Chapter 1
The IMS Infrasound Network: Current Status and Technological Developments

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Abstract The International Monitoring System (IMS) comprises 337 globally distributed facilities for seismic, hydroacoustic, infrasound, and radionuclide monitoring. This chapter focuses on the infrasound component of the IMS, often referred to as the IMS infrasound network. The chapter begins with an overview of the network and of the main challenges associated with its establishment, sustainability, and detection capability. It follows with a general description of IMS stations as well as with a review of the latest advances in array geometry, wind-noise reduction systems, infrasound sensors, calibration, meteorological data, data acquisition systems, and station infrastructure. This chapter is intended for researchers and engineers who are interested in the specifications, design, status, and overall capabilities of the IMS infrasound network or in the construction of state-of-the-art infrasound stations.

1.1 Introduction

The Comprehensive Nuclear-Test-Ban Treaty (CTBT) prohibits States Parties from carrying out, encouraging, or in any way participating in the execution of a nuclear explosion. The Treaty was adopted by the United Nations General Assembly on September 10, 1996 and opened for signature in New York on September 24, 1996. Twenty years later, it enjoys near-universality with 183 States Signatories and 166 ratifying States. Even with this high level of adherence, the CTBT has not yet entered into force. It still awaits ratification from 8 States out of the 44 specific nuclear technology holder States listed in Annex 2 to the Treaty. In the meantime, the Preparatory Commission (PrepCom) for the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) is responsible for promoting the CTBT and establishing a verification regime. The objective of the verification regime is to ensure compliance with the Treaty. It is composed of four elements, one of them being the International Monitoring System (IMS). The IMS comprises 337 globally distributed facilities for seismic, hydroacoustic, infrasound, and radionuclide monitoring as well as

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respective means of communication between these facilities and the International Data Centre (IDC) located in Vienna, Austria. This chapter focuses on the infrasound component of the IMS, often referred to as the IMS infrasound network. The main objective of the IMS infrasound network is the monitoring of atmospheric nuclear explosions although this network can also contribute to the monitoring of near-surface underwater explosions and shallow underground explosions. The most recent examples of such a contribution are the detection by two IMS infrasound stations of clear infrasound signals generated by the subsurface nuclear tests announced by the Democratic People's Republic of Korea (DPRK) on February 12, 2013 and September 3, 2017 (CTBTO 2013d, 2017b).

The development of the infrasound monitoring technology began soon after the first atmospheric nuclear explosions were carried out in 1945. The technology evolved rapidly over the following decades with advancements in measurement systems as well as in propagation and source models (Thomas et al. 1971). These advancements began to slow after the Partial Test Ban Treaty, prohibiting the testing of nuclear weapons in the atmosphere, underwater, and in the outer space, was signed in 1963. The last atmospheric nuclear explosion was conducted in 1980 and it is estimated that, between 1945 and 1980, 520 nuclear tests were carried out in the atmosphere for a total yield of 545 Mt (Pavlovski 1998). When CTBT negotiations started in 1994, research in the field of infrasound had made little progress over the preceding decades (Evers and Haak 2010). The urgent need to define requirements for the IMS infrasound network revitalized research on this technology (Dahlman et al. 2011). Whereas global seismological networks were already operational as the Treaty opened for signature, the IMS infrasound network was a first attempt at establishing a global infrasound network. Most specifications for this new network were, therefore, defined based on studies carried out during the Treaty negotiations and shared similarities with the seismic technology. In 2001, continuous and high-quality data started flowing in near real time from the first IMS infrasound stations to the IDC. The processing of this unique set of data quickly led to studies on station performance and brought about optimizations in infrasound station design and specifications (Christie and Campus 2010). Research also focused on global network detection capability, demonstrating through modeling that any atmospheric explosion with a yield greater than 1 kT TNT equivalent would be detected by the IMS infrasound network anywhere on Earth at any time (Le Pichon et al. 2009; Green and Bowers 2010). These theoretical results were confirmed through ground truth calibration experiments (Fee et al. 2013) and by the detection of explosion-like events, such as the breaking up of meteors in the atmosphere (Le Pichon et al. 2013).

Beyond explosion monitoring, data from the IMS infrasound network was rapidly found beneficial in the study of a number of natural (volcanoes, tornadoes, meteorites, lightning, calving of icebergs and glaciers, large earthquakes, auroras, etc.) and man-made (industrial activities, quarry blasts, rocket launches, supersonic aircraft, etc.) sources (Campus and Christie 2010). It has been known since the 1883 explosion of the Krakatoa volcano that natural sources can produce low-frequency sounds capable of propagating several times around the globe (Symons 1888). However, the continuous recording of global infrasound data has allowed civil and scientific applications such as volcano information systems (Marchetti et al. 2019), the detection of near-Earth objects impacting the atmosphere or the better modeling of the middle atmosphere dynamics (Le Pichon et al. 2015). Furthermore, it was recently demonstrated that IMS infrasound data were not only accurate in the IMS frequency band (0.02–4 Hz) but also as down to 1-day period, paving the way to the global monitoring of atmospheric acoustic-gravity and gravity waves (Marty et al. 2010). Since the last atmospheric nuclear test occurred well before the establishment of the first IMS infrasound station, these growing civil and scientific applications based on IMS infrasound data are essential for supporting the sustainability of the IMS infrasound network and ensuring that the infrasound technology remains at the state of the art for Treaty verification purposes.

This chapter begins with an overview of the IMS infrasound network (Sect. 1.2) and of IMS infrasound stations (Sect. 1.3). The latest advances in array geometry (Sect. 1.4), wind-noise reduction systems (Sect. 1.5), sensors (Sect. 1.6), calibration (Sect. 1.7), meteorological data (Sect. 1.8), data acquisition systems (Sect. 1.9), and station infrastructure (Sect. 1.10) are then reviewed in the framework of the IMS specifications for infrasound stations.

1.2 The IMS Infrasound Network

1.2.1 Overview

The IMS infrasound network is composed of 60 globally distributed stations, whose locations are defined in Annex 1 to the Protocol to the Treaty (Fig. 1.1). Each of these stations is composed of an array of infrasound measurement systems capable of recording the micro-pressure changes produced at ground by the propagation of infrasonic waves. IMS infrasound stations continuously transmit these pressure fluctuation data together with state-of-health information to the IDC through the Global Communication Infrastructure (GCI). The data are then processed in near real time, with IDC automatic detection algorithms extracting infrasonic wave parameters from pressure fluctuation measurements for each station independently (Mialle et al. 2019). These wave parameters, together with station processing information from the seismic and hydroacoustic monitoring technologies, are used as inputs to IDC automatic source localization algorithms. The output of the IDC automatic processing of seismo-acoustic data includes event parameters, which are collected in Standard Event Lists (SELs). SELs are reviewed by IDC seismo-acoustic analysts within 2 days and the resulting events recorded in Reviewed Event Bulletins (REBs) (CTBTO 2011b). Natural events are automatically screened out from REBs within a few hours and the final results are published in Standard Screened Event Bulletins (SSEBs). The automatic and interactive processing of infrasound data has been operational since 2010 in the IDC. States Signatories have the right of full access to all IMS data and IDC products.

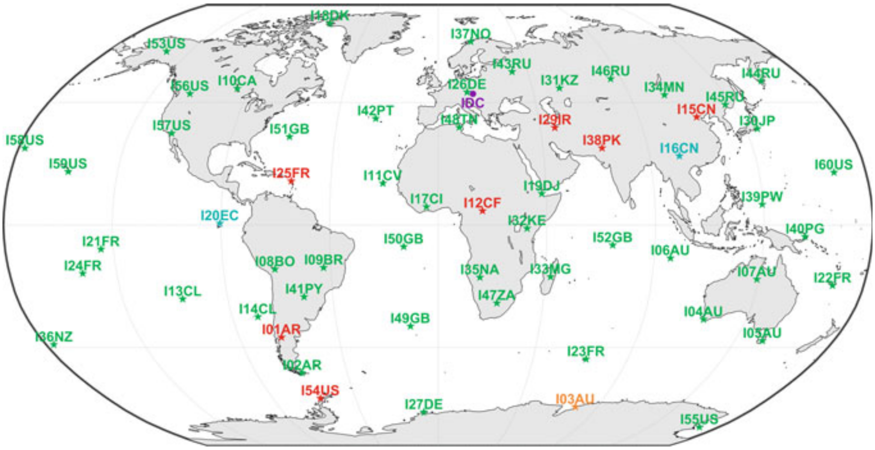


Fig. 1.1 Overview of the IMS infrasound network as of June 2017 with certified stations (green), installed stations (turquoise), stations under construction (orange), planned stations (red), and the IDC (purple)

When the CTBT opened for signature in 1996, only a few research infrasound stations were operating across the globe (Campus and Christie 2010). The establishment of 60 new infrasound stations was, therefore, a huge engineering challenge, especially since the international community was initially targeting an early Entry into Force (EiF) of the Treaty. From 1997 to 2006, the PrepCom focused its efforts on station constructions and certifications. The first IMS infrasound station was certified in 2001, and till 2006 between five and eight new infrasound stations were certified every year (Fig. 1.2). At this point, the total number of certified stations reached 37. Following this intense station construction period, the number of new certifications decreased to one or two stations per year for two main reasons. First, the remaining stations proved to be the most difficult to build primarily because of land availability, engineering, and political factors. Second, ensuring continuous operation of the existing stations became a competing priority. Stations that had failed since certification or had low data availability were repaired or upgraded. By 2012, 45 stations, representing 75% of the network, were certified with network data availability approaching 92% (Fig. 1.2). By this time, because of further reduced opportunities to build new stations, the progressive degradation of older stations and the PrepCom mandate to protect the investment already made by States Signatories, resources were progressively shifted from station construction to station upgrade. Nevertheless, efforts to establish the remaining stations continued with one new certification per year on average.

As of June 2017, the IMS infrasound network includes 49 certified stations, representing 82% of the network (Fig. 1.1). The installations of stations I16CN and I20EC were completed in January and June 2017, respectively. Stations I03AU is currently under construction. These three stations are planned to be certified over

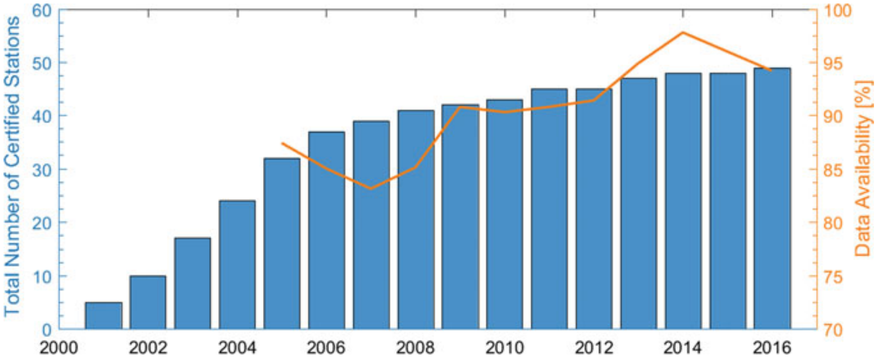


Fig. 1.2 Total number of certified stations (blue bars) and data availability for the overall IMS infrasound network (orange curve) as a function of time

the 2017–2018 time period. The minimum requirement for the infrasound network completeness to support the commissioning of the IMS specifies that 85% of the IMS infrasound stations shall be sending data to the IDC (CTBTO 2011c). This important milestone in the commissioning of the IMS is, therefore, expected to be met by 2018. The construction of the eight remaining stations has yet to be started. Site surveys were recently carried out for stations I01AR and I25FR. With land permits currently under negotiation with relevant authorities, it is expected that both these stations will be certified by 2020. This would bring the network to a 90% completion level and allow for the fulfillment of the minimum requirement for network completeness even in the case of outage of three stations. Negotiations for establishing stations I12CF, I15CN, I29IR, I38PK, and I54US are currently on hold because of pending resolution of land availability, security, or political issues. Finally, the last station with code 28 does not appear in Fig. 1.1 because its location is currently under the status “To be determined”. During Treaty negotiations, this station was intended to be located in India. However, in June 1996, because of disagreement of the terms in the Treaty, India requested that this station be removed from the protocol to the Treaty (Dahlman et al. 2011). It is worth noting that Fig. 1.1 displays stations at their current locations, which do not always correspond to initial Treaty locations. For the majority of stations, the difference between the two locations does not exceed a few tenths of a degree and resulted from identifying a suitable piece of land in the area of the Treaty coordinates. However, for 11 stations the change exceeds 100 km, including 2 stations where the distance was about 1500 km. These more significant changes of coordinates were often due to the absence of a sustainable or high-performance solution in the vicinity of the Treaty coordinates. The impact of these coordinate changes on station performance and global network detection capability was carefully assessed before being officially approved by the PrepCom.

1.2.2 Data Availability

The IMS infrasound network is designed to detect an atmospheric nuclear explosion conducted at any given time and any point on the Earth. For this reason, the network must be continuously operational and strict specifications for Data Availability (DA) are defined in the draft Operational Manual for Infrasound Monitoring and the International Exchange of Infrasound Data further referred to as the IMS Operational Manual (CTBTO 2009, 2016d). Minimum requirements for DA are defined at the station level with each IMS infrasound station required to exceed the DA threshold of 98% over a 1-year period. It is worth noting that the DA definition has evolved since the first version of the IMS Operational Manual (CTBTO 1999) and currently includes data quality criteria. In order to be accounted for, data must be geophysical (segments with zeros, constant values, or absence of input from the sensor are discarded) and secure (authenticated, absence of site tampering). DA is also now computed on the minimum number of channels for an IMS infrasound station to be mission capable. Requirements for mission capability are defined in the IMS Operational Manual and will be discussed in Sect. 1.4.

Although all IMS infrasound stations currently include digital signing capability, the definition of the relevant data surety procedures is still underway. Since DA, as defined in the IMS Operational Manual, discards non-authenticated data, it is currently not very representative of the network status. For this reason, a Data Availability Unauthenticated (DAU) metric is also computed in the IDC. It is this metric which is represented in Figs. 1.2 and 1.3. Figure 1.2 shows that DAU at the network level increased from about 83% in 2007 to almost 98% in 2014. Since then, a slight decrease to 95% has been observed. As for all IMS Operational Manual requirements, the threshold of 98% will strictly apply after EiF. In the meantime, the network is in provisional operation with a DA midterm objective of 90% over the 2014–2017 time period (CTBTO 2013c) and a requirement of 96% for the commissioning of the IMS (CTBTO 2011c). Figure 1.3 shows the percentage of stations fulfilling DA requirements for these different thresholds. Since 2013, about two- thirds of the IMS infrasound stations are fulfilling the 98% threshold on a yearly basis, with a peak of nearly three quarters in 2014. Over the past 4 years, about 80% of the stations have been meeting the midterm objective of 90% with an increase of nearly 95% in 2014.

With the majority of IMS infrasound stations being installed in remote and harsh environments, fulfilling DA requirements for each of them is a real challenge. The CTBT assigns to the Technical Secretariat the responsibility of supervising, coordinating, and ensuring the operation of the IMS network in accordance with the IMS Operational Manuals. Since the Treaty has not yet entered into force, this responsibility currently falls upon the Provisional Technical Secretariat (PTS) located in Vienna, Austria (CTBTO 1996). The IMS Operational Manual defines the Station Operator (SO) as the entity responsible for the operation and maintenance of a specific station. SOs are typically designated by the States hosting the stations. They must ensure that their stations are operating properly, especially in meeting the data availability, data quality, and data surety requirements (CTBTO 2009). The duties

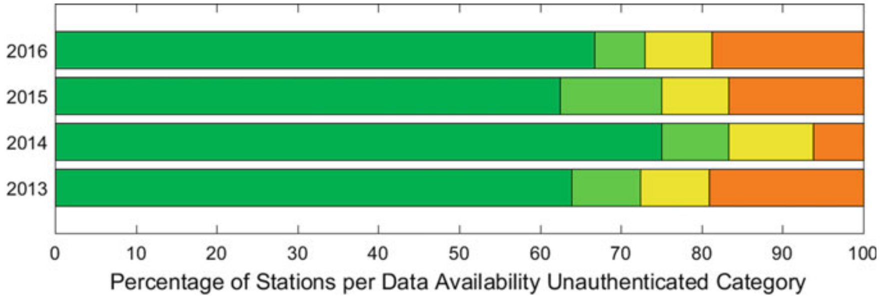


Fig. 1.3 Number of certified IMS infrasound stations with DAU above 98% (green), between 96 and 98% (light green), between 90 and 96% (yellow) and below 90% (orange) in percentage of the total number of stations

of the SOs include performing preventive maintenance and providing timely troubleshooting and repair in case of unexpected data outages. Proactivity, responsiveness, and technical skills of SOs are, therefore, by far the main drivers for achieving high data availability. For this reason, it is essential that capacity building efforts continue, including regular training and follow-up activities with the objective of encouraging SOs to define their own station monitoring routines and strengthening collaboration within the SO community. In parallel, SOs' performance should be evaluated against the IMS Operational Manual to ensure that all SOs comprehensively fulfill their duties (Nikolova et al. 2015).

Beyond the crucial role of SOs, IMS infrasound stations must be designed to be as reliable and resilient as possible within the available resources. To do so, data storage and retransmission capabilities are included at different levels, with these capabilities being verified at the time of certification or revalidation (Sect. 1.3). Except in the case of a complete station outage, data should be retransmitted to the IDC at the end of the outage and most stations should fulfill DA requirements. In reality, this is not always the case for three main reasons. First, the older stations have limited capabilities and will need to be upgraded in the future (Sect. 1.3.3). Second, minor equipment upgrades or configuration changes are from time to time performed without testing all station capabilities again. Third, data losses sometimes result in a combination of issues which are often hard to anticipate or simulate at the time of station testing. IMS infrasound stations shall also include redundancy at the array geometry level to ensure that mission capability and thus data availability are preserved even in case of the loss of array elements (Sect. 1.4). Stations shall also be designed to avoid single points of failure through the deployment of automatic or semiautomatic back-up systems. The adequate level of spare equipment shall be continuously available at the stations, especially for equipment necessary to maintain station mission capability. While equipment diversity is limited through the network because of the specificity of IMS requirements, attention shall be given to rely on different equipment models to avoid catastrophic network failure (Sect. 1.9). Finally, beyond standard manufacturer testing, station equipment shall undergo extensive testing in

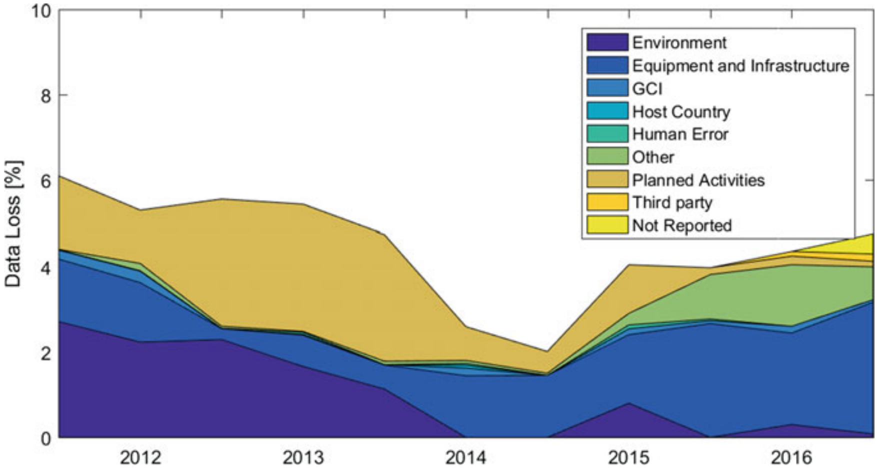


Fig. 1.4 Causes of station failure in percentage of data loss computed for the IMS infrasound network on a biannual basis over the 2011–2016 time period

operational conditions before being approved for deployment in the IMS network (Sects. 1.6 and 1.9).

In parallel with these station design measures, statistics on station failures are computed by the PTS with the objective of verifying whether the implemented engineering solutions and processes lead to reliability improvements. Figure 1.4 shows the causes of station failure in percentage of data loss for the IMS infrasound network from 2011 to 2016. A significant decrease of failures because of "Environment" (dark blue) and "Planned Activities" (brown) can be observed since 2011. The first is primarily due to the repair of stations that failed under harsh environmental conditions and to the development and implementation of earthing and lightning protection standards throughout the network (CTBTO 2010). The second relates to the development of strategies for preserving data availability during preventive maintenance and upgrade activities (Sect. 1.3.3). "Equipment and Infrastructure" is currently the main source of station downtime with power issues accounting for 50% of the total downtime. This has already triggered changes in station power system designs to ensure that noncritical equipment be installed on independent power sources from that of critical equipment. It has also led to the launch of a series of engineering projects such as (a) the development of a standard software solution to provide SOs with state-of-health information on the power systems installed at their stations (Sect. 1.9), (b) the review of state-of-the-art power solutions with the objective of defining and testing a set standard power systems for IMS stations (Sect. 1.10) and (c) the definition of standard procedures for the regular testing of station back-up power systems.

While providing a useful overview of failures at a network level, the current failure analysis approach has shown several limitations. First, it rarely allows identifying issues that are not already known by the PTS through the daily operation of the network. Second, it is often difficult to determine if equipment failures occurred because of the equipment itself or because of external factors such as environment or misuse. Third, information on failure causes is retrieved from the IMS Reporting System which has not been designed to meet the requirements of failure analysis (CTBTO 2017a). These factors combined decrease the level of confidence in the reported results. The current approach, therefore, needs to be complemented by additional engineering activities. As discussed above, these activities could include (a) the definition of processes to ensure that the adequate level of spare equipment is available at the stations, (b) the storage in a common database of station-specific information such as fine-tuning configuration parameters, frequent operational issues, identified risks, and mitigation plans, (c) the regular monitoring of station data retransmission patterns after station outages in order to detect malfunctions, and (d) the implementation of state-of-health monitoring and alert systems at the stations to help SOs anticipating station failures and ease station troubleshooting when necessary. To conclude this section, the fulfillment of DA requirements by all IMS infrasound stations is a real challenge. It can only be achieved with the commitment of all stakeholders (SOs, PTS, States Signatories) and the implementation of specific engineering activities dedicated to this objective.

1.2.3 Detection Capability

Infrasonic waves are elastic waves with frequencies ranging from the acoustic cut-off frequency (about 3 mHz for standard atmospheric conditions) to the low-frequency limit of human hearing (20 Hz). In the atmosphere, the propagation of infrasonic waves is mainly driven by wind and temperature (De Groot-Hedlin et al. 2010). As the temperature typically decreases with altitude in the lower atmosphere, infrasonic waves produced close to the ground propagate upwards. They can then be refracted back to the ground if the effective sound velocity becomes larger than its surface value (Evers and Haak 2010). This always happens in the thermosphere because of the strong temperature gradient but also commonly occurs at lower altitudes. In the troposphere, temperature inversion or jet streams near the tropopause can lead to highly effective sound velocities. Infrasound waveguides are also commonly formed between the stratosphere and the ground because of the solar radiative heating of stratospheric ozone combined with strong seasonal stratospheric winds. Except when the measurement systems are located at a few kilometers from the source, infrasonic waves are, therefore, observed at the ground after one or several bounces in the atmosphere. Because of their relatively small attenuation, infrasonic waves can be detected at great distances from the source through the pressure fluctuations they produce. To illustrate the complexity of infrasonic wave propagation in the atmosphere, Fig. 1.5 displays the simulated infrasound propagation paths for the meteor explosion observed offshore Portugal on March 9, 2017 (CNEOS 2017).

The capability to detect and locate an atmospheric explosion is the ultimate goal of the IMS infrasound network. For practical purposes, the IMS Operational Manual specifications were defined for a yield greater than 1 kT TNT equivalent (Christie

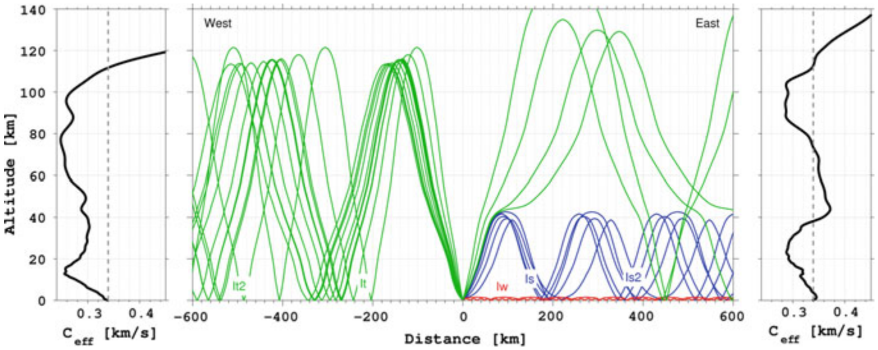


Fig. 1.5 Simulation of infrasonic wave propagation for the meteor explosion observed offshore Portugal (40.5N, 18.0W) on March 9, 2017 (CNEOS 2017) using 1-D ray-tracing (with eikonal equation) and ECMWF weather model (courtesy J. Vergoz). The red, blue, and green paths represent the tropospheric, stratospheric, and thermospheric paths respectively. The effective sound velocity models toward the West and the East are displayed in black on the left and right side of the figure, respectively, with the gray-dashed line representing the effective velocity at the ground

and Campus 2010). The capability to detect such small yield is tightly linked to the local, regional, and global dynamics of the atmosphere. Changes in atmospheric temperature or wind occurring on a seasonal, daily, or even hourly basis can completely modify parameters such as the noise level at the ground or wave propagation paths. The IMS network and stations must, therefore, be designed to minimize as much as possible the impact of these changes on global network detection capability and ensure that the 1 kT yield detection threshold is met anywhere at any time.

As IMS infrasound stations are relatively sparse around the globe, signals of interest generally travel for thousands of kilometers through the Earth's atmosphere before they reach the first stations. The amplitude of these signals is significantly attenuated before it is measured and usually relatively small compared to background pressure fluctuations produced at the ground by wind turbulence (Walker and Hedlin 2010). One of the main challenges of the infrasound technology is, therefore, the detection of signals with low signal-to-noise ratios (SNRs) as soon as the wind velocity at the ground exceeds a few tenths of meters per second. To mitigate this effect, it is absolutely crucial that infrasound stations are installed in areas with as little wind as possible and protected from local wind turbulence (Sect. 1.3). Those are key requirements when selecting the station location during the site survey process (CTBTO 1997a). Dense forests are usually the best locations for infrasound stations but even small bushes can help in reducing the noise when it is not possible to find forested areas around Treaty coordinates. To further reduce wind-generated noise, the IMS Operational Manual also requires that acoustic filtering systems are installed at all IMS infrasound measurement systems (Sect. 1.5). These systems, commonly referred to as Wind-Noise-Reduction Systems (WNRS), can reduce the amplitude of background pressure fluctuations by tens of decibels in high wind conditions while preserving the integrity of infrasound signals. Finally, the IMS Operational

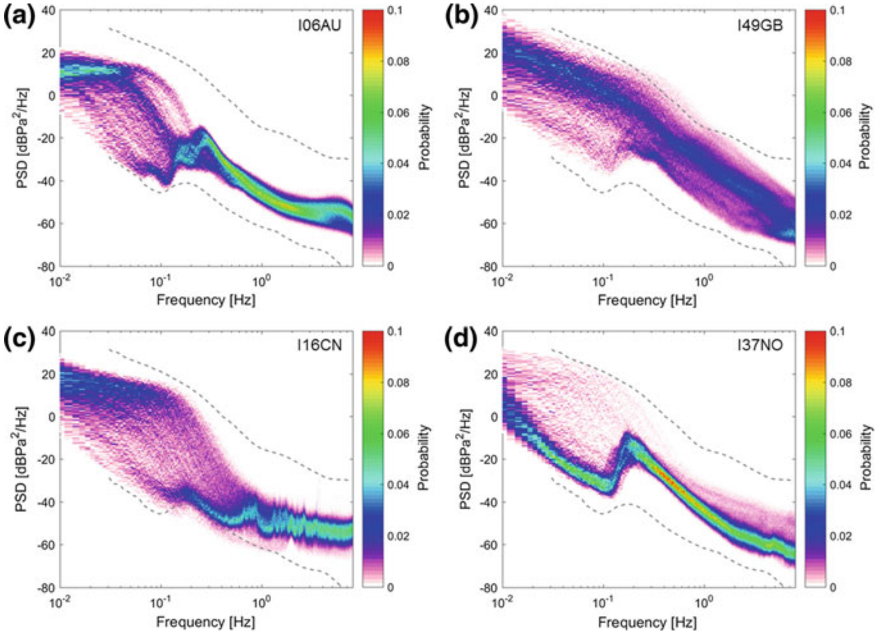


Fig. 1.6 Probability density functions as a function of noise power for each frequency band in February 2017 for stations **a** I06AU (H6), **b** I49 GB (H2), **c** I16CN (H3), and **d** I37NO (H7). The Power Spectral Densities (PSDs) are computed over 1-h time period using Welch's method (Welch 1967; McNamara and Buland 2004) and are corrected from the system response including WNRS, sensor, and data acquisition system. The gray-dashed lines represent a high- and low-noise model (Bowman et al. 2005)

Manual recommends installing additional array elements when the station is located in a noisy environment with the objective of improving the SNR at the data processing stage (Sect. 1.4). As an illustration, Fig. 1.6 displays, for four IMS stations, the Probability Density Functions (PDF) as a function of noise power for each frequency band. It shows, for example, that the spectral levels observed at station I49 GB are in average well above that of station I06AU. Both stations are located on remote oceanic islands but station I49 GB is located at a much windier location with no vegetation around and its WNRSs have a slightly reduced efficiency (because of land constraints). In comparison, station I06AU is installed within a dense forest and include standard WNRSs. The high level of background noise recorded at station I49 GB explains for the most part the very limited contribution of the station to the global IMS network detection capability (Fig. 1.7).

Apart from wind-generated background noise, the other main challenge of the infrasound technology is the complexity and the dynamics of the wave propagation medium. Unlike seismic waves which travel in the relatively stable medium of the Earth's interior, infrasonic waves propagate through the complex and continuously changing medium of the atmosphere (Fig. 1.5). Depending of the atmospheric

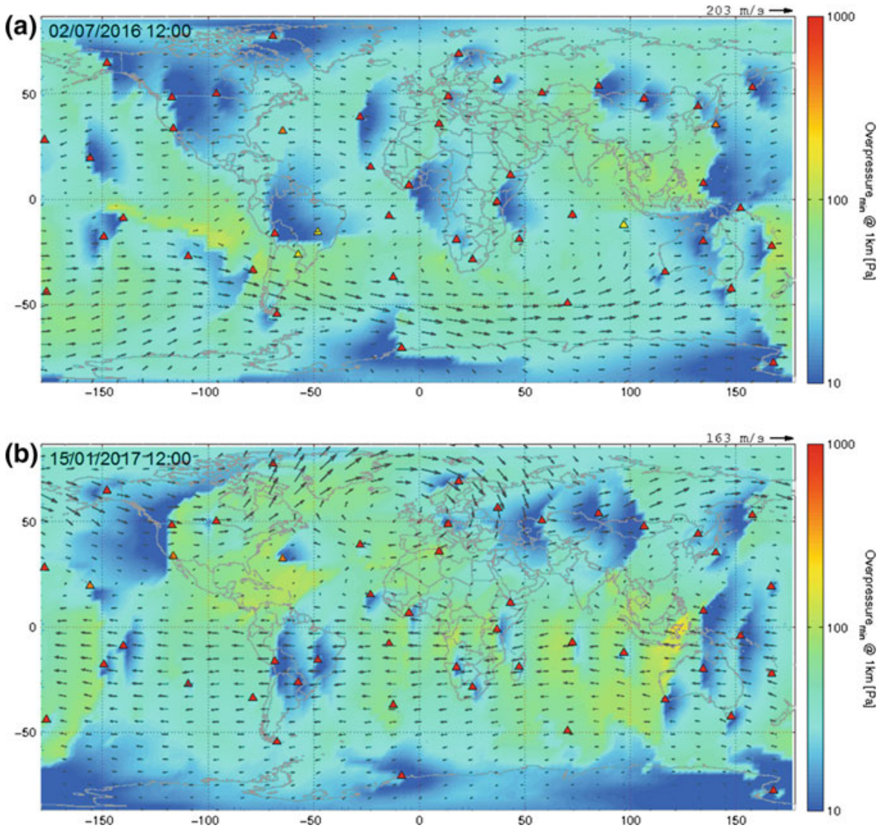


Fig. 1.7 Detectability maps computed for the IMS infrasound network with DTK-NetPerf, the PTS infrasound threshold monitoring software using frequency-dependent attenuation relation (Le Pichon et al. 2012), real-time atmospheric specifications from ECMWF and real-time station noise computed in the IDC. The computations are made for single-station coverage, frequencies of 1 Hz, source on the ground, and background noise levels estimated in the 0.2–2 Hz frequency band. The color codes the minimum detectable source amplitude at a reference distance of 1 km from the source (in Pa peak-to-peak). The arrows represent the wind direction and maximum speed (arrow length) between 40 and 50 km altitude. IMS infrasound stations are indicated by triangles, with the following color codes: red for mission capable stations, orange for non-mission capable stations but partially sending data, and yellow for stations sending no data at the time of the simulation

conditions, the same source can generate multiple arrivals, one arrival or no arrival at all at the same station. The network must, therefore, include a sufficient number of stations to ensure a continuous level of detection capability. At the time of the Treaty negotiations, intense expert discussions occurred on this topic with estimations ranging from 20 to 120 for the minimum number of infrasound stations required to continuously detect a 1 kT-TNT-equivalent atmospheric explosion all over the globe (Conference on Disarmament 1995). Experts finally agreed on a 60-station network as defined in the Treaty. Since then, network detection capability models have confirmed that any yield greater than 1 kT TNT equivalent would be detected at any time by at least two IMS infrasound stations (Green and Bowers 2010; Le Pichon et al. 2009, 2012, 2019). As an illustration, Fig. 1.7 shows network detection capability maps for the IMS infrasound network at two points in time in Summer 2016 and Winter 2017. It can be seen that the seasonal oscillation of the zonal (East–West) component of stratospheric winds in both hemispheres significantly modify the area covered by each station. Even though the detection capability of the IMS infrasound network is generally well below the 1 kT threshold, modeling results have shown that it can move closer to this threshold at certain time periods when stratospheric wind velocity vanishes in certain areas of the globe (Le Pichon et al. 2019). The computation of network detection capability maps in near real time is, therefore, seen a valuable tool for decision-making. Such maps can be used for prioritizing maintenance actions when stations are down or impacted by unusual high-noise levels and for focusing reliability efforts on stations without which the network would go above the required detection threshold.

Recurrent sources of infrasound can also increase the noise level in the IMS frequency range and reduce station detection capability. The most well-known example of such sources are the microbaroms which commonly produce one or several bumps in the pressure fluctuation spectra around the 0.1–0.5 Hz frequency band (Fig. 1.6). Microbaroms are detected all over the globe and are produced by the nonlinear interaction of ocean surface waves traveling in different directions (Waxler and Gilbert 2006). Although microbaroms energy reduces station detection capability, the continuous monitoring of such infrasound source can be used as a means to assess station performance (Sect. 1.3.3). Other recurrent infrasound sources are generally local and produce signals above 1 Hz. They include surf noise, dams, gas flares, ice cracks, airports, industrial activities, etc. IMS infrasound stations shall obviously be installed far enough from such sources so these sources do not reduce the station detection capability. In reality, it is not always the case for two main reasons. First, it is sometimes not possible to find an available piece of land far enough from local sources (on small islands for example). Second, array processing techniques that could have allowed characterizing such sources at the time of site selection (and discarding noisy locations) have only started being used over the past years during the site survey process (Sect. 1.3.2). Figure 1.8 shows, for example, the large number of high-frequency detections continuously observed at stations I10CA (surrounded by two dams, North (red) and South (green) azimuths) and I06AU (surf noise, East (blue) azimuths) potentially limiting the detection capability of these two stations in the high- frequency part of the IMS frequency band. Another example is the high-frequency spikes continuously recorded at station I16CN and linked to industrial activities surrounding the station location (Fig. 1.6).

Finally, station detection capability is also linked to data quality. As per the IMS Operational Manual, both the SO and the PTS have the responsibility to monitor data quality and to inform each other when unusual signals such as bursts, spikes, and constant values are detected. It is then the responsibility of the SO to seek a solution to the problem. Both the SO and the PTS also need to monitor station noise levels in order to track long-term changes and help identifying instrumental

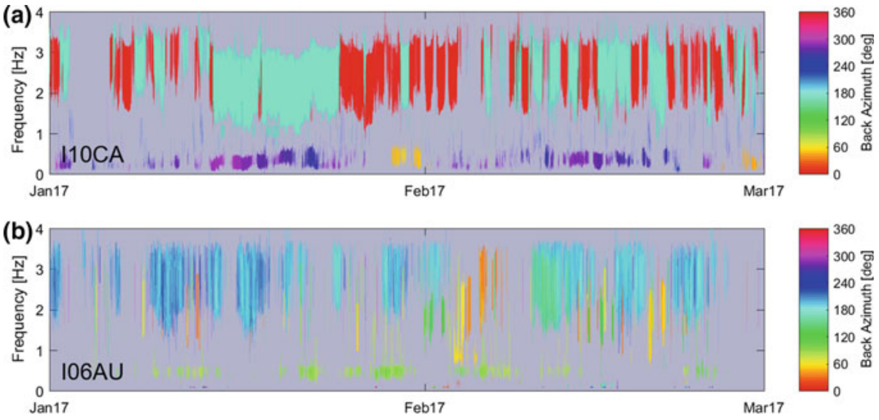


Fig. 1.8 IDC SEL3 detections in function of time, frequency, and back azimuth (color) for stations **a** I10CA and **b** I06AU

malfunction or problems with WNRS. When due to external factors, increased noise levels can lead to station or array element relocation. In reality, SOs are currently more often contacted by the PTS for data availability issues rather than data quality issues unless the data quality issues significantly affect IDC processing results. On the other hand, not all SOs regularly assess data quality as required in the IMS Operational Manual. Stations with highest data quality are often those for which SOs work in close cooperation with National Data Centres (NDCs) or associated research institutions. In that case, because data is also of interest for national applications, data quality issues are reported by national institutions. For this reason, capacity building efforts shall also target NDCs with the objective of improving data quality and station detection capability.

1.3 IMS Infrasound Stations

1.3.1 General Description

Each IMS infrasound station is composed of an array of distant measurement sites located in a 1–4 km-diameter area and commonly called array elements. The spatial distribution of these elements will be discussed in Sect. 1.4. Each of these array elements includes an infrasound measurement system composed of a WNRS, an infrasound sensor, and a data acquisition system. These three components will be discussed in Sects. 1.5, 1.6, and 1.9 respectively. The main function of infrasound measurement systems is to measure atmospheric pressure fluctuations and convert them into digital, time-stamped and digitally signed data packets. Apart from the infrasound measurement system, each array element also includes systems for power

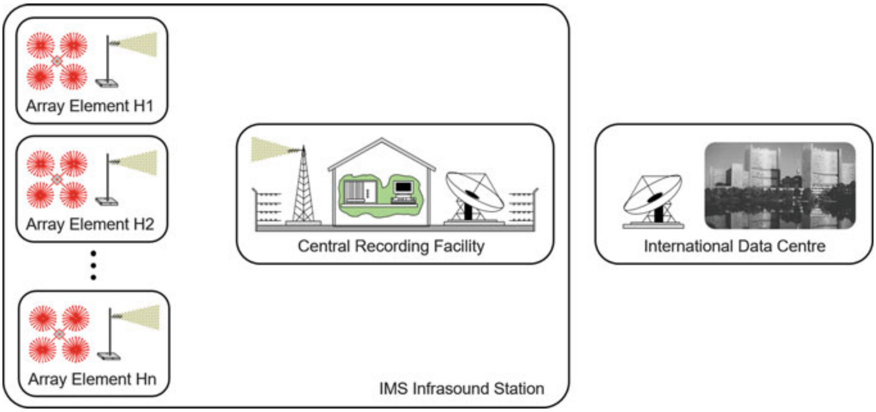
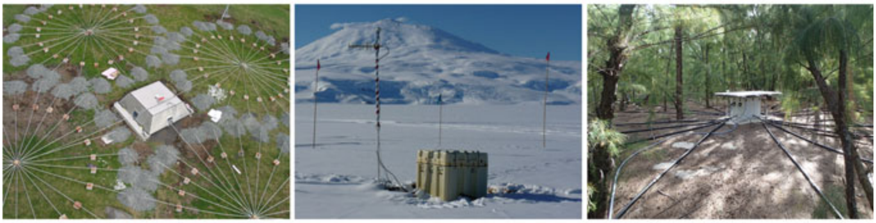


Fig. 1.9 Schematic illustration of an IMS infrasound station

and data communication with the Central Recording Facility (CRF). All equipment at the array elements are usually installed inside a single equipment vault, whose purpose is to protect the equipment from the environment and vandalism. Equipment vaults are secure, generally fire resistant, thermally insulated, and waterproof when necessary.

Equipment vaults are typically powered through standalone photovoltaic systems or power cables coming from the CRF. Since without power no data can be recorded, a lot of attention is given to the reliability and resilience of the power solutions implemented at IMS infrasound stations (Sect. 1.10). Communication systems between the array elements and the CRF are usually based on radio (UHF historically and now more frequently SHF) or fiber optic communication systems. CRF equipment includes hardware and software for data acquisition, buffering, formatting, digital signature, and transmission to the IDC. The GCI is commonly implemented through satellite communication and GCI equipment at the CRF consists of an integrated services router, satellite router, and VSAT antenna. CRF equipment is usually less ruggedized than that installed at the array elements and requires more stable and clean operating environment. Apart from critical equipment, CRFs typically include a small workbench, a data analysis computer, and an adequate storage environment for spare equipment. For this reason, CRFs require more power than array elements and are usually powered through a combination of diesel generators, photovoltaic systems, or mains power when available. Host Countries can decide to collect data at a central communication node before forwarding the data to the IDC. Communication between the station and the central communication node is in that case done through an Independent Sub-Network (ISN) which is the responsibility of the Host Country. The link between the central communication node and the IDC remains through the GCI. Figure 1.9 displays a schematic illustration of an IMS infrasound station and Fig. 1.10 pictures IMS infrasound stations in various environments.

I19DJ, Damerdjog, Djibouti I21FR, Marquesas Islands, France I26DE, Freyung, Germany



I49GB, Tristan da Cunha, UK I55US, Windless Bight, Antarctica, USA I60US, Wake Island, USA

Fig. 1.10 Pictures of IMS infrasound stations in different environments and with distinct WNRS and vault designs: I19DJ (hexagonal closed pack pipe array, underground vault), I21FR (star pipe array, surface vault), I26DE (T-rosette pipe array, underground vaults), I49 GB (rosette pipe array, surface vault), I55US (radial pipe array, above ground box), and I60US (radial pipe array, above ground box)

1.3.2 Establishment

The standard process for establishing a new IMS infrasound station starts with the negotiation of a Facility Agreement between the Host Country and the PrepCom. This agreement constitutes the legal framework for the establishment and operation of the stations to be hosted by the Country. To enter into force, the Facility Agreement must be ratified by the Host Country. As this can take some time, it is not rare that the Host Country initiates the station establishment process prior to the ratification of such agreement. Facility Agreements are recently more often a prerequisite for starting a new station establishment process because of the political or legal nature of the issues delaying the construction of the remaining stations. The next step is the identification of an appropriate location for the station. The Host Country must propose several suitable locations that are assessed by the PTS during the Site Survey process (CTBTO 1997a). Site Survey requirements include that IMS infrasound stations should be located in areas with as little wind as possible, preferably inside dense forests, and as far as possible from local and continuous sources of infrasonic waves. The station location shall also be secure with the possibility to install a robust power and data communication infrastructure. At the end of the Site Survey process, the location of all array elements and the CRF is approved by the PTS. If the identified station location is not located within Treaty coordinates, a change of coordinates is officially requested to the PrepCom (Sect. 1.2.1). Once the station infrastructure is built and the equipment installed, a period of testing and evaluation starts to verify that the station functions reliably and in agreement with IMS specifications (CTBTO 2009). After this period which usually lasts from 6 months to a year, the PTS determines or is notified by the Host Country that the station is ready for certification. Once the PTS is assured that the site, the station equipment, and the infrastructure meet, or in some specific cases substantially meet, the technical specifications for IMS stations, the station is certified and promoted into IDC operation.

1.3.3 Sustainability

Maintaining and operating a sparsely distributed global network such as the IMS infrasound network presents multiple complexities of a technological, logistical, environmental, and administrative nature (CTBTO 2017c). Station operation and maintenance activities, therefore, require a high level of coordination between SOs, Host Countries, and the PTS. With the first IMS infrasound stations built more than 15 years ago, many stations are now due for major upgrades to address equipment obsolescence, deteriorating infrastructure, or necessary engineering enhancements. Station major upgrades are often much more challenging than station establishment because of the necessity to preserve station DA during the upgrade process, to integrate new and legacy components together, and to fulfill the latest IMS requirements (calibration, authentication, command and control, etc.). Major upgrades are, therefore, often multiyear projects requiring extensive planning, detailed design, and mock-up testing of the equipment. Upgrading a station also provides a good opportunity to review and improve the station performance in terms of detectability and contribution to the network. This can lead to relocation of some array elements (Sect. 1.4), modification of the WNRS design (Sect. 1.5), use of infrasound sensors with self-noise more adapted to the station noise conditions (Sect. 1.6), or significant changes in power and data communication systems to improve DA or noise reduction through the preservation of vegetation (Sect. 1.10). As an example, Fig. 1.11 shows the significant increase in the number of infrasound arrivals detected by station I56US after 2010. About I07AU, although the number of detections remained stable after the 2013 upgrade, the contribution of the station to the network was enhanced because of reduction of the uncertainties associated with the computation of wave parameters. It can be seen, for example, that the azimuth (in dark blue in Fig. 1.11) and trace velocity (Fig. 1.12) distribution of the microbaroms detections is much more narrow after than before the upgrade. This is mainly due to the installation of WNRSs with much more stable responses and to the relocation of one of the array elements (Marty et al. 2013).

When stations are first established, they undergo a long period of testing and evaluation before being certified and promoted into operations. However, during a station upgrade, even in case of quasi-complete reconstruction, the station must continue fulfilling IMS DA requirements. This is probably the main challenge when upgrading a station, since the total downtime cannot exceed a few days (Sect. 1.2.2). To achieve this result, the PTS has developed different strategies based on lessons learned from

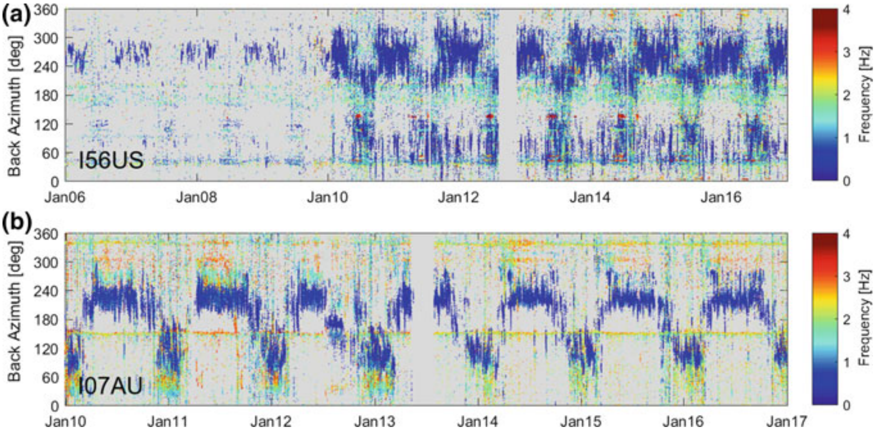


Fig. 1.11 IDC SEL3 detections in function of time, back azimuth, and frequency (color) for stations **a** I56US and **b** I07AU

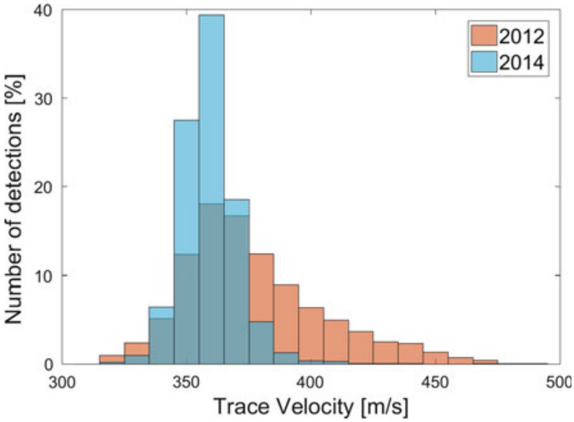


Fig. 1.12 Trace velocity distribution of IDC SEL3 microbaroms detections for station I07AU in 2012 (red) and 2014 (blue)

past upgrades. These include (a) the replacement of devices that do not include data storage and retransmission capability with equipment having such capabilities, (b) the progressive upgrade of the array elements to ensure that the minimum number of channels for the station to be mission capable is always available, (c) the installation of a new station in parallel to the existing with the old station only decommissioned after the new station is fully tested and promoted into operations, or (d) the installation of a temporary station in parallel to the IMS station to cover the gap during the station upgrade process. Finally, when the major upgrade is completed, the station is revalidated by the PTS to ensure that it continues fulfilling all technical specifications for IMS stations (CTBTO 2008). Revalidation uses similar procedures as for station certification.

1.4 Array Geometry

1.4.1 General Requirements

In 1996, the Infrasound Expert Group to the Ad Hoc Committee on a Nuclear Test Ban Working Group on Verification made several recommendations on infrasound array geometry (Conference on Disarmament 1995). These recommendations were included as minimum requirements for infrasound station specifications in the Report of Working Group B to the Second Session of the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO 1997b). These minimum requirements were later on integrated into the IMS Operational Manual (CTBTO 2009). They include that the minimum number of array elements shall be four, the array geometry shall be a triangle with a component at the center and the array aperture shall range from 1 to 3 km with 3 km as recommended spacing. These minimum requirements also specify that the number of array elements can be increased in case of noisy station locations or whenever an increased capability for the station is required. This latter specification provides a high degree of freedom in the design of infrasound arrays with no stringent requirement for element positioning for stations with more than four elements. This specification together with land constraints and the different views of Host Countries on the infrasound technology can explain for the most part the wide range array geometries that were implemented across the IMS infrasound network. Figure 1.13 displays the array geometry of the 49 certified IMS infrasound stations as of June 2017.

The IMS Operational Manual also defines mission capability requirements. These requirements are used to prioritize corrective maintenance actions through the network with non-mission capable stations getting categorized as the highest priority for repair (CTBTO 2009). Mission capability requirements have a significant impact on DA because the DA metric is computed on the minimum number of channels for the station to be mission capable (Sect. 1.2.2). This means that it is possible for a station to have 100% DA even with nonoperational array elements. A four- element infrasound station is considered mission capable if at least three of the elements are operational. For stations with more than four elements, the array geometry determine the combinations of element failures that may occur before mission capability is lost (CTBTO 2009; Carter 2011). Mission capability rules for such arrays are, therefore, station specific but they shall ensure in any case that at least 70% of the elements of the same station are operational for the station to be considered mission capable.

1.4.2 Number of Elements

Shortly after the installation of the first IMS infrasound stations, concerns were raised regarding the potentially limited capability of stations with four elements only (CTBTO 2001). At the time, the main reasoning for increasing the number of array

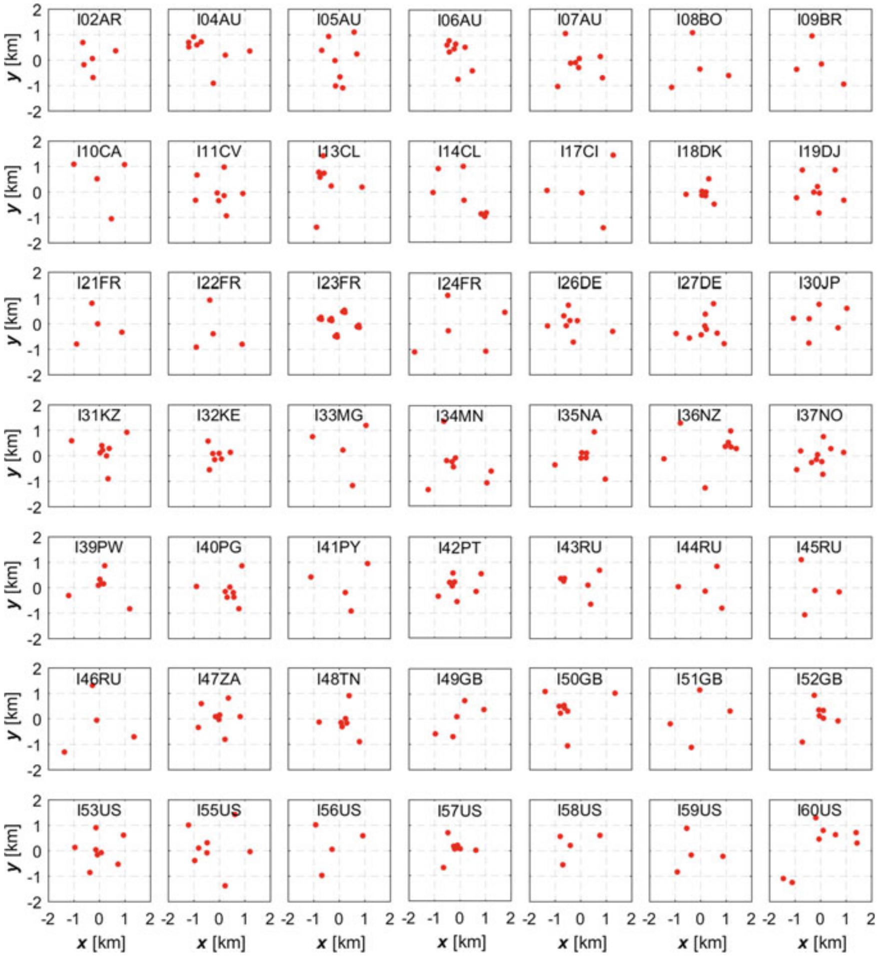


Fig. 1.13 Array geometry of the 49 certified IMS infrasound stations

elements was the risk of array aliasing. It , however, probably relates more to the need of finding an acceptable compromise between signal detection and wave parameter estimation and of minimizing the impact of element loss on the overall station detection capability (Sect. 1.4.3). Based on the fact that it was less costly to correct this potential problem by installing stations with additional elements at the beginning rather than to retrofit already installed stations, the WGB to the Fifteenth Session of the Preparatory Commission for the CTBTO recommended in its report that IMS infrasound stations be installed with up to 8 elements (CTBTO 2001). A few years later, the benefits of adding array elements were summarized by the 2003 Expert Group Meeting on array geometry (CTBTO 2003). It was shown, for example, that four element stations had a very limited detection capability when one element was

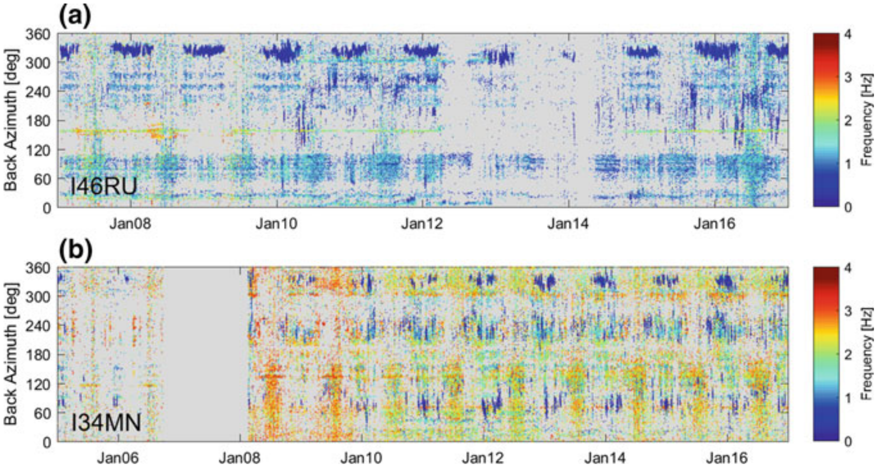


Fig. 1.14 IDC SEL3 detections in function of time, back azimuth, and frequency (color) for stations **a** I46RU and **b** I34MN

not sending data or was subject to high noise (Firbas and Brachet 2003; Le Pichon 2003). As an illustration, Fig. 1.14 shows the significant drop in detection capability of the four-element station I46RU over the 2012–2014 time period because of the loss of an element.

As a result, the Expert Group recommended building stations with more than four elements, with eight elements being seen as a good comprise between detection capability, and construction and operational costs (CTBTO 2003). Based on these WGBs and Expert Group's recommendations, the majority of IMS infrasound stations constructed since then have been built with a minimum of eight elements except when this was not possible because of land restrictions or prohibitive costs. When possible, existing four array element stations have also been upgraded with additional elements, usually at the time of a major equipment or infrastructure upgrade (Sect. 1.3.3). Figure 1.14 shows the significant increase in detection capability of station I34MN after the upgrade from four to eight elements in 2007. As of 2016, the number of array elements at IMS infrasound stations varies from 4 to 15 with most stations including either 4 or 8 array elements (Table 1.1). Only two stations include more than 8 array elements: I23FR which was installed with 15 elements with the objective of improving the SNR at an extremely noisy location and I37NO which includes 10 array elements because of the interest of the Host Country in the monitoring of sources with frequency above the IMS frequency band (requiring shorter inter-distances between elements).

Table 1.1 Number of IMS infrasound stations with a defined number of array elements

Number of array elements	Number of stations
4	15
5	3
6	2
7	5
8	21
9	1
10	1
15	1

1.4.3 Aperture and Element Distribution

The aperture of IMS infrasound arrays ranges from 1 to 3.9 km. Only two stations (I24FR, I60US) exceed the 3 km aperture IMS Operational Manual requirement because of land constraints but both these stations include elements that allow forming triangles with an aperture smaller than 3 km. As discussed in Sect. 1.4.1, since the IMS Operational Manual does not specify any requirements for element positioning for stations with more than four elements, a wide range of array geometries can be found in the IMS infrasound network (Fig. 1.13). These geometries can be roughly grouped as follows:

(a) Triangle with an element at the center—14 stations;
(b) Small aperture array (4–5 elements) embedded in the center of a larger aperture triangle—10 stations;
(c) Small aperture triangle embedded inside a larger aperture pentagon—6 stations;
(d) Small aperture array (3–5 elements) outside a larger aperture array (3–5 elements)—7 stations;
(e) Other distributions—12 stations.

Based on experience gained from the processing of data from the first IMS infrasound stations, the 2003 Expert Group Meeting drew several conclusions on the array element distribution (CTBTO 2003). The Expert Group first recommended that the array geometry be adapted to local meteorological conditions and second that the array elements be positioned in an irregular manner in order to have a better distribution of inter-element spacing than a completely symmetric configuration. These two general recommendations were not always followed in the design of the next generation of IMS infrasound stations with some stations still built with symmetrical geometries and apertures not optimized for local noise conditions (Christie and Campus 2010). In 2012, after the certification of 43 stations, a second Expert Group Meeting on array geometry was organized in Korea (Marty et al. 2012b). The Expert Group started by reviewing the existing models for the design of IMS infrasound array geometries. It concluded that although some of these models could

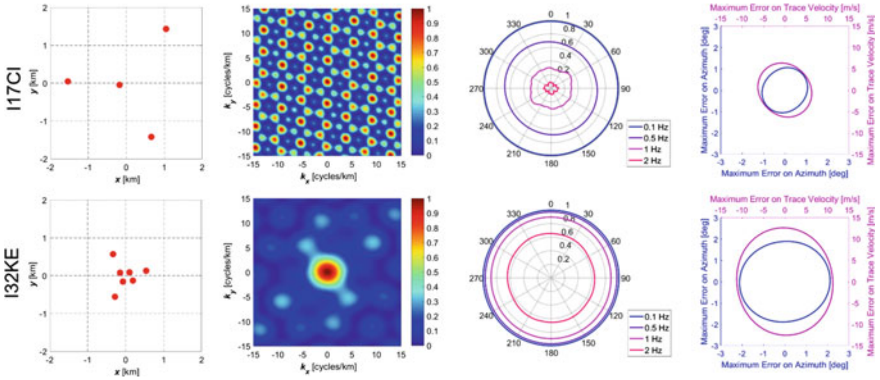


Fig. 1.15 Array layout, frequency–wavenumber power spectral density, array correlation coefficient (Christie and Campus 2010), and estimation of wave parameter uncertainties (Szuberla and Olson 2004) for station I17CI and I32KE

provide qualitative information, none of them could really be used to determine an optimal aperture and element distribution for IMS infrasound stations.

The frequency–wavenumber power spectral density (Capon 1969) frequently referred to as "array response" has often been mentioned in the literature as a meaningful tool for designing infrasound array geometries and especially to characterize array aliasing (e.g., Evers and Haak 2001; Christie and Campus 2010). However, the objective of the IDC detection algorithms is the estimation of wave parameters based on the computation of time delays between signal arrivals at the different elements of the same array. This does not relate to the concept of spatial aliasing and the frequency–wavenumber power spectral density does not really provide relevant information for designing of IMS infrasound arrays. If spatial aliasing was to be a criteria, the minimum requirements from the IMS Operational Manual would be completely inadequate because avoiding spatial aliasing at 4 Hz would require four-element arrays to have an aperture smaller than 100 m and not around 1–3 km as per IMS requirements. Figure 1.15 shows the frequency–wavenumber power spectral density for two IMS infrasound stations. If array aliasing would be relevant for IDC processing, data from four- element IMS stations such as I17CI would be unusable.

A second modeling technique consists in estimating the averaged degree of signal coherence expected between all array elements in function of the wave azimuth (Christie and Campus 2010). This technique is derived from the coherence loss model proposed by Mack and Flinn (1971). Although this technique integrates the concept of coherence loss, which is a central issue for infrasound signal detection, it does not take into account the concept of wave parameter estimation which is the final output of IDC detection algorithms. With this technique, the closer the array elements are, the better the results, with the best results obtained when all array elements co-located. In addition, the technique does not take into account wind-generated background noise at the station, which is one of the main factors driving coherence loss in the IMS frequency band. Figure 1.15 shows that the best results are obtained for station I32KE, which is the station with the smallest aperture. However, such a small aperture design does not always allow for the precise estimation of wave parameters especially in low frequency. Poor parameter estimation affects the output of IDC localization algorithms which primarily use signal arrival time, back azimuth, and velocity at multiple stations to locate events (Mialle et al. 2019). A third type of model consists in using the Cramér–Rao Bound (CRB) to estimate the uncertainties on wave parameters due to potential errors on intercorrelation-based delay measurements (Kay 1993; Szuberla and Olson 2004). Although this model covers the concept of wave parameter estimation, it does not take into account the loss of coherence. With this model, the larger the distances between the array elements are, the better the results, with the best results obtained for infinite distances. The best performance is, therefore, obtained for larger aperture arrays (Fig. 1.15). This leads to opposite results from those obtained with the array correlation coefficient method described above.

Because of the absence of models providing quantitative results, the 2012 Expert Group Meeting decided to define general recommendations for the design of IMS infrasound arrays instead of proposing a standard configuration. As in 2013, the Expert Group emphasized the importance of avoiding symmetrical designs and adapting the design to station environmental conditions. It also listed the following recommendations:

(a) The overall IMS infrasound network detection capability shall be considered when designing or upgrading infrasound array geometries;
(b) The station detectability, resolution, and robustness to the loss of elements shall be optimized to the station location;
(c) Since the computation of wave azimuth and velocity are of same importance for the data processing, infrasound arrays shall remain omnidirectional and not directive;
(d) IMS infrasound array geometries shall be optimized to the 0.1–1 Hz frequency band.

In parallel, the Expert Group identified the need to develop a new model that would take into account the two main concepts of the IDC automatic processing, i.e., the detection of spatially coherent signal and the estimation of wave parameters. This includes the development of a coherence loss model for the IMS frequency band as the model proposed by Mack and Flinn (1971) is based on acoustic-gravity wave observations across a 45 km aperture array. Following the Expert Group's recommendation, several coherence loss models were proposed based on the analysis of explosive events with high SNR (Nouvellet et al. 2013; Rakotoarisoa et al. 2013; Green 2015) or of microbaroms (Charbit 2015). This is a complex task because coherence loss is due to a combination of factors such as slightly different propagation paths within the atmosphere between the source and the different array elements or the background noise level at the array elements. Coherence loss, therefore, depends on parameters such as the frequency content of the source, distance between the source and the receiver, state of the atmosphere, and background noise levels at the station. It, therefore, seems difficult to define a general model that would be valid for any event, any station location, and any time. Assuming that an averaged coherence loss model is defined for a specific station location, it is then possible to use the CRB to estimate an optimized array geometry and aperture (Charbit 2015). Mission capability criteria should also be considered and the model should be run for any sub-combination of array geometries to ensure that the station performance is not significantly affected by the loss of one or two specific array elements. As an example, with the exception of the most southern element, the I04AU elements are almost all aligned along the same axis (Fig. 1.13). The loss of the southern element would, therefore, make difficult the accurate estimation of wave parameters for most azimuths.

1.4.4 Conclusion

The design of IMS infrasound arrays is a trade-off between detection and accurate estimation of the wave parameters. This trade-off is primarily driven by the coherence loss of infrasound signals with distance and the background noise levels at the station location. Background noise levels mainly relate to wind-generated turbulence, whose intensity can significantly and rapidly vary through time. The lower the noise conditions, the larger the array aperture can be and the better wave parameters can be estimated. For this reason, installing array elements at locations with background noise as low as possible is of much higher importance than designing the "perfect" theoretical array geometry. This usually means identifying locations in forests as dense as possible. Noise levels recorded during station site surveys should play a crucial role in the design of infrasound array geometries (Sect. 1.3.2). It is important that the geometry is optimized to the station location during the design phase because it can be difficult and costly to move array elements once the station has been constructed. As discussed in Sect. 1.4.2, IMS infrasound stations should also, whenever possible, include at least eight array elements in order to be resilient to the loss of array elements. To conclude, because of the absence of quantitative models, the main criteria to be considered for the design of IMS infrasound arrays are land constraints, noise levels, homogeneous inter-distance and azimuth distributions, aperture adapted to averaged wind conditions, resilience to loss of elements, and costs.

1.5 Wind-Noise Reduction Systems

1.5.1 General Requirements

Atmospheric turbulence, which is often the main source of pressure fluctuations in the IMS infrasound frequency band, can be divided into two categories: convective and mechanical (Walker and Hedlin 2010). In the atmospheric boundary layer, mechanical turbulence is usually due to the interaction between the wind and the Earth's surface (topography, buildings, forests, etc.) whereas convective turbulence is primarily produced by the diurnal heating of the Earth's surface by solar radiation. The influence of wind velocity on the background noise of pressure fluctuations is significant with pressure fluctuation spectra increasing with a steep averaged rate of 5–7 dB per m/s in the IMS frequency band (Hedlin and Alcoverro 2005). For this reason, the IMS Operational Manual requires that an acoustic filtering system consisting of "noise reduction pipes" be installed at all IMS infrasound array elements with the objective of attenuating the pressure fluctuations produced by wind turbulence (CTBTO 2009). This type of acoustic filtering system is often referred to as a "pipe array". The IMS Operational Manual requires that the acoustic response of each infrasound measurement system, including the acoustic filtering system, be flat and stable within ±5% over the 0.02–4 Hz passband (Sects. 1.6 and 1.7). It also states that the response of the acoustic filtering systems installed at all of the array elements of the same station shall be identical. This latter requirement is essential to ensure proper computation of wave parameters as IDC detection algorithms are based on array processing (Brachet et al. 2010).

1.5.2 Pipe Arrays

A pipe array consists of a number of low-impedance air inlets distributed over a spatial area and linked to the infrasound sensor through a network of pipes and manifolds. Pipe arrays are the most common type of wind-noise reduction system (WNRS) and they are currently installed at all IMS infrasound stations. The noise reduction comes from the fact that, at similar frequencies, infrasound signals remain coherent over much larger areas than wind turbulence (Mack and Flinn 1971; McDonald and Herrin 1975). By averaging pressure fluctuations over an area small in comparison with infrasound wavelengths but large with regards to the turbulence scale, it is possible to attenuate the pressure fluctuations produced by wind turbulence while preserving the integrity of infrasound signals (McDonald and Douze 1971). The maximum theoretical noise reduction to be expected with pipe arrays is equal to the square root of the number of air inlets. This corresponds to about 20 dB for the standard PTS 18-m diameter pipe array composed of 96 air inlets (Hedlin and Alcoverro 2005). This maximum theoretical threshold is usually reached in the

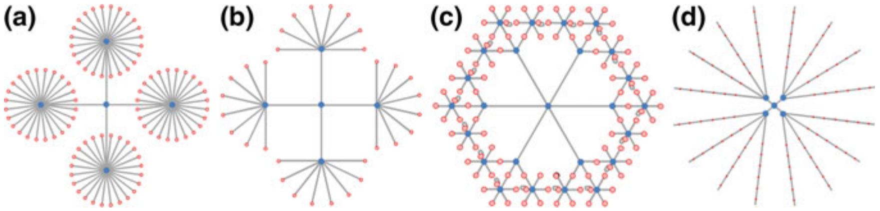


Fig. 1.16 Four most common types of pipe array configurations installed at IMS infrasound stations with **a** rosette, **b** star, **c** hexagonal closed pack, and **d** radial

higher part of the IMS frequency band because of the small scale of wind turbulence eddies in comparison with the inter-distance between two air inlets.

A wide range of pipe array designs have been studied over the past 60 years (e.g., Daniels 1959; Grover 1971; Hedlin et al. 2003; Alcoverro 2008). In the course of the establishment of the IMS infrasound network, different pipe array designs have also been implemented at IMS infrasound stations (Marty et al. 2012a). IMS pipe arrays can be grouped into four categories: rosette, star, hexagonal closed pack (HCP), and radial (Figs. 1.10 and 1.16). For each category, different pipe array diameters ranging from 10 to 70 m can be found in the IMS infrasound network. The acoustic responses for the most common types of IMS pipe arrays are shown in Fig. 1.17. It can be seen that the acoustic response of all pipe arrays display a flat amplitude response (±3 dB) over the IMS frequency band with the exception of the 70-m rosette configuration. It should be noted that the acoustic response of the 70-m rosette and 36-m HCP include significant phase variations over the IMS frequency band. These phase variations are not only due to the larger diameter of the systems but also to the use of resonance suppressors (Hedlin et al. 2003; Marty et al. 2017). Resonance suppressors are capillaries with a diameter of about 1 mm that are installed within manifolds or along pipes. Without these capillaries, the acoustic response of pipe arrays with larger diameter would exhibit large resonances within the IMS frequency band (Fig. 1.18). These resonances relate to the length of pipes terminated by low impedance outputs.

The installation of resonance suppressors at IMS infrasound stations has been a controversial topic (Christie and Campus 2010; Walker and Hedlin 2010). Although such devices can allow for pipe arrays with large diameter to comply with the flat amplitude response requirement of the IMS Operational Manual, they also introduce significant instabilities in the system response (Marty et al. 2017). By introducing a device with such a small diameter, any minor partial obstruction of the device can significantly distort the response of the measurement system and lead to an increased error in the computation of wave parameters, including a possible nondetection (Alcoverro 2008; Marty et al. 2011a). Figure 1.18 displays the acoustic response of a 70-m rosette pipe array with slightly different resonance suppressor diameters around the adapted diameter (1.2 mm). It can be seen that a simple particle (moisture, dirt, humidity) with a diameter of a few tenths of a millimeter and lodged within the resonance suppressor would significantly alter the system response. Such particles were found within some operational IMS pipe arrays, and the impact on

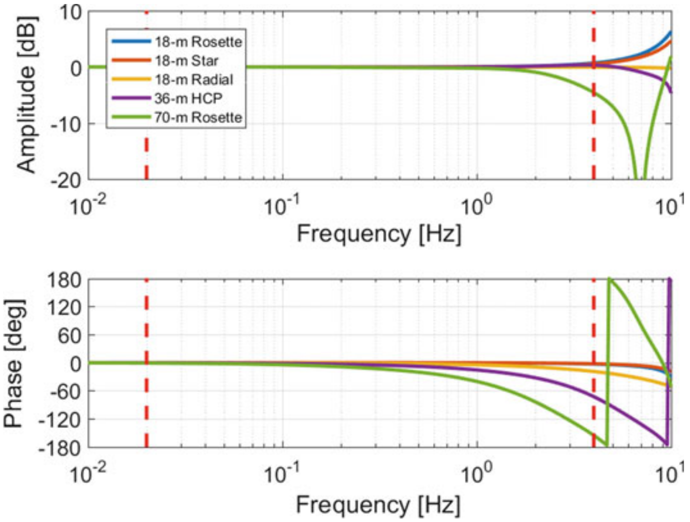


Fig. 1.17 Acoustic responses of five main types of pipe arrays installed at IMS infrasound stations to the arrival of an infrasound signal with a 30° angle from the horizontal using model developed by Gabrielson (2013). The vertical dashed red lines delimit the IMS frequency band. The phase response of the 18-m rosette pipe array does not appear in most of the frequency band because it almost perfectly overlaps with phase response of the 18-m star pipe array

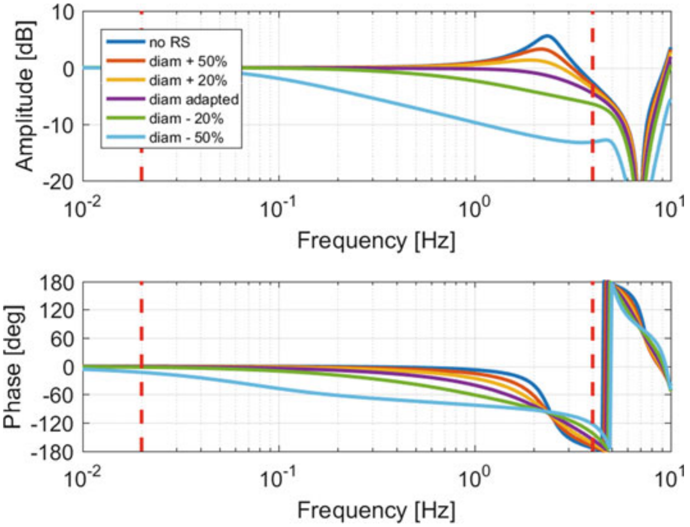


Fig. 1.18 Acoustic responses of the 70-m rosette pipe array to the arrival of an infrasound signal with a 30° angle from the horizontal using model developed by Gabrielson (2013) without Resonance Suppressors (RS) and with RS with different diameters around the adapted value. The vertical dashed red lines delimit the IMS frequency band

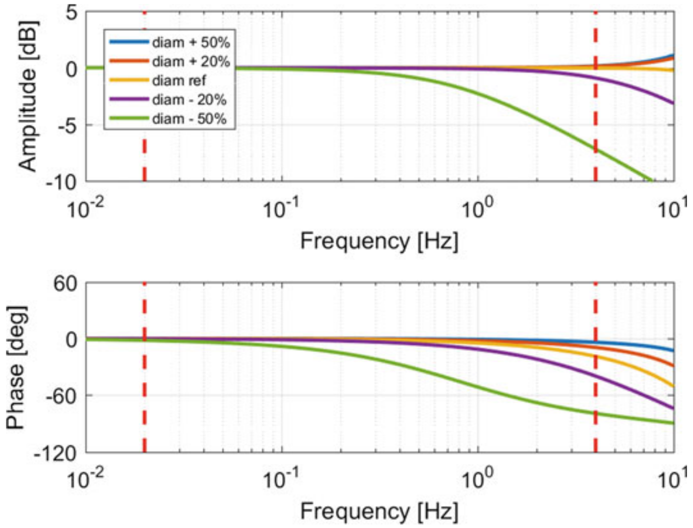


Fig. 1.19 Acoustic responses of the 18-m radial pipe array to the arrival of an infrasound signal with a 30° angle from the horizontal using model developed by Gabrielson (2013) with different hole diameters. The vertical dashed red lines delimits the IMS frequency band

the overall system response and on the results of the IDC automatic processing was demonstrated (Marty et al. 2011a, 2013). In addition, since the induced phase shifts are not constant over the IMS frequency band, the different frequency components of the same signal are shifted with different time delays (Fig. 1.18). The form of the wave packet is, therefore, altered, leading to potential misestimation of event magnitudes. For these reasons, the Infrasound Expert Group Meeting on WNRS organized in Jordan in 2011 recommended that resonance suppressors be removed from IMS pipe arrays (Marty et al. 2011b). This recommendation has been progressively applied across the IMS infrasound network since 2012 as stations undergo major upgrade (Sect. 1.3.3).

The IMS infrasound network still includes a few radial systems which exhibit similar issues as pipe arrays with resonance suppressors. The diameter of the holes drilled into the pipes is usually of the order of 1 mm which makes the system response very sensitive to any minor obstruction or inaccurate drilling. It can be seen in Fig. 1.19 that variations in hole diameter of a few tenth of millimeters have a significant impact on the overall system response. Such variations of responses were observed during PTS station revalidation visits (CTBTO 2013a). As with resonance suppressors, the response of the system is, therefore, highly sensitive to the environment (dust, ice, etc.) making it difficult to ensure stable and identical responses between all of the array elements of the same station. Additionally, radial pipe array layouts at IMS infrasound stations were found to differ from the theoretical layout primarily because of the thermal dilation of the hose material. Under direct solar radiation, the hoses tend to curve and move away from their original position.

Whereas radial pipe arrays are currently not recommended by the PTS, it seems that their performance in term of noise reduction could slightly exceed that of the standard PTS pipe arrays in the highest part of the IMS frequency band (Fee et al. 2016). This could be due to the holes of radial pipe arrays being located closer to the ground than the air inlets of standard PTS pipe arrays.

It must also be noted that the acoustic response of pipe arrays with diameters larger than 18 m can significantly depend on the wave elevation angle (Hedlin et al. 2003). This is an issue for the IDC automatic processing because an elevation angle would have to be assumed and the phase response corrected prior to running IDC detection algorithms. A compromise should be found between SNR improvement and flat and stable acoustic response as required by the IMS Operational Manual. The 2011 Expert Group recommended that the PTS is provided with acoustic response models for pipe arrays (Marty et al. 2011b). At the time, three acoustic models for pipe arrays were identified (Alcoverro and Le Pichon 2005; Gabrielson 2013; Brown et al. 2014b). A benchmark study was organized between three models and an experiment carried out with the objective of experimentally validating the models (Marty et al. 2017). The experiment validated two of the models including that developed by Gabrielson (2013), which was made available to the PTS. Using this model, it was determined that the PTS standard 18-m rosette pipe array was one of the best compromises in terms of stability of the response over the IMS frequency band, noise reduction (Denis and Le Floch 2015), and cost. Although the system does not perform much noise reduction below 0.04 Hz, it is compliant with IMS requirements. IMS stations are, therefore, being progressively upgraded with the standard PTS 18-m pipe array configuration in the framework of station major upgrade (Sect. 1.3.3).

Apart from modeling, the PTS has also made significant efforts since 2012 to improve the robustness of the standard PTS pipe array. Pipe array components which were originally made of plastic, galvanized steel, copper, or aluminum are now all made of stainless steel. These changes have allowed increasing the system lifetime and prevent issues such as rusting or destruction from wildfires. In addition, the number of connections between the different pipe array components was reduced and the connection seals reinforced to reduce chances of pressure leakage. This has significantly reduced SO maintenance activities with the standard PTS pipe array now considered nearly maintenance free. In parallel, the PTS is testing flexible high-pressure hydraulic hoses including two metallic mesh hoses (Tecalemit T214). The objective is to replace stainless steel pipes when dense vegetation does not allow for the installation of rigid pipes or ease transportation in extremely remote locations. In the past, vegetation was systematically cut in order to install the pipe array and protect it from falling trees and fruits. Since no pipe array can be more efficient than a dense forest, the PTS strategy now consists of adapting the pipe array design to the environment. The development of solutions with flexible hoses has shown to be extremely useful in that framework though they cannot be deployed in places subject to wildfire. It was also demonstrated that the addition of gravel over air inlets can help further increasing the SNR (Denis and Le Floch 2015). Gravel is, therefore, added over the air inlets of IMS pipe arrays wherever it is logistically possible and does not significantly increase SO maintenance activities. Finally, as wind velocity increases with height, installing air inlets as close as possible to the ground is an important factor to consider for an efficient noise reduction.

Standard procedures are currently being developed for type approval and acceptance testing of IMS pipe arrays in accordance with the IMS Operational Manual. To support these efforts, a standard pipe array system has been installed at the manufacturer's facilities in order to thoroughly test any minor design change before implementation throughout the IMS network. Pressure valves have also been added on the top of each air inlet of operational pipe arrays in order to have to the capability to pressure test pipe arrays at the time of certification, revalidation or whenever it is suspected that there is an issue with the performance of the system. In parallel, data quality metrics based on the regular computation of PSDs are being tested at the PTS to track potential increases in station noise and trigger pipe array maintenance actions. Finally, the progressive implementation of IMS calibration requirements allows for the regular monitoring of pipe array acoustic responses and performance at IMS stations (Sect. 1.7).

In conclusion, the PTS has made significant efforts since the 2011 Expert Group Meeting to develop a standard pipe array system with well-characterized and stable acoustic response, extended lifetime, reduced maintenance, and fully compliant with IMS Operational Manual requirements. Since the frequency responses of IMS pipe arrays are now well characterized, it has become possible to integrate them into the IDC response files. IDC response files currently only the response of the sensor and data acquisition system for infrasound channels. Although the acoustic response of the standard PTS pipe array is close to one across the entire IMS frequency band, it departs from unity at higher frequencies. For this reason, pipe array responses are planned to be progressively integrated into IDC responses files over the next years.

1.5.3 Other Methodologies

Apart from pipe arrays, most other WNRSs consist of either wind protection structures, digital filtering with dense sensor network or sensors measuring spatially integrated pressure. The objective of wind protection structures is to try to isolate the measurement system from wind turbulence (Walker and Hedlin 2010). A number of wind protection structures of different sizes, shapes, and porosity have been designed over the past 40 years (e.g., Shams et al. 2005; Liszka 2008; Christie and Campus 2010; Raspet et al. 2019). Depending on the structure porosity, spatial averaging can also occur over the surface of the structure leading to further attenuation of wind-generated noise (Hedlin and Raspet 2003). The advantage of wind protection structures is that large systems can be designed without having to worry about resonances as with pipe arrays. The drawback is that these systems can "catch" more wind than pipe arrays because of their three-dimensional structure and the increase of wind velocity with height. The structures necessary to achieve a similar noise reduction as with pipe arrays could also not be adapted to installation within dense forests, which are the primary location for IMS infrasound stations. Wind protection structures could, however, be considered for open field locations on the top of existing pipe arrays (Hedlin et al. 2003; Christie and Campus 2010). Prior to considering deployment at IMS infrasound stations, the acoustic response of such systems should be well characterized and it should be demonstrated that it remains stable through time. The system lifetime should also be evaluated in operational conditions.

Dense sensor networks could also be used to improve the SNR. The basic averaging of data from n sensors obviously leads to similar performance as with a pipe array with n air inlets located at the same location as the sensors (Dillion et al. 2007). However, advanced signal processing techniques could be used to better separate pressure fluctuations produced by wind turbulence and infrasound waves (Walker and Hedlin 2010; Frazier 2012, 2014). Similar noise reduction as with standard pipe arrays could, therefore, be achieved with a reduced number of sensors. Sensors could also be distributed over an area larger than standard pipe array dimension due to the absence of concern with resonances. The costs of such systems is currently prohibitive as the price of a single IMS-compliant sensor is similar to that of complete standard PTS pipe array. Operation and maintenance costs would also significantly increase and further development would be required for testing and validating the associated data processing technique. However, as technology evolves such solutions could become progressively less expensive and should be reviewed in the future.

The main example of a sensor measuring spatially integrated pressure is the optical fiber infrasound sensor (OFIS). This sensor is composed of two optical fibers that are helically wrapped around a sealed silicone tube. This creates a Mach–Zender interferometer that measures diameter change of the tubular diaphragm due to a pressure change (Zumberge et al. 2003; De Wolf et al. 2013). The fiber-wrapped tube is encased in insulation and installed inside a perforated drainage tube. An advantage of such systems is that they can be deployed over larger areas than pipe arrays due to the absence of resonance. The defined layout should ensure that the acoustic response of the system does significantly depend on wave azimuth and is identical at all array elements. More work may be required to characterize the susceptibility of the system to temperature and develop calibration methods in agreement with IMS requirements (Sect. 1.7). More importantly, as the system includes the sensing device, it should be thoroughly tested against all IMS Operational Manual requirements for infrasound sensors (Sect. 1.6).

In conclusion, it is likely that other wind-noise reduction methodologies could provide in the future better performance in terms of noise reduction than standard PTS pipe arrays. In order to comply with IMS Operational Manual requirements, the acoustic response of the new systems should be accurately modeled and it should be demonstrated that the system response remains flat and stable through time over the entire IMS frequency band including in harsh environments. The new systems should also ensure that the same response can be achieved at all array elements of the same station. In addition, the lifetime of the structure should be similar as that of the PTS standard pipe array (at least 15 years) and the cost not to be prohibitive. If such a new system would demonstrate to outperform the standard PTS pipe arrays and to meet all IMS requirements, the IMS Operational Manual would need to be updated as it currently only allows for the installation of pipe arrays as acoustic filtering systems (CTBTO 2009). Finally, the progress made over the past 10 years to model the four main types of wind-generated noises, namely turbulence–sensor interactions, turbulence–turbulence interactions, turbulence–mean shear interactions, and acoustic noise generated by the wind, should be highlighted (Shields 2005; Raspet et al. 2006, 2019). The better understanding of these different types of noises could lead to the design of a new generation of WNRSs better adapted to local wind-noise conditions.

1.6 Infrasound Sensors

1.6.1 General Requirements

The IMS Operational Manual lists eight minimum requirements for infrasound sensor specifications, further referred to as the IMS requirements in this Section (Table 1.2). Infrasound sensors must be microbarometers with response flat and stable within ±5% in amplitude over the 0.02–4 Hz passband. They must be able to operate between −10 and +45 °C and sometimes even beyond for stations located in extreme locations. Since calibration requirements will be extensively discussed in Sect. 1.7, this section will mainly focus on self-noise, dynamic range, and response requirements.

The IMS requirement for sensor noise was defined in 1996 based on knowledge on the minimum infrasound background noise and on the performance of the most advanced sensors at the time (CTBTO 1997b). More recent studies have shown that the minimum infrasound noise level recorded in the IMS network at 1 Hz is in fact about 16 dB lower than the reference value specified in the IMS Operational Manual (Bowman et al. 2005). This means that sensors with a self-noise equal to the

Table 1.2 IMS minimum requirements for infrasound sensor specifications (CTBTO 2009)

Characteristics	Minimum Requirements
Sensor type	Microbarometer
Measured parameter	Differential pressure
Passband	0.02–4 Hz
Sensor response	Flat-to-pressure over the passband
Sensor noise	⩽18 dB below minimum acoustic noise[a]
Calibration[b]	⩽5% in absolute amplitude
Dynamic range	⩾108 dB
Standard temperature range[c]	−10 °C–+45 °C

[a] Minimum acoustic noise level at 1 Hz: ~5 mPa/$\sqrt{\text{Hz}}$

[b] Periodicity: once per year (minimum)

[c] To be adapted for some specific sites

IMS requirement would have in reality a self-noise only 2 dB below the minimum measured infrasound noise at 1 Hz. It is generally assumed that in order to obtain a reliable measurement, the sensor self-noise needs to be at least 10 dB below the minimum acoustic noise (Ponceau and Bosca 2010). The IMS requirement for sensor self-noise is also defined at a single frequency only whereas the intent is for the sensor self-noise to be below the minimum infrasound noise over the entire IMS passband. The IMS requirement for sensor self-noise could be updated by specifying a minimum ratio between the minimum noise level expected at the station and the sensor self-noise over the IMS passband. This is what is done for the IMS seismic technology for which the sensor self-noise is required to at least 10 dB below minimum earth noise at the site. Such a requirement obviously implies knowing the minimum noise level at the station location or using a standard worldwide low noise model as a reference. The development of a accurate global low-noise model in the IMS frequency range should be a priority task in the near future. This model would be used not only for refining IMS specifications but also as a reference for equipment testing and data quality control. The development of such model is not an easy task as the input data need to be of the uppermost quality and must be corrected from the responses of the measurement systems. As seen in Sect. 1.5, a few IMS stations include, for example, nonstandard WNRS designs whose responses are not well characterized or fluctuate throughout time. Data from these stations should be discarded when computing a global low-noise model. For this reason, the model proposed by Bowman et al. (2005) is still used as a reference in this chapter as it is less affected by low quality data as the model proposed by Brown et al. (2014a). It is suspected that this latter model underestimates the minimum noise level in high frequency by up to a factor of 10 because of issues with the WNRS response of station I55US (Fee and Szuberla 2012).

Dynamic range corresponds to the ratio between the largest and the smallest amplitudes that can be recorded by a sensor. It is commonly derived from the ratio between the maximum level before signal clipping and the self-noise level. The objective of the dynamic range requirement is to ensure that the infrasound measurement system and the sensor specifically are able to accurately record both small and large amplitude infrasound signals. As seen in Sect. 1.5, the infrasound background noise level is highly frequency- and wind-dependent. The analysis of IMS worldwide measurements has shown that the infrasound background noise decreases with a slope of about −20 dB/decade in the IMS frequency band and can vary by as much as 60 dB at a single frequency depending of the wind conditions. This leads to a ratio of about 110 dB between the largest and smallest signal amplitudes commonly observed in the IMS frequency band (excluding close source measurements) (Bowman et al. 2005). With the addition of 10 dB for ensuring that the sensor self-noise is sufficiently below the minimum acoustic noise, the minimum requirement for infrasound sensor dynamic range should in reality be at least 120 dB. This value is slightly larger than the IMS requirement, which was defined as 108 dB in 1996 (CTBTO 1997b). A high dynamic range does not imply that the sensor is able to cover the entire infrasound amplitude range. A sensor with an extremely low self-noise could, for example, exceed the requirement for dynamic range while not being

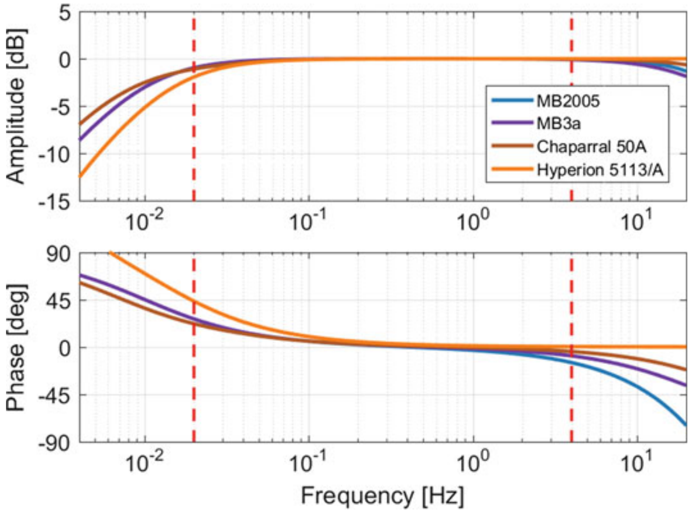


Fig. 1.20 Responses of MB2005, MB3a, Chaparral Physics 50 A and Hyperion 5113/A sensor models as per manufacturer data (CEA/Martec 2005; CEA/Seismowave 2014a; ChaparralPhysics 2010; Merchant 2015). The MB2005 response does not appear in low frequency because it perfectly overlaps with the MB3a response. The amplitude response of all sensors is flat ±3 dB in the IMS frequency band (vertical red dashed lines)

able to record high-amplitude infrasound signals. The IMS requirement for dynamic range could be updated with defining threshold values for the smallest and highest amplitudes to be recorded. Since there is already a defined specification for sensor self-noise, the specification for dynamic range could, in fact, be replaced by a specification on "signal clipping level". The maximum threshold before signal clipping should obviously be greater than the maximum background infrasound noise level observed in the IMS frequency band but could also be defined in relation with a maximum amplitude of explosion-generated infrasound signals to be expected to be recorded by IMS infrasound stations.

Finally, the flat-to-pressure requirement for the sensor response seems rather strict and probably not adapted to the shape of the infrasound background noise. The use of sensors with flat-to-pressure-derivative response could, for example, allow better matching of typical infrasound background noise levels in the IMS frequency band. The requirement for sensor response could, therefore, be updated similarly as for the IMS seismic technology for which different shapes of sensor responses are allowed. In addition, the term "flat" is not defined and could lead to different interpretations. It is commonly interpreted as flat in amplitude within 3 dB with no specific requirement for the phase. Figure 1.20 displays the responses (as per manufacturer data) of the main infrasound sensor models to be discussed in the next section.

1.6.2 Description

Infrasound sensors are commonly composed of a mechanical device sensitive to pressure fluctuations and of a transducer. Pressure fluctuations induce a distortion on the mechanical device that is then converted into a dynamic voltage by the transducer (Ponceau and Bosca 2010). In the first years of the network construction, two infrasound sensor models were successfully tested against IMS requirements: MB2000 and Chaparral 5 (CEA/DASE 1998; Kromer and McDonald 2000). Shortly after, the MB2005 model with slightly improved operational characteristics compared to the MB2000 was also approved for deployment in the IMS infrasound network (CEA/Martec 2005; Hart 2009). Over the past two decades, the MB2000/MB2005 sensors have been demonstrated to perform well in operating conditions with excellent response stability through time and very low sensitivity to temperature and absolute pressure fluctuations (Ponceau and Bosca 2010; Hart et al. 2013). For this reason, by 2012, MB2000/MB2005 sensors were deployed at over more than 90% of the network. Because of the high stability of their response, MB2000/MB2005 sensors are also used by expert infrasound laboratories such as the Commissariat à l'énergie atomique et aux énergies alternatives (CEA) and Sandia National Laboratories (SNL) as reference sensors for laboratory calibration (Sect. 1.6.3). The two drawbacks of this sensor model are (a) the level of the self-noise in high frequency, which can exceed the minimum acoustic background noise above 1 Hz at the quietest IMS stations (Fig. 1.21) and (b) the susceptibility to ground motion (Alcoverro et al. 2005). The sensitivity to ground motion is flat to acceleration and small enough that it rarely impacts measurements in the IMS frequency band. Although using data from mixed modality sensors can generate complications, IMS infrasound stations equipped with MB2000/MB2005 sensors currently contribute to the detection of high-amplitude seismic events for which regional IMS seismic stations sometimes clip due to the tuning of these stations to the detection of extremely low-amplitude events (Mialle et al. 2019). Seismic and infrasound arrivals are differentiated by IDC categorization algorithms due to different wave velocities.

The case of the Chaparral Physics 5 model is almost opposite. The sensor self-noise as measured in laboratory is very low compared to the minimum acoustic noise in the IMS frequency band and the sensor susceptibility to ground motion is negligible. However, the sensor response and self-noise are highly sensitive to environmental conditions. It was demonstrated that even when installed in a thermally insulated vaults at IMS stations, the sensor response could vary well outside IMS requirements (Szuberla et al. 2013) and the noise due to the sensor susceptibility to temperature could be higher than the minimum infrasound background noise (CTBTO 2011a). For this reason, starting from 2013, Chaparral Physics 5 sensors were progressively replaced by Chaparral Physics 50 A sensors across the IMS network (Chaparral-Physics 2010; Hart and Rembold 2010). This new generation of sensors was shown to be less sensitive to the environment while keeping some issues such as amplitude distortion and sensitivity stability (Hart and Jones 2011; CTBTO 2013b).

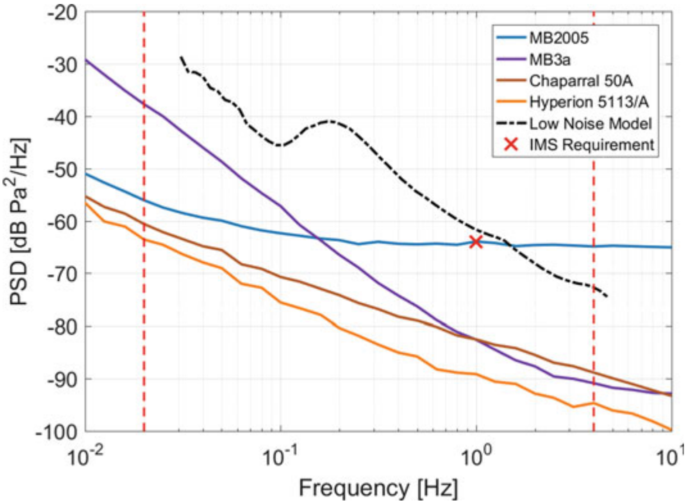


Fig. 1.21 Independent laboratory self-noise measurements for MB2005, MB3, Chaparral 50 A, and Hyperion 5113/A sensors (Merchant 2015; Merchant and Slad 2015). The red cross and the black-dotted line represent the IMS minimum requirement for sensor noise and the infrasound low-noise model (Bowman et al. 2005) respectively. The vertical dashed red lines delimits the IMS frequency band

Over the past years, two new sensor models were successfully tested against IMS requirements: MB3a (CEA/Seismowave 2014a; Merchant 2014) and Hyperion 5113/A (Merchant 2015; Nief et al. 2019). Unlike the MB2005 sensor, the MB3a sensor self-noise is at least 10 dB below the minimum acoustic noise in the entire IMS frequency band (Fig. 1.21). The MB3 power consumption is much smaller thanks to the use of a passive transducer. The sensor also includes a calibration coil that allows verifying the stability of the sensor in the field. In addition to the successful laboratory testing of the sensor against IMS requirements, the MB3 sensor was installed in operational conditions for 3 months in parallel with an existing IMS station before it was accepted for deployment in the network (Marty 2014b). The objective of this extensive testing was to ensure that the sensor would fulfill IMS requirements not only in laboratory but also in operational conditions. The self-noise of the Hyperion 5113/A sensor is at least 25 dB below the minimum acoustic noise in the IMS frequency band. The sensor measures both pressure and acceleration and the sensitivity of its pressure channel to acceleration is very low (Nief et al. 2019). The sensor has not yet been deployed at an IMS station. As of June 2017, MB2000/MB2005, Chaparral Physics 50 A and MB3 sensors were, respectively, installed at about 80, 15 and 5% of the network.

1.6.3 Type Approval

Since infrasound sensors are the key piece of equipment at an infrasound station, much attention is given to their design and testing (Nief et al. 2019). This section will focus on the testing of new sensor models against IMS requirements before approval for deployment into the IMS network. Acceptance testing of each individual sensor after manufacturing will be discussed in Sect. 1.7. The PTS has to date relied on two infrasound expert laboratories, SNL and CEA, for type approval of a new infrasound sensor. Testing results provided by these two laboratories have formed the baseline for the PTS to approve a sensor for deployment in the IMS network. With the increasing number of infrasound sensors in the market, the need to define standard definitions for IMS specifications as well as standard testing procedures has become more and more important. This task is challenging because there are no internationally recognized measurement standards available for the IMS infrasound frequency range. The current state of the art has a lower limiting frequency of 2 Hz and suitable primary calibration methods are still under development by the National Measurement Institute (NMI) community (Avison and Barham 2014). For this reason, the PTS organized two expert group meetings on infrasound sensors in 2013 and 2014 (Marty 2013, 2014a). As an outcome of these meetings, it was proposed that the PTS coordinates a pilot interlaboratory comparison study over the 2015–2016 time period. Three expert laboratories welcomed the initiative and agreed to participate: CEA, SNL, and the University of Mississippi. The outcome of this first study was far beyond initial expectations with a very high level of collaboration and information sharing between the three expert laboratories on topics that had been seen as quite sensitive (Doury et al. 2015). The three laboratories agreed on definitions for infrasound sensor specifications and provided a full description of their testing equipment and methodologies (CTBTO 2015). The same set of infrasound sensors was sent to the three expert laboratories for testing and results compared between the laboratories (Fig. 1.22).

Based on this success, all three laboratories agreed to repeat the study over the 2017–2018 time period. The PTS reached out the expert community with the objective of increasing the number of participants to the study. As a result, Los Alamos National Laboratories (LANL) agreed to join the study as a fourth expert laboratory. For this second pilot interlaboratory comparison study, the objectives were (a) further refinement of definitions for IMS sensor specifications based on lessons learned from the first pilot study, (b) homogenization of methods for the computation of measurement uncertainties, (c) inclusion of a reference microphone calibrated by a NMI, (d) contracting of NMIs for supervising the study and analyzing the results, and (e) focus on two main specifications encompassing most IMS requirements: self-noise and frequency response (CTBTO 2016d). Different midterm objectives were defined for these two specifications. Since results provided by the three laboratories during the first study were in good agreement for the frequency response, working with the International Metrology Community to provide measurement traceability was defined as a midterm goal. As results were significantly different for sensor

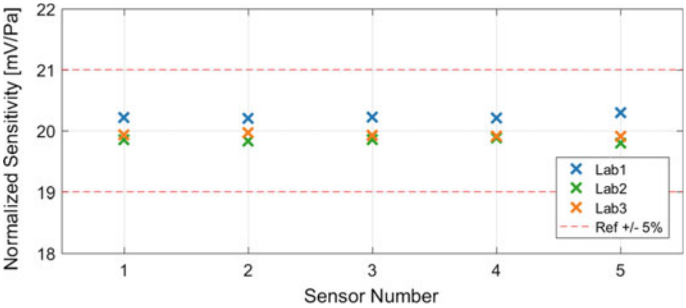


Fig. 1.22 Example of results obtained during the Pilot Interlaboratory Comparison Study 1 for the sensitivity at 1 Hz measured by the three laboratories for the same set of five sensors. Measurement uncertainties are not displayed since they were computed differently by the laboratories. Since no reference values were defined for the sensor sensitivities, the values were normalized by the mean of the values obtained by the three laboratories. All values are within the ±5% IMS minimum requirement for calibration (red dashed lines)

self-noise, the laboratories decided to focus on converging toward a standard and state-of-the-art measurement methodology. While the main objective of these pilot studies remains to fine-tune IMS infrasound sensor specifications and testing methodologies, it is also expected that these efforts lead in the long term to the definition of international standards for the infrasound technology and support the development of the next generation of infrasound sensors.

The successful laboratory testing of a new infrasound sensor model against current IMS requirements is, however, not enough to ensure that the sensor model will properly perform once deployed in the operational conditions. This is primarily due to the fact that (a) IMS requirements were defined at a time when knowledge of infrasound technology was much more limited and (b) laboratory testing is performed in stable and controlled environments masking potential susceptibility of a sensor model to environmental conditions or power source quality. For these reasons, in parallel of the pilot studies, the four expert laboratories agreed to support the PTS on the definition of more detailed sensor specifications for optimal operation (Marty 2013). The four laboratories have started defining sensor requirements for susceptibility to temperature, absolute pressure, and ground motion (Marty 2017). It is expected that the measurement of such specifications in a laboratory environment will help to anticipate undesirable sensor behavior in operational conditions. Since these additional specifications are still under development, the PTS currently requests that a new infrasound sensor model be deployed in operational conditions for a least 3 months in parallel to an IMS station as part of the type approval process for a new sensor (Marty 2014b). The objective of such a test is to compare the performance of the new sensor model in operational conditions against the well- characterized performance of an existing station through regular calibrations and array processing.

1.7 Calibration

1.7.1 General Requirements

Calibration is an essential process to ensure data quality and trustworthiness. As defined in the IMS Operational Manual, it encompasses three distinct processes: "acceptance testing", "initial calibration", and "on-site calibration". When an infrasound measurement system is to be deployed at an IMS station, specification data provided by the manufacturers for each individual piece of equipment are first reviewed to ensure that the delivered equipment meets sensor model specifications. This initial phase is called acceptance testing. The initial calibration is then performed with two objectives: (a) verifying that the system response remains within tolerances of the manufacturer-supplied data once the equipment is installed in operational conditions at the station (b) establishing a baseline for future calibrations (CTBTO 2009). The on-site calibration consists of measuring the system response and comparing it against the baseline response established at the time of the initial calibration. It shall be performed at least once a year or whenever it is suspected that the baseline calibration is affected (after equipment replacement for example). If the results of the on-site calibration are not within tolerances of the baseline, the SO must inform the PTS and initiate the necessary maintenance actions.

Both initial and on-site calibration must be full frequency response calibration. This means that a broad range of frequencies covering the entire 0.02–4 Hz passband shall be excited. The IMS Operational Manual also specifies that both sensor and WNRS shall be calibrated. The result of the on-site calibration shall be within 5% in amplitude of the baseline results over the IMS passband (Table 1.2). Unlike for the IMS seismic technology, there is currently no requirement on the phase response. This is probably due to the fact that estimating the phase response was seen as difficult at the time of the requirement definition. However, the IMS Operational Manual states that phase measurements are necessary to establish the full system response that is required for data processing at the IDC. In the case of the IMS seismic technology, the minimum calibration requirement of 5° accuracy is defined for the phase response. The same threshold is currently used as a reference for the IMS infrasound technology although defining a frequency-dependent requirement would probably be advisable. Finally, the IMS Operational Manual states that in order to perform on-site calibration activities, each infrasound array element shall be equipped with an internal or external calibration unit. It also specifies that initial calibration shall include a self-noise measurement at each array element.

1.7.2 Calibration Technique

Over the past decade, different techniques were investigated for the calibration of infrasound measurement systems. These include the use of active sources such as pistonphones (Starovoit et al. 2006) or infrasound generators (Park et al. 2009), or the development of self-calibrated microbarometers (Nief et al. 2019). However, none of these techniques have solved the two main challenges for calibration of IMS infrasound measurement systems: the inclusion of the WNRS and the coverage of the entire IMS frequency band. The calibration of infrasound measurement systems started taking a new turn when Gabrielson (2011) observed that coherent signals at a scale much larger than the size of wind turbulence structures could be generally observed in the entire IMS frequency band for extremely low-wind conditions. This meant that for such wind conditions, the background noise of pressure fluctuations in the IMS frequency band was most likely formed by a superposition of pressure fluctuations produced by the propagation of infrasonic waves. It was, therefore, possible to use this ambient background noise of pressure fluctuations as a broadband source of infrasound waves.

An in-situ response estimation technique based on the comparison between the background measurement recorded by an IMS measurement system and a reference system was developed by Gabrielson (2011). The same year the PTS organized an expert group meeting to review infrasound sensor calibration methodologies (Marty et al. 2011c) and the decision was made to test the newly developed in-situ response estimation technique at three IMS infrasound stations (Gabrielson 2013). While the results were very positive two main issues remained: (a) the difficulty to obtain results within 5% in amplitude of the nominal response over the entire IMS frequency band and (b) the estimation of the uncertainties associated with the reference measurement systems. The first issue was solved through the enhancement of the data processing technique (Charbit et al. 2015; Marty et al. 2017) and the second one mitigated through the use of independent, stable and, whenever possible, regularly calibrated reference measurement systems (Marty 2014b). Two additional expert group meetings were organized in 2013 and 2014 to refine the calibration methodology (Marty 2013, 2014a) and in 2014, following a PTS recommendation (Marty 2014b), the PrepCom encouraged the PTS to integrate this new calibration technique into the IMS infrasound network (CTBTO 2014b). The PrepCom reiterated this statement in 2016 after the long-term testing and validation of the calibration technique at the first IMS infrasound station (Marty 2016; CTBTO 2016b). Calibration equipment and results will be further described in the next two sections dedicated to initial and on-site calibration.

1.7.3 Initial Calibration

Since no technique fulfilling IMS requirements was available for initial calibration before 2012, only basic functionality checks were performed at the time of station certification or revalidation. The objective of these checks was to ensure that both the sensor and Data Acquisition System (DAS) were performing in general agreement with manufacturer specifications. The WNRS response was not measured, no full frequency calibration was performed, and no response sensitivity was computed.

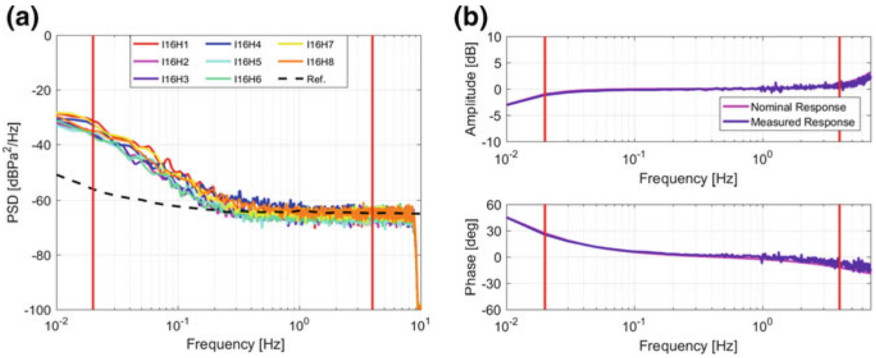


Fig. 1.23 **a** Self-Noise of all I16CN array elements with sealed sensors. The self-noises overlap very well above 0.3 Hz with the reference self-noise (black-dashed line) measured in the laboratory. Discrepancies in low frequency are a known bias from the method (with sealed sensors, any minor change of temperature leads to significant change in pressure) **b** Full frequency response of I16H3 infrasound measurement system (WNRS, sensor and DAS). Both measured and modelled responses overlap very well and the measured sensitivity at 1 Hz is within 0.8% of the nominal value (IMS requirement $\leqslant$5%). The vertical dashed red lines delimits the IMS frequency band in both figures

Therefore, there was no reference system response established at the time of certification and manufacturer specifications were always used as a baseline. Starting in 2012, the development of a full frequency calibration technique (Sect. 1.7.2) has allowed the PTS to progressively go through the entire initial calibration process at the time of station certification or revalidation. To accomplish this, the PTS uses an external and portable calibration unit composed of a reference MB2005 sensor and Taurus 24-bit DAS. Since 2015, the calibration units are complemented with MB3d sensors, which correspond to the 24-bit digital version of the MB3a sensors discussed in Sect. 1.6 (CEA/Seismowave 2014b). The calibration unit is deployed next to the operational measurement system as close as possible to the center of the WNRS. The sensor is connected to a short pipe terminated by a static pressure head (Vaisala 2005; Lanzinger and Schubotz 2012). When possible the static pressure head is covered by gravel to improve noise reduction. The full frequency response of the infrasound measurement system (WNRS, sensor, and DAS) is then computed from the comparison between the operational and reference data streams. As an illustration, initial calibration results measured at station I16CN are presented in Fig. 1.23.

The comparison of initial calibration results with manufacturer supplied data and the definition of a baseline for future calibration as required by the IMS Operational Manual mainly depends on the sensor model used at the station. Deviations from manufacturer values for DASs and from modeling results for WNRSs are usually negligible in the IMS frequency band. If they are not, the DAS is replaced or the WNRS characteristics measured again. In the case of MB2000/MB2005 sensors, initial calibration results are almost always within a few percent of manufacturer-supplied data with the difference smaller than the uncertainties of the initial calibration technique. In the rare cases when the difference in sensitivity exceeds the

5% IMS requirement, the sensor is replaced with a spare and the non-compliant sensor sent back to the manufacturer. Due to the very close values between sensor model response, manufacturer-supplied data for a specific sensor, and initial calibration results, it is the sensor model response that is used as a baseline for future calibration. This significantly simplifies the on-site calibration process and equipment replacement procedures because the same baseline response is used for all the array elements of all IMS stations using MB2000/MB2005 sensors. The process for Chaparral 50 A sensors is more complex because the response of these sensors (a) depends on the altitude at which the sensor is deployed and (b) varies from sensor to sensor (Sect. 1.6). Initial calibration results cannot be compared with manufacturer-supplied data and distinct baseline values are defined for each array element.

The PTS together with the infrasound expert laboratories and NMIs is currently working on the definition of standard procedures for the calibration of the PTS reference equipment (Marty 2017). Currently, the process mainly focusses on sensors since it is here again assumed that deviations from manufacturer values are negligible for the reference DAS. The response of the PTS reference sensor is regularly (before and after shipment to a station for example) compared at the PTS against the response of a group of reference sensors based in Vienna. From this group of sensors, there are some that always remain in Vienna while others are sent on a regular basis for calibration to expert laboratory such as CEA or SNL. This process allows the establishment of a chain of calibration between the reference sensor deployed at the station during initial calibration and a laboratory standard (Kramer et al. 2015).

1.7.4 On-site Calibration

The on-site calibration implemented in operations for the IMS seismic technology is a quite complex and resource-demanding process (CTBTO 2016a). Since the calibration process requires a series of actions from the SO and the IMS seismic stations can be non-mission capable during calibration, a precise worldwide schedule is necessary to ensure that the SO is available and that not two stations in the same region are calibrated at the same time. The SO has to then perform a series of actions which can take up to several days for the larger IMS seismic arrays. The SO is also responsible for processing calibration data and reporting results to the PTS. SO training dedicated to calibration activities are, therefore, organized on a regular basis. In addition, the calibration process highly depends on the type of equipment installed at the station. This means that station-specific procedures are required and that new procedures and training are needed when equipment at the station is upgraded or when a new SO is appointed. Lessons learned from the rolling-out of on-site calibration activities across the IMS seismic network were taken into account when defining the on-site calibration process for the IMS infrasound technology.

The on-site calibration technique for the IMS infrasound technology is based on the installation of a reference infrasound measurement system within the existing equipment vault (Fig. 1.24). The reference system is connected to a short pipe terminated by an air inlet. Both operational and reference infrasound data are sent to the IDC and the system response is derived from the comparison of these two data streams (Sect. 1.7.2). The advantages of this calibration technique are numerous. First, the operational data stream is never affected by the calibration process and the calibration does not need to be scheduled. Second, the technique does not require any action from the SO. Third, the technique is independent from the operational measurement system and no extra costs are involved for updating calibration equipment, procedures, or training when operational equipment is upgraded. Fourth, the same technique is used at all IMS infrasound stations and the computation of the results is automatically performed in a standard way in the IDC. Fifth, the system response can be computed retroactively allowing the verification of the proper functioning of the measurement system before or after an event of interest, for example. For all the above reasons, the on-site calibration process for the IMS infrasound technology is seen as reliable and cost-effective (Marty 2014b). In addition, the technique allows for computation of the system response at any time and allows closely monitoring the stability of the system response through the year. Whereas the calibration method for the IMS seismic technology is currently not traceable to standards, it is expected that the setup used for the calibration of IMS infrasound stations will allow linking the reference sensor installed in the vault with laboratory standards (Kramer et al. 2015). Such process as well as standard procedures for the on-site calibration of IMS infrasound stations are currently being defined with the support of the infrasound expert laboratories and NMIs (Marty 2017).

On-site calibration equipment was deployed for the first time at station I26DE in May 2015. Before this, the response of IMS infrasound measurement systems had never been measured at IMS stations. It was previously assumed that the responses were in agreement with the theoretical responses and stable through time with no means to verify it. This is still the case at most IMS infrasound stations. Since the MB2005 sensors were already in use at station I26DE and the response of these sensor models is known to be very stable in operational conditions (Sect. 1.6), it was decided to use the MB2005 sensors as reference sensors and to install MB3a sensors as operational sensors. This provided the added advantage of reusing existing sensors and improving the station detection capability thanks to the use of sensors with lower self-noise in high-frequency. In order to validate the on-site calibration technique, full system responses were computed every 2 days for more than a year. The stability of the method was found to exceed initial expectations and the responses of I26DE eight array elements were measured in agreement with IMS specifications (Fig. 1.25). Following this long-term testing phase, the PrepCom encouraged the PTS to continue the deployment of the infrasound station calibration capabilities through the IMS infrasound network (CTBTO 2016b). On-site calibration equipment was installed at station I37NO in 2016. At this station as well, the decision was made to use the existing MB2005 sensors as reference sensors and to install MB3a sensors as operational sensors. Full frequency system responses were measured at all array

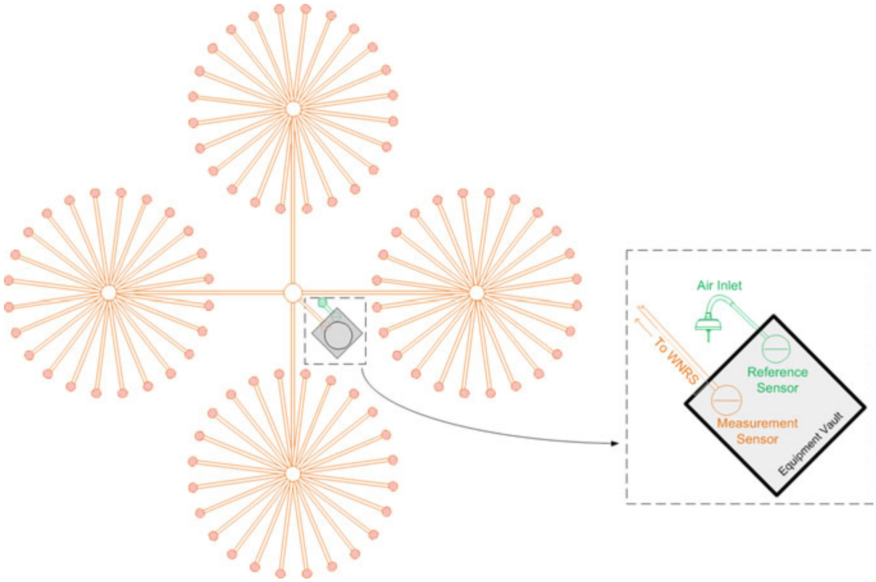


Fig. 1.24 Drawing of operational measurement system (orange) and reference system (green) used for on-site calibration at a standard IMS infrasound array element

elements in agreement with IMS specifications and the method demonstrated again to be very stable through time (Fig. 1.25). In addition to validating this method, the calibration results at these two stations provided a unique feedback on the stability of IMS infrasound measurement systems. These results also validated all the efforts described in Sect. 1.5 to model and improve the stability of the WNRS responses.

1.8 Meteorological Data

In addition to differential pressure measurements recorded at all array elements, the IMS Operational Manual requires that meteorological measurements including wind speed, wind direction, and temperature, be made at one or more of the array elements. These measurements will be further referred to as IMS meteorological measurements. The goal of IMS meteorological measurements is to provide information on station environmental conditions to support the interactive analysis of infrasound data. IMS Operational Manual minimum requirements for meteorological sensor specifications are listed in Table 1.3.

Although required, meteorological measurements were never made a priority in comparison with differential pressure measurements. This probably relates to the fact that these auxiliary measurements are not used by IDC automatic processing algorithms, nor taken into account in data availability statistics. As a consequence, the

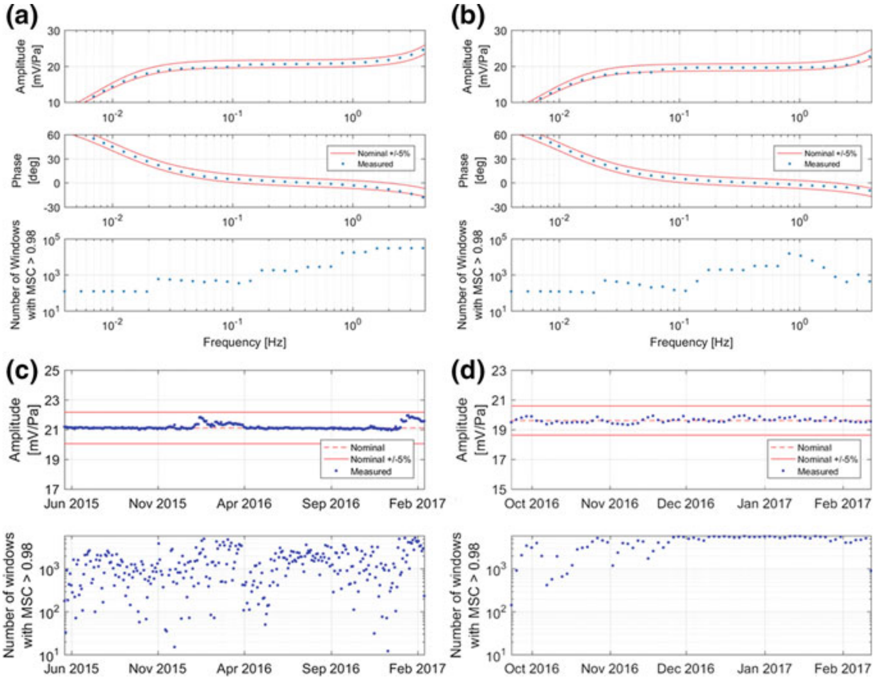


Fig. 1.25 On-site calibration results for station I26DE and I37NO. Figures **a** and **b** display the measured full frequency response (amplitude, phase, and number of time windows with magnitude squared coherence >0.98 between the measurement and reference signals) for stations I26DE (H7) and I37NO (H3) respectively. Figures **c** and **d** display the measured sensitivity at 1 Hz through time (including number of time windows with magnitude squared coherence >0.98 between the measurement and reference signals) for stations I26DE (H7) and I37NO (H3) respectively. All results in the four figures are within IMS requirements (red lines)

availability and quality of meteorological measurements have been generally much lower than that of differential pressure measurements and a significant number of IMS meteorological channels do not currently fulfill all IMS minimum requirements. An infrasound expert group was organized in the Republic of Korea in 2012 with the main objectives of reviewing the status of IMS meteorological measurements, discussing state-of-the-art developments in the area, and providing recommendations to the PTS (Marty et al. 2012c). The expert group reinforced the fact that meteorological measurements were useful for operational (information on station detection capability, estimation of trace velocities, and incidence angles) and engineering purposes (information for adapting WNRSs and array geometry to station-specific environmental conditions). However, the expert group highlighted that it was currently difficult to use IMS meteorological data due to their low quality. It was, therefore, recommended that more attention be given to the installation, maintenance, and documentation of meteorological channels and measurement systems.

Table 1.3 IMS minimum requirements for meteorological sensor specifications (CTBTO 2009)

Sensor	Characteristics	Minimum requirements
Wind speed[a]	Range[b]	0–50 ms^{-1}
	Threshold	$\leqslant 0.2\ \mathrm{ms}^{-1}$
	Accuracy	$\pm 0.2\ \mathrm{ms}^{-1}$
	Resolution	$\leqslant 0.2\ \mathrm{ms}^{-1}$
	Sampling rate	$\geqslant$1 sample per minute
Wind direction[a]	Range	0–360°
	Threshold	$\leqslant 0.2\ \mathrm{ms}^{-1}$
	Accuracy	±2.5°
	Resolution	1.0°
	Sampling rate	$\geqslant$1 sample per minute
Temperature[c]	Range[b]	−40 °C–+50 °C
	Accuracy	±0.3 °C
	Sampling rate	$\geqslant$1 sample per minute

[a] includes heater for anemometer where required
[b] to be adapted for some specific sites
[c] includes appropriate radiation shield

Part of the issue with meteorological measurements is related to data acquisition at the array elements. The same DASs used for differential pressure recording have often been used to acquire meteorological data in order to benefit from developments already made on DASs for IMS-specific requirements such as data formatting or authentication (Sect. 1.9). However, the acquisition of meteorological data is different in many ways from that of differential pressure. Meteorological measurements correspond to absolute and not differential values and meteorological sensors are usually not designed for sampling rates as high as those required for differential pressure. Integration of meteorological sensors with DASs was not always thoroughly tested resulting in a number of issues such as overshooting (due to high sampling rate), variable offset (change of electronic channel offset through time), or scaling (wrong sensitivities). For this reason, the 2012 expert group recommended (a) standardizing meteorological equipment across the network, (b) performing advanced integration testing with DASs, (c) developing on-site calibration procedure at the time of station certification and revalidations, and (d) providing SOs with spares (Marty et al. 2012c). While these recommendations are progressively implemented through the network, the PTS is also investigating the use of off-the-shelf digital meteorological packs, which can now be integrated with the new generation of DASs or with microcomputer devices (Sect. 1.9). These types of solutions are expected to solve most of the above-mentioned integration issues and are seen as the way forward for reliable IMS meteorological measurements.

At the time of the expert group meeting in 2012, IMS meteorological data were sampled with frequencies ranging from 0.05 to 20 Hz (Marty 2012). These sampling frequencies are significantly greater than the IMS minimum requirement of

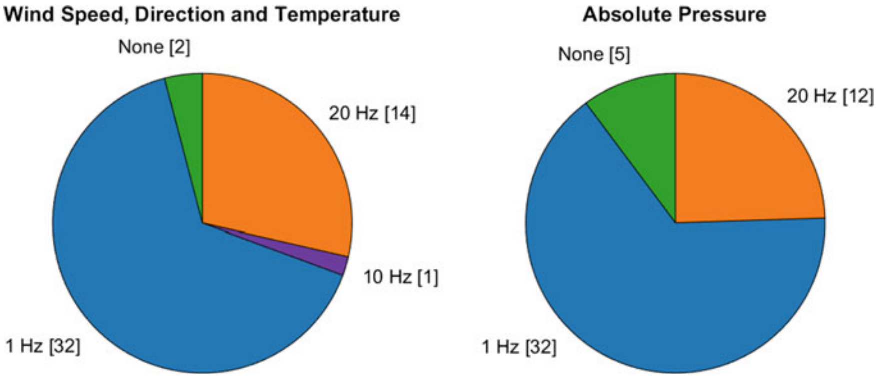


Fig. 1.26 Sampling frequencies distribution for wind speed, direction, and temperature (same distribution) and absolute pressure data recorded at IMS infrasound stations as of 2016 (with number of stations within bracket)

1 sample per minute (Table 1.3). The expert group, therefore, proposed to standardize the sampling frequency to 1 Hz across the network as this appeared to be a reasonable compromise for scientific, engineering, and operational purposes. This recommendation has progressively been implemented through the network and is still a work in progress (Fig. 1.26). Although IMS requirements specify that meteorological measurements be made at one or more of the array elements, currently all of the IMS infrasound stations only include one meteorological station which typically is located in the center of the array. The 2012 Expert Group reiterated that there could be value added by installing several meteorological sensors at the same infrasound station in case of environmental conditions significantly different from one array element to another. This could help adapting WNRSs and array geometry to station-specific locations. With the same objective in mind, the expert group also proposed the use of 3D wind sensors to better characterize local wind turbulence (Sect. 1.5).

Although there is no IMS requirement for absolute pressure measurements, most IMS stations send absolute pressure data. Unlike the required IMS meteorological data, absolute pressure information is commonly sent from all array elements of the same station. This is because MB2000/MB2005 sensors are installed in most of the networks (Sect. 1.6) and that these sensors measure both differential and absolute pressure. As for the required IMS meteorological measurements, little attention was given to the quality of absolute pressure data leading to significantly inaccurate values across the network (wrong sensitivities, sensor output not properly adjusted). It was also demonstrated that there was very little value added by recording the data since the differential pressure output from the MB2000/MB2005 sensors could be deconvolved up to several-day period (Marty et al. 2010). Whereas the 2012 Expert Group recognized that absolute pressure can provide useful state-of-health information, it recommended measuring this variable at one array element of each station only and using a dedicated external absolute pressure sensor instead of the absolute pressure output of MB2000/MB2005 sensors. As for the required IMS meteorological channels, the expert group recommended homogenizing sampling frequencies of absolute pressure data to 1 Hz across the network (Fig. 1.26).

Finally, the 2012 Expert Group proposed to investigate possible standardization of meteorological equipment at IMS infrasound stations with meteorological equipment deployed at IMS radionuclide stations and with World Meteorological Organization (WMO) specifications. It was later determined that IMS meteorological data could have limited value for the WMO because of differences between IMS and WMO requirements (mainly in terms of equipment and sitting) (Martysevich et al. 2015). Since IMS infrasound stations are often located in remote areas with no WMO weather station close by, the WMO nevertheless expressed its interest in the IMS meteorological measurements (Krysta 2015). These data could be integrated into meteorological data assimilation models, which are of high importance for the modeling of infrasound propagation, network detection capability, and atmospheric transport. The PTS recently contacted the Zentralanstalt für Meteorologie und Geodynamik (ZAMG) as the representative institute in Austria for WMO activities in order to discuss the sharing of IMS meteorological data with the WMO community.

1.9 Data Acquisition Systems

1.9.1 General Requirements

Data acquisition is usually done in two steps at IMS infrasound stations. First a data acquisition system (DAS) installed within the equipment vault converts the analog output of the infrasound sensor into a digital, time-stamped, digitally signed and formatted data packet known as a subframe, which is transmitted to the CRF. This type of DAS is often called digitizer because its main function is analog-to-digital conversion. A second type of DAS located at the CRF receives subframes from all the array elements and groups them into a larger data packet known as a frame. Frames are also time-stamped and digitally signed before they are sent to the IDC. All these actions at the CRF are performed by software running on industrial class or rugged computers. The IMS Operational Manual lists minimum requirements for DAS specifications (Table 1.4). IMS Infrasound data must be sampled at a rate higher than 10 samples per second and each data frame must be shorter than 30 s. All IMS infrasound stations use a standard sampling rate of 20 samples per second and a frame length of 20 s. IMS data must be formatted to Group of Scientific Experts (GSE) format. The GSE defined the CD-1.0 and later on the CD-1.1 data format for continuous data transmission to the IDC (IDC 2001). Data from all IMS infrasound stations are currently received in one of the two CD formats at the IDC with stations progressively upgraded to CD-1.1.

DAS resolution is required to be higher than 1 count per 1 mPa. This requirement is rather loose since the infrasound background noise level can reach 0.2 mPa in the IMS passband. The minimum requirement on resolution could, therefore, be

Table 1.4 IMS Operational Manual requirements for infrasound DAS specifications (CTBTO 2009)

Characteristics	Minimum requirements
State-of-health	Status data transmitted to the IDC
Sampling rate	⩾10 samples per second
Resolution	⩾1 count per 1 mPa
Timing accuracy	⩽1 ms
Standard temperature range[a]	−10 °C–+45 °C
Buffer at station or NDC	⩾7 days
Data format	Group of scientific experts format
Data frame length	⩽30 s
Data transmission	Continuous

[a] To be adapted for some specific sites

updated by specifying a minimum ratio between the lowest infrasound noise at the station and the DAS self-noise. A requirement for sensor noise is already defined in such a way (Sect. 1.6). Therefore, the specifications for sensor and resolution could be unified into a single "system noise" specification that would be required to be at least 10 dB below the minimum local infrasound noise. The minimum requirement of 7 days for data buffer at the station or NDC is easily fulfilled with existing data storage devices. In addition, typical DASs installed at the array elements also include extended data storage capacity. Therefore, the minimum requirement for data buffering at the CRF could be raised and extended to the array elements. This would increase the amount of data that could be retransmitted after a communication outage with the CRF or the IDC and support the effort to fulfill IMS DA requirements (Sect. 1.2.2). Although the CTBT only requires uninterrupted data transmission for IMS primary seismic stations, the IMS Operational Manual specifies that data transmission from IMS infrasound stations shall be continuous (CTBTO 2009) and the IDC Operational Manual specifies that data should be received in the IDC with a maximum delay in transmission of 5 min (CTBTO 2011b).

In addition to the minimum requirements for DAS specifications, the IMS Operational Manual also describes data surety requirements for IMS stations. Each array element and the CRF must include digital signature and anti-tampering devices. These devices are used by DASs to digitally sign data and trigger state-of-health security bits. Commands sent to IMS stations from remote locations are also required to be authenticated and this process is handled by DASs as well on the station side (CTBTO 2000). The need to integrate DASs with IMS infrasound and meteorological sensors has led to the definition of additional operational requirements. Examples include the capability to acquire both analog and digital meteorological data, power sensors, handle central timing solutions, or send integrated broadband calibration signals. It has also led to the definition of advanced requirements for specifications such as cross-talk, common mode rejection, harmonic distortion, or anti-aliasing filtering. Limiting DAS power consumption is another critical requirement as it ensures that no upgrade of the power system is required when installing a new DAS at the station. The list of current operational requirements for IMS DASs, therefore, goes much beyond the list of the minimum requirements listed in Table 1.4 (CTBTO 2016c).

1.9.2 Description

In order to differentiate the two types of DASs described in the previous section, the DAS located inside the equipment vault will be further referred to as the digitizer and the DAS located at the CRF as the Data Acquisition and Forwarding Software (DAFS). There are currently five different digitizer models used across the IMS infrasound network (Fig. 1.27). Digitizer lifetime is estimated to be within 10–25 years depending on the models and the environment in which the digitizers are deployed. Since the first IMS infrasound stations were installed more than 15 years ago approximately 25% of the digitizers have already been upgraded. It is the intent of the PTS to keep at least four different models of digitizers across the IMS infrasound network. The objective is to prevent a major network outage in case of malfunctioning of one of the models. As an example, in 2016, due to a bug in GPS receiver firmware, the timing system of two digitizer models started drifting with time. Because of the diversity of the digitizer models used across the network, this issue only affected a part of the network. All digitizer models used in the IMS network have been successfully tested against IMS specifications by independent expert laboratories before they were approved for deployment. As discussed in Sect. 1.9.1, the lists of type approval tests was progressively extended with additional specifications in order to ensure the proper integration of digitizers with infrasound and meteorological sensors. More recently the PTS also started defining additional functionality and field tests for type approval of new digitizers with the support of expert laboratories. Functionality tests allow covering areas such as data formatting, calibration, authentication or command and control. Field tests allow stressing digitizers in operational conditions similarly as what is done for infrasound sensors (Sect. 1.6). The objective of all these tests is to ensure that digitizers will fulfill IMS requirements once deployed at IMS stations.

At the beginning of the network construction, all DAFS were proprietary software associated with the digitizer model used at the array elements. Such a solution was difficult to sustain due to the uniqueness of IMS requirements and their evolution with time. The PTS, therefore, decided in 2000 to start developing a standard software solution to interface with all types of digitizer models installed at IMS array elements. This solution, called Standard Station Interface (SSI), was deployed at the first IMS station in 2001 and is now deployed on more than 80% of the IMS infrasound network. The development of this solution resulted in reduced development costs, improved data availability, and flexibility to quickly incorporate new requirements. Apart from data acquisition, buffering, formatting, and digital signature, the SSI software also handles tasks such as calibration and command and control. After more than a decade of steady development, the SSI is now able to interact with all

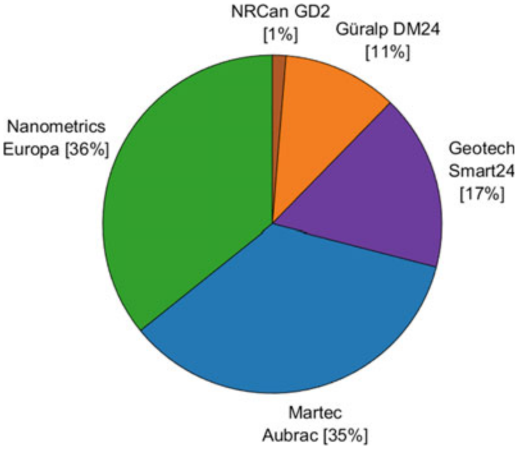


Fig. 1.27 Distribution of DAS models (digitizers) through the IMS infrasound network as of 2016

digitizer models deployed across the IMS network. The PTS is currently focusing on consolidating the last software release through the completion of the documentation, integration of the software into a standard testing environment, and improvement of the release process. The objective is to have a well-tested, documented, and robust version of the software by beginning of 2018. In parallel, a state-of-health component of the software is being developed for monitoring the status of the different SSI processes as well as of most station components (digitizers, communication and power systems). It is expected that this new module will ease SO monitoring activities. The storage of station state-of-health information at the CRF will also support station troubleshooting activities when required. Finally, it must be noted that the SSI software is currently being tested by Host Countries and the PTS on ruggedized microcomputer devices. It is expected that such devices could handle tasks such as data formatting and digital signature at the few stations for which digitizers currently do not have this capability.

1.10 Station Infrastructure

A robust infrastructure has been and will remain the basis for a high-performance station. No infrasound equipment can properly perform without a reliable power supply and protection against the environment. The analysis of station failures over the past 5 years have confirmed that power and environment are two of the main sources of data loss (Sect. 1.2.2). A lot of attention should, therefore, be given to station infrastructure design and station-specific environmental conditions should be taken into account. The IMS Operational Manual requires that a reliable primary power source capable of meeting DA requirements be installed at all IMS infrasound stations. Secondary sources of power are also required at the CRF and the array elements. The

IMS Operational Manual also recommends that stations consume as little power as possible in order to limit power back-up capacity, reduce maintenance costs, and increase DA. At the array elements, the replacement of obsolete DASs and sensors during station upgrade contributes to the reduction of power consumption. The PTS is also testing ultralow power consumption (below 5 W) computers to replace the current standard CRF SSI computers which consume about 400 W. This would significantly reduce power needs at the CRF and would allow for the installation of smaller, more robust, and maintenance-free power solutions. A few DC-powered CRFs were also recently upgraded with DC equipment in order to discard inverters and further reduce power consumption. In parallel, the PTS is reviewing state-of-the-art power solutions with the objective of defining and testing a set standard power systems for IMS stations. Particular attention is being given to solutions deployed in polar regions. Damage done to stations due to direct or indirect lightning has led to the definition of strict IMS standards for earthing and lightning protection (CTBTO 2010). Low-power consumption and redundancy are criteria that have also been made mandatory in the framework of the third GCI contract. GCI equipment will be replaced at all IMS stations over the 2017–2018 time period, and for the first time, all stations will include a back-up GCI link.

As discussed in Sect. 1.2.3, IMS infrasound measurement systems should be installed wherever possible inside dense forests in order to reduce the influence of wind on infrasound measurements. However, in the past vegetation has often been cleared around infrasound array elements to allow open sky access for solar panels and GPS antennas as well as direct line of sight for radio communication. The PTS has, therefore, decided to change its approach for building IMS infrasound array elements in recent years. The preferred solution for power and data communication is now through cables coming from the CRF (CTBTO 2014a). This type of solution allows using central timing and does not require the use of a GPS unit at array elements. It also allows installing one single-power source for the entire station. This reduces maintenance activities and simplifies the installation of back-up power systems. In addition, radio communication systems are more likely to fail under harsh environment than fiber optic systems. The use of fiber optic systems also reduces power consumption and generally eliminates the need for masts, which can increase the probability of lightning strike. When it is not possible to bring power and communication at the array elements through cables, a second vault is now installed in an open area at a reasonable distance from the equipment vault, which remains within dense vegetation. In the past, very large and deep underground vaults were often installed as it was assumed that temperature fluctuations could affect infrasound measurements. This led to a number of flooded vaults through the network due to high-water tables, snow melts, or heavy rains. The PTS now installs small surface vaults with high ingress protection levels, long life time, and thermal protection adapted to equipment operating ranges. Finally, the station infrastructure needs to be properly and regularly maintained by the SOs in order to ensure high data availability. This includes the planning and execution of well-defined preventive maintenance activities, such as the regular maintenance of diesel generators, timely replacement of batteries, cleaning of solar panels, clearing of access roads, or measurement of grounding system resistivity.

1.11 Conclusion and Perspectives

The IMS infrasound network is a unique network. It is the only global infrasound network and its very strict operational requirements makes IMS infrasound data relevant not only for nuclear explosion monitoring, but also for a growing number of civil and scientific applications. As of June 2017, 82% of the IMS infrasound network is certified and it is anticipated that this number will reach 90% by 2020. Since the publication of the first version of this book in 2010, significant advances have been made in the characterization and optimization of IMS infrasound measurement systems. Development in array geometry, WNRSs, and calibration have allowed enhancing data quality and, therefore, network detection capability. Engineering processes have also been put in place to increase data availability at all IMS infrasound stations. The two main engineering challenges across the network are currently the fulfillment of IMS requirements for data availability and quality assurance. Sustaining high data availability requires robust and station-specific design, skilled and proactive SOs, continuous performance monitoring, and timely equipment and infrastructure upgrades. Although significant progress has been made over the past years with the development of a quality assurance infrastructure for the IMS infrasound technology, additional engineering efforts are required to define standard procedures, reach measurement traceability and roll out on-site calibration equipment through the network. Due to the uniqueness of the IMS infrasound network and of the IMS requirements, the PTS plays a key role in the development the infrasound technology. As highlighted in this chapter, it is expected that over the next 5 years engineering and development activities around the IMS infrasound network focus on the following:

(a) Deployment of robust, well-characterized and IMS-compliant WNRSs across the network;
(b) Refinement of standard procedures for type approval, acceptance testing, and calibration of IMS infrasound measurement systems;
(c) Integration of WNRS frequency responses into IDC responses files to enhance amplitude and phase corrections of IMS infrasound data;
(d) Strengthening of collaboration with the international metrology community to provide measurement traceability in the IMS frequency range;
(e) Update to the reference infrasound low-noise model;
(f) Development of advanced models for the design of infrasound array geometries;
(g) Enhancement of station state-of-health monitoring capabilities;
(h) Definition of standard and state-of-the-art power solutions for IMS stations;
(i) Standardization of meteorological equipment installed at IMS infrasound stations and sharing of data with the international meteorological community;

(j) Implementation of network detection capability models in operations for prioritizing maintenance actions.

The objective of these development activities is to reach compliance with IMS Operational Manual specifications at all IMS infrasound stations. These activities will also contribute in reinforcing the credibility of the IMS infrasound technology and support preparation for the Entry into Force of the CTBT. In parallel, the PTS will continue technology watch activities to stay at the forefront of scientific and technical innovation and ensure that the IMS infrasound technology stands at the state of the art for Treaty verification purposes. All these activities will lead to the provision of infrasound data with enhanced quality to States Signatories and open new possibilities to the scientific community for the monitoring of the atmosphere and of infrasound sources.

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