The International Monitoring System: Overview, Measurement Systems and Calibration

Workshop of the Consultative Committee for Acoustics, Ultrasound and Vibration - Measurement of imperceptive matters, 20 September 2017

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Comprehensive Nuclear-Test-Ban Treaty Organization
Vienna International Centre
P.O. Box 1200
1400 Vienna, Austria
• The Treaty, The Organization
• The International Monitoring System
• Seismo-Acoustic Measurement Systems
• Calibration – Infrasound Technology
• Calibration – Seismic and Hydroacoustic Technologies
1. Each State Party undertakes not to carry out any nuclear weapon test explosion or any other nuclear explosion, and to prohibit and prevent any such nuclear explosion at any place under its jurisdiction or control.

- Opened for signature on 24 September 1996
- Near-universality: 183 signatures, 166 ratifications
- Entry-into-Force pending ratification of 8 States (out of 44 specific nuclear technology holder States listed in Annex 2 of the Treaty)
The Preparatory Commission for the CTBTO is responsible for promoting the CTBT and establishing a verification regime.

Seat of the Organization in Vienna, Austria.

The Preparatory Commission consists of two main entities: a plenary body composed of all States Signatories (PrepCom) and the Provisional Technical Secretariat (PTS).

The PTS assists the plenary body in carrying out its activities. It currently employs over 270 staff members from over 85 countries.
1. In order to verify compliance with this Treaty, a verification regime shall be established consisting of the following elements:

(a) An **International Monitoring System**;

(b) Consultation and clarification;

(c) On-site inspections; and

(d) Confidence-building measures.

At entry into force of this Treaty, the verification regime shall be capable of meeting the verification requirements of this Treaty.
16. The International Monitoring System shall comprise facilities for seismological monitoring, radionuclide monitoring including certified laboratories, hydroacoustic monitoring, infrasound monitoring, and respective means of communication, and shall be supported by the International Data Centre of the Technical Secretariat.

17. The International Monitoring System shall be placed under the authority of the Technical Secretariat. All monitoring facilities of the International Monitoring System shall be owned and operated by the States hosting or otherwise taking responsibility for them in accordance with the Protocol.
IMS Network – Overview

Workshop of the CCAUV
20 September 2017
## IMS Network – Status

<table>
<thead>
<tr>
<th>IMS station type</th>
<th>Installation completed</th>
<th>Under construction</th>
<th>Not started</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Certified</td>
<td>Not Certified</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Primary seismic</td>
<td>42</td>
<td>3</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Auxiliary seismic</td>
<td>107</td>
<td>8</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Hydroacoustic</td>
<td>11</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Infrasound</td>
<td>49</td>
<td>2</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>Radionuclide</td>
<td>67</td>
<td>3</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Radionuclide Lab</td>
<td>13</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>289</td>
<td>19</td>
<td>9</td>
<td>20</td>
</tr>
</tbody>
</table>

**Network nearing completion: 85% of stations already certified**
IMS Monitoring Technologies

Infrasound

Seismic

Radionuclide

Hydroacoustic
DPRK Announced Nuclear Tests

41 PS, 90AS, 2 HA and 1 IS stations detected signals associated with DPRK event on 3 Sep 2017
Civil and Scientific Applications

- Tsunami Agreement
- Volcano Alert System
- Earthquakes/Seismicity
- Radiation studies
- Natural and man-made sources
- Atmospheric studies
Seismo-Acoustic Measurement Systems
# Infrasound – Minimum Requirements

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Minimum Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor type</td>
<td>Microbarometer</td>
</tr>
<tr>
<td>Number of sensors</td>
<td>Four element array</td>
</tr>
<tr>
<td>Geometry</td>
<td>Triangle with a component at the centre</td>
</tr>
<tr>
<td>Spacing</td>
<td>Triangle basis: 1 to 3 km</td>
</tr>
<tr>
<td>Measured parameter</td>
<td>Differential pressure</td>
</tr>
<tr>
<td>Passband</td>
<td>0.02 to 4 Hz</td>
</tr>
<tr>
<td>Sensor response</td>
<td>Flat to pressure over the passband</td>
</tr>
<tr>
<td>Sensor noise</td>
<td>$\leq 18$ dB below minimum acoustic noise</td>
</tr>
<tr>
<td>Calibration</td>
<td>$\leq 5%$ in absolute amplitude</td>
</tr>
<tr>
<td>Sampling rate</td>
<td>$\geq 10$ samples per second</td>
</tr>
<tr>
<td>Resolution</td>
<td>$\geq 1$ count per 1 mPa</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>$\geq 108$ dB</td>
</tr>
<tr>
<td>Timing accuracy</td>
<td>$\leq 1$ ms</td>
</tr>
<tr>
<td>Standard temperature range</td>
<td>$-10^\circ$C to $+45^\circ$C</td>
</tr>
</tbody>
</table>

![Images of MB2005, C50A, MB3 sensors]

CTBT/WGB/TL-11,17/17/Rev.5
Infrasound – Sensor Description

**MB2005**
- Air inlet
- LVDT
- Metallic bellows
- Reference cavity (under vacuum)
- Measurement cavity

**MB3**
- Magnet and coil transducer
- Metallic bellows
- Reference cavity (under vacuum)
- Measurement cavity
- Air inlet
Seismic – Minimum Requirements

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Minimum Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position (with respect to ground level)</td>
<td>Borehole or vault</td>
</tr>
<tr>
<td>Three component station passband</td>
<td>Short period: 0.5 to 16 Hz plus long period: 0.02 to 1 Hz or broadband: 0.02 to 16 Hz</td>
</tr>
<tr>
<td>Array station passband</td>
<td>Short period: 0.5 to 16 Hz</td>
</tr>
<tr>
<td></td>
<td>Long period: 0.02 to 1 Hz</td>
</tr>
<tr>
<td>Sensor response</td>
<td>Flat to velocity or acceleration over the passband</td>
</tr>
<tr>
<td>Number of sensors for new arrays</td>
<td>9 short period (one component) plus (1 short period (three component) plus 1 long period (three component))</td>
</tr>
<tr>
<td>Calibration</td>
<td>Within 5% in amplitude and 5° in phase over the passband</td>
</tr>
<tr>
<td>Sampling rate</td>
<td>≥40 samples per second</td>
</tr>
<tr>
<td></td>
<td>Long period: ≥4 samples per second</td>
</tr>
<tr>
<td>Seismometer noise</td>
<td>≤10 dB below minimum earth noise at the site over the passband</td>
</tr>
<tr>
<td>System noise</td>
<td>≤10 dB below the noise of the seismometer over the passband</td>
</tr>
<tr>
<td>Resolution</td>
<td>18 dB below the minimum local seismic noise</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>≥120 dB</td>
</tr>
<tr>
<td>Absolute timing accuracy</td>
<td>≤10 ms</td>
</tr>
<tr>
<td>Relative timing accuracy</td>
<td>≤1 ms between array elements</td>
</tr>
<tr>
<td>Operation temperature</td>
<td>−10°C to +45°C</td>
</tr>
</tbody>
</table>

CTBT/WGB/TL-11,15/17/Rev.5
Hydroacoustic – Minimum Requirements

### Hydrophone Stations

- **Sensor type**: Hydrophone with wet-end digitizer
- **Passband**: 1 to 100 Hz
- **Sensor response**: Flat to pressure over the passband
- **Number of sensors**: 1 operational sensor with 2 backup sensors per cable
- **Sensors’ location**: In the Sound Fixing and Ranging channel
- **Location precision**: ≤500 m
- **Number of cables**: 2 at a site when necessary to prevent local blockage
- **System noise**: ≤10 dB below Urick’s deep ocean low noise curve
- **Calibration**: Within 1 dB, no phase requirements
- **Sampling rate**: ≥240 samples per second
- **Timing accuracy**: ≤10 ms
- **Sensitivity**: ≤60 dB per μPa (1 Hz band) ≤81 dB per μPa (wideband)
- **Dynamic range**: 120 dB

### Seismometer

- **Sensor type**: Seismometer
- **Position (with respect to ground level)**: Borehole or vault
- **Passband**: 0.5 to 20 Hz
- **Sensor response**: Flat to velocity or acceleration over the passband
- **Seismometer noise**: ≤10 dB below minimum earth noise at the site over the passband
- **Calibration**: Within 5% in amplitude and 5° in phase over the passband
- **Sampling rate**: ≥50 samples per second
- **Resolution**: 18 dB below the minimum local seismic noise
- **System noise**: ≤10 dB below the noise of the seismometer over the passband
- **Dynamic range**: ≥120 dB
- **Absolute timing accuracy**: ≤10 ms
- **Operation temperature**: –10°C to +45°C
Calibration – Infrasound Technology
Calibration – Goals

Demonstrate quality assurance in IMS infrasound measurement to ensure trustworthiness and credibility of IMS infrasound data.

Ensure consistency in IMS infrasound measurement and equivalence in data produced across the IMS infrasound network.

Ensure continuity and transparency of best practices independent of changes in instrumentation/service provider, or individual personnel.
IMS Infrasound Station

Wind Noise Reduction system (WNRS)

Equipment vault

Communication equipment

Infrasound Sensor

Digitizer

Array Element H1

Array Element H2

Array Element Hn

Infrasound Sensor

Digitizer

Central Recording Facility

International Data Centre

IMS Infrasound Station

Gravity wave

Infrasound

Audible sound

Ultrasound

~24 h

8 min

5 min

50 s

4 Hz

20 Hz

20 000 Hz

I21FR, Marquesas Islands, France

I49GB, Tristan da Cunha, UK

I60US, Wake Island, USA
1. **Type Approval**

   Extensive testing of a set of a new device against IMS and manufacturer type specifications. Most of the tests are performed by a designated Expert Laboratory, which performance is regularly assessed by the PTS. If the Type Approval report is approved by the PTS, the new model is approved for use in the IMS.

2. **Acceptance testing**

   Testing of an individual device against manufacturer type specifications. The tests are performed by the manufacturer, whose performance is regularly assessed by the PTS. Once the data sheet is approved by the PTS, the device is declared ready for installation in the IMS.

3. **Initial calibration**

   Testing performed at the time of the installation in operational conditions of a new measurement system to verify that the new system performs within tolerances of the manufacturer type specifications. The tests mainly include full frequency response and self-noise measurements. The results of the initial calibration is used to establish the baseline for future calibrations.

4. **On-site Calibration**

   Yearly measurements of the full frequency response of a measurement system to determine if the performance of the operational device remains within the tolerance of the baseline established at the time of the Initial Calibration. When the results are not within tolerances, the required maintenance actions are initiated.
Challenges in 2011

• Technical
  (a) No international or national standards for infrasound technology
  (b) No technique available for the initial and on-site calibration of infrasound measurement systems (WNRS + sensor) within IMS specifications
  (c) No validated models for acoustic response of WNRSs
  (d) WNRSs introducing response instabilities at some IMS infrasound stations

• Potential field calibration techniques
  (a) Pistonphone -> does not include WNRS
  (b) Microbarometers including calibration coil -> does not include WNRS
  (c) Infrasound generator -> Does not cover full IMS frequency band
  (d) Use of reference infrasound sensors -> Possible for very low background noise conditions
Stakeholder Map

Metrology Community
- BIPM – CCAUV
- Regional Metrology Organisations
- National Metrology Institutes

Metrology Consultants
- Acoustic Sensor Networks (ASN)
- Laboratoire national de métrologie et d’essais (LNE)

Third Party Community
- National Data Centres
- Data user community

Scientific Community
- Commissariat à l’énergie atomique et aux énergies alternatives (CEA)
- Pennsylvania State University (PSU)
- Sandia National Laboratories (SNL)
- University of Mississippi (UMiss)

Preparatory Commission (PrepCom / WGB)

Provisional Technical Secretariat

Station Operators
- Bundesanstalt für Geowissenschaften und Rohstoffe (BGR)
- Instituto Oceanográfico de la Armada (INOCAR)
- Norwegian Seismic Array (NORSAR)

Sensor Manufacturers
- Chaparral Physics
- Seismo Wave

Digitizer Manufacturers
- FEDD
- Geotech
- Guralp
- Kinematics

WNRS Manufacturers
- Enviroearth

Expert Laboratories
- Commissariat à l’énergie atomique et aux énergies alternatives (CEA)
- Los Alamos National Laboratory (LANL)
- Sandia National Laboratories (SNL)
- University of Mississippi (UMiss)
Achievements 2011 – 2016

**2011**
- IMS infrasound system response measured for the first time during certification process.

**2012**
- Development of new standard PTS WNRS based on state-of-the-art models.
  - Update of station certification /revalidation procedures with system response estimation.
- First deployment of standard PTS WNRS at an IMS station.
- Enhancement of processing algorithms for system response estimation.

**2013**
- Midterm Strategy (2014-2017) with emphasis on fulfillment of IMS calibration requirements.
- Development of On-site Calib technique compliant with IMS specifications.
- MB3a sensor identified as potential improvement to the verification system during SnT 2013.
- Comparison and validation of acoustic response models for WNRS.

**2014**
- WGB43 encourages PTS to pursue integration of On-site Calib technique.
- Establishment of call-off contract for provision of state-of-the-art WNRS.
- Testing of MB3 sensor at CEA and SNL.
- Expert discussions on need for comparison studies on infrasound sensor testing.
- Definition of PS1 Technical Protocol.

**2015**
- WGB46 encourages PTS to continue implementation of On-site Calib capability.
- Refinement of On-site Calib processing based on I26DE data.
- Design of WNRS for extreme environmental conditions.
- Testing of MB3 sensor at I24FR in operational conditions.
- Deployment of MB3 sensor at first IMS station.

**2016**
- Development of software for automatic processing of On-site Calib data.
- Establishment of call-off contract for provision of state-of-the-art infrasound sensors.
- Conduction of PS1.
- Definition of PS2 Technical Protocol.
- Deployment of On-site Calib capability at station I26DE.
- Deployment of On-site Calib capability at station I37NO.
- Establishment of call-off contract for provision of metrological services.

**Key Activities**
- IEC TC29 discussion on infrasound calibration.
- Key comparison CCAUV.A-K5 for sound pressure modulus and phase down to 2 Hz.

**Milestones**
Type Approval for Infrasound Sensors

**PTS**
Periodic compliance assessment

Requirements for Type Approval service providers

**PTS**
1. Review of Testing Report against IMS and manufacturer type specifications
2. Additional testing in operational conditions
3. Assessment of manufacturer QA & measurement & calibration capabilities against IMS specifications
4. Assessment of integration issues within IMS network infrastructure

**Expert Lab**

- IMS specifications
- Traceable measurements with calibrated reference devices
- Results collated into Testing Report (standard report format)

**Manufacturer**

- Three sensors of a new model + type specifications

**Expert Labs need traceable calibration services from metrology community**
Acceptance Testing for Infrasound Sensors

Manufacturers need traceable calibration services from metrology community
Support from metrological community required to achieve PTS objectives
Calibration – Seismic and Hydroacoustic Technologies
Seismic Technology

- No standard written IMS procedures for Type Approval, Acceptance Testing or Initial Calibration of IMS seismic measurement systems
- On-site Calibration implemented since 2011 through the yearly sending of electrical signals into seismometer calibration coils
- Part of seismological community moving from electrical calibration to calibration with reference sensors
- Project for definition of seismic calibration infrastructure to be initiated by the PTS in 2018
- Standard procedures for Type Approval of seismic sensors under definition with support of expert community (SNL, USGS, IRIS/IDA, etc.)
- Same set of seismic sensors sent to 2 Expert Labs (CEA, SNL) for testing in 2017 with the objective of gathering information on Expert Labs testing methodologies
Hydroacoustic Technology

- Same processes as for seismic technology applied to T-phase stations
- Processes for hydrophone stations significantly different from those for the infrasound and seismic stations
- Acceptance testing for hydrophones currently performed in laboratory (Navy calibration facility) including calibration through the use of reference hydrophones in pressurized tanks
- Electronic part of the hydroacoustic measurement systems calibrated on yearly basis by injecting electrical calibration signal from acquisition system
- Comparison between recording of different hydrophones within the same triplet can also be performed for periodic quality control checks
Conclusion and Collaboration Perspectives

- Significant efforts made by the PTS since 2011 to define standard calibration infrastructure for infrasound technology.
- Efforts to be continued to demonstrate quality assurance in IMS infrasound measurements.
- Project for the definition of standard calibration infrastructure for seismic technology to be started in 2018.
- Support from metrological community required for the development of primary standards in IMS frequency bands.
- Target for infrasound technology: Availability of traceable calibration services by end of 2020.
the comprehensive nuclear-test-ban treaty
putting an end to nuclear test explosions

Thank you!

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