Chapter 15

CTBTO: Goals, Networks, Data Analysis and Data Availability

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15.1 Introduction

15.1.1 The Treaty

The Comprehensive Nuclear-Test-Ban Treaty (CTBT) was opened for signature on 15 September 1996. The CTBT prohibits nuclear test explosions in all environments: underground, in the oceans, and in the atmosphere. As of 1 April 2011, the CTBT has been signed by 182 States, and has been ratified by 153 States. The CTBT will enter into force once it has been ratified by 40 States specified in Annex 2 of the treaty, the so called “Annex 2 States”. As of 1 April 2011, 35 of the Annex 2 States have ratified the CTBT.

The Comprehensive Nuclear-Test-Ban Treaty Organization Preparatory Technical Secretariat (CTBTO/PTS) was established in 1997 to prepare the systems for monitoring compliance with the CTBT once the Treaty enters into force. During this preparatory phase a great amount of work is being done to establish the International Monitoring System (IMS), the Global Communication Infrastructure (GCI), the International Data Centre (IDC) in Vienna, Austria and the On-Site-Inspection (OSI) capabilities.

Fig. 15.1 shows a map with the countries who have as of April 2011 ratified, not ratified or not yet signed the Treaty.

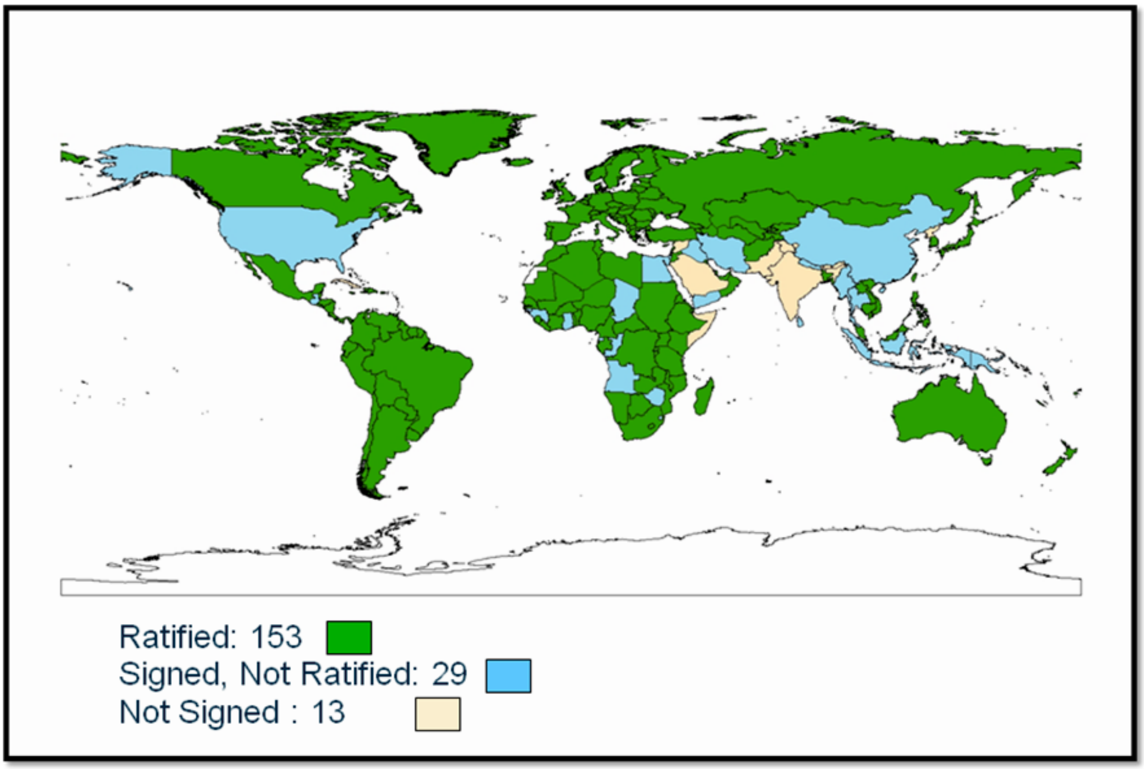

Fig. 15.1 Ratification status of the CTBT as of 1 April 2011.

15.1.2 Nuclear explosions

A nuclear explosion unleashes a tremendous amount of energy. Part of this energy can travel through the Earth, atmosphere, and oceans as seismic, infrasound, and hydroacoustic waves, respectively. The amount of energy travelling through each of these media is a function of where the explosion takes place, i.e., whether the explosion is underground, in the atmosphere, or underwater. The energy can also transfer from on media to another, depending on the site of the explosion. For example, an explosion on a boat will generate both infrasound and hydroacoustic signals, and the hydroacoustic signals can be converted into seismic signals.

A nuclear explosion also generates tremendous amounts of radioactive particles and gases, known as radionuclides. Observing these nuclides can provide unequivocal evidence that a nuclear explosion has occurred, since many of the radionuclides that can be detected and identified are fission products and can only arise from nuclear fission. Moreover, it is possible to distinguish between fission products from a nuclear explosion and those arising from atmospheric releases from civil nuclear power and reprocessing plants. The primary role of radionuclide monitoring is to provide unambiguous evidence of a nuclear explosion through the detection and identification of fission products. These fission products can be sampled from ambient air as particulates or noble gases.

In addition to nuclear explosions, there are many other signals, which can be generated by other natural or man-made sources in the environments of interest. These include earthquakes, other non-nuclear explosions (e.g., mining explosions, quarries, accidental explosions), volcanic activity, airgun surveys, lightening, microbaroms, and biological sources (e.g., whales, elephants, etc.). Fortunately, not all of these sources generate signals similar to those generated by nuclear explosions.

Signals which are not of interest for CTBT purposes include repetitive sources (e.g., air gun surveys), very low energy events (e.g., lightening), signals outside the frequency range of interest (e.g., whale noise), signals outside the velocity range of interest, quickly moving objects (e.g., aircraft), and long, continuous signals (e.g., microbaroms). These distinguishing characteristics can be used to identify these signals as being noise during automatic processing, and are not considered further.

While signals from some sources can be discarded as noise, there is a wide range of sources which generate signals which must be processed, analyzed, and reviewed. The location and time of these sources are subsequently reported by the IDC in its bulletins. Potential sources in the bulletins include earthquakes, non-nuclear explosions, volcanoes, and meteorites. These sources may have similar characteristics of a nuclear explosion in terms of size, impulsive energy release, or frequency content.

Due to the nature of nuclear explosions and the environments in which they may take place, the IMS network was designed to have seismic, infrasound, hydroacoustic, and radionuclide sensors. The notional concept of monitoring the earth for a 1 kiloton nuclear explosion was used during the negotiations of the Treaty for illustrative purposes, and for comparisons between various proposed designs. This lead to the design of the network in terms of number of stations, passband, and sensitivity. The provision for an onsite inspection following a suspicious event and its associated timelines as well as security concerns contributed to the timeliness requirements concerning IMS data acquisition and the issuance of IDC products.

While a nuclear weapon can be detonated in any environment, a clandestine test is most likely to take place underground. This is due to the fact that a nuclear explosion in the atmosphere would generate significant amounts of infrasound energy and copious quantities of radionuclides which would clearly indicate that a nuclear explosion took place. An underwater test would generate clear hydroacoustic signals as well as a release of radionuclides which would indicate a nuclear explosion.

Due to these reasons, environmental concerns, as well as to the Partial Test Ban Treaty (which prohibits nuclear weapon tests in the atmosphere, in outer space and under water), all nuclear explosions since 1980 have been underground. Since underground nuclear explosions generate significant seismic energy, seismic monitoring is particularly well suited for locating an underground nuclear explosion and determining its magnitude. The conversion of seismic magnitude to explosive yield is a complicated process, which relies on many different factors including geology and hydrology (e.g., Ringdahl, et al., 1992; Richards and Wu, 2011).

A number of techniques have been developed to discriminate between underground nuclear explosions and earthquakes (Bowers and Selby, 2009). Currently, the most effective technique used at the IDC is the mb/Ms screening criterion, which relies on the fact that for an explosion and an earthquake with the same mb magnitude, the explosion will have a smaller Ms magnitude than the earthquake (see section 11.2.5.2 in Chapter 11, and Fig. 2 in Richards and Wu, 2011). Other criteria used for screening at the IDC consider event depth, the offshore location of an event, and regional seismic characteristics. Each of these criteria relies heavily upon seismic observations.

15.2 CTBTO networks

The International Monitoring System (IMS) is comprised of monitoring facilities as specified in the CTBT. The monitoring facilities are explicitly listed in the CTBT, and consist of 50 primary seismic stations and 120 auxiliary seismic stations, 11 hydroacoustic stations (6 hydrophone stations and 5 T-phase stations), 60 infrasound stations, and 80 radionuclide stations (80 stations capable of monitoring particulate radionuclides in the atmosphere, where 40 of those stations will be capable of monitoring for noble gases at the time the Treaty enters into force), and 16 radionuclide laboratories, which provide support activities.

The technical and operational requirements of each type of facility are specified in the appropriate IMS Operational Manual. Each new facility is certified and added to the IMS network once it is built and passes the certification process, in which it is demonstrated that it meets all technical specifications, including requirements for data authentication and transmission through the Global Communications Infrastructure (GCI) link to the IDC.

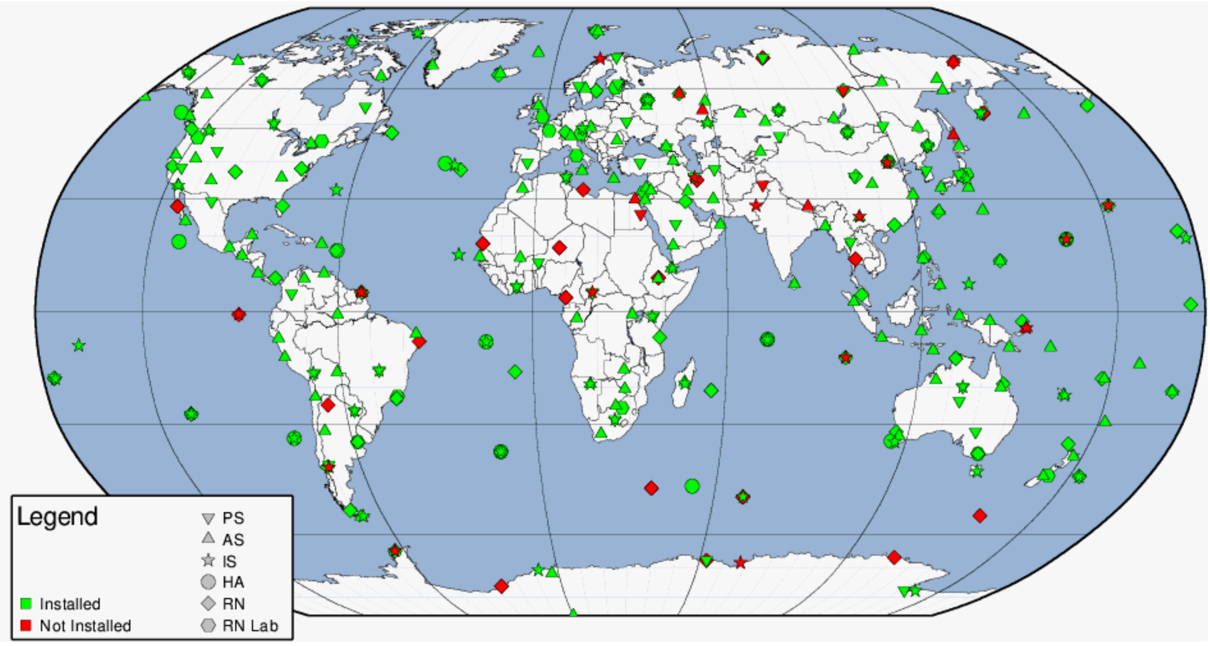

Fig. 15.2 The complete IMS Network. The legend shows Primary Seismic (PS), Auxiliary Seismic (AS), Infrasound (IS), Hydroacoustic (HA), Radionuclide Particulate (RN (P)), Radionuclide Noble Gas (RN (NG)), and Radionuclide Laboratory (RN LAB) facilities.

15.2.1 Seismic station

A seismic station has three basic parts; a seismometer to measure the ground motion, a recording system which records the data digitally with an accurate time stamp, and a communication system interface.

Within the primary and auxiliary seismic networks, there are two types of seismic stations, three-component (3C) stations and array stations. The primary seismic network is mostly composed of arrays (30 arrays out of 50 stations), whereas the auxiliary seismic network is mostly composed of 3 C stations.

As of 1 April 2011 42 primary seismic and 99 auxiliary seismic stations have been certified. The specifications for primary and auxiliary seismic stations are summarized in Tab. 15.1.

15.2.1.1 Three-component station

A three-component seismic station requires recording of broadband ground motion in three orthogonal directions. This type of recording can be done using either a single three-component broadband seismometer that covers the combined long-period and short-period frequency ranges, or with separate long-period and short-period seismometers (see DS 5.1).

15.2.1.2 Array station

An IMS seismic array station consists of multiple short-period seismometers and three-component broadband instruments. Some existing short-period arrays also have associated multiple long-period seismometers. Both short-period and long-period seismometers are typically deployed in a geometrical configuration designed to allow ground motion signals to be combined to enhance the signal-to-noise ratio (see Chapter 9). New arrays should contain at least 9 vertical short-period elements and at least one three-component broadband element. The broadband element can use a single broadband instrument or one three-component short-period instrument with one three-component long-period instrument (see Tab. 15.1).

A teleseismic array is a seismic array designed for optimum detection and slowness estimation of seismic phases from sources at distances greater than 3000 kilometres. The distances between the array sensors are typically between 1000 and 3000 metres, and the total aperture is up to 60 kilometres.

A regional array is a seismic array designed for optimum detection and slowness estimation of seismic phases from sources at distances less than 3000 kilometres. The distances between array sensors are typically between 100 and 3000 metres, and the total aperture is up to 5 kilometres.

Primary seismic stations send continuous near-real-time data to the International Data Centre. Auxiliary seismic stations provide data upon request from the International Data Centre. In order to provide information on their operational state, in addition to ground motion data, seismic stations transmit state-of-health information such as:

- Clock status, to indicate whether the clock is synchronized to Coordinated Universal Time.

- Calibration status, to indicate whether a calibration signal is on or off.
- Vault/borehole status, to indicate whether the lid or door of the equipment vault or borehole is closed or open as a data surety measure

Tab. 15.1 Specifications for primary and auxiliary seismic stations (minimum requirements; from CTBT/PC/II/Add.2 16 May 1997, p.43).

CHARACTERISTICS	MINIMUM REQUIREMENTS
Sensor type	Seismometer
Station type	Three-component or array
Position (with respect to ground level)	Borehole or vault
Three-Component Passband [1]	Short-period: 0.5 to 16 Hz plus Long-period: 0.02 to 1 Hz or Broadband: 0.02 to 16 Hz
Sensor response	Flat to velocity or acceleration over the passband
Array Passband	(Short-period: 0.5 to 16 Hz Long-period: 0.02 to 1 Hz) [2]
Number of sensors for new arrays [3]	9 short-period (one component) plus 1 short-period (three component) plus 1 long-period (three component) [4]
Seismometer noise	$\leq$ 10 dB below minimum-earth noise at the site over the passband
Calibration	Within 5% in amplitude and 5 degrees in phase over the passband
Sampling rate	$\geq$ 40 samples per second [5] Long-period: $\geq$ 4 samples per second
System Noise	$\leq$ 10 dB below the noise of the seismometer over the passband
Resolution	18 dB below the minimum local seismic noise
Dynamic range	$\geq$120 dB
Absolute timing accuracy	<10 ms
Relative timing accuracy	<1 ms between array elements
Operation temperature	-10 ^{o}C to + 45 ^{o}C [6]
State of health	Status to be transmitted to the International Data Centre: clock, calibration, vault and/or borehole status, telemetry
Delay in transmission to International Data Centre	<5 minutes
Data frame length	Short-period: <10 seconds; long-period: <30 seconds

[1] For existing Global Telemetered Seismic Network stations, upgrading needs further consideration.

[2] For one-component element of teleseismic arrays, the upper limit is 8 Hz.

[3] In case of noisy sites or when increased capability is required, number of sensors could be increased.

[4] Can be achieved by a single broadband instrument.

[5] This applies to three-component and regional arrays. For existing teleseismic arrays, 40 samples per second are necessary for three-component but 20 samples per second are suitable for other sensors.

[6] Temperature range to be adapted for some specific sites.

Buffer at station or at National Data Centre [1]	>7 days
Data availability	> 98%
Timely data availability	> 97%
Mission-capable arrays	>80% of the elements should be operational
Precision on station location	<100 m absolute for stations (World Geodetic System 84) < 1 m relative for arrays elevation above sea level <20 m
Seismometer orientation	< 3 degrees
Data format	Group of Scientific Experts (GSE) format
Data transmission	primary : continuous auxiliary : segmented

15.2.2 Hydroacoustic station

In order to detect the acoustic energy ducted through the SOFAR channel a network composed of 11 hydroacoustic stations is being implemented. Six stations will be equipped with hydrophones. The other five hydroacoustic stations are located on steep-sloped islands and will make use of seismic sensors to detect the waterborne energy which is converted to a seismic wave at the boundary of the island. This type of propagation has long been known to the seismic community as T-phase propagation. T-phase stations are not as effective in detecting and identifying hydroacoustic signals from explosions, but they are considerably cheaper than hydrophone stations. The mixture of hydrophone and T-phase stations selected for the IMS hydroacoustic network was chosen as a cost-effective compromise. As of 1 April 2011 10 hydroacoustic stations have been certified.

An International Monitoring System hydroacoustic station can consist of either ocean-deployed hydrophone sensors and data acquisition systems, referred to herein as a *Hydrophone Station*, or one or more island-deployed seismometer sensors and data acquisition systems, referred to herein as a *T-phase Station*. There are 6 hydrophone stations and 5 T-phase stations.

15.2.2.1 Hydrophone station

A hydrophone station consists of an underwater segment and a data acquisition segment. When the hydrophone station is located on an island, two distinct cables and hydrophone sensors are deployed nominally off opposite shores. The hydrophone sensor elements are placed at or near the axis of the Sound Fixing and Ranging (SOFAR) channel, using a subsurface float and an ocean-bottom anchor. Each cable has three sensors with electronics for digitizing the signal. In order to provide the station with some directional capabilities, the three hydrophones are placed in a triangular configuration and each sensor is separated horizontally by a distance of approximately 2 kilometers. A single cable is used to bring the signals from the hydrophone sensors to shore. Hydrophone locations are selected considering

[1] Procedures for buffering to ensure minimum loss of data and single point failure should be addressed in the International Monitoring System Operational Manual.

the best combination of these factors: local optimum of low noise, wide viewing azimuth, and ease of cable installation.

All hydrophone stations, except for Cape Leeuwin, are located on relatively small islands. They generally consist of two undersea trunk cables, each with three hydrophones sensors. To avoid bathymetric blockage, by the island, cables and sensors are deployed on opposite shores of the island. Each hydrophone sensor has an independent wet-end digitizer. The digital signals are transmitted to the shore facility via a non-repeatered fiber optic cable for processing and transmission to the IDC in Vienna. The (minimum requirement) specifications for hydrophone stations are summarized in Tab. 15.2.

Tab. 15.2 Specifications for IMS Hydrophone Stations (minimum requirements; from CTBT/PC/II/Add.2 16 May 1997, p.46)

CHARACTERISTICS	MINIMUM REQUIREMENTS
Sensor type	Hydrophone with wet-end digitiser
Passband	1 to 100 Hz
Sensor Response	Flat to pressure over the passband
Number of sensors	1 operational sensor with 2 back-up sensors per cable
Sensors location	In the Sound Fixing and Ranging channel
Location precision	$\leq$500 meters
Number of cables	2 at a site when necessary to prevent local blockage
System noise	$\leq$10 dB below Urick's deep ocean low noise curve
Calibration	Within 1 dB, no phase requirements
Sampling rate	$\geq$240 samples per second
Timing accuracy	$\leq$10 ms
Delay in transmission to the Technical Secretariat	$\leq$5 minutes
State of health	Status to be transmitted to the International Data Centre: hydrophone, clock, calibration, telemetry
Data availability	$\geq$ 98%
Timely data availiabiltiy	$\geq$ 97%
Sensitivity	$\leq$60 dB per μPa (1-Hz band) $\leq$81 dB per μPa (wide band)
Dynamic range	120 dB
Data transmission	Continuous
Data format	GSE format
Data frame length	$\leq$10 seconds
Buffer at dry end	$\geq$7 days
Mean time between failures for wet-end equipment	20 years (to be confirmed)

15.2.2.2 T-phase station

A T-phase station consists of one or more seismometers and one or more data acquisition systems. The T-phase station is sited near the shore of small islands with steep bathymetry in order to detect seismic waves generated by the coupling of waterborne energy along the flanks of the island. Each T-phase station location is chosen to provide as large an azimuthal monitoring coverage as possible while minimizing the background seismic noise level. Up to three T-phase seismometer systems may be required at different island locations to provide full azimuthal monitoring coverage. For specifications of T-phase stations see Tab. 15.3.

Tab. 15. 3 Specifications for IMS T-phase stations (minimum requirements; from CTBT/PC/II/Add.2 16 May 1997, p.45

CHARACTERISTICS	MINIMUM REQUIREMENTS
Sensor type	Seismometer
Station type	Minimum of one vertical component
Position (with respect to ground level)	Borehole or vault
Passband	0.5 to 20 Hz
Sensor response	Flat to velocity or acceleration over the pass band
Seismometer noise	$\leq$ 10 dB below minimum-earth noise at the site over the passband
Calibration	Within 5% in amplitude and 5 degrees in phase over the passband
Sampling rate	$\geq$50 samples per second
Resolution	18 dB below the minimum local seismic noise
System Noise	$\leq$ 10 dB below the noise of the seismometer over the passband
Dynamic range	$\geq$120 dB
Absolute timing accuracy	$\leq$10 ms
Operation temperature [1]	-10 ^{o}C to + 45 ^{o}C
State of health	Status to be transmitted to the International Data Centre: clock, calibration, vault and/or borehole status, telemetry
Delay in transmission to Technical Secretariat	$\leq$5 minutes
Data frame length	$\leq$10 seconds
Buffer at station or at National Data Centre [2]	$\geq$7 days
Data availability	$\geq$98%
Timely data availability	$\geq$97%

[1] Temperature range to be adapted for some specific sites

[2] Procedures for buffering to ensure minimum loss of data and single point failure should be addressed in the International Monitoring System Operational Manual.

Precision on station location	≤100 m absolute for stations (World Geodetic System 84); Elevation above sea level ≤20 m
Seismometer orientation	≤3 degrees
Data format	Group of Scientific Experts format
Data transmission	Continuous

15.2.3 Infrasound station

An infrasound station consists of an array of 4 up to 15 elements; typical designs have 4 to 8 elements. Each array element has three basic parts: 1) a microbarometer connected to a wind noise reduction system to measure the infrasound signals, 2) a recording system to record digital data with an accurate time stamp, and 3) a communication system interface.

A typical infrasound station is designed for infrasound signals detection along with slowness and azimuth estimation in the frequency regime of 0.02 to 4 Hz. The arrays are usually shaped either, as irregular triangles with an internal element or an inner sub-array, or as pentagons with a triangular inner sub-array. The aperture of the main arrays (outer) varies between 1 and 3 km while the sub-arrays (inner) usually have an aperture of 100 to 300 m.

The total number of the arrays in the IMS infrasound network is 60. As of 1 April 2011, 43 stations are installed. All the stations in the IMS infrasound network are new and are or will be constructed under the IMS program. All the infrasound stations send continuous near-real-time data to the International Data Centre, in Vienna.

In order to provide information on their operational status, in addition to micropressure data, infrasound stations transmit also state-of-health information, such as:

- Clock status, to indicate whether the clock is synchronized to Coordinated Universal Time.
- Vault status, to indicate whether the lid or door of the equipment vault is closed or open as a data surety measure

The minimum requirements for the installation and certification of an infrasound station are summarized in Tab. 15.4.

Tab. 15.4 Specifications for IMS Infrasound Stations (minimum requirements; from CTBT/PC/II/Add.2 16 May 1997, p. 47)

CHARACTERISTICS	MINIMUM REQUIREMENTS
Sensor type	Microbarograph
Number of sensors	4-element array [1]
Geometry	Triangle with a component at the centre
Spacing	Triangle basis: 1 to 3 km [2]
Station location accuracy	≤100 m
Relative sensor location	≤1 m
Measured parameter	Absolute [3] or differential pressure
Passband	0.02 to 4 Hz

Sensor response	Flat to pressure over the passband
Sensor noise	≤18 dB below minimum acoustic noise [4]
Calibration	<5% in absolute amplitude [5]
State of health	Status data transmitted to the IDC
Sampling rate	≥10 samples per second
Resolution	≥1 count per 1 mPa
Dynamic range	≥108 dB
Timing accuracy	≤1 msec
Standard temperature range	-10 °C to +45 °C [6]
Buffer at station or at National Data Centre	≥7days
Data format	Group of Scientific Experts format
Data frame length	≤30 seconds
Data transmission	Continuous
Data availability	≥98%
Timely data availability	≥97%
Mission capable array	≥3 elements operational
Acoustic filtering	Noise reduction pipes (site dependent)
Auxiliary data	Meteorological data [7]

[1] In case of noisy sites or when increased capability is required, number of components could be increased.
[2] 3 km is the recommended spacing
[3] Used for daily state of health.
[4] Minimum noise level at 1 Hz : ~ 5 mPa
[5] Periodicity: once per year (minimum).
[6] Temperature range to be adapted for some specific sites.
[7] Once per minute (minimum).

15.2.4 Radionuclide particulate station

Among the monitoring technologies in the IMS network, radionuclide monitoring is the only technique that provides the forensic or confirmatory evidence that a detected explosion is nuclear in nature. . Eighty radionuclide stations are being established in the IMS for sampling and radionuclide analysis of airborne particulates. Forty of these stations will also have the capability for sampling and analysis of noble gases. The radionuclide network was designed to achieve a detection capability of not less than 90% within approximately 14 days (including 3 days reporting time) for a 1 kt nuclear explosion in the atmosphere or from venting by an underground or underwater detonation.

Following a nuclear explosion, the radioactive materials released consist mainly of fission products and neutron activation products (from the interaction of the neutrons released during fission with elements in the device and surrounding materials). For particulate samples, there are 84 fission and neutron activation products which are regarded as relevant to CTBT. From their relative abundance or mutual ratios in the sample, it will be possible to determine whether they are from a nuclear explosion or other possible sources of radioactivity such as nuclear power or reprocessing plants.

In a radionuclide particulate station, at least 12,000 m^3 of air is pumped daily through a filter with high collection efficiency in order to produce a large volume of air sample for high detection sensitivity. This sample is then analyzed using high-resolution gamma-ray spectrometry since the fission products and neutron activation products are gamma-emitters. The data is directly transmitted to the IDC thru the GCI for processing, analysis and review.

The main components of a radionuclide particulate station are:

- High-volume air- sampler – for collection of large volume of airborne particulates or aerosols;
- Filter material - for trapping particulates with high efficiency; after sampling, this is compressed or cut into a geometry best suited for gamma spectrometry;
- Detection equipment – high-purity germanium crystal with good resolution, high efficiency and encased inside lead shielding to reduce background radioactivity;
- Multi-channel analyzer, computer system, station operation software - for production of spectral raw data for transmission to the IDC for analysis and operation of the system;
- State-of-health (SOH) sensors - status of station monitors, i.e., air flow rate, detector temperature, indoor temperature and humidity, filter position monitor, power supply status, lead shield status, that could be used to interpret the measured radionuclide data and provide an indication of normal and secure operation;
- Meteorological sensors - meteorological data monitors, i.e., precipitation, temperature, wind speed, wind direction;
- Very small aperture antenna (VSAT) - for transmission of data to IDC via satellite;
- Uninterruptible power supply and auxiliary generator - for power stability and alternate source of electrical power.

There are two types of radionuclide particulate stations: (1) manual station which requires an operator to perform the daily operations such as filter change and preparation, and (2) automatic station. The two types of automatic systems in the IMS network are the Radionuclide Aerosol Sampler/Analyzer (RASA) and Automatic Radionuclide Air Monitoring Equipment (ARAME). The minimum technical requirements for certification of a particulate station are listed in Tab. 15.5.

Tab. 15.5 Specifications for IMS Radionuclide Particulate Stations (minimum requirements; from CTBT/PC/II/Add.2 16 May 1997, p. 48)

CHARACTERISTICS	MINIMUM REQUIREMENTS
System	Manual or automated
Airflow	500 m^3 h^{-1}
Collection time	24 h
Decay time	≤ 24 h

Measurement time	≥ 20 h
Time before reporting	≤ 72 h
Reporting frequency	Daily
Filter	Adequate composition for compaction, dissolution and analysis
Particulate collection efficiency	For filter : ≥ 80% at ∅ = 0.2 µm Global ≥ 60% at ∅ = 10 µm
Measurement mode	HPGe high resolution gamma spectrometry
HPGe relative efficiency	≥ 40%
HPGe resolution	< 2.5 keV at 1332 keV
Base line sensitivity	10 to 30 µBq m^{-3} for ^{140}Ba
Calibration range	88 to 1836 keV
Data format for gamma spectra and auxiliary data	RMS (Radionuclide Monitoring System) format
State of health	Status data transmitted to IDC
Communication	Two-way
Auxiliary data	Meteorological data Flow rate measurement every 10 minutes
Data availability	≥ 95%
Down time	≤ 7 consecutive days ≤ 15 days annually

As of 1 April 2011, of the 80 radionuclide stations which comprise the IMS radionuclide particulate network, 60 have been certified as meeting the requirements above.

15.2.5 Radionuclide noble gas station

For underground or underwater nuclear explosions, the radioactive materials with greater probability of being vented and released into the atmosphere are noble gases rather than particulates. Noble gases are chemically inert and will not be attached to its surrounding environment; thus these can leak from an underground cavity through vents or cracks or be transported from underwater to the surface. Once in the atmosphere these remain gaseous, travel long distances and unlike particulates, are not washed out by precipitation. . Among the noble gases likely to be released into the atmosphere following a nuclear explosion, radioactive xenon isotopes (radioxenons) are presently the most suitable for monitoring purposes. They are produced with a relatively high yield in nuclear explosions and have suitable half-lives. By examining the ratios of xenon isotopes in a sample, it is possible to distinguish whether the radioxenons detected are from a nuclear explosion or other civilian applications such as nuclear reactor releases. The 4 radioxenons monitored by the noble gas stations are ^{131m}Xe, ^{133m}Xe, ^{133}Xe and ^{135}Xe, which are beta (or conversion electron) and gamma emitters. The technology for sampling and analysis of noble gas under field conditions is less mature and more complex than that for particulates. Thus, the noble gas systems have been tested and evaluated under the International Noble Gas Experiment (INGE) conducted by the Technical Secretariat.

In a noble gas station, the air sample collected undergoes processing to separate and concentrate xenon from other constituents. The activity of the purified/concentrated radioxenons is then measured by high-resolution gamma-ray spectrometry or beta-gamma coincidence counting. The volume of air analyzed is determined from the volume of non-radioactive xenon (stable xenon), taking into account the natural abundance of xenon in air (0.087 ppmV at STP). Stable xenon is measured using gas chromatography or thermal conductivity detector.

The three types of noble gas systems in the IMS network, all of which operate automatically are: (1) SPALAX (**S**ystème de **P**rélèvement **A**tmosphérique en **L**igne avec l'**Á**nalyse du **X**énon) (2) SAUNA (**S**wedish **A**utomatic **U**nit for **N**oble **G**as **A**cquisition) and (3) ARIX (**A**nalyzer of **R**adioactive **I**sotopes of **X**enon). The SPALAX uses high-resolution gamma-ray spectrometry while the SAUNA and ARIX use beta-gamma coincidence counting.

The minimum technical requirements for certification of noble gas stations are listed below in Tab. 15.6.

Tab. 15.6 Specifications for IMS Radionuclide Noble Gas Stations (minimum requirements; CTBT/PC/II/Add.2 16 May 1997, p. 49)

CHARACTERISTICS	MINIMUM REQUIREMENTS
Air flow	0.4 m^3/h
Total volume of sample	10 m^3
Collection time	≤24 h
Measurement time	≤24 h
Time before reporting	≤48 h
Reporting frequency	Daily
Isotopes measured	^{131m}Xe, ^{133m}Xe, ^{133} Xe, ^{135} Xe
Measurement mode	Beta–gamma coincidence or high resolution gamma spectrometry
Minimum Detectable Concentration [1]	1 mBq/m^3 for ^{133}Xe
State of health	Status data transmitted to IDC
Communication	Two way
Data availability	95%
Downtime	≤7 consecutive days ≤15 days annually

As of 1 April 2011, there are 27 noble gas stations installed out of the 40. Certification started in 2010, with 3 noble gas stations certified as meeting the abovementioned requirements.

[1] Smallest concentration of radioactivity in a sample that can be detected with a 5% probability of erroneously detecting radioactivity, when in fact none was present (Type I error) and also, a 5% probability of not detecting radioactivity, when in fact it is present (Type II error).

15.2.6 Radionuclide laboratories

In accordance with the CTBT, the network of radionuclide monitoring stations is supported by 16 radionuclide laboratories which perform re-analysis of samples from stations. The purpose of re-analysis of samples from stations by a laboratory is: (1) to corroborate the results of the routine analysis of a sample from an IMS station, in particular to confirm the presence of fission products and/or activation products; (2) to provide more accurate and precise measurements; and (3) to clarify the presence or absence of fission products and/or activation products in the case of a suspect or irregular analytical result from a particular station (CTBT/WGB/TL-11, 17-18 /Rev. 4).

These laboratories have a quality system to include sample handling, preparation, measurement, data analysis and reporting. Their software enables data transmission to the IDC in a standardised format. The Technical Secretariat organizes annual proficiency test or intercomparison exercises as part of a quality assurance program. These laboratories are certified by the Technical Secretariat according to rigorous management and technical requirements contained in PTS/INF.96 Rev. 7. As of 1 April 2011, ten of the 16 radionuclide laboratories are certified.

15.3 Data acquisition

15.3.1 Introduction

The stations in the IMS network send data to the International Data Centre (IDC) according to the Formats and Protocols specified in the corresponding IMS Operational Manual. Stations in the primary seismic, hydroacoustic, and infrasound networks send data in Continuous Data (CD) format. As the name implies, data from these stations are sent continuously to the IDC.

Stations in the auxiliary seismic network send data to the IDC in response to a data request received from the IDC. Each data request is formulated based on IDC data processing results from stations in the primary seismic, hydroacoustic, and infrasound networks. Consequently, only segments of data from auxiliary seismic stations are sent to the IDC. Radionuclide stations send data to the IDC on a regular daily schedule as the data become available at the station.

All IMS data received at the IDC are parsed and are accessible through the IDC relational database management system (RDBMS). After the data are stored in the RDBMS, they are available for automatic processing.

All stations in the IMS network can be securely managed using command and control messages. The communication between IMS stations and the IDC, and between the IDC and users is done over the Global Communications Infrastructure (GCI).

15.3.2 Security concerns

The security concerns of the IMS data are addressed in the following ways. Data collected at IMS stations are signed with a private key, and the resulting signature from that process is transmitted along with the data. The recipient of the data can then use the data, the signature, and the public key from the station to authenticate the data. If the data passes this authentication process, it means that the data were signed by the private key at the station, and that the data have not been modified.

The private key is stored in a hardware device, and with tamper resistant features. Any attempt to tamper with the private key is reported.

The private and public keys are issued and maintained using a Public Key Infrastructure (Xenitellis, 2000), which is operated and maintained by CTBTO. This process of authentication and verification is also used for command and control messages, which are elaborated in section 3.6.

15.3.3 Continuous data stations

Primary seismic, hydroacoustic, and infrasound stations send data to the IDC in Continuous Data (CD) format. At present there are two versions of CD format, namely CD-1.0 format and CD-1.1 format. Both are currently in use, but all new stations employ CD-1.1 format.

The data completeness and timeliness requirements for continuous data stations are quite stringent. These stations are required to send at least 98% of all expected data to the IDC, and 97% of the data should be received at the IDC within 5 minutes after the data have been recorded at the station. Consequently, after any type of outage of sending data, it is very important to restore the real time data flow to the IDC in order to meet the timeliness requirement. Consequently, the CD format specifies a Last In First Out (LIFO) sequence of sending data after an extended outage. This means that the newly recorded data are sent first, which can be interspersed with older data, progressing from younger data to older data.

CD protocol is based on socket level communication. The data sender initiates the data flow by sending a Connection Request Frame to the receiver’s well known port and IP address. The receiver responds by sending a Port Assignment Frame to the sender, which specifies the IP address and port where the sender should begin sending data. In case of CD-1.1 format, there is additional exchange of Option Request Frames at this stage.

The sender then begins to send the data to the receiver at the specified IP address and port. In case of CD-1.0, this consists of a Data Format Frame (DFF), which specifies the format of the subsequent Data Frames (DF). All DFs will adhere to the format specified in the DFF, and can only be interpreted with the DFF information. If there is a change of format, for example if a channel is added or removed from the DF, then a new DFF, preceded by an Alert Frame, must be sent by the sender. The data flow can be terminated by either party by sending the appropriate Alert Frame.

The fact that the data format information is only sent once in CD-1.0 format leads to an efficient use of communication bandwidth. However, it also means the Data Frames can only be interpreted with information from the corresponding Data Format Frame. In order to address this shortcoming, and to add additional functionality, CD-1.1 format was created.

In the case of CD-1.1 format, the Option Request Frames are exchanged after the Port Assignment Frame is sent to the sender, as mentioned above. The sender will then begin to send Data Frames (DF). In CD-1.1, each DF fully describes the data, so there is no need for Data Format Frames, as is required for CD-1.0 format. The CD-1.1 Data Frames also contain a sequence number, which can be used to record which frames have been sent and received. The receiver and sender exchange Acknack Frames to synchronize this information. Every frame in CD-1.1 format can also be signed, to ensure integrity of the data.

CD-1.1 format also include the capability for Command and Control Frames, which can be used to manage IMS stations. More information concerning Command and Control can be found in Section 3.6.

In both CD-1.0 and CD-1.1 the Data Frame contains Channel Sub-Frames (CSF), where each CSF contains the data from a particular data channel or sensor. For example, a typical three component station will have three CSFs, with one CFS for each of the three channels BHZ, BHN, and BHE. The waveform data in each CSF is signed, and the resulting signature is also stored in the CSF. In the case of CD-1.1, the entire data frame will also be signed, and the signature of the entire frame will be sent in the frame trailer. The components of a CD-1.1 Data Frame are summarized in Fig. 15.3.

Frame Header and Channel Subframe Header	
Channel Subframe 1	*signature*
Channel Subframe 2	*signature*
…	
Channel Subframe n	*signature*
Frame Trailer	*signature*

Fig. 15.3 Components of a CD-1.1 Data Frame. Note that each channel subframe is signed, as well as the frame itself. The data frame signature is found in the frame trailer.

15.3.4 Segmented data stations

IMS auxiliary seismic stations send data to the IDC in response to a waveform data request from the IDC. The data request and the response adhere to IMS 2.0 Formats and Protocol. The request specifies the start and end time, as well as the station and channels which should be returned to the requestor.

The data request is based on a preliminary event location made using data from primary stations, i.e., stations which send data in continuous mode. Once an event is detected by the primary network, a data request is sent to all auxiliary stations within 30 degrees of this preliminary location plus auxiliary stations which have a high probability of detecting the event. In this way, the auxiliary data assist in refining the location by providing additional regional observations.

The messages exchanged in IMS 2.0 format are sent via e-mail. The original concept of using email for waveform data exchange was pioneered by Urs Kradolfer (Kradolfer, 1996). Prior to IMS 2.0, there were a number of earlier revisions of the format, including GSE 2.0, GSE 2.1, and IMS 1.0 (see also Chapter 10 and IS 10.1 and 10.2). While additional data types and features have been added with each revision, the data request and response messages have remained relatively stable.

Since IMS 2.0 data are typically sent via email, the waveform data are converted into ASCII representation in the email message. There are a few different supported waveform data types. One data type is integer format, named "INT", where the waveform digital counts are reported as integer values. The second format is named "CM6", where the digital waveform counts are processed with an algorithm to compress the data and transmit the data in ASCII format. A third option allows waveform data to be sent along with corresponding data signatures. This format is named "CSF", and is formed by converting a CD-1.1 Channel Sub-Frame (see Section 3.3), into ASCII format using base 64 encoding.

15.3.5 Radionuclide stations

Radionuclide stations send data to the IDC on a regular daily schedule as the data become available at the station. The data are sent in IMS 2.0 format via e-mail. Particulate systems produce one radionuclide spectrum per day which is sent to the IDC. Noble Gas systems produce one or two radionuclide spectrum per day, depending on the type of measurement system. In additional, radionuclide stations send state of health information on a regular basis, ranging from 2 to 6 hours, depending on the type of system. Radionuclide stations also send various spectra types for calibration purposes, including blank spectra, detector background spectra, and calibration source spectra.

15.3.6 Command and control

Command and Control messages are used to securely command IMS stations. The process is typically initiated by sending a signed command message from the IDC to the station. At the station the command is checked for authenticity, the requested action is carried out, and a command response message is returned to the IDC. The commands are used for seismic station calibration. Command messages are sent in IMS 2.0 format via email. There are also provisions in CD-1.1 format to support the exchange of command and control frames.

15.3.7 Global Communication Infrastructure

Data are sent from the IMS stations to the IDC over the Global Communication Infrastructure (GCI). The GCI is also used to send IMS data and IDC products from the IDC to authorized users. The topology between stations and the IDC is typically done in one of two ways; one option is basic topology, and the other is the Independent Sub Network (ISN).

In the case of basic topology, data are sent from the station over a Very Small Aperture Terminal (VSAT) through a satellite link to a satellite ground station, which in turn is connected to the IDC via a terrestrial link. In the case of an ISN, a country may take the responsibility to transport data from several stations on its territory to a central location. The data at that central location are then sent onward to the IDC, typically over a terrestrial connection.

The complete GCI is a large operation which includes 215 VSAT connections and 6 terrestrial connections. The GCI link availability requirement is 99 %, which is currently being routinely achieved.

15.4 Waveform data processing

17,4.1 Introduction

Waveform data are automatically processed once they have arrived at the IDC. Waveform station processing for continuous data stations is done in fixed time intervals (Fig. 15.4). The duration of those time intervals is 10 minutes for primary seismic and hydroacoustic stations, and 30 minute intervals for infrasound stations. Each interval is processed after 95 % of data used for station processing from that station has arrived in the RDBMS. Data from auxiliary seismic stations are processed once the requested data segments have been parsed into the RDBMS and a sufficient amount of requested data has been received.

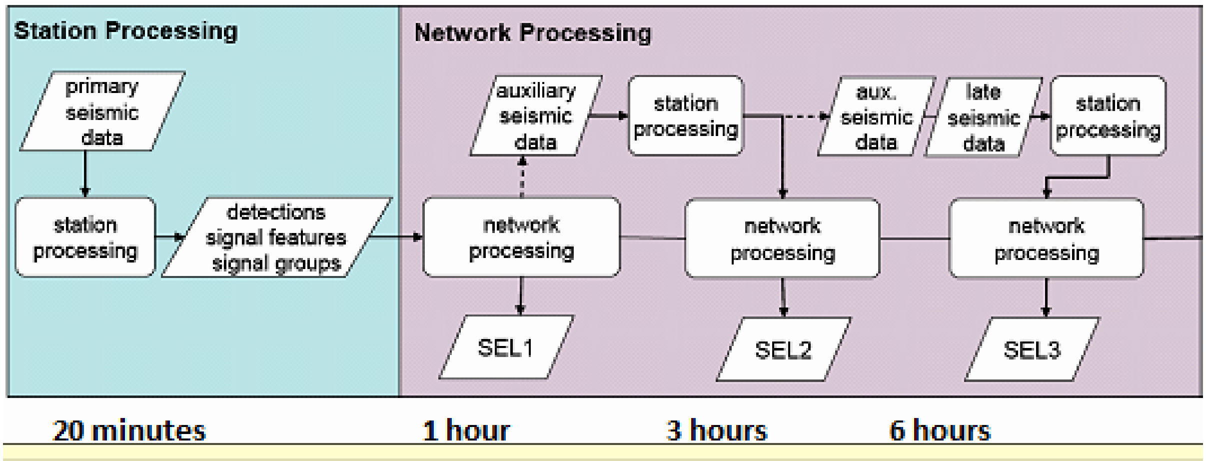

Fig. 15.4 Overview of station processing and network processing. Note that network processing is run three times, to accommodate data from auxiliary stations and late arriving data. Network processing results in the Standard Event Bulletins (SEL) 1, 2, and 3, which are automatically generated 1, 3, and 6 hours after real time.

Waveform station processing performs quality control checks, band-pass filtering and beamforming (see Chapters 4 and 9) to improve the signal-to-noise ratio and detect signals in the data interval. Feature extraction is then performed for each detection and the resulting detection time (see also Chapter 16), amplitude, period, azimuth and slowness are written to the RDBMS. The final stages of station processing include signal grouping, initial phase identification, and location of single station events. The arrivals resulting from station processing are the input in network processing, where the arrivals are combined to form events which are published as automatic bulletins, named SEL1, SEL2, and SEL3 where SEL is an abbreviation for Standard Event List.

After the final automatic bulletin is produced, the data are ready for review by the IDC analysts. The analysts correct mistakes in the automatic bulletin, refine the results, and add events which were missed. The result of this work is published as the Reviewed Event Bulletin (REB). Currently, during provisional operations, the target timeline for publishing the REB is within 10 days of real time. After Entry Into Force (EIF) of the Treaty, the target timeline is reduced to 48 hours.

15.4.2 Seismic station processing

Broadly speaking, there are three types of IMS seismic stations; three component stations, array stations (which typically vary in aperture up to 20 kilometers), and one large array, which has an aperture of more than 60 kilometers. Different processing techniques are applied to these three station types, as described below.

Station processing is performed by a series of two applications, DFX (**D**etection and **F**eature E**x**traction) and StaPro (**Sta**tion **Pro**cessing). DFX is used to detect signals and extract their features. The output of DFX includes detection time, amplitude, period, signal to noise ratio (SNR), azimuth, azimuth uncertainty, slowness, and slowness uncertainty. The StaPro application recognizes noise arrivals, assigns initial phase names, and locates single station events. The output of StaPro includes the initial phase name and single station event locations.

15.4.2.1 DFX

DFX performs the following processing steps:

1. Data Quality Control (DQC) – removes bad channels, repairs data gaps and spikes;
2. Improve and Estimate SNR – performs filtering and beaming to improve SNR for all detection beams;
3. Find detection – use STA/LTA detector (see IS 8.1), best beam and trigger time;
4. Refine time – use Akaike Information Criteria (AIC) to refine onset time;
5. Measure amplitude and period;
6. Estimate azimuth and slowness – perform frequency-wavenumber (f-k) (cf. Chapter 9) or polarization analysis (see Fig. 2.6 of Chapter 2) to estimate slowness, azimuth, and associated error estimates;
7. In the case of array data, steps 4 and 5 are repeated, based on the results from step 6.

Data Quality Control

Data Quality Control (DQC) is the initial step in data processing. Problematic data are identified as spikes, continuous zeros, repeated amplitude values, gaps, and channels with anomalous amplitude values. Spikes are recognized by the difference in amplitude relative to the surrounding data values. Repeated amplitude values are recognized by the number of consecutive samples with the same amplitude value (usually between 4 and 10). In some cases, problematic data can be repaired through interpolation, or detrending. If the data cannot be repaired, then a mask is created indicating where the data have quality problems and should be excluded from processing. If a large percentage of the data (usually more than 33%) on a given channel are masked, then the channel is excluded from processing for the entire processing interval. Recall that processing intervals are typically 10 minutes long for seismic data.

Improve and estimate SNR

The SNR is improved at three component stations by filtering the vertical channel in various filter bands, and incoherent beams are made from the two horizontal channels. An example beam recipe for a three component station is shown in Fig. 15.5 and the filtered vertical channel at the station SIV is shown in Fig. 15.6.

An array station consists of sensors which are spatially distributed. When a signal traverses an array, it is recorded by individual sensors at different times. Time delays relative to the reference beam point can be calculated by using the relative distance to the reference point, and an assumed slowness vector (Fig. 15.7). Based on the coherence of the signal and the incoherence of noise, beaming delay-corrected signals from array elements can significantly improve the SNR of a signal.

Typical beam recepies for 3-C stations:

name	type	rot	std	snr	azi	slow	phase	flo	fhi	ford	zp	ftype	group
Z0515	coh	no	0	3.50	0.0	0.000	-	0.50	1.50	3	0	BP	vertical
Z1020	coh	no	0	3.50	0.0	0.000	-	1.00	2.00	3	0	BP	vertical
Z1530	coh	no	0	4.00	0.0	0.000	-	1.50	3.00	3	0	BP	vertical
Z2040	coh	no	0	4.00	0.0	0.000	-	2.00	4.00	3	0	BP	vertical
Z3060	coh	no	0	5.00	0.0	0.000	-	3.00	6.00	3	0	BP	vertical
Z4080	coh	no	0	6.00	0.0	0.000	-	4.00	8.00	3	0	BP	vertical
H0515	inc	no	0	5.50	0.0	0.000	-	0.50	1.50	3	0	BP	horizontal
H1020	inc	no	0	5.50	0.0	0.000	-	1.00	2.00	3	0	BP	horizontal
H1530	inc	no	0	5.50	0.0	0.000	-	1.50	3.00	3	0	BP	horizontal
H2040	inc	no	0	5.50	0.0	0.000	-	2.00	4.00	3	0	BP	horizontal
H4080	inc	no	0	5.50	0.0	0.000	-	4.00	8.00	3	0	BP	horizontal

Fig. 15.5 Example of a beam recipe for a three component station. The column headings are: name – channel name for the beam; type – beam type, coh – coherent or inc – incoherent; std – specifies whether or not this is a standard beam (1 if yes); snr – threshold snr for declaring a detection; azi – azimuth to use for beamforming at an array; slow – slowness to use for beamforming at an array; phase – phase to use for beamforming when making origin beams; flo – low cut value of the applied Butterworth filter; fhi – high cut value of the applied butterworth filter; ford – specifies the order of the applied Butterworth filter; zp – specifies if the applied Butterworth filter should be zero phase (1 if yes); ftype - filter of the applied Butterworth filter (BP – band pass; HP – high pass; LP – low pass); group – specifies which channels from the station should contribute to forming the beam.

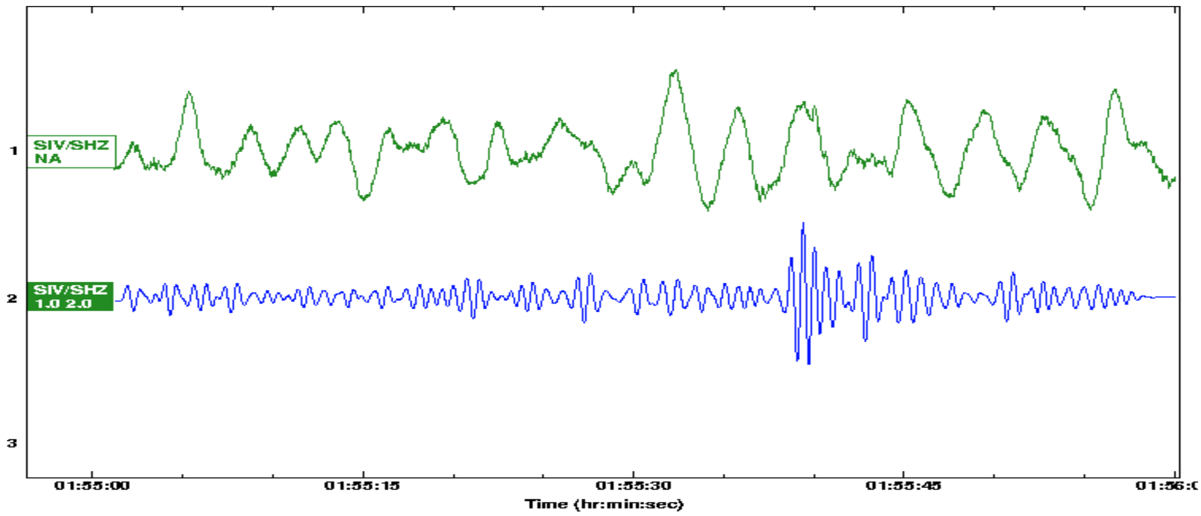

Fig. 15.6 Filtered (1.0 to 2.0 Hertz) vertical channel from the station SIV, in San Ignacio, Bolivia for arrival at 01:55:38.9 for event on 09-Oct-2006 resulted in a good signal-to-noise ratio (lower trace), in comparison with the more broadband velocity raw data (upper trace).

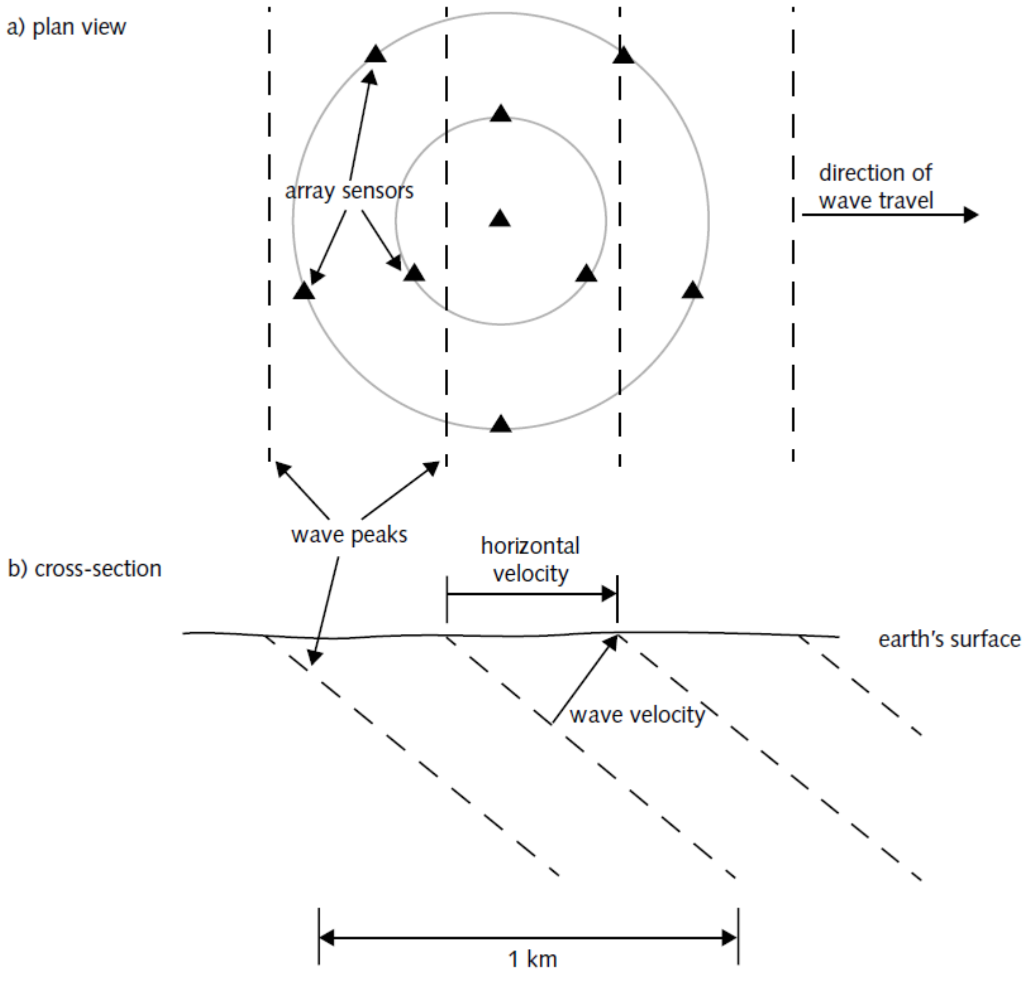

Fig. 15.7 Illustration of a seismic plane wave passing through an array.

For each IMS array, there are several beams which are created, where each beam specifies a specific azimuth and slowness to steer the beam, specific filter band, and a list of which elements to use to form the beam. A beam recipe for an array station uses the same format as for 3-component stations, as was shown in Fig. 15.5.

Find detection

An STA/LTA detector is used at the IDC for detecting signals in seismic data. STA (short-term-average) is a time-average of some function of data (for example, amplitude, power, or energy) over a short period of time relative to the LTA (long-term-average) (see IS 8.1). The STA/LTA detector for seismic and hydroacoustic data uses a running average for the STA and a recursive average for the LTA. The LTA "lags" the STA in time by half the width of the STA window. The STA and LTA are defined as:

STA: $$\boldsymbol{STA}(\boldsymbol{k}) = \boldsymbol{STA}(\boldsymbol{k}-1) + \tfrac{1}{S}[\left|\, \boldsymbol{x}(\boldsymbol{k} + \tfrac{S}{2})\right| - \left|\, \boldsymbol{x}(\boldsymbol{k} - 1 - \tfrac{S}{2})\right|]$$

LTA: $$\boldsymbol{LTA}(\boldsymbol{k}) = (1 - \tfrac{1}{L})\boldsymbol{LTA}(\boldsymbol{k}-1) + \tfrac{1}{L}\boldsymbol{STA}(\boldsymbol{k} - \boldsymbol{S})$$

The initial value of the STA is: $$\boldsymbol{STA}(\tfrac{S}{2}) = \tfrac{1}{S}\sum_{\boldsymbol{S}=0}^{\boldsymbol{S}-1}\left|\, \boldsymbol{x}(\boldsymbol{S})\right|$$

where: x(n): time series
S: the number of samples in the STA window
L: the effective number of samples in the LTA window.

The typical STA length is one second (1.5 seconds for the large array NOA), and 60 seconds for the LTA length.

The STA/LTA threshold (SNR) is specified in the associated beam recipe. When the SNR threshold is exceeded, there is a potential detection. When the SNR thresholds are exceeded for many beams at nearly the same time, the beam with the largest SNR is identified as the best beam. This beam and related parameters are saved for subsequent station processing. An example of identifying the best beam is shown in Fig. 15.8.

Onset time refinement

Once a detection is declared, the trigger time is refined using the Akaike Information Criteria (AIC) (Akaike, 1974). The AIC is applied with a signal window of four seconds with a three second lead time, and a noise window of three seconds which starts six seconds prior to the initial trigger time. The maximum adjustment time is up to two seconds compared to the initial trigger time. The onset time picking error is constrained in the range from 0.685 s to 1.72 s for automatic processing and from 0.12 s to 1.07 s for interactive processing.

For arrays, the AIC is applied twice, i.e., once for the detecting beam after the trigger time is declared, and again for the f-k beam after f-k analysis is performed.

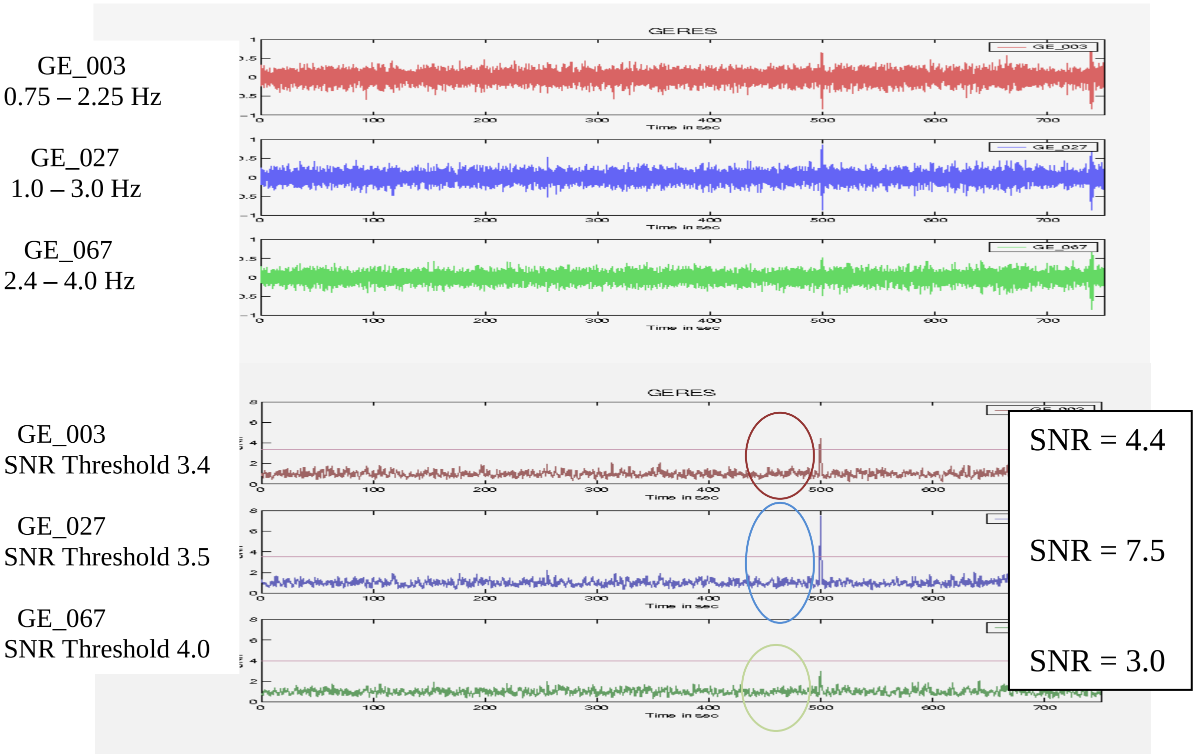

Fig. 15.8 The best beam for this detection at GERES is the beam with the highest SNR. Top three panels show three beams of GERES, while bottom panels show the SNR traces for these three beams. The beam named GE_027 has an SNR of 7.5, which is the highest.

Measure amplitude and period and determine magnitudes mb, Ms and ML

There are two amplitude types measured by DFX during seismic station processing (Tab. 15.7) which are used for calculating magnitude values. The A5/2 amplitude type is used for calculating the IDC mb magnitude during automatic processing, while the SBSNR amplitude is used to calculate the ML magnitude. After interactive review, the IDC mb magnitude is calculated using A5/2 amplitude type measured from the origin beam.

Tab. 15.7 Amplitudes computed by DFX during station processing.

Amp Type	Beam Type	Filter Band	Time Window	Magnitude
A5/2	Coherent	0.8 – 4.5 Hz	6.0 (0.5 + 5.5) s	mb
SBSNR	Incoherent	2.0 – 4.0 Hz	4.0 s	ML

The A5/2 amplitude used for IDC mb magnitude is measured as half the maximum peak-to-trough (or trough-to-peak) amplitude on the vertical channel at three component stations using the fixed filter band 0.8 – 4.5 Hz, while at array stations the A5/2 amplitude is measured on the f-k beam using all vertical sensors at the array using the same filter band and the azimuth and slowness based on the origin for which the mb magnitude is being calculated. The time window used for finding the maximum amplitude is 0.5 s before the first P onset and 5.5 s after the first P onset. Thus, the name A5/2 refers to half peak-to-peak amplitude in a 6 second time window. The period of the A5/2 measurement is based on the three half periods around the observed maximum amplitude (Fig. 15.9). The A5/2 amplitude measurement is made based on the maximum amplitude found in the time window specified in Tab. 15.7.

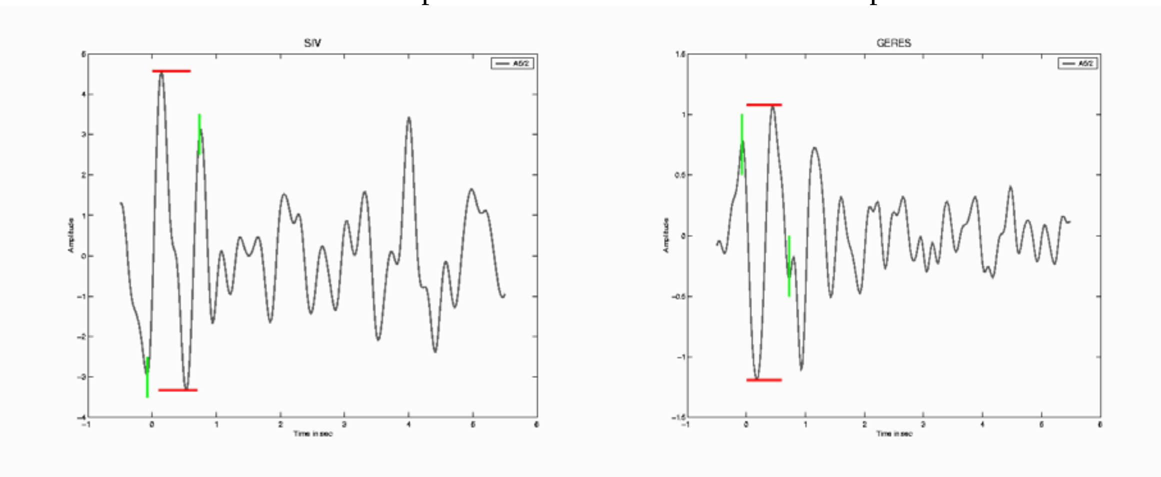

Fig. 15.9 The mb amplitude is measured on filtered vertical channel for arrival at SIV (3-C) (left) and on a coherent f-k beam for all vertical channels at GERES (array) (right). The final period is based on the three half periods between the two green lines. The peak-to-trough amplitude is measured between the interpolated peaks indicated by red lines in the diagrams above.

In contrast to standard mb, which is calculated by calibrating the measured P-wave amplitude, depending on epicentral distance Δ and source depth h, with the Gutenberg and Richter (1956) Q(Δ,h) values (see Fig. 1a in DS 3.1), the IDC amplitudes A5/2 are calibrated with the Veith and Clawson (1972) calibration function for 1 Hz vertical component P-waves, which is given for peak-to-trough amplitudes (see Figure 2 in DS 3.1).

The specifics of the IDC measurement procedure for mb has been optimally tuned to the mandate of the CTBTO. This is to assure, amongst others, the best possible detection of and discrimination between underground nuclear explosions (UNE) and natural earthquakes. It should be noted, however, that on average mb(IDC) values are systematically too small for stronger earthquakes when comparing mb(IDC) with mb resulting from NEIC or the new IASPEI (2005 and 2011) standard procedure for mb (Bormann et al., 2007 and 2009). These difference grows with magnitude. While it is negligible for mb (NEIC) < 4 it amounts already to almost -0.5 magnitude units for events with mb(NEIC) between 5.0 and 5.9. For the great 2004 Mw9.3 Sumatra-Andaman earthquake it even reached extreme values between -1.5 and -1.8 m.u., respectively (mb(IDC) = 5.7, mb(NEIC) = 7.2 and mb(IASPEI 2005) = 7.5). The reasons for the more pronounced magnitude saturation of mb(IDC) are discussed in detail in Chapter 3 as well as in Bormann et al. (2007) e.g., the filter band and length of the time window used for calculating amplitude and period.

The SBSNR amplitude for three component stations is measured on the vertical channel using the filter band 2.0 – 4.0 Hz, while at array stations the SBSNR amplitude is measured on a beam using all vertical channels with no steering with the same filter band. No period is measured for the SBSNR amplitude (as for classical ML measurements; see Chapter 3, Section 3.2.4), and the amplitude is calculated as:

$$amp = \sqrt{(MAX(STA))^2 - LTA^2}. \tag{15.1}$$

In contrast to amplitude measurement for mb, based on the maximum P-wave amplitude within the first 5.5 seconds after the first onset of P, the largest short-term-average MAX(STA) is taken over the whole (2-4Hz)-filtered wave train of the considered local event. The SBSNR amplitudes are measured in the distance range $2^o < \Delta < 20^o$ and when the difference between estimated depth - depth error is < 40 km.

The attenuation correction for ML is calculated from the formula:

$$a + b * r + c * \log_{10}(r) \tag{15.2}$$

where r is the epicentral distance (in km) and the coefficients a, b, c have been tailored for each station that contributes to the REB to maximize agreement between ML and mb. Each station has its own a, b, and c values, and the values of these coefficients may change from time to time as part of tuning work to make more consistent magnitudes. The REB MLmagnitude is obtained from:

$$ML = \log_{10}(amp/per) + a + b * r + c * \log_{10}(r) \tag{15.3}$$

where *amp* is the short-term average amplitude as it appears in the REB in nm (0-peak). It has been transformed from a short-term average value, corrected for long-term noise and measured in a 2-4 Hz bandpass. The period *per* in the formula above is always 1/3 sec (0.33 in the REB) for ML, as the amplitude is measured from a bandpass filtered channel (between 2-4 Hz) with a center frequency of 3 Hz. Note that for stations with instrument calibration periods different from 1 sec, the instrument calibration period will enter the formula.

Thus, the IDC ML, based on rms amplitudes being measured on a narrow-band filtered vertical component trace and on coefficients in the ML formula being deliberately tailored to assure best possible agreement between local ML and teleseismic mb, differs from the IASPEI standard ML as outlined in Chapter 3, section 3.2.7.

As mentioned in 15.1.2, the most effective technique used at the IDC for discriminating between natural earthquakes and underground nuclear explosions is the mb/Ms screening criterion. Therefore, additionally to the two body-wave magnitudes, the IDC determines for individual stations also the surface-wave magnitude Ms(sta). It is based, as the classical NEIC and now standard Ms(20) procedure on reading the maximum vertical component surface-wave amplitude at periods between 18 s and 22 s. However, the IDC Ms values are not calibrated with the IASPEI standard Prague-Moscow calibration formula for surface-wave amplitude readings, but rather with the modified formula (18) in Rezapour and Pearce (1998). The latter avoids distance-dependent biases in Ms when applying the IASPEI standard formula to exclusively 20 ± 2 s surface waves readings. The reason for these distance-dependent biases in Ms_20 are that the IASPEI standard formula used for calibration was derived on the basis of (A/T) max readings that were not restricted to periods around 20 s but allowing for periods in a much wider range between 2 s and < 30 s (see Vanek et al., 1962; Karnik et al., 1962). Indeed, observations of surface-wave (A/T) max from globally distributed earthquakes confirm that for earthquakes with magnitudes < 7 and/or recorded at distances < 50° (A/T) max is measured mostly at periods well below 18 s, down to about 3 s (see Bormann et al., 2009). The Ms formula used at the IDC reads:

$$Ms(sta) = \log_{10}(amp/per)_{max} + B(\Delta) \tag{15.4}$$

where Ms(sta) is the Ms Magnitude for a given station, *amp* and *per* are from the **amplitude** table (*amptype* = ALR/2, or ANL/2). ALR/2 identifies Rayleigh wave signal measurements, and ANL/2 identifies noise measurements. *amp/per* is the maximum amplitude/period ratio within the allowed period range of 18 to 22 s (Stevens and McLaughlin, 2000). $B(\Delta)$ is identical with the Rezapour and Pearce (1998) calibration function (which is a scaled inverse attenuation formula) for 20 s surface waves. When *amp* is measured in nm instead of µm, then this calibration function reads:

$$B(\Delta) = 1/3\,\log_{10}(\Delta) + 1/2\,\log_{10}(\sin\Delta) + 0.0046\Delta + 2.370, \qquad (15.5)$$

where the term 0.0046 is γ times $\log_{10}(e)$ (= 0.4343), and γ, the attenuation coefficient. γ was determined empirically by Rezapour and Pearce (1998) to be 0.0105 using a very large data set.

Estimate azimuth and slowness

Azimuth and slowness are measured in DFX using different techniques for three component stations (polarization analysis), arrays (f-k analysis), and for the large array (beampacking technique) as shown in Tab. 15.8.

Tab. 15.8 Azimuth and slowness estimation methods for different station types. The filter band used for f-k analysis at arrays is dependent on the band of the best beam.

Station type	Method	Time Window	Filter band	Channel
3-C	polarization	5.5 sec	1.0 – 4.0 Hz	Z/N/E
Array	f-k analysis	3.15 – 10.8 sec	~beam*	Z channels
Larray	beampacking	6.0 sec	1.2 – 3.2 Hz	Z channels

*the filter band depends on the band of the best beam, i.e., the beam with the highest SNR

In polarization analysis for three component stations, polarization analysis is done over a series of overlapping windows near the detection. In each of the overlapping windows a covariance matrix is estimated for the three components of motion and then the eigenvalues (λ_1, λ_2, λ_3), and eigenvectors ($\mathbf{u}_1$, $\mathbf{u}_2$, $\mathbf{u}_3$) are solved for the covariance matrix. The signal rectilinearity is a measure of the linearity of the particle motion, and is calculated as:

$$rect = 1 - \frac{\lambda_3 + \lambda_2}{2\lambda_1} \qquad (15.6)$$

In the overlapping window with the maximum rectilinearity for the short-period filtered P wave the incident angle *inang* is estimated as:

$$inang = \frac{\mathrm{acos}(|u_{11}|)}{90} \qquad (15.7)$$

where u_{11} is the direction cosine of the eigenvector $\mathbf{u_1}$ associated with the largest eigenvalue.

The observed azimuth, *seazp*, of the signal (assuming that the signal is a P-phase) is the azimuth of the eigenvector ($\mathbf{u}_1$) associated with the smallest eigenvalue:

$$seazp = \operatorname{atan2}(\frac{u_{13}}{u_{12}}) \quad (15.8)$$

The final slowness *s* during polarization analysis is calculated as:

$$slowness = polar\_alpha \cdot \sin(\frac{inang}{2}) \quad (15.9)$$

where polar_alpha = A/(2·B^2), and A = P-wave velocity at the station site (km/sec), and B = S-wave velocity at the station site.

In f-k analysis for seismic arrays, spectra are computed from the vertical channels in a station-dependent time window. For each slowness vector, the f-k power spectrum is calculated as:

$$P(s_n, s_e) = \frac{\sum_{f=f_1}^{f_2} \left| \sum_{i=1}^{J} F_i(f) \cdot e^{2\pi\sqrt{-1} f (s_n \cdot dnorth + s_e \cdot deast)} \right|^2}{J \cdot \sum_{f=f_1}^{f_2} \left\{ \sum_{i=1}^{J} (F(i))^2 \right\}} \quad (15.10)$$

where $deast_i$ and $dnorth_i$ are the east-west and north-south coordinates, respectively, of the ith sensor array element relative to the reference station.

The slowness vector with the maximum f-k power is selected for estimating the azimuth and slowness values.

The beampacking technique, also called time domain f-k analysis is used for estimating azimuth and slowness for the large array NOA. This scheme is based on beamforming over a predefined grid of slowness points and measuring the power. The relative power is the signal power of the beam for the peak slowness divided by the average channel power in the same time window.

15.4.2.2 StaPro

StaPro performs the following processing steps:

1. Determine initial wave type – categorize seismic detections as one of four initial wave types: noise (N), teleseismic (Δ > 20°), regional P or regional S (Δ < 20°)
2. Group detections – place signals into groups in which each member has similar characteristics suggesting that they were generated by the same event.
3. Assign initial phase name – regional phase identification is done by examining all arrivals from the same group. Phase names for teleseismic data are limited to a simplified phase naming convention used by StaPro.
4. Locate single station events – compute a single-station event location and estimate local magnitude for association groups.

Determine initial wave type

The initial wave types at seismic arrays are mainly dependent on the velocity estimates from DFX. Tab. 15.9 shows the velocity ranges for determining the initial wave types in StaPro. There are several noise screening functions used at the IDC to recognize noise arrivals.

Tab. 15.9 Relationship between initial wave types and velocity ranges at seismic arrays. *Note that the exact velocity ranges are station dependent.

Initial wave type	Velocity range*
P (teleseismic)	≥ 11.0 km/s
P (regional)	5.7 – 11.0 km/s
S (regional)	2.9 – 5.7 km/s
N(oise)	≤ 2.9 km/s

The initial wave types at three component seismic stations are determined using default rules or neural networks. The default rules are shown in Tab. 15.10.

Tab. 15.10 Default rules for determining initial wave types at 3-C stations. Rect = rectilinearity, hvrat = horizontal to vertical ratio, and freq = central frequency of the detecting channel.

Signal Type	Rule
Teleseismic P	rect > 0.7 and hvrat ≤ 1.0 and freq < 3 Hz
Regional P	rect ≥ 0.7 and hvrat ≤ 1.0 and freq ≥ 3.0 Hz
Regional S	rect < 0.7 or hvrat > 1.0

Alternatively, neural networks can be applied to determine the initial wave types for three component stations. The neural networks use the signal period, the polarization features, and the context of the given arrival (the relative time difference and the number of arrivals in a window centered on the arrival of interest) as inputs and produce a probability for each of the four classes as output. Three neural networks are used: the first distinguishes between noise and signals, the second one between teleseismic and regional phases, and the last one for regional P and S.

Group detections
Signals are grouped together by StaPro based on the compatibility of the signal type, azimuth, associated azimuth error, amplitude, and relative time difference. The logic flow of the grouping process is shown in Fig. 15.10.

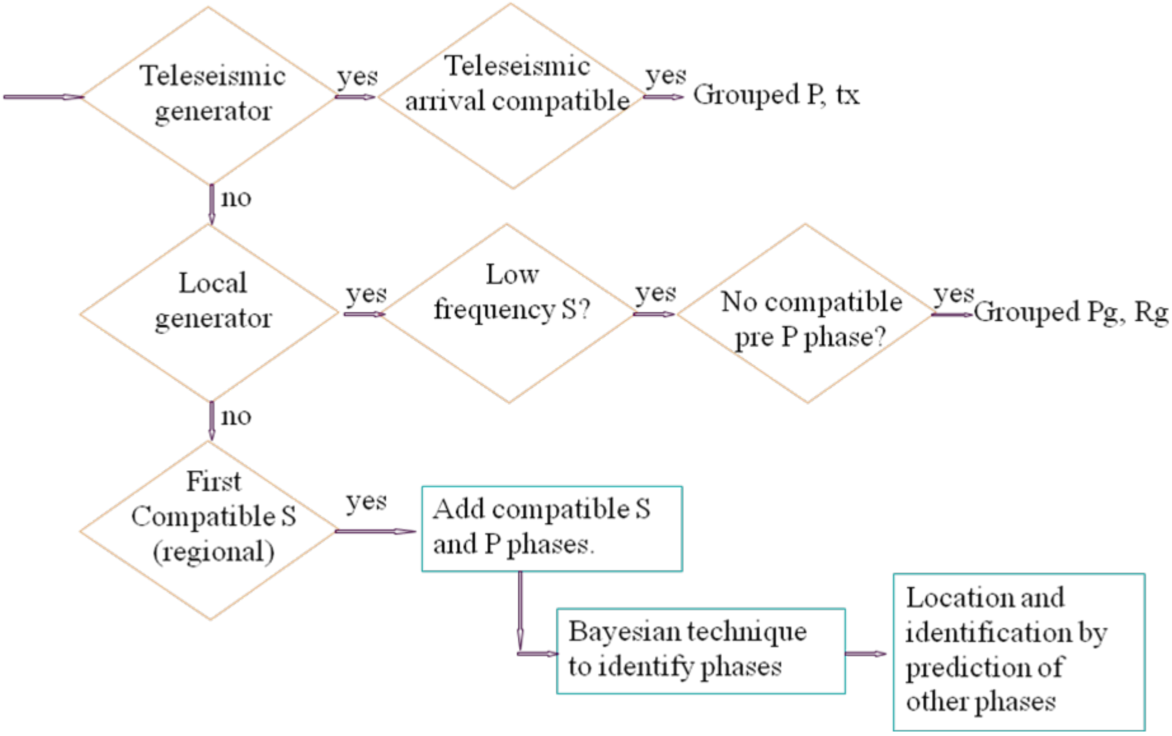

Fig. 15.10 Logic of the phase grouping algorithm in StaPro, used to group together phases from the same event.

Assign initial phase name

The initial phase names are assigned based on the initial wave type and the grouping process. The relationship between initial wave type and initial phase name is shown in Table 11.

Table 15.11 Initial phase names based on initial wave types.

Initial Wave Type	Initial Phase Name
P (teleseismic)	P, tx
P (regional)	Pn, Pg, Px
S	Sn, Lg, Rg, Sx

Locate single station events

Compatible phases which are grouped together can be used to form single station events. During the location process, time, azimuth and slowness values can be defining when locating the event. Each observation which is defining (time, azimuth or slowness) is assigned a certain weight, as shown in Tab. 15.12. Single station events must have a phase weight for 2.6 or more for the single station event to be saved in the automatic bulletin.

Tab. 15.12 Seismic phase weights used in StaPro for forming a single station event at a primary seismic station.

Phase type	Station	Time defining	Azimuth defining	Slowness defining
Primary	Array	1.0	0.5	0.5
Secondary	Array	0.7	0.5	0.5
Primary	3-C	1.0	0.25	0.25
Secondary	3-C	0.7	0.25	0.25

15.4.3 Event location

The determination of event hypocentral locations is a core functional element of many automatic and interactive applications within the IDC system. Hypocenters are determined via an iterative non-linear least-squares inversion. A flow chart of this process is shown in Fig 15.11.

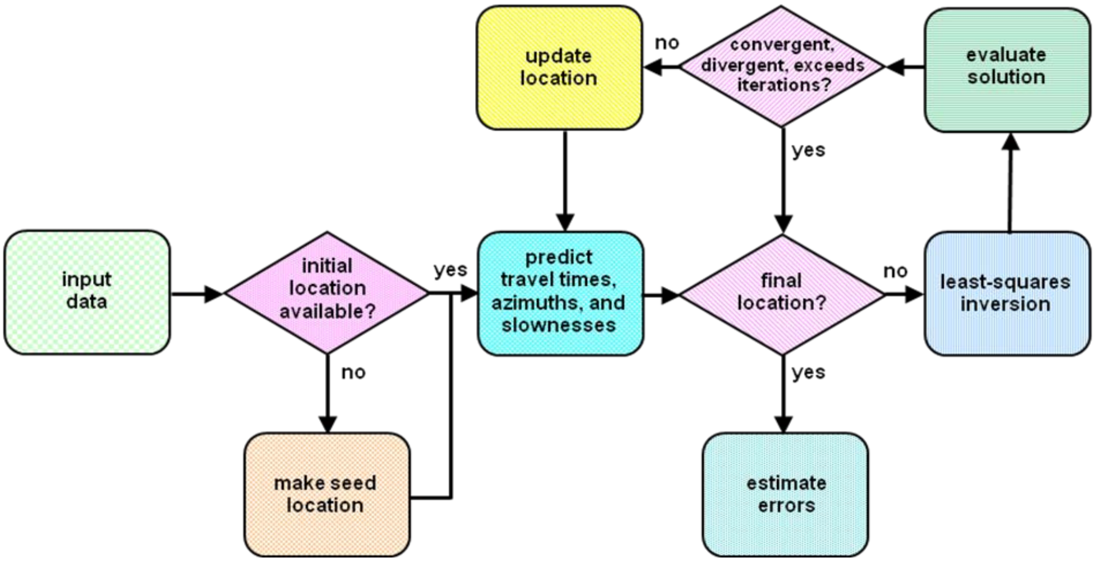

Fig. 15.11 Flow chart of the location process used at the IDC.

15.4.3.1 Input data

Phases used in the location process are known as ***defining*** phases. A defining phase may have one or more of three attributes that are used in the location process: ***time***, ***azimuth*** and ***slowness***. Time-defining phases are the most common.

For seismic data azimuth and slowness defining phases are generally more useful from array stations than from 3-C stations because the standard deviation of the errors tends to be much smaller for array stations.

All infrasonic stations of the IMS are arrays, so for infrasonic data azimuth and slowness information are available for all stations. The hydroacoustic data from the IMS are processed as groups of hydrophones, so azimuth and slowness is available for these data. However, the slowness at hydroacoustic stations is treated as a constant.

Use of time, azimuth, and slowness observations

Arrival time information is often the best information to use in event determination, but it is often unavailable in sufficient quantity. In such instances, azimuth and slowness information, as obtained from f-k or 3-C analysis, can be added to obtain more reliable hypocenters with smaller uncertainties. In particular, azimuth/slowness estimates are critical when a location is required at a single station.

Pre-determined uncertainty estimates associated with arrival time information are typically better than that of azimuth/slowness information, these latter data can actually prove counterproductive to the goal of accurate event location.

In practice, the IDC analysts exclude azimuth and slowness estimates from seismic data when more than **six defining arrival times of primary stations** are available to the hypocentral location process.

Establishing the initial location

A reasonable seed (starting) location increases the likelihood of finding the global minimum. The initial locations in preferential order are:

1) a previously determined hypocenter;
2) a location based on an exhaustive grid search as determined by the *GA* (Global Association) subsystem;
3) an internal “best guess” algorithm built into the location library.

In the rare situation when a best guess seed location must be made, the strategy is to use the combination of arrival time, azimuth, and slowness information. The seed algorithm uses a list of ***location scenarios*** to find a starting location:

- Use the time defining S–P time at the closest seismic station and the best-determined defining azimuth from a seismic station to compute a seismic epicentral location.
- Use various combinations of defining S–P times and defining P-wave arrival times from seismic stations to compute a seismic epicentral location.
- Use the two best defining azimuths available from two different stations to define two great circles whose intersections are candidates for the seed location. Choose the location that is closest to the two stations.
- Compute a seismic epicentral location by using the best P-wave azimuth (for direction) and slowness (for distance) from a single seismic station.
- Put the epicentral location near the closest station. Use azimuth information, if available.

Predicting travel-time, azimuth and slowness values

Travel-time, slowness, and azimuth of seismic phases can all be used for locating seismic events. The IASPEI-91 travel time tables contain travel-time parameterized by distance and depth. The modeling error associated with a given phase-dependent travel-time table is also explicitly specified. Travel-time corrections include:

- Ellipticity correction
- Elevation correction
- Source-specific station correction (SSSC)

Source-Specific Station Correction (SSSC)

Source-specific station corrections to the travel time of a seismic phase attempt to correct for the travel-time effects of lateral heterogeneity. SSSC tables are specified by a two-dimensional parameterization along latitudinal and longitudinal nodes. By introducing SSSC information the phase-dependent modeling errors assumed within the one-dimensional travel-time tables should be reduced.

Predicting seismic slownesses and azimuth values

The slowness model is based on the derivative of travel time with respect to distance. Azimuth modeling is based on the exact azimuth between the station and the hypothesized event location.

Azimuth and slowness data from seismic stations are most useful for locating small events, especially when their data importances are high. Unfortunately, significant biases that can map into large event mislocations exist within these data. These biases, coupled with relatively large modeling and measurement errors, also produce very large error ellipses. The goal of the slowness-azimuth station corrections (SASC) is to remove these systematic biases from these azimuth-slowness measurements

Slowness-Azimuth Station Corrections (SASC)

The slowness/azimuth station corrections and related modeling errors are represented on a binned polar slowness/azimuth grid (Bondar, et al, 1999). A constant correction and modeling error is defined over the entire bin. A background correction and modeling error can be defined for those bins without a specified SASC. The background correction is parameterized as a vector slowness correction to adjust for large-scale structural features near the station. In addition, rotational coefficients are specified. These are to be applied to each slowness vector. The total background correction is thus an affine transformation of the slowness vector with a constant component and a rotational component.

Hydroacoustic measurements

Hydroacoustic stations with hydro-channel groups can be used to estimate azimuth (typically under the assumption of fixed slowness). Travel-times and, if available, azimuths of hydroacoustic phases and knowledge of all possible source locations for those phases (expressed as blockage grids for each hydroacoustic station) are used for locating events detected by hydroacoustic network.

The hydroacoustic travel-time model is complicated by the dynamic nature of the oceans through which the hydroacoustic phases propagate. Unlike the seismic travel-time predictions for which corrections are applied to a standard one-dimensional model, seasonally varying travel-time models are used to predict the propagation times for hydroacoustic phases. One-dimensional models are used only if the seasonal models are unavailable.

Because of the slow propagation velocity in the ocean and spatial and seasonal variations in temperature that induce velocity variations, actual travel times may depart substantially from constant-velocity travel times. To account for these spatio-temporal variations, the system provides for the use of seasonally varying, azimuth, and range-dependent travel-time tables specifically calculated for each hydroacoustic station. The travel times and their modeling uncertainty are specified on a polar grid centered at the station.

Hydroacoustic blockage

Hydroacoustic phases propagate long distances with limited attenuation in the water column. The phases are converted at the water-land interface of sizable islands or continents, but the converted waves do not propagate efficiently and are effectively blocked by the island or continental mass.

Blockage is modeled for each hydroacoustic station as the maximum distance of propagation along a set of azimuths. The blockage subsystem is not used as an integral part of the location algorithm. Rather, it is invoked directly by several applications (*ARS* and *GA* for instance) to check if a path is topographically blocked. ARS is the software used by IDC analysts to review waveform data. The Global Association software is used during automatic processing to associate phases and form events.

Infrasound measurements

All of the infrasonic stations of the IMS are arrays and thus the data from these stations yield travel-time, azimuth, and slowness values.

Infrasound does not propagate with a constant velocity in a straight line from its source to the receiver. Rather, there appear to be two basic mechanisms for transporting low frequency acoustic energy in the atmosphere. The first is via reflections between the Earth’s surface and the Stratosphere at an altitude of around 50 km. The second is via reflections between the Earth’s surface and the thermosphere at an altitude of around 120 km. This ‘ducting’ can be responsible for the horizontal transmission of infrasound over many thousands of kilometers.

Currently at the IDC the initial infrasonic phase is used during location, and is designated with the phase name I. The propagation model shown in Tab. 15.13 is used, and a large modeling error is attributed to that value. Travel times are specified as an extension of the IASPEI-91 travel time curves.

Tab. 15.13 Infrasound wave propagation model used at the IDC.

Infrasound wave type	Distance Range (deg)	Velocity (km/s)
Direct arrival and Tropospheric regime	0 to 1.2	0.330
Stratospheric/Thermospheric regime	1.2 to 20	0.295
Stratospheric regime	20 - 60	0.303

15.4.3.2 Nonlinear least-squares inversion

Hypocentral inversion or event location is performed as a nonlinear least-squares inversion of travel time, azimuth and slowness measurements from stations at local, regional and teleseismic distances.

Input data: ***N*** observations (travel times, slownesses, azimuths);
initial guess of event location and origin time (lat_{org}, lon_{org}, $depth_{org}$, t_{org}).

Goal: Minimize the sum of squares of ***N*** non-linear functions (weighted residuals) that depend on a set of parameters (***lat_{org}, lon_{org}, $depth_{org}$, t_{org}***).

$$\begin{bmatrix} res_1^{tt}/\sigma_1^{tt} = t_1^{obs} - t_{org} - t_1^{pred}\left(lat_{org}, lon_{org}, depth_{org}, lat_{sta1}, lon_{sta1}\right) \\ res_1^{sl}/\sigma_1^{sl} = sl_1^{obs} - slow_1^{pred}\left(lat_{org}, lon_{org}, depth_{org}, lat_{sta1}, lon_{sta1}\right) \\ res_1^{az}/\sigma_1^{az} = az_1^{obs} - az_1^{pred}\left(lat_{org}, lon_{org}, lat_{sta1}, lon_{sta1}\right) \\ res_2^{tt}/\sigma_2^{tt} = t_2^{obs} - t_{org} - t_2^{pred}\left(lat_{org}, lon_{org}, depth_{org}, lat_{sta2}, lon_{sta2}\right) \\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ res_N^{tt}/\sigma_N^{tt} = t_N^{obs} - t_{org} - t_N^{pred}\left(lat_{org}, lon_{org}, depth_{org}, lat_{staN}, lon_{staN}\right) \end{bmatrix}$$

where $\sigma = \sqrt{\sigma^2_{model\_err} + \sigma^2_{measure\_err}}$

15.4.3.3 Evaluating the solution

Events are located through an iterative procedure. The procedure is continued, while stable, until convergence is achieved, divergence is recognized, or the maximum number of iterations has been exceeded.

Stability
If the location adjustment at a given iteration is extremely large, then the revised location may be suspect; the stability of the solution is questionable. If the adjustment has been identified as being very large, then the first step is to scale down the adjustment. In the early iterations this means not permitting the location to move more than 3000 km in a single step. For latter iterations this step is reduced to 1500 km.

Divergence tests
Local divergence is associated with a single iteration where the location seems to be getting worse because the current adjustment vector is larger than that encountered during the previous iteration. Global divergence is established when local divergence of sufficient magnitude is identified over two consecutive iterations. A single local divergent iteration is harmless and permits the iterative process to continue. If two consecutive locally divergent steps are identified, the last more than 10% worse than that two iterations prior, then global divergence is declared, and the iterative location process is terminated with an appropriate error message.

Convergence tests
If the total spatial adjustment vector in all dimensions is less than 0.5 km coupled with an origin time change of less than 0.5 s, then the solution has converged.

Maximum iteration test
If convergence has not been achieved, iteration is terminated when the maximum number of iterations is reached. The maximum number of iterations for location is set to 60 for analyst review. A minimum of four iterations are always performed.

The iteration number is also used to control the conditions of the inversion. The depth element of hypocentral parameters is constrained (fixed) during the first two iterations.

Updating hypocenters
After all of the stability and convergence tests have been completed the hypocenter is updated based on the newly-determined adjustment solution vector. When convergence or divergence has been declared, the prediction process has to be invoked one last time so the data residuals and network statistical measures coincide with the most recently adjusted hypocenter.

Estimating errors
Estimating errors includes calculating the model covariance matrix, data resolution matrix, the resultant 90th percentile error ellipse, depth error, and origin time error.

15.4.4 Event definition criteria

The IMS network records a variety of signals from events throughout the world. A criterion is applied in order to decide which events to include in the automatic and reviewed bulletins produced by the IDC. Considering the mission of the organization, to look for evidence of potential Treaty violations, the concept of the event definition criteria was introduced.

Each event recorded by the network is composed of defining phases used in the location process. Each of these defining phases is assigned a weight, and the sum of these weights is the weight of the event (Tab. 15.14). Note that defining phases at auxiliary seismic stations do not contribute to the weight of an event, but auxiliary seismic stations are used to refine the event solution. Events must have a weight of 3.55 or above to appear in the SEL1, SEL2, or SEL3 bulletins, and an event must have a weight of 4.6 or above to appear in the REB (reviewed event bulletin). This essentially means that an event must be observed by at least two primary stations to appear in the automatic bulletins (SEL1, SEL2, SEL3), and must be observed by at least three primary stations to appear in the REB. Primary stations in this case refer to primary seismic stations, hydroacoustic stations, and infrasound stations.

Tab. 15.14 Phase weights used for event definition criteria. A primary seismic type phase is the first P-type phase (from the list P, Pn, Pg, or PKP) and the secondary seismic type phases are all subsequent defining phases.

Phase Type	Station Type	Arrival Time	Azimuth	Slowness
Primary seismic	Primary seismic array	1.0	0.4	0.4
Secondary seismic	Primary seismic array	0.7	0.4	0.4
Primary seismic	Primary seismic 3-C	1.0	0.2	0.2
Secondary seismic	Primary seismic 3-C	0.7	0.0	0.0
H	Hydroacoustic	1.2	0.6	0.0
I	Infrasonic	0.8	1.0	0.0

15.5 Data availability

The data from the IMS network and the bulletins from the IDC are available to authorized users in close to real time. Each country that has signed the CTBT may designate a National Data Centre (NDC). Staff at the NDC and other institutes may be designated as authorized users.

Additionally, the Review Event Bulletin (REB) is also provided to the International Seismologic Centre (ISC), who includes the REB as one of their contributed bulletins. The ISC bulletin is freely available from http://www.isc.org.

There is also a new CTBTO initiative known as the Virtual Data Exploitation Centre (VDEC), which aims to make data and products more widely available to the broader scientific community. More information about this project can be obtained by sending your inquiry to the email address vdec@ctbto.org.

Moreover, many products of the former Prototype International Data Center (PIDC) are available at the Defense Threat Reduction Agency (DTRA; http://www.dtra.mil/Home.aspx) Verification Data Base (http://www.rdss.info). This website permits access to and data retrieval from an extensive (>18 Terabytes) archive of hydroacoustic, infrasound and seismic waveform data covering 1994-present, and access to an archive of event bulletins from the PIDC (1995-Sept. 2003) as well as of the IDC with several years delay (as of 2011 IDC data 2000-2004). On this website one finds data availability statistics and infrasound station metadata from stations that are part of the IMS as well as from a few selected non-IMS sites A research data base provides access also to waveforms, signal measurements and source information drawn from a wide variety of official and unofficial sources for nuclear explosions, GT locations and infrasound events. When available, also waveform data from these events can be retrieved via AutoDRM.

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Disclaimer

Recommended overview readings

Barrientos et al. (2001)
Bowers and Selby (2009)
Dahlmann and Israelson (1977)
Dahlmann, Mykkeltveit, and Haak (2009)
Husebye, and Dainty (1996)
Richards (2002)
Richards and Wu (2011)

References

Akaike, H. (1974). A new look at the statistical model identification. *IEEE Transactions on Automatic Control*,**19** (6), 716–723.

Barrientos, S., Haslinger, F., and IMS Seismic Section (2001). Seismological monitoring of the Comprehensive Nuclear-Test-Ban Treaty. *Carl Hanser Verlag*, München, Kerntechnik, **66**, 3, 82-89.

Bondár, I., North, R. G., and Beall, G. (1999). Teleseismic slowness-azimuth station corrections for the International Monitoring System Seismic Network. *Bull. Seism. Soc. Am.*, **89**(4), 989 - 1003.

Bormann, P., Liu, R., Ren, X., Gutdeutsch, F., Kaiser, D., and Castellarao, S. (2007). Chinese National Network magnitudes, their relation to NEIC magnitudes, and recommendations for new IASPEI magnitude standards. *Bull. Seim. Soc. Am.*, 97, 114-127; doi: 10.1785/0120060078

Bormann, P., Liu, R., Xu, Z., Ren, K., Zhang, L., Wendt S. (2009). First application of the new IASPEI teleseismic magnitude standards to data of the China National Seismographic Network, *Bull. Seism. Soc. Am.* **99** (3), 1868-1891; doi: 10.1785/0120080010

Bowers, D., and Selby, N. D. (2009). Forensic seismology and the Comprehensive Nuclear-Test-Ban Treaty. *Annual Reviews of Earth and Planetary Sciences*, **37**, 209-236.

CTBT/PC/II/Add.2 16 (May 1997). Report of Working Group B to the Second Session of the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization, Vienna.

CTBT/WGB/TL-11,17/15/Rev.4 (2009). Operational manual for seismological monitoring and the international exchange of seismological data (draft).

CTBT/WGB/TL-11,17/16/Rev.4 (2009). Operational manual for hydroacoustic monitoring and the international exchange of hydroacoustic data (draft).

CTBT/WGB/TL-11,17/17/Rev.4 (2009). Operational manual for infrasound monitoring and the international exchange of infrasound data (draft).

CTBT/WGB/TL-11, 17-18 /Rev. 4 (2010). Operational manual for radionuclide monitoring and the international exchange of radionuclide data (draft).

CTBT/PTS/INF.96/Rev. 7 (2005). Certification of radionuclide laboratories.

CTBTO Noble Gas Monitoring Handbook (2003), 105 pp.

Dahlman, O., and Israelson, H. (1977). Monitoring underground nuclear explosions. *Elsevier Scientific Publishing Company*, Amsterdam-Oxford-New York, 440 pp.

Dahlman, O., Mykkeltveit, S., and Haak, H. (2009). Nuclear test ban – converting political visions to reality. Springer Verlag, xviii+277 pp., ISBN 978-1-4020-6883-6, doi: 10.1007/978-1-4020-6885-0.

Gutenberg, B., and Richter, C. F. (1956). Magnitude and energy of earthquakes. *Annali di Geofisica*, **9**, 1-15.

Husebye, E. S., and Dainty, A. M. (Eds.) (1996). Monitoring a comprehensive nuclear test ban treaty. Dordrecht: *Kluwer Academic. NATO ASI series E*, Vol. 303, 247-293.

IASPEI (2005). Summary of Magnitude Working Group recommendations on standard procedures for determining earthquake magnitudes from digital data. http://www.iaspei.org/commissions/CSOI/summary_of_WG_recommendations_2005.pdf

IASPEI (2011). Summary of Magnitude Working Group recommendations on standard procedures for determining earthquake magnitudes from digital data. http://www.iaspei.org/commissions/CSOI/Summary_WG-Recommendations_20110909.pdf

Karnik, V., Kondorskaya, N. V., Riznichenko, Yu. V., Savarensky, Ye. F., Soloviev, S. L., Shebalin, N. V., Vanek, J., and Zatopek, A. (1962). Standardisation of the earthquake magnitude scales. *Studia Geophysica et Geodaetica*, **6**, 41-48.

Kradolfer, U. (1996). AutoDRM - The first five years. Seism. Res. Lett., **67**, 4, 30-33.

Rezapour, M., and Pearce, R. G. (1998). Bias in surface-wave magnitude M_S due to inadaquate distance corrections. *Bull. Seism. Soc. Am.*, **88**, 1, 43-61.

Richards, P. G. (2002). Seismological methods of monitoring compliance with the Comprehensive Nuclear Test-Ban Treaty. In: Lee, W. H. K., Kanamori, H., Jennings, P. C., and Kisslinger, C. (Eds.) (2002). International Handbook of Earthquake and Engineering Seismology, Part A. *Academic Press, Amsterdam,* 369-382.

Richards, P., and Wu, Z. (2011). Seismic monitoring of nuclear explosions. In: Gupta, H. (Ed.) (2011), *Encyclopedia of Solid Earth Geophysics*. Springer, Dordrecht, Vol. 1144-1156.

Ringdahl, F., Marshall, P. D., Alewine, R. W. (1992). Seismic yield determination of Soviet underground nuclear explosion at the Shagan river test site. *Geophys. J. Int.*, **109**, 160-179.

Stevens, J. L. and K. L. McLaughlin (2000). Optimization of surface wave identification and measurement. *Pure and Applied Geophysics*, 158, 8, 1547 – 1582.

Vaněk, J., Zapotek, A., Karnik, V., Kondorskaya, N.V., Riznichenko, Yu.V., Savarensky, E.F., Solov'yov, S.L., and Shebalin, N.V. (1962). Standardization of magnitude scales. *Izvestiya Akad. SSSR., Ser. Geofiz.*, **2,** 153-158.

Veith, K. F., and Clawson, G. E. (1972). Magnitude from short-period P-wave data. *Bull. Seism. Soc. Am.*, **62**, 435-452.

Xenitellis, S. (2000). The Open–source PKI Book. http://ospkibook.sourceforge.net