. (T2.2−P12), who test a list of seismic events against anomalous radionuclide observations made at RN38 (JPX38), the IMS station at Takasaki, Japan, in April 2013. One question is whether these observations could be related to the DPRK announced nuclear test on 12 February 2013. The authors identify a list of possible sources, including known nuclear power plants, and assign a cost function to each event or source, with high cost-function members eliminated and the remaining prioritized by the value of their cost function. The authors conclude that such an association is valid, but it forms one of a number of associations that would be compatible with the data.

Data fusion is also important in planning an OSI, where a seismic event may need to be considered with radionuclide observations together with results from the analysis of satellite and aerial images of different types, including synthetic aperture radar. This type of fusion is considered by Pabian (T2.2−O1).
This Section includes all contributions on the study of properties of the earth, including those of its oceans and atmosphere. Such studies are central in supporting the processing and interpretation of verification data. For example, the processing and interpretation of seismic and acoustic signals rely crucially on an understanding of the media through which those signals have passed, in particular the variation of wave speed along the signal ray paths. Seismoacoustic events such as earthquakes and explosions cannot be located, or their signals interpreted, without that information. Likewise, natural sources of radioactivity affect the interpretation of radionuclide observations. All atmospheric radionuclide observations depend on knowledge of atmospheric transport in order to narrow down the geographic origin of such signals.

Other earth properties that support the interpretation of verification-related data include subsurface permeability and near-surface barometric pressure variations, both of which can influence the transport of radioactive material from an underground nuclear explosion to the earth’s surface.

Although many studies characterizing earth properties may be aimed at supporting CTBT verification methods, many are aimed at supporting other civil, scientific and industrial uses of data from the IMS. For example, seismic hazard estimation depends on studies of earthquake seismicity and tectonic strain rates; volcanic ash hazard estimation relies on the monitoring of volcanoes; and tsunami warning depends on knowledge of earthquake seismicity, earthquake mechanisms and the effect of seismogenic fault displacement on the transport of water in the oceans. Such topics are therefore included in this Section. Where seismoacoustic sources are investigated in the context of discriminating different types of source in order to identify explosions, results appear in section 7. Studies that cover both data interpretation and the determination of earth properties, such as earthquake moment tensors used to infer tectonic stress, are cited in both this Section and section 7.

Where civil and scientific uses of IMS data do not depend directly on earth characterization, they appear in other Sections. For example, the use of infrasound data to identify meteorites and other non-CTBT-relevant sources is considered data interpretation and hence is included in section 7.
6.1 SOLID EARTH

6.1.1 SEISMIC WAVE SPEED

The earth’s seismic wave-speed field for $P$ waves is one of the most important properties of the earth for CTBT verification because detailed knowledge of it is an essential prerequisite for the accurate location of seismic events, which includes any underground nuclear explosion. Although the seismic wave speed deep within the earth depends, to a very close approximation, only on depth, there are significant lateral variations nearer the surface, and these can greatly complicate the determination of accurate seismic source locations and, equally importantly, it can complicate the determination of errors in those locations.

It is convenient to distinguish errors relating to the measurement of signal arrival time, azimuth and slowness from errors that arise from inadequate definition of the wave-speed model, which are often termed ‘model errors’. Because lateral variations are largest near the surface, they tend to affect signals recorded at closer distances (because those signals follow shallower ray paths). This can lead to the paradox of greater location errors for events determined from regional observations than those determined from teleseismic observations. Nevertheless, regional observations remain important for small events, and for source identification, as well as for helping to constrain event depth. Regional observations also offer the prospect of greater location accuracy when the wave-speed model at shallower depths is indeed accurately known.

So there have been many initiatives to improve knowledge of the earth’s seismic wave-speed model at shallower depths (say at most 500 km), and equivalently this can be expressed as improving the theoretical travel times for seismic waves that travel between any source and receiver points at regional distances (say up to 2000 km).

One such recent initiative is the RSTT model, which seeks to refine travel times up to an epicentral distance of 15° or 18°. This effort requires data from selected events whose locations are known very precisely, and these are required for every region in which the model is to be refined. Such events are referred to as ground truth (GT) events. GT5 events are those whose epicentre is known to within 5 km, and GT0 are those man-made events whose location is known precisely. An outreach programme including workshops to identify and gather data on ground truth events has therefore been launched, and this is described by Myers et al. (T1.2-05).

The measurement of uncertainty for specific paths along which travel-time corrections have been made is considered for the phase $Pn$ by Begnaud et al. (T1.2-01). The methodology is described, and the authors consider the problem of assigning well-founded errors to paths along which there is no observed data.

Nippress and Bowers (T1.2-P7) present an evaluation of RSTT performance. They reflect on a previous initiative to generate source-specific station corrections (SSSCs) for Eurasia, Fennoscandia and North America, which have long been used in IDC processing. They compare the effect on REB event locations of the SSSC and RSTT $Pn$ travel-time residuals, and they raise a number of issues. For example, they ask how the RSTT model, which is valid to an epicentral distance of 15°, should deal with $Pn$ when this phase can, in reality, exist at greater distances and can be picked by analysts at distances up to 20°. They also point out that the triplication in the travel-time curve at around 18° needs adequate treatment, bearing in mind that the assumption of a positive wave-speed gradient is violated if there is a depth range where wave speed decreases with depth (‘low-velocity zone’).

A number of contributions report work to define region-specific wave-speed structure. Raykova and Panza (T1.2-P11) determine wave-speed structure down to 350 km depth in the Balkan peninsula region from surface-wave dispersion analysis, while Georgieva (T1.2-P1) uses 11 stations of the Bulgarian national seismic network to examine upper mantle structure, and in particular the lateral variation in the depth of discontinuities at 410 and 660 km. Syracuse et al. (T1.2-P16) report a study to determine the wave-speed structure beneath the Iran region using seismic body-wave travel times, surface-wave dispersion curves and gravity data. A seismic wave-speed model for West Africa determined from surface-wave dispersion is the topic of a study reported by Ouattara (T1.2-P6). Adiya et al. (T1.5-06) report on an earthquake swarm recorded near Ulaan Baatar, Mongolia, used to estimate a local three-dimensional wave-speed structure based on double-difference tomography.

Hao and Zheng (T1.2-06) show mislocation vectors for earthquakes observed at the Naqu array in western China (with ray paths sampling the Tibetan Plateau), and compute slowness-azimuth station corrections (SASCs). These represent another consequence of imperfect three-dimensional seismic wave-speed models, with rays being bent from their great circle path by lateral wave-speed variations.

Simmons et al. (T1.2-P8) present a three-dimensional global model for $P$- and $S$-wave speed determined from
tomographic imaging using three-dimensional ray tracing for travel-time computation (Figure 6.1). The authors use 3 million P- and S-wave travel times, including teleseismic, regional and crustal phases. Validation is reported by observing an average reduction of 30–60% in the mislocation of 116 well-located validation events relative to a one-dimensional model.

Ground truth events, for which the location and ideally origin time are well known to a given accuracy, are important for determining wave-speed structure and are essential for validation of a wave-speed model. In regions with few earthquakes, and perhaps until recently also regions with few stations, there has been little potential to define GT events. Brazil is such a place, and Vieira Barros et al. describe the concept of a ‘pseudo ground truth’ event where aftershocks that are well recorded locally and regionally are used to relocate the main event. These events are augmented by recent mining blasts after the installation of the Brazil national seismic network. Plans are described for temporary station deployments, for enhancements to the permanent national seismograph network, and for a programme of ‘calibration explosions’ to improve the coverage of GT events in support of developing a three-dimensional wave-speed model for the South American region.

Surface-wave dispersion curves offer one way to determine wave-speed profiles for S waves. Raykova describes a method for non-linear optimized inversion of surface-wave dispersion data. Formalized computation of error bounds for the best-fit model is included.

The distribution of GT events in the former USSR has benefitted from the existence of more than 100 widely distributed underground nuclear explosions that were carried out for peaceful purposes (so-called peaceful nuclear explosions). Mackey and Fujita use a range of data, including satellite imagery, to improve the locations of these explosions.

Seismic noise imaging is presented by Saygin et al. as a method of determining crust and upper mantle seismic wave speeds. They use full waveform seismic noise tomography across different domains of Australia and Indonesia. The authors use broadband data from over 400 stations of the Australian and Indonesian national networks, and they cross-correlate seismic noise simultaneously recorded at each pair of stations to recover Green’s functions (response of the wave-speed field) between each pair of stations. They investigate surface-wave group velocity dispersion, travel-time tomography and full waveform tomography, comparing synthetic and observed waveforms to iteratively improve the model.

The Sandia and Los Alamos global seismic wave-speed model with a three-dimensional mantle (SALSA3D) is described by Ballard et al. One feature of this model emphasized by the authors is the path-specific uncertainty in travel times, which is claimed to result in more realistic estimates of model uncertainty. A process of model validation using a global suite of validation events is described.

The seismic wave-speed field includes the discontinuities in wave speed within the earth. PKiKP is the phase that corresponds to a P wave reflected from the inner core boundary. Correlation detectors may offer the possibility to detect and examine the nature of PKiKP, and hence deduce properties of the inner core boundary.
Solid materials are never perfectly elastic, and as a result energy is lost as seismic waves propagate; this results in loss of amplitude and a preferential loss of higher frequencies. This ‘anelastic attenuation’ has several effects on the characterization of seismic signals, one of which is to reduce amplitude measurements, with a corresponding effect on magnitude calculations. This in turn can affect event screening since the \( m_c \)/\( M_b \) criterion is one of several event screening criteria used experimentally in IDC standard products. Seismic shear (\( S \)) waves have a different (normally higher) attenuation rate than primary (\( P \)) waves because of their different mechanism of energy loss.

The amplitudes of regional seismic phases such as \( P_g \), \( P_n \), \( L_g \) and \( S_n \) can be used to infer seismic attenuation at regional distances, and such a study focusing on various regions is reported by Pasyanos et al. (T1.2-P29). Najafipour and Rahimi (T1.2-P17) present a study of the variation of attenuation with location and depth in the Makran region of south-east Iran from coda waves observed on seismograms at epicentral distances of less than 100 km.

The presence of fluid in the rock mass can affect anelastic attenuation, so that in principle the subsurface migration of fluid can create a temporal variation. Kopnichev and Sokolova (T1.2-P14) report on a spatio-temporal study of short-period \( S \) wave attenuation in the region of the former Nevada Test Site (now known as the NNSS), USA. They conclude that observed temporal variations are associated with fluid migration resulting from nuclear tests. In an investigation of spatial and temporal variations in \( S \) wave anelastic attenuation in the region of the former Semipalatinsk nuclear test site, Kazakhstan, Sokolova and Kopnichev (T1.2-P10) report much higher attenuation beneath the Balapan area of the test site than the Degelan area. They also observe temporal changes in attenuation from the 1960s to the 1980s, which they attribute to fluid migration, and they correlate this with a temperature anomaly in the test site region.

Seismicity studies, described in section 6.1.4, are often associated with the determination of focal mechanisms, also known as fault plane solutions and now often generalized to moment tensor inversions. The results enable the principal stress directions to be estimated at each earthquake hypocentre. For example, the seismicity of the Gulf of Suez region recorded by the Egyptian National Seismic Network (ENSN) is used by Shater and Mahmoude (T1.2-P9) to determine the regional principal stress directions along the Gulf of Suez from earthquake fault plane solutions. In another example Raykova and Panza (T1.2-P11) perform a moment tensor inversion using whole waveforms recorded from an earthquake in the Aegean Sea on 29 March 2003.

The global distribution of earthquakes is associated with CTBT verification in several ways. First, the vast majority of seismic disturbances (‘seismic events’) are earthquakes recorded by regional and global seismic networks, including the IMS, so earthquakes are ubiquitous in underground nuclear test monitoring. Second, large earthquakes are often followed by large aftershock sequences, which may contain hundreds or even thousands of additional events capable of being detected by the IMS and located; this poses a special challenge for interactive analysis. It also makes it more time-consuming to ensure that near-simultaneous events in other regions are not missed. Moreover, the global seismic noise originating from the largest earthquakes temporarily degrades the global detection threshold. All this poses challenges for analyst workload, and in particular the workload dedicated to ensuring that events are not missed.

Another way in which earthquake seismicity is relevant to CTBT monitoring is the apparent distortion it creates in the measurement of IMS station performance, or more precisely the relative contribution of IMS stations to CTBT monitoring. Approximately one-third of natural seismicity lies in the western Pacific, so that IMS primary seismic stations in Australia contribute an inordinately large proportion of signal detections to the REB. Given that all events meeting the event definition criteria should be detected and located in the REB, it follows that such stations are especially important. But this, of itself, is not a measure of these stations’ contribution to nuclear
test monitoring, because a nuclear explosion can occur anywhere. A high-noise station contributing little to the REB may have a special role in detecting a small nuclear explosion that occurred in an otherwise aseismic area.

A range of SnT2015 contributions describe seismicity in different geographic regions and use this information for various purposes. Jonsdottir et al. (T1.5-05) describe recent developments in both the seismic and infrasound networks in Iceland to monitor natural hazards including those of earthquakes and volcanoes (Figure 6.2). Abdurakhmatov (T1.5-P36) presents seismicity and probabilistic seismic hazard maps for Kyrgyzstan. Tsereteli et al. (T1.5-03) present seismicity and seismotectonic maps of Georgia for natural hazards estimation. The seismicity of the Himalayan belt is investigated by Shonker (T1.5-P15) for the purpose of hazard assessment. IMS stations are used by Arisiova et al. (T1.5-P48) to prepare a new seismic zoning map of Kazakhstan for earthquake hazard assessment. Adiya et al. (T1.5-06) describe an earthquake swarm near Ulaan Baatar, Mongolia, with focal depths between 5 and 15 km.

Olimat (T1.5-P1) describes the study of microearthquakes in Jordan as a means to identify non-bedrock sites where earthquake hazard is greater due to amplification of specific frequencies. This leads to the seismic microzonation of cities in Jordan in support of earthquake hazard assessment. Semin et al. (T1.5-P21) present a ground motion scaling study for the central Anatolia region of Turkey, in support of earthquake hazard assessment. Nurtaev (T1.3-P01) presents seismicity maps and gravity data for Uzbekistan to trace Palaeozoic suture zones, while strong earthquakes in Uzbekistan are presented by Usmanova (T1.5-04), with maps of isoseismals and seismotectonic interpretation. Gernser et al. (T1.5-P1) report a cluster of crustal seismicity in the northern Alpine foreland of Austria.

The seismicity of Brazil is described by Carvalho et al. (T4.1-04), and they present seismicity maps derived from Brazil earthquake catalogues. The lack of stations at regional distances from small earthquakes in Greenland is pointed out by Larsen et al. (T2.3-P7), who report data on earthquake swarms whose larger events have been recorded at teleseismic distances by IMS seismic arrays. Seismicity of the Arabian peninsula as it appears in the REBs is described by Medinskaya (T1.5-P26), who points out that many well-located events do not appear in the REB because they do not meet the event definition criterion of three primary IMS stations.

Earthquake hazard in the Ukraine region is discussed by Lyashchuk (T1.5-P42) with reference to seismicity as well as possible precursors detectable by other geophysical methods. They also discuss earthquake early warning, in which rapid notification of a large earthquake is made to those ahead of the travelling seismic waves.

Earthquake early warning should not be confused with earthquake prediction. Earthquake early warning is the issuance of a warning after an earthquake has occurred, for the benefit of locations that the seismic waves have not yet reached. Methodology to develop an earthquake early warning system in Iran is described by Safepour and Gholami (T1.5-P15). Ayoniyi (T1.5-P16) describes an Internet and database system for earthquake early warning, with emphasis on the need for speed in issuing useful warnings.

Discussion of an earthquake prediction experiment proposed by the China Earthquake Administration (CEA) is provided by Wu (T4.3-P9). This is described as a project designed either to make progress in the field of prediction or to provide evidence that earthquakes are intrinsically unpredictable. An analogy is drawn between the complexities in the planning, design, installing, operating and maintaining of the IMS, and the complex needs of a well-designed set of scientific experiments to explore the potential or otherwise of earthquake prediction.

Some very large earthquakes located beneath the sea generate tsunamis, in some cases with major loss of life and property. As with earthquake early warning, tsunami warning is also possible and must extend for thousands
of kilometres if there is open ocean extending that far from the epicentre.

Tsunamis are generated by some large under-sea earthquakes, depending in part on the source mechanism that itself depends on the tectonic stress regime. So a tsunami warning centre must first locate large earthquakes rapidly, then apply further tests to minimize the frequency of false alarms being issued. Roudil et al. (T1.5-P44) describe the French Tsunami Warning Centre (CENALT), which has been operating since 2012. The Tsunami Early Warning System for the North-Eastern Atlantic, the Mediterranean and Connected Seas (NEAMTWS) is described by Necmioglu et al. (T1.5-08).

Kaneda et al. (T3.1-03) describe developments in tsunami warning systems in Japan following the 11 March 2011 Tohoku earthquake and tsunami (which led to the Fukushima Daiichi nuclear power plant accident). They describe the sea-floor networks of observatories (DONET1 and DONET2) and the real-time monitoring system. Kaneda (T2.3-P5) describes broadband hydroacoustic pressure variations recorded by DONET in association with tsunamigenic earthquakes. Historical evidence of tsunamis goes back many centuries. Evidence that the 11 September 1921 Java earthquake created a tsunami is presented by Hidayanti and Yatimantoro (T1.5-P29), including a tide gauge recording and deposits at Prigi beach, east Java.

Noting that earthquakes are not predictable, Shanker et al. (T4.1-03) presents arguments in favour of focusing on precursory anomalies in seismicity that have been known to precede some destructive earthquakes, in particular earthquake swarms (clusters of earthquakes with no predominant event of largest magnitude). The authors present seismicity maps of the Himalayas and the Tibetan Plateau and look at examples of three medium-sized earthquakes in the western Nepal region that were preceded by anomalous seismicity.

Finally, Babayev et al. (T1.5-P24) describe mud eruptions in Azerbaijan and their relationship to earthquake activity. They discuss the role of earthquake-induced strain in promoting mud eruptions.

### 6.1.5 SUBSURFACE FLUID TRANSPORT AND RADIONUCLIDES

Interest in the transport of gases in the subsurface is directed towards understanding of the migration of radioactive noble gases from the site of an underground nuclear explosion to the surface, and hence into the atmosphere. Such migration is essential if the radionuclides are to be detected by the IMS, and the design of atmospheric and soil sampling during an OSI is also dependent on such understanding. Where appropriate the contributions in this field are also cited in Section 3.3.3.

Guillon et al. (T1.3-P15) consider the effect of topography on soil gas sampling during an OSI. They find a strong variability of subsurface gas dynamics, not only due to barometric pumping (enhancement or suppression of subsurface gas migration by changes in atmospheric pressure) but also due to local topography. A comparison of the shallow sampling method (from under a tarpaulin) and the deep sampling method (via a drilled borehole) indicates that atmospheric infiltration could occur when sampling too close to cliffs, a topic that needs more study in order to further develop OSI processes.

Adler et al. (T1.3-P5) go into significant detail on their study of computer modelling simulations for the transport of tracers in slightly compressed fluids going through a fractured porous medium while under external pressure variations. It is concluded that rapid surface breakthrough is favoured by a barometric low, but with the caveat that barometric pumping is more efficient than diffusion only under specific conditions.

The migration of fluids through fractured and porous media is much investigated in the context of oil-bearing reservoirs, and Osinowo (T1.4-02) focuses on the anisotropy of fluid flow that arises from the preferential alignment of fractures and from structural layering. The computer model simulation methods presented may be of use in simulating the migration of fluids at a site of interest once sufficient is known about the characteristics of the subsurface.

Computer model simulations of noble gas migration in the subsurface in combination with field measurements are pursued by Guillon et al. (T1.3-08), with a view to better understand the mechanisms and factors controlling gas migration underground, and they investigate how to best take subsoil noble gas samples during an OSI. The authors conclude that gas migration depends on the rock properties, boundary conditions and the soil composition. They also conclude that barometric pumping does not always drive subsoil gases to the surface, and that major water infiltration events induce large variations in subsoil gas concentrations; they conclude that more field data and computer simulations are required for better understanding. One overriding conclusion of the work is that the local subsoil and
atmospheric noble gas background should be monitored during OSI field sampling.

Pili et al. (T1.3–P13) consider a range of issues concerning the mechanisms by which radioactive noble gases may become detectable from an underground nuclear explosion; from the source–geosphere interactions that influence the radionuclide source term through, for example, fractionation; via the factors that affect subsurface gas migration; to dilution resulting from interaction with the geology. They refer to tracer experiments conducted at the Roselend Natural Laboratory, France, and three-dimensional numerical simulation of pressure and atmospheric pumping. The authors conclude that strong interactions with the geology may inhibit the detectability of radioactive noble gas evidence, as might the very large dilutions expected during migration. The authors reason that the likelihood of detection is larger for late seepage than for prompt release.

The need to ensure the quality of subsoil noble gas samples, especially during an OSI, includes ensuring that the sample is not contaminated with atmospheric air. Rizzo et al. (T3.1–P1) propose using the carbon isotopic composition of carbon dioxide and methane captured during subsoil noble gas sampling to determine whether there has been atmospheric infiltration, since the presence of these gases in the atmosphere and in the subsoil require a fundamentally different interpretation.

In an OSI context the relevant radioactive noble gases include argon-37, in addition to the xenon isotopes. In their work on argon-37 in the environment, Purschert and Raghoo (T1.3–P3) note that the background concentration of argon-37 in soil 2 m below the surface may be two orders of magnitude higher than in the atmosphere and is highly variable depending on calcium content and subsoil gas migration parameters. It is also concluded that water plays a critical role in the efficiency of containment of noble gases in the subsoil, which results in great variability in the argon-37 concentration in line with water infiltration; this leads to problems in determining the natural argon-37 background concentrations. The authors conclude that an upper limit of the natural background of argon-37 in the atmosphere is 10 mBq/m³.

Guillon et al. (T1.3–P9) conduct numerical studies of the variability in argon-37 background in fractured porous media and go into detail through various controlling parameters and mechanisms. It is concluded that high variability in background and the strong influence of water infiltration means that detectability of a release in OSI subsoil gas samples would be highly dependent on local conditions. It is recommended that the quality control of OSI noble gas sampling is important, and that this may include background noble gas monitoring in both the atmosphere and in the subsoil.

Another study of argon-37 background in the atmosphere and the subsurface is reported by Raghoo and Purschert (T1.3–P14). They report measurements of argon-37 concentration in stratospheric air in the range of 4–7 mBq/m³, which they note is in good agreement with both computer model simulations and prior measurements. Also in this work, the importance of variability in subsurface noble gas background is emphasized.

Olsen et al. (T1.3–O4) describe the noble gas migration experiment (NGME) carried out at a former nuclear test site (the NNSS) in the USA in 2013 to investigate the physical processes associated with subsoil gas transport as well as to develop noble gas field sampling protocols for OSI. In the experiment, the transport properties of radioactive tracers are studied as well as any potential impact of atmospheric and subsurface noble gas backgrounds.

Soil samples also contain long-lived isotopes of various radionuclide particulates, and Puzas et al. (T1.3–P10) interpret isotopes (mainly iodines and plutonium) measured in widely distributed soil samples in Lithuania in terms of the global fallout from past nuclear weapon testing and the Chernobyl nuclear reactor accident. The radionuclide background in the subsurface has a variety of origins, and Puzas et al. (T1.3–P11) consider radioactive plutonium and caesium from past nuclear tests and their migration in lake ecosystems. They present a scheme for computer model simulations of several physical factors that contribute to the migration process. Quintana (T1.5–P3) report on the distribution of strontium-90 and cesium-137 in the environment, based on milk samples taken over several decades.

Kachalin and Kasymyrov (T1.2–P17) describe the use of a portable field gamma spectrometer to measure radon concentration in limestone caves in Slovenia in order to investigate the levels of naturally occurring and potentially anthropogenic background. They report daughter products of naturally occurring radon-226 and thorium-232, but no caesium-137.

### 6.2 OCEANS

The acoustic wave–speed field of the oceans is governed by ocean temperature and salinity, and its variation with depth is additionally governed by pressure. It follows
that the travel times of acoustic waves in the oceans can in principle provide information on one or more of these variables. Evers (T1.5−O7) concludes that acoustic wave speeds sufficiently accurate for this purpose can be measured both directly, using mid-ocean-ridge earthquakes as sources, and indirectly, using adjacent hydrophones in an IMS station triplet treated as an interferometer. The authors plan to study long-term variations using large data sets over the years since the stations were installed.

The modelling of a tsunami's progress from the tsunamigenic earthquake source to the coast is governed by the bathymetry, and particularly by shallow coastal bathymetry and the shape of the coastline, with major amplification caused by such features as narrow inlets and coves. The assessment of tsunami hazards therefore depends crucially on an ability to model these effects. Yatimantoro (T1.5−P46) presents numerical models for predicting the tsunami that could arise in the Ujung Kulon area in Indonesia from an earthquake in the south-west of the Sunda Strait. A potential earthquake magnitude of 8.7 $M_W$ is used, based on the inferred seismic gap, and the simulations predict a tsunami with maximum height of 9.8 m and run-up of 11.6 m arriving at Ujung Kulon 13 minutes after the earthquake.

The USArray transportable array, which has occupied successive temporary sites working eastwards across the USA, included infrasound sensors for the latter (eastern) part of its deployment. Data from these are used by Hedlin and de Groot-Hedlin (T1.1−O2) to study atmospheric gravity waves (FIGURE 6.4). These exist on account of the restoring force imposed by gravity when the atmosphere is disturbed from equilibrium; they are analogous to waves on the sea surface, which are subject to the restoring force of gravity acting on a surface disturbance created by wind. They are distinguished from acoustic or seismic waves, whose restoring force is derived from the compressive or elastic properties of the medium. The authors compare gravity waves observed (at ground level) using the transportable array with those observed in the stratosphere from space; they find general agreement. Using triads of sensors to locate infrasound sources, they conclude that there are extensive, large and repeating sources in certain regions.

Gravity waves perturb the transmission of atmospheric acoustic waves via perturbations to the acoustic wave speed. Pilger and Ceranna (T1.1−P21) use probabilistic infrasound reflectivity modelling to investigate this and use data from the Buncefield (UK) explosion on 11 December 2005 as an example. Näsholm et al. (T1.1−P5) use the reflectivity method to

FIGURE 6.3
Different stages ((a)–(d)) in the manifestation of the fine structure of the atmosphere in the exhaust trail of a Soyuz rocket launched from Plesetsk on 25 May 2009 at 21:53 UTC. Time after launch: (a) 204 s; (b) 253 s; (c) 610 s; (d) 19 m 39 s. (b) is annotated with altitudes. From Kulichkov (T1.1−O3) and Dalin, P., Perpinov, N., Pertsev, N. et al. “Optical studies of rocket exhaust trails and artificial noctilucent clouds produced by Soyuz rocket launches”, J. Geophys. Res. 118 7850–7863 (2013).
model infrasound propagation to improve the location of infrasound events and to perform tomographic inversions of the state of the atmosphere. Application to a chemical explosion in Norway demonstrates the ability of the method to model the main infrasonic arrivals at IS37 (I37NO) at a distance of 410 km.

Blanc (T1.1-P7) describes the work of the Atmospheric dynamics Research InfraStructure in Europe (ARISE) consortium, including research on advanced data products for use as benchmarks for weather forecast models in support of monitoring of extreme events such as volcanic eruptions, geomagnetic storms and hurricanes. One point of relevance to CTBT verification is the move towards a better understanding of atmospheric dynamics that control the acoustic wave-speed structure of the atmosphere, which is crucial for the location of infrasound events.

The problem of describing the dynamic acoustic wave-speed field of the atmosphere is also addressed by Blom and Arrowsmith (T1.1-P3). They use stochastic methods to estimate the atmosphere state, based on an archive of historic states specific to a geographic region, time of day and time of year. A test of the method is described using a large explosion in the western USA recorded at a distance of less than 1000 km.

Millet et al. (T1.1-P16) explore the use of random functions in representing winds and temperatures and consider models with and without atmospheric gravity waves that have a high degree of accuracy. Näsholm et al. (T1.1-P17) compare observed and modelled infrasound signals at IS37 (I37NO), Norway; they determine travel times by ray tracing through the wind and temperature profiles and explore the effects of perturbing wind models with atmospheric gravity waves. Zasimov et al. (T3.4-P1) explore the variation in phase velocities and azimuths of the detected signals and relate these to variations in atmospheric conditions.

6.3.2 ACOUSTIC ATTENUATION

SnT2015 contributions on the structure of the atmosphere applied to the transmission of acoustic waves do not focus specifically on attenuation. However, the complexity of atmospheric dynamics, as addressed for example by Blanc (T1.1-P7), results in a close link between the acoustic wave-speed field and the attenuation of acoustic waves.

6.3.3 ATMOSPHERIC TRANSPORT

The use of ATM to estimate the movement of the air mass based on a synthesis of massive sets of meteorological observations is essential if the sources of anomalous radionuclide observations are to be attributed to a limited source region or regions. The precision of the
ATM calculations depends on the spatial and temporal resolution of the meteorological data, with higher resolution expected to provide more reliable results. However, the benefit depends on the spatial scale of the variations in the meteorological parameters and their speed of change. Krysta (T1.3-P7) uses forward and backward simulations to model atmospheric dispersion in the case of anomalous radioactive xenon observations that are believed to be associated with releases at known medical isotope production plants that have been provided by the plant operators. Several conclusions are drawn, for example that forward simulations need further work since backward simulations seem to be more reliable, and that the dependence on spatial resolution of meteorological fields is not as strong as expected.

Straightforward ATM calculations assume that radionuclides travel in the atmosphere and are dispersed along with the air mass. For particulate radionuclides this omits to take account of effects that may be highly significant. Potentially, the two most important of these are ‘dry deposition’, in which particles drift to the ground under gravity, and ‘wet deposition’, also referred to as ‘washout’, in which precipitation accelerates this process by ‘washing’ the particles to the ground. The main consequences of these processes for radionuclides is a dilution in the concentration expected at a location remote from the radionuclide release, although of course neither process applies to gases. Delcloo and Camps (T1.3-P8) compare the performance of three schemes that take dry deposition into account. The authors obtain a range of different results and point out that this arises from the complex factors that influence deposition and the associated uncertainties. However, it is pointed out that the uncertainty in deposition should be specifically assessed if release reconstructions are made based on actual measurements of deposited radioactive particles. Philipp and Seibert (T1.3-O2) describe a detailed systematic and automated software testing environment used for testing of ATM software. This scheme includes evaluation of various parts of the software, systematic testing of input values and evaluation of results, which in this case are focused specifically on wet deposition analysis that is directly relevant for CTBTO operations.

Although the effect of wet deposition can be local, as for example when particles are washed out by a rainstorm, the averaging effect over a whole region subjected to a specific climate can be observed. Kusmierczyk-Michalec and Gheddou (T1.3-P8) examine the latitudinal distribution of beryllium-7 as inferred from background measurements made at IMS radionuclide stations, and conclude that there is a deficit in the intertropical convergence zone that they attribute to deposition by rain and humidity.

Cosmogenic radioactive isotopes are produced by the interaction of cosmic radiation with nuclei in the upper atmosphere. Such isotopes that have a half-life from months to a few years may be particularly useful as tracers in measuring atmospheric transport. If an isotope is produced uniformly in the upper atmosphere at a constant rate and decays on a timescale comparable with the time taken for the air mass to migrate to lower altitudes, then spatial variations in concentration at the surface provide information on air movement over timescales comparable to the isotope’s half-life. Beryllium-7 is such an isotope. Complications are created by the sunspot cycle, which influences the production rate through changes in the cosmic radiation flux, and by changes in the earth’s magnetic field, which may introduce non-uniform production through deflection of the charged particles in cosmic radiation approaching the earth. Hoffman and Ungar (T1.3-O5) consider the possibility of using sodium-22 as such a tracer; they use spectrum summation methods to retrieve observations of what are very low concentrations of sodium-22 at IMS stations and examine variations due both to changes in the earth’s magnetic field and to atmospheric dynamics. The authors report that they successfully retrieved the sodium-22 signals and conclude that variations in production rate do not appear to have a significant impact on the surface observations at IMS stations, whose variation appears to be dominated by atmospheric motion.

ATM can be of interest at different spatial scales. Global modelling is especially relevant for interpreting radionuclide observations made at IMS stations, while for OSI applications local modelling over a length scale of, say, 100 km or several hundred kilometres may be relevant depending on the purpose. Regmi and Maharjan (T4.1-P22) present a regional study focusing on the Nepalese Himalayas, with the aim of establishing the controlling factors in atmospheric transport and predicting extreme weather events. They conclude that the model they use is successful in predicting extreme weather events in this extreme topography; they also conclude that the Nepalese Himalayas are especially susceptible to pollutants transported from the southern lowlands, and that a specific river valley (the Kaligandaki) is an important transport route from the Ganges Plain.

The application of ATM to OSI is considered by Sugiyama et al. (T1.3-O3). They point out the importance of ATM in planning the radionuclide sampling activities during an OSI, and that if ATM is unreliable as a result of insufficient resolution or input data, flawed planning could result. The authors identify two essential elements as first the use of probabilistic estimates in ATM, and second the issuance of operational products that
communicate to inform the planning. They also see tools for source reconstruction using radionuclide field measurement data as essential. They advocate ensemble modelling as a means to estimate detection probabilities, and they conclude that many current emergency response ATM tools could be adapted for OSI application.

A convenient opportunity for testing large-scale ATM models was provided by the extended release of many thousands of tons per day of sulphur dioxide over several weeks from the Holuhraun volcanic fissure in Iceland, beginning on 28 August 2014. Maurer and Wotawa (T1.5-P6) present forward and backtracking ATM models and use near-continuous measurements from four high-altitude observatories in the Alps, all of which recorded an anomalous sulphur dioxide signal, to validate their models. The authors highlight deviations from the forward model and the observations due to the complex meteorological situation and multiple plume branches. Backtracking shows consistency with the known source location but also shows deviations in concentration, again attributed to the complex meteorological conditions prevailing in north-west Europe during the release period.

The quantification of uncertainties in ATM using ensembles created by perturbation of the model is investigated by de Meutter et al. (T1.3-O7). The authors compare observation of xenon-133 at the IMS radionuclide station RN33 (DEX33) in Germany with ATM predictions assuming a source term comprising emission data from the medical isotope production plant in Belgium plus assumed constant emissions from nuclear power plants in Europe. The authors confirm that ensembles allow the estimation of dispersion forecast uncertainty and confirm previous results showing that nuclear power plants are the major contributor to observed activity at that station, whereas the highest peaks at RN33 (DEX33) arise from the medical isotope production plant.

The use of ATM for modelling the dispersal of radioactive isotopes is presented by Veleva et al. (T1.5-P17) in support of the emergency response system of Bulgaria. Results from scenarios involving the accidental release of radionuclides from a nuclear power plant are presented.

Possible interpretations of anomalous radionuclide observations at two IMS stations in Japan and one in the Russian Federation during mid-May 2010 are discussed by Ross et al. (T2.2-P5). Without reference to any possibly related seismic event, these authors use high-resolution backward ATM to constrain the location of a possible nuclear fission source whose existence and origin time is inferred from the radionuclide observations.

Hofman and Seibert (T2.2-P11) present an inverse method for estimating a radioactivity release source term using ATM, with or without constraining the known source location. A supposed release in April 2013 at the site of the DPRK announced nuclear tests is used as an example, with xenon isotope ratios observed at the IMS stations RN38 (JPX38), Japan, and RN58 (RUX58), Russian Federation. The problem of combining (fusing) the event determined from seismic data with the radionuclide observations possibly attributed to the same event is considered by Seibert et al. (T2.2-P12) as reported in SECTION 5.3.
7 Interpretation

7.1 GEOPHYSICAL SIGNATURES

7.1.1 EXPLOSION

Zheng and Hao (T2.2-P23) present data from three announced nuclear tests in the DPRK recorded at two GSN stations in China: MDJ, Mudanjiang, and BJT, Baijiatuau. They present amplitude ratios for $P_g$ and Rayleigh waves and also determine relative locations of the events using waveform correlation. Relative and absolute locations of announced nuclear tests in the DPRK are also carried out by Sianipar et al. (T2.2-P17) using modified joint hypocentre determination and double-difference methods. The authors associate their event locations with specific tunnel entrances.

Depths and source characteristics of announced nuclear tests in the DPRK are presented by Kim et al. (T2.3-O2). From teleseismic surface reflection delay times they infer a depth of 2.3–2.4 km for the first three announced tests. Using surface-wave spectra and particle motions at regional stations to constrain the moment tensor, they infer a vertically distributed source for the 2006 event and a horizontally distributed source for the 2009 and 2013 events; they conclude that these results are compatible with emplacement in a shaft and in a tunnel, respectively.

Recording and processing of the 2013 announced nuclear test in the DPRK using data from the Ukrainian national networks and stations in global networks are reported by Kolesnykov (T2.2-P15). Yedlin et al. (T2.3-P8) report on a study to determine explosion source seismic magnitudes using singular value decomposition.

The source–time function of a nuclear test at the former Semipalatinsk test site in Kazakhstan is extracted...
from observed signals for underground nuclear tests using the cube-root scaling method; this work is reported by Salter (T2.3-P3).

Tsereteli and Kereselidze (T2.3-P4) consider the energy of a point explosion source determined from the energy spectrum of body waves. They discuss the difficulties in estimating explosion yield given the difficulties of representing the complexities of the source, including source volume change, and they consider various models that have addressed this issue.

Belyashov et al. (T3.4-P9) report an active seismic study of the spall zones above the site of several nuclear tests at the former test site at Semipalatinsk, Kazakhstan. They determine the shallow wave-speed structure with a view to mapping any wave-speed anomaly associated with the spall zone above the sites of these tests.

7.1.2 EARTHQUAKE

Studies of earthquake sources have occupied seismologists for many decades. Three examples that appear in SnT2015 presentations are summarized here. First, Yatimantoro and Tanioka (T2.3-P2) study the rupture process of the 28 March 2005 Nias earthquake off Sumatra, Indonesia (Mw 8.6), using joint inversion of teleseismic, geodetic (GPS) and tsunami tide gauge data. They calculate a seismic moment and estimate the slip distribution.

Gholami (T2.3-P13) presents a study of the 2009 Tehran (Mw 4.0) earthquake, Iran. The author computes a ground motion simulation using finite difference and modal summation methods, in support of microzonation for seismic hazard.

The nature of an earthquake source is of particular interest when associated with volcanic activity, because such events might either be tectonic or directly volcanic in origin. Yatimantoro et al. (T1.5-P98) study the M 2.7 Merbabu, Indonesia, earthquake of 17 February 2014. After computing a focal mechanism and precise location of the event, the authors conclude that the event was tectonic.

7.1.3 VOLCANO

The monitoring of volcanoes using infrasound is highly dependent on the types of infrasound source that the volcanic activity represents, and in particular its frequency range. Tailpied et al. (T4.1-02) use the continuous monitoring of Mount Etna, Italy, to explore this issue, noting the repetitive nature of signals from Etna. The authors use data from IMS stations as well as stations deployed under the ARISE project. They demonstrate the ability to retrieve source parameters from IMS infrasound observations at long range, observed from the 22–23 April 2015 eruption of Calbuco, Chile. Applbaum and Price (T1.1-P4) also focus on Mount Etna and report on signals concluded to be from Mount Etna based on four years of data recorded at the Meron experimental infrasound array in Israel. They are able to detect continuous lava fountain events as well as explosive eruptions at this array, which is 2000 km from the source.

In some cases infrasound was used to monitor volcanic explosions using local networks prior to the installation of the IMS infrasound network, although the explosions were often also observed on seismometers. Itikarai (T1.1-P4) describes the history of infrasound monitoring of the Rabaul volcano in Papua New Guinea. He describes the airwaves observed from Strombolian eruptions on Rabaul, which were full of discrete explosions. He notes that the nearby IMS infrasound station IS40 (I40PG) has improved the detection threshold of Rabaul activity. The study of active volcanics in the Comoros Islands using seismic and infrasound data is reported by Madi (T1.5-P01).

The importance of infrasound as a method of monitoring volcanic processes is stressed by Lacanna et al. (T1.1-P22), who point out that infrasound provides direct evidence of injection of volcanic material into the atmosphere. However, they also point out that the signals are highly dependent on topography at local distances and on atmospheric structure at longer distances. They use the examples of a volcanic landslide on the Askja volcano, Iceland, and recurrent activity of the Sakurajima volcano, Japan, to compare observations at local and longer distances. They compare observations with numerical simulations that include topography and atmospheric effects.

The monitoring of volcanoes in Ecuador using infrasound is reported by Ruiz Romero and Steele (T1.1-P28). In particular the author reports on recent activity of the Tungurahua and Reventador volcanoes, from which a range of infrasound sources have been recorded, including pyroclastic flows, extended Strombolian activity and Vulcanian explosions.

Explosive volcanic eruptions represent an important class of infrasound source that is recorded by the IMS infrasound network and that may be recorded over
thousands of kilometres. Matoza et al. (T1.1−P10) describe a project to catalogue these sources. One motivation is to mitigate aviation hazard caused by volcanic ash plumes. Among other benefits they cite the improvement in discrimination between different classes of infrasound source. The use of infrasound in natural hazard mitigation is also pursued by Mialle et al. (T1.1−O4), who envisage a notification system that uses a library of volcano-specific signals that can help to identify the origin of new unidentified signals, and the authors provide data for probabilistic predictions. This is intended to be implemented at the Volcanic Ash Advisory Centre in Toulouse, France.

7.1.4 OTHER SOURCES

A wide range of sources contribute to signals recorded by waveform stations. One class of hydroacoustic signals of particular interest in marine biology is those from large cetaceans (whales). Le Bras et al. (T1.5−P43) describe the Baleakanta Project, which is establishing a database of hydroacoustic signatures from these sources. As well as identifying discriminating features for species, the authors are experimenting with processing to identify individuals from these signals, and they report several cases.

Smirnov et al. (T2.3−P20) describe a wide range of infrasound sources recorded by both modern and digitized analogue infrasound recordings from the Atomic Energy Committee of Kazakhstan. The sources include ocean storms, gas flares in oilfields, quarry blasts, aircraft, spacecraft launches and re-entries, earthquakes, thunderstorms, meteorites and volcanic eruptions.

7.2 RADIONUCLIDE SIGNATURES

7.2.1 NUCLEAR EXPLOSION

There was little focus in SnT2015 contributions on the radionuclide signatures of a nuclear explosion. Venting of an underground nuclear explosion represents one process through which information could be gained on the radionuclide source term. Milbrath et al. (T2.2−P3) describe an experiment conducted at the NNSS, USA, in which lanthanum-140 was injected into the atmosphere to simulate a small-scale vent, and which created a narrow ground plume extending about 1.5 km downwind of the release point. This allowed different gamma-ray survey methods that might be used in an OSI to be compared, regarding technical performance related to the OSI task, as well as from a practical standpoint especially related to performing tasks in the presence of a background radiation field.

Yamba (T2.2−P6) considers the problem of dating a nuclear event using isotopic ratios. The author considers the yttrium-92/strontium-92 ratio, the lanthanum-140/barium-140 ratio and the niobium-95/zirconium-95 ratio using data from 2010, while also pointing out the importance of reliable nuclear reference data.

7.2.2 NUCLEAR REACTOR

Estimates of radionuclide releases from the Fukushima Daiichi nuclear power plant, Japan, following the earthquake and tsunami of 11 March 2011 are presented by Chai et al. (T1.5−O2). They use ATM with the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) algorithm and global observations from the IMS and three other radionuclide monitoring networks to infer the timeline of caesium-137 and iodine-131 releases. The determination of radionuclide release following a reactor accident is also taken up by Gueibe et al. (T2.4−P12), who use local observations and ATM to estimate an argon-41 source term for releases from a Belgian nuclear reactor used for medical isotope production.

Ake (T2.4−P9) describes a nuclear research reactor in Nigeria. The author introduces a scenario for a leak caused by corrosion and presents local radionuclide measurements consistent with normal background.

7.2.3 MEDICAL AND INDUSTRIAL ISOTOPE PRODUCTION PLANT

Medical and industrial isotope production plants are relevant to the Treaty as one of the sources of atmospheric radioactive noble gases. A prime focus is on measuring and mitigating the contributions of radioactive xenon emissions to the global radioactive xenon background (see Section 8.1.2). Indeed, WOSMIP meetings are held for this purpose; the fifth such workshop, held in May 2015, is described by Doll et al. (T2.4−O4), who outline the goals and outcomes of that meeting.

Gueibe et al. (T2.4−O1) report on the development of a prototype xenon trap to reduce releases from medical isotope production facilities using adsorption by
silver zeolites, which is to be tested at the Institute for Radioelements (IRE) facility in Fleurus, Belgium. They discuss a number of issues and options for adsorption material and trap design. The measurement of gaseous emissions at such plants, and in particular the plant in Argentina operated by INVAP, is considered by Di Tada et al. (T2.4–03). They report a number of developments including nuclide-specific online measurements to match the requirements of pulsed batch emissions, the introduction of a cadmium telluride detector to improve detection isotope discrimination, and new operator software.

Carranza (T2.4–P1) describes the production of molybdenum-99 (whose daughter product technetium-99 is important in nuclear medicine) at the Ezeiza Atomic Centre in Argentina. The author describes the transition from highly enriched uranium (HEU) to low-enriched uranium (LEU) targets as the reactor source of molybdenum-99. The inventory of released xenon-133 during the production process is also described. The long experience in Argentina of designing and building medical and industrial radioisotope production facilities is pointed out by Alessi et al. (T2.4–P1), who describe design criteria and tools for modelling the effects of radionuclide releases.

From the perspective of CTBT verification, the consequence of medical and industrial isotope production is specific xenon releases from production plants, which contribute to the background levels and which need to be discriminated from Treaty-relevant radionuclide releases. Cameron et al. (T2.4–P9) focus on one mitigating action, which is to incorporate stack monitoring data from such radioisotope plants into IDC processing. Schoepner (T2.4–P8) describes the use of ATM simulations made with the benefit of observed stack monitoring data to better describe and explain the radioactive xenon background observed at the nearest radionuclide stations. They do this using data from the production facilities in Sydney, Australia, and at the IRE, Fleurus, Belgium.

Accurate source term estimations based on measurements are important for discrimination of industrial releases from Treaty-relevant events. Radioactive xenon is not the only radioactive noble gas released in industrial processes. Gueibe et al. (T2.4–P12) perform ATM simulations using data observed at stations local to a reactor in Belgium to estimate the source term for argon-41 release. This is compared with the known release values, and it is noted that a similar approach could be useful for estimating radioactive xenon releases from medical isotope production plants.

7.3 IDENTIFICATION OF NUCLEAR EXPLOSIONS

7.3.1 IDENTIFICATION OF EXPLOSIONS USING WAVEFORM DATA

A method of discriminating between earthquakes and explosions using diffusion maps is presented by Bregman et al. (T3.3–P33). The method uses waveform information and the concept of a diffusion distance, which respects the fact that waveforms from a given source change as the source or station position are moved. They show examples using data from the IMS stations AS049 (MMAI), Mount Meron, and AS048 (EIL), Eilath, both in Israel. Another method of discriminating between earthquake and explosion waveforms is proposed by Fergany (T3.4–01) using ambient noise.

The identification of atmospheric nuclear explosions is considered by Kemerait and Clauter (T3.3–P20), who use melcestral coefficients as input to a neural network to characterize bolides and a series of nuclear explosion sources in 1962.

7.3.2 IDENTIFICATION OF NUCLEAR EXPLOSIONS USING RADIONUCLIDE DATA

Following the third announced nuclear test by the DPRK on 12 February 2013, anomalous radionuclide observations were recorded in Japan in April; two presentations consider the important verification question as to whether these observations could be related to this announced test. Hofman and Seibert (T2.2–P11) report inverse modelling of xenon-131m assuming either a known source location or an unknown location. They conclude that more investigation is necessary, for example to carry out an inversion using xenon-133 and xenon-131m simultaneously, assuming their expected ratios. This type of data fusion problem is discussed further by Seibert et al. (T2.2–P12).

Ross et al. (T2.2–P5) investigate the possible origin of anomalous radionuclides at two IMS stations in Japan and one in the Russian Federation during mid-May 2010; these observations have attracted interest in view of publications (unrelated to SnT) suggesting that these observations may be evidence of a small nuclear test in the DPRK. Without reference to any possibly related seismic event (see Richards et al. (T2.2–P9) and Koch et al. (T2.2–P14) in Section 5.1.2), the authors use high-resolution
backward ATM to constrain the location of a possible nuclear fission source whose existence and origin time they infer from the radionuclide observations.

The identification of radionuclide sources by the rapid acquisition of several types of data is considered by Puzas et al. (T2.2–P16). They use four techniques for the measurement of soil samples, including alpha spectrometry for the determination of plutonium isotopes; an inductively coupled plasma mass spectrometer for plutonium-239 and plutonium-240; a gamma spectrometer for caesium-137; and a beta counter for strontium-90.

7.3.3 EVENT SCREENING FOR IDC PRODUCTS

The $m_b$-$M_s$ event screening criterion is well established in nuclear explosion monitoring but is essentially an empirical criterion supported by extensive studies of earthquake and explosion magnitudes. Selby (T2.2–06) considers that a physical basis for the criterion would facilitate its improvement (FIGURE 7.1). The possibility of different scaling of $m_b$ and $M_s$ with depth, regional variability of $m_b$ and $M_s$, regional variation of $M_s$ path effects, and variations in magnitude yield relations are considered.

Guilhem et al. (T2.3–04) propose a modified surface-wave magnitude $M_s(V\text{MAX})$, which is characterized by allowing a broader range of frequencies (or periods) at which the amplitude can be measured and by extending its distance range, using both Love and Rayleigh waves, and performing calibration relative to $M_s$ at 20 seconds period. They apply this magnitude scale to earthquake–explosion discrimination using the $m_b$-$M_s$ criterion and conclude that the revised scale provides an increase in the number of events that can be subjected to the criterion.

Expert technical analysis by the IDC at the request of a State Party is mandated under the Treaty. Possible methods to be used for special technical analysis, and the basis on which these methods would be applied, are considered by Rozhkov et al. (T3.3–P10).

Guilhem et al. (T2.3–04) propose a modified surface-wave magnitude $M_s(V\text{MAX})$, which is characterized by allowing a broader range of frequencies (or periods) at which the amplitude can be measured and by extending its distance range, using both Love and Rayleigh waves, and performing calibration relative to $M_s$ at 20 seconds period. They apply this magnitude scale to earthquake–explosion discrimination using the $m_b$-$M_s$ criterion and conclude that the revised scale provides an increase in the number of events that can be subjected to the criterion.

The categorization of radionuclide spectra in IDC standard products is akin to waveform event screening in that the categorization is forming a conclusion as to the likelihood of the spectrum being potentially indicative of a nuclear explosion. A categorization scheme for noble gas spectra has only been applied since September 2012 and is likely to be refined. Schoepner (T2.4–P11) investigates possible noble gas categorizations that use statistical parameters based on three factors: first,
whether the observed concentration is abnormal for that station; second, the likelihood, based on ATM, that an elevated concentration results from a known non-CTBT-relevant source; and, third, whether there are isotopic ratios that point to a nuclear reactor source.

7.3.4 NOVEL METHODS FOR SOURCE IDENTIFICATION

Nuclear explosions are characterized by the emission of an electromagnetic pulse (EMP) via the Compton effect, in which photons are inelastically scattered by electrons. EMPs provide a discriminant between nuclear explosions and chemical explosions. However, non-explosive sources of EMPs are dominated by lightning strikes, which are omnipresent worldwide. Lipshtat et al. (T3.2-P6) note that a nuclear EMP is much shorter in time than that from lightning discharge, and this permits discrimination of the two EMP sources on the basis of their power spectra. Noting that EMP phenomena are routinely recorded, the authors propose an automated method of discriminating chemical from nuclear explosions by correlating infrasound observations with EMPs.
8 Capability, Performance and Sustainment

This Section deals with issues that relate to the quality, performance and sustainability of the CTBTO verification regime, or CTBT verification in general, and its overall effectiveness. The topics in this Section are best addressed from an independent standpoint, standing back and taking a broad approach. The overall capability of the verification regime, together with analysis of factors that have an impact on its performance and sustainment, are considered separately following the convention of modern performance assessment. This Section includes both performance-related methodologies and results from studies of the system’s capability, performance and reliability.

Contributions on the accuracy and validity of results obtained from methods to determine properties of the earth, or the validity of the methods themselves, are considered together with the description of those methods in Section 6. This applies, for example, to the determination of seismoacoustic wave-speed fields.

8.1 BACKGROUND SIGNALS AND NOISE

8.1.1 SEISMOACOUSTIC

Traditional sources of seismic noise are classified as naturally occurring (dominated by the oceanic microseismic noise peaks at periods of 2 s and 6 s) or anthropogenic ‘cultural’ noise, which is typically of high frequency with a relatively short range. An important new source of anthropogenic seismoacoustic noise is wind turbines, which are typically installed in large numbers to create the ‘wind farms’ that are now common in rural areas and which have become a significant problem at several IMS stations. Edwards (T2.3-P9) describes an experiment to monitor noise from wind turbines using a network of four temporary seismic and infrasound stations recording also meteorological data including wind speed, at a distance of between 125 m and 10 km. Power spectra are plotted and attenuation with distance is estimated.

Several experiments on noise from wind turbines conducted by, or on behalf of, the British NDC since 2004 are described by Bowers et al. (T2.3-O5). These studies have been designed to establish a regime for informing decisions on wind farm development in the neighbourhood of the Eskdalemuir auxiliary seismic array AS104 (EKA), UK. The authors develop a physics-based model for describing a worst-case noise scenario, validated by experiment. The main governing parameters of hub height, rotor diameter and distance from the station are integral to any application for wind farm development, and the estimated contribution of any new farm is added to the allowable budget that protects the station from increased noise. An exclusion zone of 15 km around the station ensures that close-in contributions do not dominate, and hence exhaust, the available noise budget.

A project described by Pasyanos et al. (T4.1-P29) includes a study of seismic noise at specific stations and notes the widely differing diurnal and seasonal variations observed. This contribution also considers the minimum number of stations required to detect, locate and identify a seismic source (see Section 8.2.1). Noise levels at IMS seismic stations in Indonesia are studied by Wibowo et al. (T4.1-P18), who present power spectral densities and find differences of up to 50 dB between noise levels among six stations, as well as significant diurnal differences at frequencies below 1 Hz.

The nature of noise at infrasound stations is studied by Ramanantsoa et al. (T4.1-O5), who use observations
at stations IS35 (I3SNA), Namibia, and IS47 (I47ZA), South Africa, to infer characteristics of infrasound noise. Substantial increase in noise during daytime, controlled by temperature, is a feature of lower frequencies, while seasonal variations at higher frequencies are controlled by wind speed. These lead to a conclusion that a temperature of $15^\circ$ and wind speed of 1.5 m/s are the thresholds above which noise has a major influence.

Noise data from broadband seismic and infrasound stations in East Antarctica are reported by Kanao et al. (T11.1−P2). The sources characterized include microbaroms derived from storms in the Southern Ocean, shock waves from airbursts of meteorites and regional earthquakes. Kramer and Marty (T13.1−P33) discuss the design and verification of wind noise reduction systems for mitigating their effects through station design or special data processing methods, where this is possible. Other sources of background are anthropogenic; in that case it may be possible for the sources themselves to be reduced or removed, but this is in general outside the control of the operator of the monitoring system. An example would be guidance against the siting of wind farms close to IMS seismic or infrasound stations.

In all four CTBTO monitoring technologies there can be a motivation for making the background itself a signal of interest. This applies when the presence of background degrades the ability to record Treaty-relevant signals. This could be temporary, as in the period following a very large earthquake described above. Alternatively it could be permanent, an example being the installation of a wind farm close to an IMS seismic or infrasound array that creates continuous background noise, degrading the signal detection threshold for distant sources.

A particular problem arises when repeated events that each create a temporary elevated background conspire to create a continuous, variable level of elevated background. In the case of very large earthquakes, the overall increase in background is caused by seismic signals persisting in the earth from the main shock and large aftershocks, but this background dissipates after a few hours. Since such earthquakes occur typically every few months, the overall effect is not permanent. This is not the case for multiple releases of radioactive xenon from nuclear facilities. Even though the radioactive xenon signatures resulting from a single puff release from the site of a nuclear facility disperse and die away according to the half-lives of the relevant isotopes, these tend to be significantly longer than the typical interval between such releases when all nuclear facilities worldwide are taken into account. The result can be a permanently elevated and variable background, resulting in a persistent degradation of the detection threshold for other (possibly Treaty-relevant) radioactive xenon signals.

The CTBTO is mandated by the Treaty to progressively enhance the effectiveness of its verification regime\(^{20}\), and the IDC is mandated to monitor the performance of each IMS facility and to take immediate action if the performance of any element of the IMS fails to meet the relevant requirements\(^{21}\). Moreover, States hosting IMS stations are required to ensure that these stations operate effectively as part of the verification regime\(^{22}\). Signal background can be a relevant factor and, with these requirements in mind, the CTBTO has taken steps to understand sources of background and to consider ways of mitigating the degradation of signal detection threshold that they cause.

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19 CTBT Article IV, paragraph 11.
20 CTBT Protocol Part I, paragraph 23.
21 CTBT Article IV, paragraph 6.
infrasound stations. Although strictly part of the data acquisition system (see Section 3.1.3) the design of such noise reduction systems depends on the characteristics of the noise to be suppressed.

### 8.1.2 RADIONUCLIDE

The focus of contributions on radionuclide background at SnT2015 is the radioactive xenon background derived from radioisotope production facilities. The emphasis on this results both from the importance of radioactive xenon in the identification of underground nuclear tests and from the realization that radioactive xenon emissions from radioisotope production facilities contribute substantively to the overall global background, bearing in mind that the background level is the determining factor in the network detection threshold (Section 8.2.2).

The characteristics of the global background of xenon-133 are considered by Achim et al. (T2.4-02), beginning with a reminder that medical isotope production facilities are believed to release a total of $\sim 10^{12}$–$10^{14}$ Bq per day, compared with nuclear power plants at $\sim 10^9$ Bq per day per reactor. The total release is seen to give rise to average typical background levels of >0.1 mBq/m$^3$ in the northern hemisphere, with higher levels in Europe and lower levels in the southern hemisphere. The authors point out that an MDC of 0.2 mBq/m$^3$ would result in detections on ~25% of spectra over the whole IMS network. Ringbom et al. (T2.4-013) report an update on a continuing study of the global radionuclide background that has now used 80,000 samples. Their results reveal that 7 of the 26 stations analysed have detections of the three isotopes xenon-133, xenon-133m and xenon-135 at the 99% confidence level; it is concluded that the majority of these detections are caused by isotope production facilities.

Hoffman et al. (T2.4-010) report on monitoring of radioactive xenon in the Canadian Arctic. By identifying examples of elevated concentrations at both of the stations RN15 (CAX15) and RN16 (CAX16) and at only one of the two stations, the authors discriminate sources of background including known sources in the form of radioisotope facilities. They point out that stations such as these two, that are far from any specific radioactive xenon sources, are especially valuable in monitoring the overall global background. The radioactive xenon background in Africa is studied by Ouédraogo (T2.4-P2) using the IMS stations RN13 (CMX13), Cameroon, and RN29 (FRX29), Réunion, and a temporary xenon laboratory in Burkina Faso.

Simulation of the dispersion of plumes of radioactive xenon from two medical isotope production plants are used by Schöppner (T2.4-P6) to demonstrate the value that stack monitoring data would have in understanding the radioactive xenon background. He concludes that daily or higher resolution release data would allow the background to be much better understood.

### 8.2 NETWORK CAPABILITY

#### 8.2.1 SEISMOACOUSTIC EVENT LOCATION THRESHOLDS

IMS network detection thresholds may be expected to improve as the remaining IMS stations are installed and their data begin to contribute to IDC standard products. Ben Horin and Bregman (T4.1-P16) estimate the current threshold for seismic events in the Middle East region and estimate predicted improvement when remaining stations are operational in that region. They point out that data from stations not yet operating will need to be gathered for a period before travel-time, amplitude and other corrections can be calculated (this is referred to as ‘event location calibration’) to maximize their effectiveness.

Posyanos et al. (T4.1-P29) combines noise and signal amplitude measurements for regional phases to produce network capability maps for eastern Asia and North America. The author also considers the minimum number and quality of signals needed to detect, locate and identify an event in different circumstances. Carvalho et al. (T4.1-P04) describe efforts to decrease the detection threshold in the Brazilian Amazon region by installing additional stations and provide estimates of resulting improvement.

The network event location threshold is conventionally estimated by observing the magnitude below which a plot of the logarithm of cumulative event number against event magnitude (Gutenberg–Richter curve) ceases to be linear. Storchak et al. (T3.3-01) show such a curve plotted globally for the REB, the ISC Bulletin and the United States Geological Survey (USGS) National Earthquake Information Center (NEIC) listing (Figure 8.1). As expected, the REB threshold lies between the other two.

Network detection capability is also relevant to a seismic network used for OSI. Gestermann et al. (T2.1-02) consider the detection capability of the SAMS network as deployed in IFE14. The network recorded three small
explosions detonated to simulate aftershocks, as well as three microearthquakes and one or possibly two quarry blasts. An event location threshold (assuming detections at two microarrays) of magnitude between −1.7 to −0.2 $M_L$ is estimated depending on location within the inspection area. The planned objective of −2.0 $M_L$ was not achieved, but it is pointed out that not all the available microarrays were deployed on account of inaccessible terrain and time constraints.

For infrasound stations, the detection threshold of individual stations can vary considerably according to noise derived from local winds, and also according to temperature, whose effect is seen in a diurnal variation (as presented in section 8.1.1). Network detection capability is also influenced markedly by stratospheric wind direction since this creates a large directional variation in detectability that is mainly seen as a seasonal variation. Ramanantsoa et al. (T4.1−O5) consider these effects on IMS infrasound stations IS33 (I33MG), Madagascar, IS35 (I35NA), Namibia, and IS47 (I47ZA), South Africa. Randrianarinosy et al. (T1.1−P8) also consider the performance of the same three stations.

### 8.2.2 RADIONUCLIDE NETWORK CAPABILITY

It is pointed out by Achim et al. (T2.4−O2) that, when the IMS noble gas network was being set up, the impact of industrial nuclear facilities was not clear, whereas it is now known that daily releases of xenon-133 from such facilities (figure 8.2) contribute a significant worldwide background that can degrade network detection capability. The authors present a study aimed at quantifying this effect; they assess the IMS noble gas network coverage depending on a range of source terms from atmospheric nuclear tests. Loss of coverage is minimal for very low and very high source terms because of non-detectability and universal detectability respectively, but network coverage loss reaches up to 10% at a source term of 10$^{13}$ Bq.

Ringbom et al. (T4.1−O1) adopt a different strategy to estimate the capability of the IMS noble gas network. They study the signals predicted by ATM to be recorded by the current network of stations from a hypothetical globally distributed set of nuclear explosions. In a study based on xenon isotope ratios from 144 hypothetical nuclear explosions, they conclude that the existing background would cause a false rejection of a release from a 0.1 kT test in 11% of the detectable cases, assuming all stations had the same background as a high-background station.

Another study of IMS noble gas network capability is offered by Schoeppler (T4.1−O6). A scenario defining the yield, xenon-133 release, atmospheric transport duration and station network is chosen, and calculations are made of the detectability of the radioactive xenon and the ability to locate the source using ATM backtracking. Contour maps show results for these parameters as a function of source location (figure 8.3), and it is noted that the ability to detect and the ability to locate are not necessarily correlated. It is also concluded that reduction in background would greatly increase regional capabilities,
and that larger source terms (corresponding to greater leakage of radioactive xenon to the atmosphere) greatly increases both detection and location capability. Among other conclusions it is noted that noble gas systems at the 20 equatorial IMS radionuclide stations would fill the largest detection gaps.

8.3 PERFORMANCE, QUALITY AND VALIDATION

Most contributions on the performance of IMS stations and IDC processing take a whole-pipeline approach by examining the quality of the final reviewed products that is achievable using the data and automatic products available for analysis. In such an approach there are various ways of measuring quality, including comparison with external products and spot checking of reviewed waveform events or radionuclide spectra. Factors contributing to quality shortcomings can then be investigated and can have many origins.

For the IMS primary seismic arrays, Kebede and Jonathan (T4.1–P17) look at the changes to the automatically measured parameters for signal arrival times, azimuths and slownesses made by analysts. The need to manually adjust such parameters can arise in many ways, including incorrect station or processing parameter values (colloquially referred to as incorrect ‘tuning’), incorrect station-specific corrections, and processing errors or deficiencies. Using data in the IDC databases for 2014, the authors find significant differences, including a wide range of differences between stations; this latter result suggests that station tuning is a significant quality issue. Pearce (T3.3–P37) also studies the changes made by analysts, but focusing on trends from 2000 to 2013 for all IDC waveform signals, and including a wider range of signal attributes (e.g. FIGURE 8.4). He makes 12 observations that indicate quality shortcomings, and where these are not understood suggests further investigation.

Quality assessment against an external benchmark is reported by Koch (T4.1–P20), who compares seismic event locations in the REB with those in the ISC Bulletin. The author concludes that REB quality measured against the ISC Bulletin was generally maintained between 2008 and 2012 but observes a slight reduction in the percentage of events with a location difference of less than 1° or 2°; changes that were made to the ISC location algorithm are suggested as a possible cause. The author points out that these two bulletins are not independent, because the REB events contribute to the ISC Bulletin following

FIGURE 8.3
Simulation of IMS noble gas network coverage. The average number of detections predicted for each source location, based on simulation of a 1 kt nuclear explosion source and a network of noble gas stations corresponding to the black circles (darkest shade for 1 detection to lightest shade for 10 detections). Deficiencies are observed in the equatorial zone (due to background and equatorial winds) despite the relatively uniform station coverage. From Schoeppner (T4.1–O6).
a decision of the PrepCom to make the REB available to the ISC\textsuperscript{22}. It is seen that the number of REB events rejected by the ISC for inclusion in its bulletin has risen slightly since 2008.

The assessment of REB quality against the ISC as an external benchmark is facilitated by a CTBTO link to the ISC database described by Storchak et al. (T3.3-01), whose stated objectives include specifically designed software tools for access to the ISC Bulletin, as well as to the station registry, ground-truth event database and other data sets. Enhancements to this link are described by Lentas et al. (T4.1-P8) and include a new waveform fetching scheme based on detection threshold estimates.

An integrated waveform quality tool has been developed by Brown et al. (T3.3-P35) to analyse seismic, hydroacoustic and infrasound data quality down to the sample level. The quality issues addressed include frame authentication, timing errors, missing data, constant values, single-sample spikes and unusual noise conditions. Removable data masks are constructed for quality conditioning, and all actions are recorded in quality-related database tables. Among the benefits of rigorous data quality monitoring is that it can facilitate more extensive use of negative evidence (such as the non-detection of a signal) when building events in the future.

A framework for the evaluation of waveform detection software is described by Charbit and Mialle (T3.3-P5). Although initially aimed at infrasound detectors it is applicable to other waveform types including seismic.

Randrianarinosy et al. (T1.1-P8) consider the performance in terms of noise level under different temperature and wind conditions of three IMS infrasound stations in Africa: IS33 (I33MG), Madagascar, IS35 (I35NA), Namibia, and IS47 (I47ZA), South Africa. Following a recommendation to consider more detailed infrasound sensor specifications to achieve optimal operation of the infrasound network for detecting CTBT-relevant events, Daury et al. (T3.1-P22) describe a project that is designed to obtain detailed specifications on different sensors by issuing them to several laboratories whose results are then compared. Parameterization of self-noise, dynamic range, sensitivity, frequency response and pass band are included.

The Fukushima Daiichi nuclear power plant accident highlighted the need for the CTBTO to develop procedures to transport radionuclide samples whose

\textsuperscript{22} Decisions adopted by the PrepCom: CTBT/PC-17/1/Annex II, paragraph 19; CTBT/PC-19/1/Annex II, paragraphs 22 and 23; and CTBT/PC-21/1/Annex II, paragraphs 17 and 18.
concentration brings them under the provisions of the IAEA Safety Standards on Regulations for the Safe Transport of Radioactive Material 2009 (so-called ‘hot samples’). Duran et al. (T4.1–P1) describe the development of relevant procedures, and report on a performance exercise designed to test these procedures using spiked samples that were sent to IMS radionuclide laboratories participating in the exercise.

Gamma spectrometers have an established use in monitoring radiological hazards by atmospheric sampling in view of their low cost, ease of measurement and well-understood technology. The performance of four gamma spectrometers using different innovative detector types is compared by Bell et al. (T3.2–P3), with a view to assessing their suitability for OSI applications. No clear preference emerges from the study, but this is seen as one step in a programme of comparative study focused on potential future OSI applications for gamma detectors.

One aspect of performance monitoring important in capacity building and promotion of the CTBTO is the use of IMS data and IDC products by authorized users at NDCs of States Signatories. Statistics and trends are presented by Phiri et al. (T4.1–P11) for the decade 2005–2014. They compare the evolution in the number of States Signatories in each geographic region that have opened an NDC and have a secure signatory account (which shows a large relative increase in Africa) with the evolution of the quantity of IMS data and IDC products being retrieved (FIGURE 8.5). In a targeted investigation, Phiri et al. (T4.1–P6) compare the retrieval of IMS data and IDC products by States Signatories that also host IMS stations with the retrieval by those that do not. The authors find that those hosting IMS stations have progressively become much more active in their access to IMS data and IDC products, by up to a factor of 7, and that there is an increase even for States hosting only IMS auxiliary seismic stations, even though these stations are not supported financially by the CTBTO (FIGURE 8.6).

One recent performance-related development at the IDC is the continuous automated testing system that provides automated unit testing and regression testing of automatic software components. In the future it is
proposed to extend the system to incorporate stress
testing. A description and status report are given by
Dricker et al. (T4.1-P9).

Annual NDC Preparedness Exercises (NPEs) provide
an opportunity for NDC-led performance measurement
of NDCs. These exercises have included hypothetical
scenario events that utilize real IDC signals and events
combined with simulated data, usually radionuclide
observations. Ross et al. (T2.2-O5) describe the scenario
used for the 2013 NPE, designed as a complex scenario
using data from multiple IMS technologies and offering
opportunities for data fusion studies. Gestermann et al.
(T2.2-P19) describe their seismological investigation under
the 2013 NPE.

8.4 SUSTAINMENT

Mascarenhas et al. (T4.3-P5) identify the most important
issues that pose challenges in the maintenance of data
flow from IMS stations including electric power transients,
grounding and lightning protection, and shipping and
handling of radionuclide detectors. They describe
developments in preventative maintenance designed to
mitigate these issues, including uninterruptable power
supplies (UPSs) and UPS battery recapitalization, the
standardization of data acquisition systems for manual
radionuclide particulate stations, and the station-
specific documentation project. Overall, preventative
maintenance planning is seen as a crucial factor.

Benicsak et al. (T4.3-P6) describe the CTBTO system for
logistics support analysis, which is designed to achieve
optimum cost-effective sparing policies for IMS stations
and to have an impact on the design of new stations and
the planning of major station upgrades.

A tool for failure mode analysis for the IMS
particulate and noble gas radionuclide networks is
described by Wernsperger et al. (T4.1-P2); the aim is to
increase detector up-time. Among the factors focused
on are sparing policy, streamlining and enforcing
of detector set-up procedures, and technology
improvements in cooperation with suppliers. The quest
for minimum downtime and optimized maintenance
policy is also addressed by Thursby et al. (T4.3-O2).
They describe fault tree analysis as an approach to the
description and management of troubleshooting and
maintenance, applied to seismic and infrasound stations.
Improvements in the efficiency of station maintenance
using a maintenance management information system
are explored by Sillivant and Sautter (T4.3-O1). The
presentation by Zasimov et al. (T3.4-P1) addresses the
sustainment and upgrading of IMS stations hosted by
the Russian Federation.
9
Sharing of Data and Knowledge

INTRODUCTION

Verification of the CTBT after it enters into force will be the responsibility of CTBTO Member States. It is therefore essential that all Member States have the capacity to play their full part in both the technical and the political aspects of the verification regime. In particular, the 51 Member States on the CTBTO Executive Council will receive challenges under the Treaty and will have to take decisions on how to proceed, including the consultation and clarification procedure\(^\text{23}\), and potentially whether an OSI should be conducted.

For these purposes the CTBTO has a major role in building global capacity in CTBT verification-related science and technology. This goes hand in hand with the training of station operators, who are responsible for operating IMS stations and whose work is essential to ensure the reliable flow of high-quality data to the IDC and to States Signatories. Contributions in support of these aims are included in this Section.

9.1 BUILDING GLOBAL CAPACITY

A review of the impact of the CTBTO capacity-building programme on global NDC engagement is given by Phiri et al. (T4.1-P16). Statistics are given showing that an additional 37 States Signatories have secure signatory accounts between 2008 and 2015, even though only 8 new States signed the Treaty in that period. Graphs showing an increase in the amount of IMS data and IDC products being accessed by NDCs during that period are also presented. The capacity-building programme, together with the installation of capacity-building systems using European Union and national voluntary contributions and with promotion of the ‘NDC-in-a-box’ software for NDCs, are seen as factors contributing to these results.

An NDC’s perspective of the capacity-building programme is given by Madu et al. (T4.1-P30), who analyse the results of a questionnaire sent to 30 NDC participants in the Africa region. As well as reporting positive trends in NDC activity, some challenges are identified.

Capacity building in East Asia has benefitted from a series of East Asia Regional NDC Workshops (EARNWs), which have each included a ‘common exercise’ in which participating NDCs are asked to study a specific event of interest in a verification context and to present their results for comparative study at the workshop. Four SnT2015 contributions relate to the common exercise in the 2014 EARNW held in Ulaan Baatar, Mongolia. Jih and Kalinowski (T2.2-P21) describe the exercise and summarize the results presented on seismic data by the seven teams that participated in the exercise. Seismic and infrasound observations are discussed by Fujii et al. (T2.2-P4). Yonezawa et al. (T2.2-O2) describe the preparation of fictitious radionuclide particulate data used in the exercise and present associated atmospheric transport simulations. A summary report of ATM and radionuclide analysis for the event is presented by Yonezawa et al. (T2.2-P1).

The NDC-in-a-box integrated data acquisition, processing and analysis platform provided by the CTBTO to NDCs is seen as a crucial component of the CTBTO capacity-building programme. The NDC-in-a-box has been extended and further developed, with financial support from the European Union, and is the subject of a presentation by Becker et al. (T3.3-O2). Among

\(^{23}\) CTBTO, Article IV, paragraphs 29–33.
the developments described are the integration of the SeisComP software, providing real-time automatic processing capability for waveform data, as well as the ability to import and update IMS station configuration data into an NDC processing pipeline and to integrate IDC processing results. Among other improvements reported is a new infrasound detector and viewer. Becker et al. (T3.3-P11) give the timeline of the enhancement project and describe the extensive testing, including testing by users at NDCs who participated in meetings to provide feedback before the software was released.

9.2 COLLABORATION IN TRAINING INITIATIVES

Since 2009 the Ministry of Foreign Affairs of Norway has been supporting joint work between NORSAR of Norway and Kazakhstan, including the establishment of the International Training Center in Almaty, at the NDC of Kazakhstan. Mikhailova et al. (T4.1-P12) explain that the initial aim was to train specialist seismologists for the NDCs of the former Soviet States of Central Asia. They describe later developments including workshops on the seismic monitoring of Central Asian countries, the scanning and digitizing of historical analogue seismograms, technical support for digital seismic stations, and Geotool software for data processing and scientific research. Geotool is the software provided by the CTBTO to NDCs for the processing and analysis of IMS waveform data and is part of the NDC-in-a-box software. A quite different aspect of training is considered by Zusimov et al. (T3.4-P1), who consider the training of OSI inspectors.

An assessment of the benefits accrued to the NDC of Ghana from the CTBTO Capacity Building Initiative is given by Amartey (T4.1-P9). The author also describes local training courses held within the country in order to propagate knowledge on verification methods acquired at CTBTO training courses to additional NDC staff, as well as to students, national service personnel and other stakeholders.

Most contributions related to training and education were presented at the Academic Forum and cover not only science and technology but also policy, ethics, international relations and legal aspects of the CTBT. Building on CTBTO Academic Forums previously held outside the SnT process, the broader aim of the Forum is to enhance the nexus between educational tools in diplomacy and science and to foster interaction among academics from various CTBT-related disciplines.

Contributors describe CTBT-related courses in their home institutes, and these poster presentations offer an insight into relevant training and educational initiatives in a number of countries.

Beginning in Japan, two posters describe courses at the University of Nagasaki. Hirose (AF-P14), from its Research Center for Nuclear Weapons Abolition, coordinates a course for up to 90 students that includes modules on peace and international society; the atomic bomb and Nagasaki; bomb survivors and medical assistance; literature, arts and nuclear weapons; and the law and politics of nuclear disarmament. Its theme is to take a policy-oriented approach to nuclear weapon abolition through scientific and interdisciplinary analysis. Ishizuka (AF-P3), who is Assistant Professor of International Law in the School of Humanities and Social Sciences, reports on a seminar on international law for undergraduate students in that School. He suggests that the CTBT is often regarded in Japan as a Treaty that has not entered into force, with its current IMS and IDC capabilities overlooked.

Role playing in political negotiation is the subject of a presentation by Reed (AF-P1) of the Department of Political Science at the University of Massachusetts, USA. The university course “Citizenship in the Nuclear Age” utilizes a role playing simulation developed under the International Communication and Negotiation Simulations project of the University of Maryland, USA. The role playing comprises international negotiations and their outcome following a fictitious large explosion at Yongbyon, DPRK, with debriefing and critical reflection reported as providing a particular educational benefit. Also in the USA, several courses at the Sam Nunn School of International Affairs, Georgia Institute of Technology, are reported by Dallas (AF-P4), covering policy, proliferation, science and technology as drivers of international policy.

Two initiatives are reported from the Russian Federation. Malygina (AF-P12) of the School of International Relations at St Petersburg State University reports on two courses on arms control: “Russia and International Arms Control Regimes” and “Contemporary Problems of the Evolution of International Arms Control Regimes”. At the Ural Federal University, Mikhailenko (AF-P5) of its Department of International Relations describes a course entitled “Multilateral Verification and Collective Security” that is integrated into bachelors and masters degree programmes, with a special CTBT course for masters students.

An introductory science course designed to enable policy makers to communicate with scientific
experts on CTBT-related topics is offered by the James Martin Center for Nonproliferation Studies (CNS) at the Middlebury Institute of International Studies at Monterey, USA, as reported by Dalinoki-Veress (AF-P8). This course, comprising 30 two-hour lectures, covers physics, chemistry and life science topics in nuclear treaty verification using avatar-based virtual reality for the understanding of weapons of mass destruction, in support of a master’s in Non-Proliferation and Terrorism Studies. A weekend workshop for masters students at the CNS involves role playing of the CTBTO Executive Council, and is described by Moore (AF-P21).

After a term as an executive director of the Newly Independent States Representative Office of the CNS, Aben (AF-P6) of Nazarbayev University, Kazakhstan, was motivated to promote CTBT awareness in that country. With the support of the CNS, courses at a number of universities are reported, including those organized at the Al-Farabi Kazakh National University and the Shakarim State University of Semey; these cover international relations, political science, nuclear physics and other subjects.

An annual summer school on non-proliferation and nuclear security at the Odessa I. I. Mechnikov National University, Ukraine, is described by Sirnovets (AF-P24). In addition, two courses, entitled “Military–Political Aspects of International Security” and “Preparing Nuclear Nonproliferation: National and Regional Aspects”, are introduced.

Dimitrov (AF-P15) describes a course within the master’s degree programme on nuclear security in the Department of National and Regional Security, University of National and World Economy in Sofia, Bulgaria, launched in October 2015. The author explains that it benefits from an agreement with the IAEA under its International Nuclear Security Education Network.

Liu (AF-P8) from the School of International Relations at the Beijing Language and Culture University in China reports on a course on arms control and international security given to graduate students. Courses on China’s trade and security policy and on China’s non-proliferation and export control policies at the National University of Singapore are reported by Wu (AF-P11).

The University of British Columbia, Canada, is the home of a course entitled “Focusing on the Nexus of Science and Politics” as reported by Sers and Yedlin (AF-P13). This is reported as a trans-disciplinary course for both political science students from the Faculty of Arts and engineering students from the Faculty of Applied Science. It is reported that this course will be moved to the edX edge learning platform, a massive open online course (MOOC) provider established by the Massachusetts Institute of Technology and Harvard University, USA. Taylor et al. (AF-P19), also from the University of British Columbia, Canada, describe the promotion of social media for the awareness of CTBT-related issues and refer to a related course “Living with Nuclear Weapons” from 2013 given to political science students.

Three contributions are from Africa. First, Simon (AF-P10) describes relevant courses in geophysics for undergraduate and masters students at the University of Botswana, using e-learning and materials from the CTBTO Knowledge and Training Portal and taking advantage of IMS stations in Botswana; this is in addition to promoting awareness of CTBT among general audiences. Second, Mdoe and Sungita-Mdoe (AF-P18) report the need to strengthen nuclear science education in Tanzania. They refer to the Tanzania Atomic Energy Commission and the University of Dar es Salaam and note that Tanzania is the host to IMS radionuclide station RN64 (TZP64). Third, Kadir and Ezomo (AF-P16) describe prospects and challenges associated with integrating CTBT-related topics into academic curricula in the University of Benin, Nigeria.

Vargas Elizondo (AF-P20) from the Costa Rica Institute of Technology reports on the use of materials from the CTBT Advanced Science Course for teaching and role playing. The challenge of integrating CTBTO verification technologies into geophysics lectures is described by Castillo (AF-P22) of the University of Innsbruck, Austria. IFE14 as a case study for joint team training is considered by Peldszus (AF-P23) of the Institute for Advanced Study on Media Cultures of Computer Simulation at the Leuphana University of Lüneburg, Germany.

Relevant courses at the Institute of Peace and Conflict Studies, New Delhi, India, are reported by Neog (AF-P25). The author describes the fifth annual residential young scholars’ workshop as given by 14 senior staff from academia, institutes and, for the first time, the military. Collaboration is described with the National Institute of Advanced Studies, Bangalore, with the course covering the science and policy of nuclear weapons and nuclear power. The author suggests that there is a lack of public debate in India related to the CTBT. Nazir (AF-P2) from the South Asian Strategic Stability Institute (SASSI) University describes a course that forms part of the masters programme for International Security at the SASSI University, Islamabad, Pakistan.

Finally, school students in Ireland are targeted by the Seismometers in Schools Programme described by Blake...
Virtual Data Exploitation Centre

The virtual Data Exploitation Centre (vDEC) was established in 2012 with a view to supporting the goals, mandated under the Treaty\(^\text{24}\), of continuously improving the verification regime and exploring the potential of additional monitoring technologies. At its Thirteenth Session in 2001, the CTBTO PrepCom reaffirmed\(^\text{25}\) these goals, adopting the following text from its verification working group (WGB):

> “WGB recognizes that, for purposes of the development of the IMS and IDC, the PTS is interested in interaction with the international scientific community. Therefore, in order to develop and optimize the IMS and the IDC, the PTS could request the contributions of organizations for scientific purposes. Such organizations might need to have access to IMS data and IDC products for the purpose of the contracted scientific studies. IDC products for specific verification cases are not involved.”

In establishing the vDEC, it was anticipated that a broadened use of IMS data would ensure that more experts would become involved in the further development of methodologies that could ultimately be incorporated into IDC processing in order to further enhance monitoring capabilities. The vDEC provides a means of making IMS data available to scientists and engineers in universities and similar organizations that do not have access by virtue of being a CTBT National Data Centre establishment or an IMS station operator establishment and that do not already have a contractual relationship with the CTBTO PrepCom to develop software or perform other tasks that require data access.

The vDEC is therefore closely related to the SnT process and provides an additional means of reaching out to the academic community. The vDEC can be useful for researchers who are working on new algorithms relating to nuclear explosion monitoring and offers a platform for researchers to develop and test their work on IMS data, perhaps combined with other data provided by the researcher. The vDEC also offers opportunities to investigate the potential wider use of IMS data for civil and scientific purposes. In this regard, the vDEC can be useful to those who wish to explore IMS data for a purpose not directly connected with nuclear explosion monitoring, but which can still benefit the verification regime indirectly through a greater understanding of the data being collected, as well as of the data quality and of the range of noise and signals contained within the data.

Data from all four CTBTO monitoring technologies are available in the vDEC archive. This includes continuous seismic, hydroacoustic and infrasound data collected over an extensive time period, plus the results of the processing of radionuclide gamma-ray spectra and auxiliary meteorological data recorded at IMS radionuclide stations. Also provided are results of IDC processing that are used to generate IDC standard products, such as the waveform SELs and REBs. This offers the potential for researchers to compare results of IDC processing with those of other methods being developed by researchers.

Since the inception of the vDEC, more than 70 zero-cost contracts have been entered into with research organizations in over 20 countries. The majority of these projects concern developments in nuclear explosion monitoring. Topics include machine learning techniques for infrasound signal classification; quality assessment of meteorological data collected at IMS radionuclide stations; studies on sources of broadband seismic noise; discrimination of earthquakes and explosions near nuclear test sites using regional high-frequency data; improvements in the visual analysis of seismic data; and modelling of one month of radioactive xenon detections at IMS stations.

This last example was framed as a challenge to experts of ATM. A number of research establishments participated in this exercise, including nine that had signed a vDEC contract by February 2017. This demonstrates the potential of applying the vDEC to facilitate issuing “challenges” to the research community to undertake specific processing, analysis or interpretation tasks on a particular IMS data set. Such challenges are commonly found in the industrial research community as a means to advance difficult topics.

Projects exploring civil and scientific uses of IMS data include a global catalogue of volcanism using the IMS infrasound network; a study of radioactive materials measured after the Fukushima Daiichi nuclear power plant accident in Japan in March 2011; the seismic recording of tsunamis; the detection of submarine volcanic activity using T-phase observations at IMS stations; infrasound signatures from thunderstorm activity, and several projects that focus on the provenance and behaviour of marine mammals. (FIGURE 9.1), whose sounds are often recorded at IMS hydrophone stations.

FIGURE 9.1
Humpback whale in the ‘singing’ position. Several projects on the vDEC have used IMS data to study the behaviour and migration of marine mammals.

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\(^{24}\) CTBT Article IV, paragraph 11.
\(^{25}\) CTBT/PC-13/1/Annex II, Section III A (2) (20)
(AF-P17). As well as installing low-cost seismometers in schools, the programme educates primary and secondary school teachers on the installation of these seismometers and the use of data recorded by them.

9.3 NATIONAL EXPERIENCES

There are many ways in which the data, products, training programmes and other outputs of the CTBTO can have an influence on NDCs and on other stakeholders around the world. The following describes a range of examples reported in SnT2015 contributions, many of which are also referred to in other parts of this report.

In many cases authors report that interaction with the CTBTO has had direct consequences for the development of an NDC. This was the case in Suriname, where the NDC was established in 2012 with a CTBTO capacity-building system as reported by Amierali (T4.1-P14). Data processing at the NDC of Ukraine using Geotool and SeisComP is described by Kolesnykov (T3.3-P9), and improvements in the processing of seismic array data at the NDC of Kazakhstan using updated software from NORSAR, Norway, is described by Gordiyenko et al. (T3.3-P15). Ways in which the Malaysian NDC, first established in 2005, has benefitted from collaboration with the CTBTO are described by Abdul Rashid (T4.1-P24); these benefits include the building up and improvement of data analysis capabilities, training for NDC staff, identifying gaps in competency in both waveform and radionuclide technologies, and participation in the NPE in 2013. The Tunisian NDC reports specifically on its participation in the NPE of 2013 in a poster by Ben Ltaief Ép Amouri (T2.4-P14); the author describes participation in both waveform and radionuclide aspects of this exercise.

In other cases interaction with the CTBTO has promoted the development or improvement of national networks of seismic stations. For example, the national seismic network of Namibia, installed and operated by its Geological Survey, has an operation and maintenance plan that closely follows that of the IMS infrasound station in Namibia, IS35 (I35NA), which is also operated by the Geological Survey of Namibia. This is pointed out by Titus et al. (T4.1-07). For Belarus, the optimization of the national seismic network for seismic hazard purposes is described by Aronov et al. (T4.1-P28). Belyashova (T2.4-P13) describes the determination of a local magnitude scale for Uganda using a temporary broadband network and the IMS auxiliary seismic station AS103 (MBAR), Mbarara, and Margocova et al. (T1.5-P23) describe a study with similar goals in Slovakia.

In some cases, studies of seismic wave speed or attenuation have been fostered. Nyago (T1.5-P13) describes the determination of a local magnitude scale for Uganda using a temporary broadband network and the IMS auxiliary seismic station AS103 (MBAR), Mbarara, and Margocova et al. (T1.5-P23) describe a study with similar goals in Slovakia.

In many countries there is a strong relationship between CTBT activities and national needs in natural hazard monitoring and mitigation. Responsibilities for assessing a wide range of natural hazards in Georgia are presented by Tsereteli et al. (T1.5-P5), with emphasis on estimating earthquake hazard. Earthquake and volcanic hazard in Iceland are the focus of a presentation by Jonsdottir et al. (T1.5-P5). The use of IMS stations together with other seismic stations in Kazakhstan to improve the national seismicity map is described by Aristova et al. (T1.5-P48). Amponsah and Osae (T1.5-P9) describe the use of IMS data to determine earthquake locations in Ghana in support of seismic hazard monitoring. A study of macroseismic effects of recent large earthquakes in Uzbekistan is presented by Usmanova (T1.5-P4), and for the radionuclide technology the atmospheric radioactivity monitoring system in Bulgaria for emergency response is described by Veleva et al. (T1.5-P17). Volcano monitoring in the Comoros Islands is described by Modi (T1.5-01).

An unusual application of IMS data is presented by Tiendrebeogo et al. (T1.5-P9). They show that signal detections at the primary seismic station PS26 (TORD), Niger, and the infrasound station IS17 (I17CI), Côte d’Ivoire, are consistent with the location of the ground impact of Air Algérie flight AH5017, which was lost on 24 July 2014.

Many national experiences relate to education and training. For example, Amartey (T4.1-P8) describes the strengthening of local verification capacity in Ghana arising from the CTBTO capacity-building programme. Other national experiences related specifically to training are described in Academic Forum posters reported in section 9.2.

9.4 DATA AND INFORMATION PLATFORMS

An important focus in the area of data and information platforms has been the digitization and archiving of historical analogue seismograms. There are a
number of motivations, including the value of nuclear explosion seismograms in the development of source discrimination methods and the need to maximize the historical seismogram archive in support of new methods of detecting and locating events.

An initiative to digitize 10,000 historical seismograms of nuclear explosions is a collaborative effort between the NDC of Kazakhstan and the Lamont-Doherty Earth Observatory of Columbia University, USA, described by Sokolova et al. (T2.3−P12). These included both photographic and pen-and-ink records from about 100 stations (Figure 9.2). Indeed, a workshop on the digitization of historical seismograms was held at the NDC of Kazakhstan under the training programme supported by NORSAR as reported by Mikhailova et al. (T4.1−P12). Sokolova and Kopnichev (T3.2−P16) describe a study of historic seismograms of nuclear explosions from the Novaya Zemlya test site recorded at stations of the former USSR. Digitized analogue seismograms are used to determine seismic magnitudes and the values of waveform discriminants such as Sn/Pn amplitude ratio for many of these explosions. The creation of a database of digitized seismic and infrasound recordings from atmospheric nuclear explosions recorded in Kazakhstan is presented by Sokolova (T2.3−P3). Unique recordings from the Talgar Observatory near Almaty, Kazakhstan, which was installed in 1960, are included in this database.

Another project to digitize historical seismograms from stations in Kyrgyzstan is described by Berezina et al. (T2.2−P18); this also utilizes the collaboration referred to in the above contributions. An additional motivation mentioned is that the stations in Kyrgyzstan are located at regional distances from the former nuclear test sites at Semipalatinsk (former USSR), Lop Nor (China), Pokharan (India) and Chagay (Pakistan), as well as from the sites of many peaceful nuclear explosions in the former USSR.

The Incorporated Research Institutions for Seismology (IRIS) in the USA offers one of the largest publicly available archives of seismological data. Woodward et al. (T3.1−P12) describe the continuing EarthScope project and in particular the USArray temporary deployment of a transportable array of seismic and infrasound detectors, which first occupied sites sequentially across the continental USA and was then deployed to Alaska. It is reported that the data availability of USArray stations routinely exceeds 99%. Also described is the IRIS Wavefields Initiative, providing well-sampled wavefields for waveform imaging. All data are openly available from IRIS, including infrasound detection lists and an infrasound reference event database.

In support of quality assessment of the REB, a link has been established between the ISC database and IDC authorized users, with software tools to retrieve information including ISC event locations and the contents of the ISC Bulletin. This is described by Lentas et al. (T4.1−P8).

New methods of seismic signal detection and event location, in particular those employing waveform cross-correlation, require rapid access to massive seismic data archives to extract waveforms from potentially co-located or otherwise similar events. Young et al. (T3.3−P27) describe a method for the rapid search of large seismic data archives using kernalized locality-sensitive hashing (KLSH) (Figure 9.3).

Refinement of wave-speed models is a major topic in support of seismic event location methods. The functionality to incorporate different three-dimensional models into the ISC event location software described by Bondar (T3.3−P39) provides an environment where the validity of different methods can be compared and their errors estimated.

Following the Indonesia tsunamiigenic earthquake of 26 December 2004, the CTBTO PrepCom agreed to the real-time transmission of IMS seismic and hydroacoustic data to tsunami warning centres recognized by the Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational,
Roblin and Kalinowski (T1.5–P47) report on the status of this agreement, the list of centres receiving such data under this arrangement, and a summary of data quantities. It is pointed out that tools are available from the CTBTO to convert IMS data to the miniSEED format preferred by most tsunami warning centres.

Also for tsunami and earthquake warning, a web-based platform for accessing data from the sub-sea ocean-bottom network DONET off Japan is described by Takaesu et al. (T1.5–P18). They describe a real-time earthquake information system designed for civil government and for scientific researchers.
Closing: Conference Outcomes and Continuous Improvement Through the SnT Process

Our Executive Secretary, Dr Lassina Zerbo, could not be here today. So on behalf of the Executive Secretary, I would like to extend his thanks—to you the attendees, speakers, panellists, scientists and participants for your active involvement here this week. Again on behalf of the Executive Secretary, I would like to extend his invitation to all of you to return in two years for SnT2017 (and bring more of your colleagues).

This SnT conference was bigger than last and while we look forward to the next being bigger still, quality is our goal. The SnT conferences are a component of our continuous improvement process. They help us identify emerging technologies and methods that can be applied to improve test monitoring.

We added a new theme this year—Performance Optimization. This theme will have growing relevance as we sustain and recapitalize the IMS and the IDC in the years ahead.

There are far too many noteworthy highpoints to acknowledge in this talk—otherwise I would have to talk as long as all the sessions of the past several days. I will simply note a couple of items from the extensive list of highpoints gathered by CTBTO scientist as they interacted with you and my own observations.

I saw a poster telling of recent progress identifying GT5 (ground truth) seismic events in Brazil. This poster noted the progress resulted from Latin American training and engagement to promote the use of the RSTT code. This code was presented at an earlier SnT conference, and as a result of collaborations fostered at that conference, several Latin American institutions came together to share ideas and collaborate. I’m pleased to see continued positive outcomes of that work begun at an earlier SnT conference being presented at this SnT conference. This reinforces the notion that the conferences are not simply events that take place every two years, but are integral parts of an ongoing effort to engage and advance the technology of monitoring.

Numerous civil and scientific applications were presented. Let me reiterate—civil and scientific applications are truly a win–win:

• They result in better methods: Our noise is someone else’s signal. If scientists discover methods to identify ‘civil signals’ in CTBT data, then we can use their methods to remove that noise, allowing us to peer deeper into the data for signals of monitoring interest.
• They make more practitioners aware of this data and these become potential recruits for the CTBTO and National Data Centres.
• Civil and scientific applications result in better data quality because the more eyes there are on the data, the more likely it is that discrepancies are rapidly identified and corrected.
• These applications demonstrate value and immediate utility to the States Signatories that support the Treaty. Obviously the monitoring regime has value as a cornerstone of peace and stability—but States Signatories have invested more than $1 billion in a system we all hope will never have to detect another nuclear test—so showing continuous societal benefit is an immediate return on investment that States Signatories can be proud of.

Civil and scientific applications are not altruism—it is good business.
Now on the theme of Events and Their Characterization, I was very impressed with the OSI discussions and panels (and the floor display in the Maria Theresia Apartments showing the exercise area of IFE14). Looking forward, the OSI community would benefit from further development, refinement and experience in:

- OSI radionuclide and noble gas technologies,
- Remote sensing technologies (MSIR, light detection and ranging (LIDAR)),
- Resonance seismology and drilling.

Also in this area—I would like to mention the ongoing exploration of data from May 2010. While some past papers on this topic may have been presented in provocative terms, it is important that the nuclear-test-ban community sets the precedent that enigmas will be explored. We should do this using appropriate scientific discipline—especially when we extrapolate beyond well-established experience. I was impressed with the work presented on this topic.

There was much presented on NDC Preparedness Exercises, radioxenon, and advances in networks, sensors and processing. For the sake of brevity I will simply say that these are all important and vibrant areas that are crucial to the monitoring regime.

These are just a small sample of the many relevant developments reported at this conference. As we look to the future we have many thoughts on additional areas of focus—89 such possible focus areas were listed in the report from SnT2011. Most are still relevant today.

There will be a report of this SnT conference. I encourage the scientific community (and other interested communities—journalists, academics, policy makers) to make use of our online resources such as past and current conference reports, e-learning, and the virtual Data Exploitation Centre. I would like to draw special attention to the vDEC—there is a new website and banner on our homepage to promote the vDEC and we envision more evolution to make this an even more effective conduit for technical collaboration.

Although the scientific and technical sessions will conclude today there are still important events continuing tomorrow:

- The Academic Forum brings together educators to share experiences and improve methods used to convey information and promote involvement of students at all levels.
- The NDC meetings allow important discussions among NDCs, and dialogue between the IDC and NDCs.

I hope everyone involved in these meetings sustains their high level of active participation for another day.

I must emphasize that these conferences are ‘CTBT: Science and Technology’, not ‘CTBTO: Science and Technology’. The potential contribution of citizen science to Treaty monitoring lies outside the philosophy of the IMS, but still might play a future role in the global effort. We shall have to see, but in any case, as we have heard, the contribution of a mass of citizen sensors—for example backyard seismic sensors—would also contribute to public awareness of the Treaty and its importance, which as we have heard this week is in great need of more exposure to facilitate moves towards entry into force.

One of the special aspects of the CTBT: Science and Technology conference series is that we aim to include presentations on the political and societal context of the Treaty. This year we heard several prominent political figures from a range of countries remind us of convincing arguments in favour of the Treaty and its entry into force.

I would like to stress that the CTBTO is a global organization, made up of staff from all over the world. This conference has participants from all over the world and I was very pleased that our first keynote speaker (Minister Pandor) gave all of us eloquent insight into the imperative of science and technology on the African continent—I think she clearly established the link between “science and technology” leading to “prosperity and peace”.

On that note I would like to close by paraphrasing words I saw on a video playing out in the lobby: “We are using science and technology for a good cause.” If you have not seen the video I am talking about please do so before you leave or just go to YouTube and search for “MinutePhysics—how to detect a secret nuclear test” (and if you like what you see, send the link on to your friends).

Now we shall present awards for those presentations voted on by you, but I would like to think that all the presentations are worthy of recognition because we are all advancing science and technology for a noble cause.

Thank you.
Some Highlights and Potential Focus Areas

11.1 DATA ACQUISITION

- Improved methods for sensor calibration
- Advances in radionuclide detector technology
- Use of the gamma–gamma coincidence system for radionuclide quantification
- Application of beta–gamma coincidence signatures to particulate samples
- Development of and new approaches to beta–gamma detector hardware
- Potential of multispectral sensor imaging to address the limitations of traditional ground-based surveying
- Methods of improving the realism of simulations used in OSI Integrated Field Exercises, including visual, remote sensing and shallow geophysics observables
- Potential of UAVs as versatile platforms for OSI instruments such as magnetometers, optical/thermal sensors and radionuclide detectors
- Better methods to test the OSI technologies within the context of an Integrated Field Exercise, including simulations, studies of buried sources, etc.

11.2 DATA TRANSMISSION, STORAGE AND FORMAT

- New technologies for data communications, archiving of data and accessing massive data archives during processing

11.3 DATA PROCESSING AND SYNTHESIS

- Developments in waveform correlation methods for detecting and characterizing signals and for locating events, including as an aid to processing repeat events more efficiently
- Use of a cepstral/spectral-zeros approach to the determination of source depth using regional and teleseismic signals
- Use of three-component arrays of seismic sensors
- Improvements in waveform signal detection, phase identification, association of signals to events, and event location and characterization
- Techniques to aid interactive analysis, including the use of cross-correlation methods to aid the analysis of aftershocks
- Improved methods for associating infrasound signals to events

11.4 EARTH CHARACTERIZATION

- Improvement of the RSTT model through international outreach
- Use of numerical modelling of seismic wave propagation in local geological structures to advance seismic methods for OSI
- Computational infrasound propagation simulation methods
- Studies on the effect of ATM resolution in the context of atmospheric dispersion
- Inclusion in ATM of dry and wet deposition effects
• ATM simulations in complex terrain for OSI purposes
• Improved methods for using ATM to estimate possible source regions of radionuclide releases

11.5 INTERPRETATION

• Use of infrasound data to catalogue volcanic eruptions
• Use of non-traditional radioactive xenon isotopes for source characterization
• Improved methods to compute seismic surface wave magnitudes for event characterization
• Use of inverse methods to estimate the source term of a radionuclide release

11.6 CAPABILITY, PERFORMANCE AND SUSTAINMENT

• Use of infrasound data to validate network performance algorithms and to optimize network design for monitoring infrasound sources of interest
• Application of ATM simulations to determine the coverage and optimization of the radioactive noble gas network, and to assess radioactive xenon background
• Methods to assess the performance of ATM and to quantify model uncertainties, together with associated testing
• Network performance methodology, in particular for radionuclide coverage
• Methods for evaluating RSTT models and for assigning uncertainties to them

11.7 SHARING OF DATA AND KNOWLEDGE

• Access by National Data Centres to high-quality event data and processing methods
• Incorporation of CTBT issues into the teaching programmes of educational institutes worldwide
• Enhancing CTBT awareness through academic engagement
• Availability of historical seismic and infrasound data from nuclear explosions and its use in event characterization
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THE PREPARATORY COMMISSION AND THE CTBTO

The Preparatory Commission for the Comprehensive Nuclear-Test-Ban Organization was set up by Resolution CTBT/ARR/RES/1, adopted by the States Signatories 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 PrepCom will be replaced by the Comprehensive Nuclear-Test-Ban Treaty 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 regimes is important to the context.

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LAYOUT

Aida Rodriguez

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In order to build and strengthen its relationship with the broader science community in support of the Comprehensive Nuclear-Test-Ban Treaty, the CTBTO PrepCom invites the international scientific community to conferences on a regular basis; SnT2015 was the fifth such conference since 2006.

These conferences contribute to a process whose aim is to ensure that the CTBTO’s verification regime can benefit from current scientific and technological developments in relevant fields. The Conference Goals define in more detail the scope of topics covered.

These multidisciplinary scientific conferences attract scientists and other experts from the broad range of the CTBTO’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.

SnT2015 was held in Vienna’s Hofburg Palace on 22–26 June 2015, in cooperation with the Austrian Federal Ministry for Europe, Integration and Foreign Affairs. This report summarizes the scientific contributions presented at the conference and identifies some highlights and potential focus areas for the future. The text of this report was presented to Working Group B of the Preparatory Commission in August–September 2016.