FINAL PUBLISHABLE REPORT

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RMG: -		

TABLE OF CONTENTS

1 Overview

The monitoring of extreme events such as volcanic eruptions, earthquakes, tsunamis or nuclear explosions, rely heavily on the measurement of seismic activity and low frequency sound or infrasound, both in air and in the ocean. Specialised sensor technologies supporting such monitoring were well-established at the start of this project, but their calibration required further development, and at that time lacked traceability to the international system of units (SI). Therefore, this project aimed to establish both the first primary measurement standards for low frequency sound and vibration, over the frequency range of the applications, and new calibration capabilities that could support the operation of global networks for environmental monitoring and research in areas such as climate change and non-proliferation of nuclear weapons. The project was able to extend the frequency ranges for traceable environmental measurements in the field of infrasound, underwater acoustics and seismic vibration to lower frequencies. New measurement services have also been launched by the project, based on methods that will ultimately be, or are already, embodied in international standards. Further to this, several case studies have been completed which highlight the role of key metrology concepts such as traceability and measurement uncertainty in applications for environmental monitoring.

2 Need

Studies of low frequency sound and infrasound propagation in the atmosphere and in the ocean are an important part of weather prediction and of understanding climate change; low frequency sound and vibration phenomena have long been used as indicators of major natural events such as earthquakes, tsunamis, volcanic eruptions etc.; infrasound, low frequency seismic and ocean acoustic measurements are core technologies used for monitoring compliance with the provisional Comprehensive Nuclear-Test-Ban Treaty (CTBT); and not least, low-frequency noise nuisance is a significant modern-day problem with less severe, but nevertheless widespread impact.

Despite their widespread use in vital applications for the environment and society, infrasound and low frequency acoustic and seismic measurements were not fully covered by primary or secondary measurement standards, compromising their reliability, value and wide acceptance. Even the measurement of low-frequency noise nuisance lacked basic measurement traceability for a significant part of the frequency range of interest.

Recognising this critical deficiency, the Consultative Committee for Acoustics, Ultrasound and Vibration (CCAUV), formed of the world-leading experts in these measurement technologies, gave this issue high strategic importance. The main need was for novel primary and secondary calibration methods and systems, and for transfer standards suitable for extending traceability into the field. Furthermore, the stations within the global networks monitoring seismic activity and infrasound in the air and in the oceans are mostly in remote and inaccessible locations. The stations' sensors must operate continually and cannot be taken out-of-service just for calibration, and so require in-situ or on-site methods of re-calibration to maintain the quality of the data they generate.

The remote station locations often present environmental conditions that differ significantly from those found in the laboratory. Extremes of temperature, pressure and humidity and other harsh weather conditions are also additional challenges in understanding how sensor performance is impacted by the environment.

3 Objectives

The overall objective of the project was to extend the frequency ranges for traceable environmental measurements in the field of infrasound, underwater acoustics and seismic vibration to lower frequencies. This included the development of the required calibration methods, the procedures for validation and dissemination, as well as the on-site transfer to the actual applications at environmental measurement stations.

The specific technical objectives of the project were:

1. To develop primary calibration methods and devices in the low frequency range for airborne acoustics (40 mHz – 20 Hz), underwater acoustics (0.5 Hz – 100 Hz) and vibration (seismic) sensing systems (10 mHz – 20 Hz), needed for environmental measurements but not covered by global calibration capabilities available at the outset of the project.
2. To develop laboratory-based secondary calibration methods for airborne acoustics (40 mHz – 20 Hz), underwater acoustics (0.5 Hz – 100 Hz) and vibration (seismic) sensing systems (10 mHz – 20 Hz) as the first step in transferring new primary calibration capability to working standard devices.
3. To develop facilities and methods for the dissemination of traceability for airborne acoustics, underwater acoustics and vibration (seismic) sensing systems through specific methods for on-site calibrations. Improvements will be tested through a series of case studies with additional evaluation of stability, behaviour, positioning effects, installation conditions and sensitivity to the environment, leading to enhanced knowledge of system performance under operational conditions.
4. To evaluate the outcome and impact of improvements to current global acoustic, underwater and seismic sensor networks deployment strategies gained by introducing traceable calibration and the application of measurement uncertainty principles, and to propose optimised models and parameters in the applications, leading to increased confidence in measurements.
5. To engage with stakeholders including regulators, sensor manufacturers, network providers, users of the traceable data, standardisation committees including ISO/TC 108/WG 34, IEC/TC 29, IEC/TC 87/WG 15 and ISO/TC 43/SC 3 and authorities responsible for developing and implementing EC Directives related to the environment, to facilitate the take-up of the project results.

4 Results

4.1 Objective 1: To develop primary calibration methods and devices in the low frequency range for airborne acoustics (40 mHz – 20 Hz), underwater acoustics (0.5 Hz – 100 Hz) and vibration (seismic) sensing systems (10 mHz – 20 Hz), needed for environmental measurements but not covered by global calibration capabilities available at the outset of the project.

4.1.1 Development of novel primary calibration techniques

The global infrastructure supporting measurement traceability for sound pressure and noise exposure both in air and in the ocean, and for vibration measurements, are all well established in the conventional frequency range. Furthermore, a wide range of national and international standards, guides, directives and regulations have been created concerning the measurement of noise and vibration, and its impact on humans and the marine environment.

In the case of infrasound and very low frequency vibration typical of geophysical monitoring, the situation at the start of this project was unsatisfactory, as significant elements needed for traceable and reliable measurement were missing. In particular, calibration services for measurement systems were scarce, as no suitable primary calibration methods had been developed. Therefore, this project sought to establish calibration principles, apparatus, and methods for the three commonly used monitoring technologies, (i) infrasound, (ii) vibration (seismic) and (iii) underwater sound. The following sections present the solutions developed by this project and the performance of those solutions.

4.1.1.1 LNE laser pistonphone

A laser pistonphone was developed at LNE (Figure 1) with the aim of establishing primary standards for sound pressure at very low (infrasound) frequencies down to 10 mHz. The device consists of a closed cavity which is driven by a custom-designed loudspeaker. The sound pressure within the cavity can be calculated from laser measurements of speaker membrane motion, enabling a sensor to be calibrated when exposed to this known stimulus. The pistonphone was designed with an upper frequency limit of 20 Hz to overlap with established calibration methods, and more importantly targeting 10 mHz at the lower end of the range. Special attention was given to the sealing to prevent pressure leakage losses which can reduce accuracy at very low frequencies and could ultimately render the device unusable.

Using the developed laser pistonphone calibrations can now successfully be performed on a wide variety of infrasound sensors, including microphones, barometers, manometers, and microbarometers. The achievable measurement uncertainties for the best-performing infrasound sensors are 0.03 dB in amplitude and 0.24 degrees in phase at medium to high frequencies. These uncertainties increase to 0.1 dB for amplitude and 2 degrees for phase at 10 mHz.

Finally, the performance of the laser pistonphone was demonstrated by comparing the calibration results with those obtained using alternative methods in the comparisons in section 4.1.2.

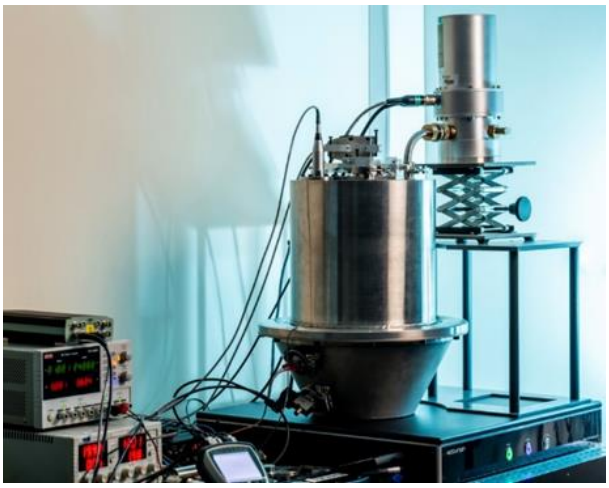

Figure 1: Photograph of the laser pistonphone.

4.1.1.2 Primary microphone calibration by the 'carousel method'

A second alternative infrasound calibration setup was developed at PTB, which uses the gradient of the ambient air pressure with altitude to generate a reference signal. For this second infrasound calibration setup, a device under test was mounted on a vertically rotating disc (Figure 2) and, thus, subjected to a sinusoidal change in altitude due to the rotation. The amplitude of the resulting alternating pressure could be determined analytically from easily measurable variables such as ambient temperature, humidity, and air pressure, while the frequency of the alternating pressure results from the speed of rotation.

The new infrasound setup covers a frequency range from 0.1 Hz to 5 Hz with potential to reach up to 10 Hz. The frequency range of the new measurement setup is currently limited at the lower end by high background noise levels. At the upper end, the ability to perform calibrations decreases due to the onset of disturbance from flow noise, which is as a result of the high rotary motion experienced by the microphone.

However, when calibrating a microphone, the measurement uncertainty is less than 0.1 dB over the entire operating frequency range.

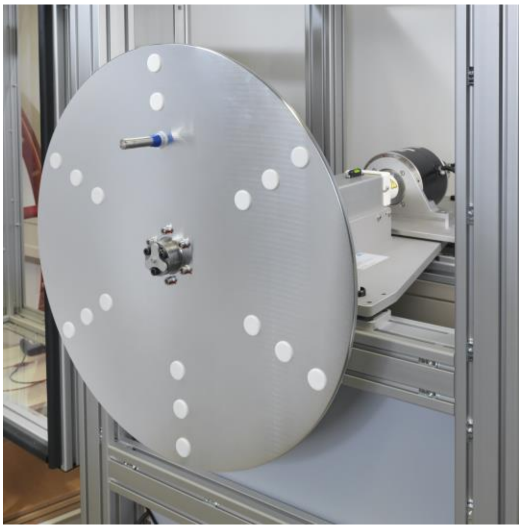

Figure 2: Photograph of the vertical disk with mounted microphone.

4.1.1.3 CNAM refractometry calibrator

A third infrasound calibration method investigated by CNAM used the principle that sound pressure results in changes in density and therefore refractive index in the medium (in this case air). Therefore, a means of measuring the optical variations can allow the sound pressure to be determined. A Fabry-Perot refractometer is a device that enables the refractive index changes to be measured in a closed cavity. Thus, the project first attempted to use such a device for acoustic measurements. The Fabry-Perot refractometer uses a laser with a single optical frequency which varies depending on the apparent length of the cavity, itself a function of the air density. Thus, measured perturbations in the optical frequency be related to air density changes and hence sound pressure, using a mix of established and new models for the physical behaviours.

The project has successfully demonstrated the feasibility of delivering primary calibrations of infrasound sensors over a range from 40 mHz to 5 Hz using such a technique.

However, temperature variations induced by the acoustic process presented a significant challenge to the method. Therefore, an analytical model was developed to quantify the influence of temperature changes on the results and can be used to correct the effect of these acoustically induced temperature changes.

The correction works well in both phase and amplitude in parts of the frequency range, but not as well when the acoustic stimulus undergoes a transition from one underlying set of thermodynamic conditions to another, as it does when the frequency reduces. Therefore, the estimated uncertainties could not be decreased to as low values demonstrated with as the other infrasound calibration methods developed by the project. A more detailed model accounting for the behaviour in the transition region can be developed in future to improve the accuracy further.

4.1.1.4 Dynamic manometer method

At the outset of the project, a completely novel calibration principle was conceived based on the vibration of a water column contained in a U-tube and connected to an infrasound generator similar to the laser pistonphone described in Section 4.1.1.1. Since this method had never been tried before, it was perhaps optimistic that a fully developed facility could be developed within the timeframe of the project. However, the project has been able to establish proof-of-concept and the unexpected behaviour observed in the first experiments has been explained by modelling the system.

As in the case of CNAM's infrasound refractometry calibrator future development and modelling should improve the accuracy. Although both techniques (i.e. the dynamic manometer method and the refractometry calibrator) have not reached the level of a calibration service system, the independent physical principles on which they are based yields great value for measurement uncertainty estimations and validation of all the methods developed in this project.

4.1.1.5 Primary seismometer calibration

The second technology addressed in the project was the extension of vibration measurement to the low-frequency range required for seismic measurements. The existing and well-established method of primary vibration calibration uses laser interferometry and covers a frequency range from 1 Hz to 10 kHz. However, this is mostly suitable for accelerometers rather than the considerably larger and heavier seismometers.

Therefore, the project developed its primary vibration calibration using laser interferometry to address this issue. A schematic of such a primary calibration set-up is depicted in Figure 3.

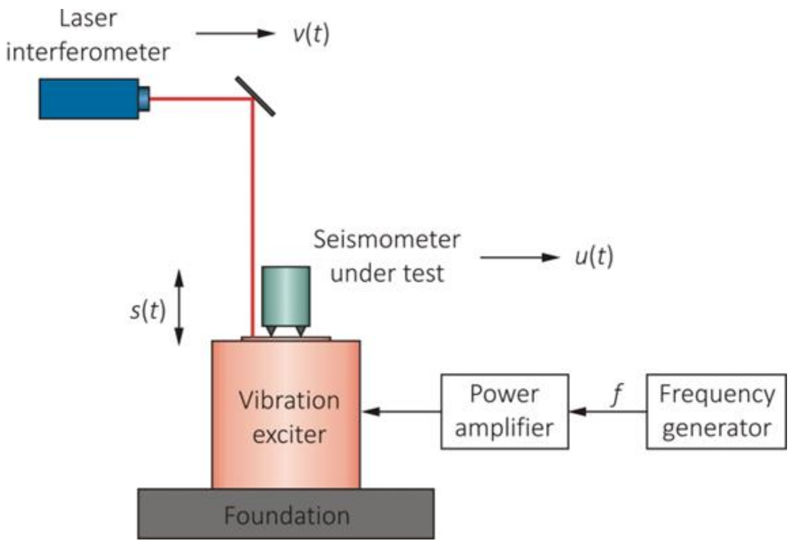

Figure 3: Schematic of a primary calibration set-up with vertical excitation

Seismometers have different handling requirements and use different instrumentation compared to accelerometers. Seismometers typically have specific mounting requirements and need sufficiently capable excitation systems to generate calibration stimuli (motion) in both horizontal and vertical directions, albeit with displacements typically less than 10 mm. Thus, changes to existing calibration methods to extend the frequency range and accommodate the larger payload, have been mostly pragmatic, requiring the application of alternative measurement hardware such as an infrared laser system, rather than requiring a completely new methodology.

Figures 4 and 5 show primary calibration set-ups for the calibration of seismometers at PTB, CEA and HBK, respectively. The set-ups of PTB consist of a horizontal long-stroke exciter and a multi-axis exciter which is mainly used for vertical excitation. The CEA set-up operates dedicated vertical and horizontal exciters from SPEKTRA, which is a manufacturer of a vibration transducers and HBK has a calibration facility for horizontal excitation.

These new primary calibration set-ups for the calibration of seismometers have not been without issue. For example, the heavier payloads resulted in bending and tilting influences that had to be solved. Nevertheless, significant progress has been made with PTB and HBK expecting to launch new calibration services in the frequency range from 10 mHz to 20 Hz within the next 12-18 months.

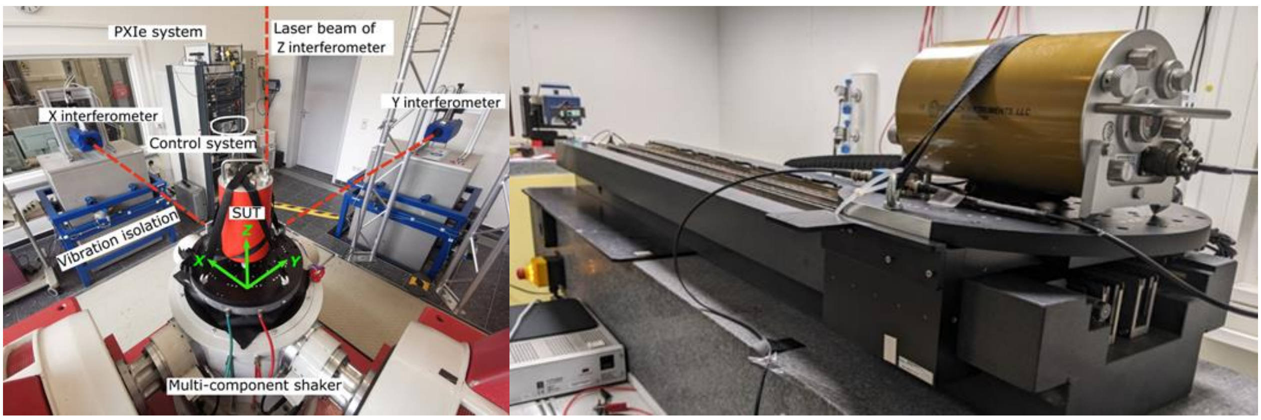

Figure 4: Primary calibration set-ups for the calibration of seismometers in three degrees of freedom at the multi-component exciter at PTB (left) and for horizontal calibration at the long stroke exciter at PTB (right).

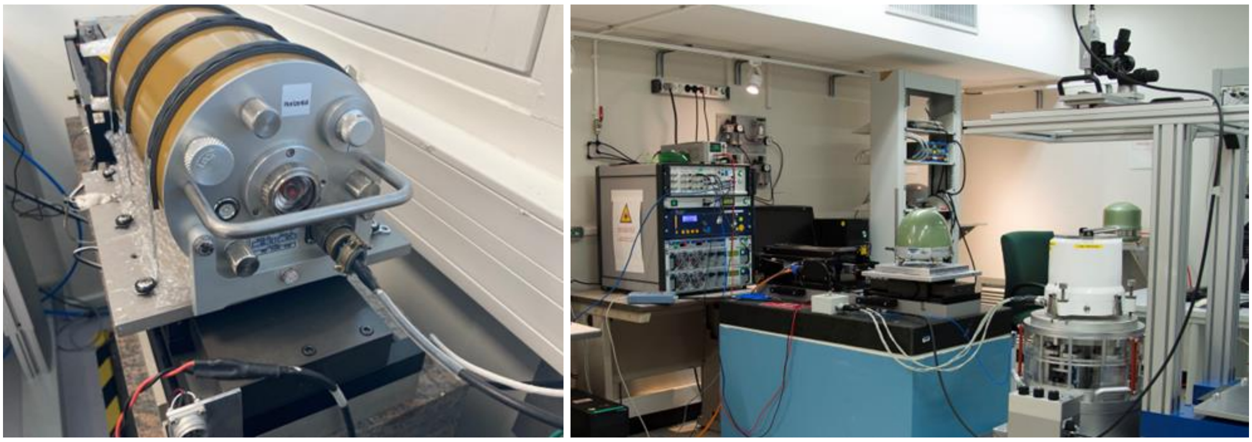

Figure 5: Primary calibration set-ups for the horizontal calibration of seismometers at HBK (left) and for horizontal and vertical excitation at CEA (right).

4.1.1.6 Primary methods for hydrophone calibration

The demand for traceable hydrophone calibrations at very low frequencies in support of ocean monitoring applications requires primary standard methods that are able to realise the acoustic Pascal at such very low frequencies. The primary standard realisation is then disseminated by use of calibrated hydrophones, devices that respond to pressure in water.

Laser pistonphone method

This method for the primary calibration of hydrophones is based on the use of a calculable pistonphone to cover frequencies from 0.5 Hz to 250 Hz. A piston driven by a stack of prestressed piezoelectric elements creates a varying pressure in an enclosed cavity. The displacement of the piston is measured by an optical interferometer from which the acoustic pressure can be calculated. The dimensions of the front cavity were designed to allow the calibration of reference hydrophones, but it may also be used to calibrate microphones.

The work here builds upon the pioneering work that established the first laser pistonphone and is analogous to pistonphones developed for microphone calibration. When applied for hydrophone calibration, the method exploits the fact that the sensitivity of an acoustically hard hydrophone is the same in air as in water at low frequencies.

The method has been successfully implemented and an uncertainty budget has been determined, with values ranging from 0.31 dB at 100 Hz to 0.45 dB at 0.5 Hz. Figure 6 shows the NPL facility and the results of the calibration of a reference hydrophone in the range from 0.2 Hz to 250 Hz, a wider frequency range than the original objective for the project. The results show good agreement with the theoretically flat response of the hydrophone, showing a slight low frequency roll-off.

The development of such a pistonphone for hydrophone calibration was a collaborative effort involving ASN, LNE and DFM together with NPL. The hydrophone calibration is the first of its kind and this facility is now adopted as the primary standard at NPL and will underpin future calibration services and participation in future key comparisons.

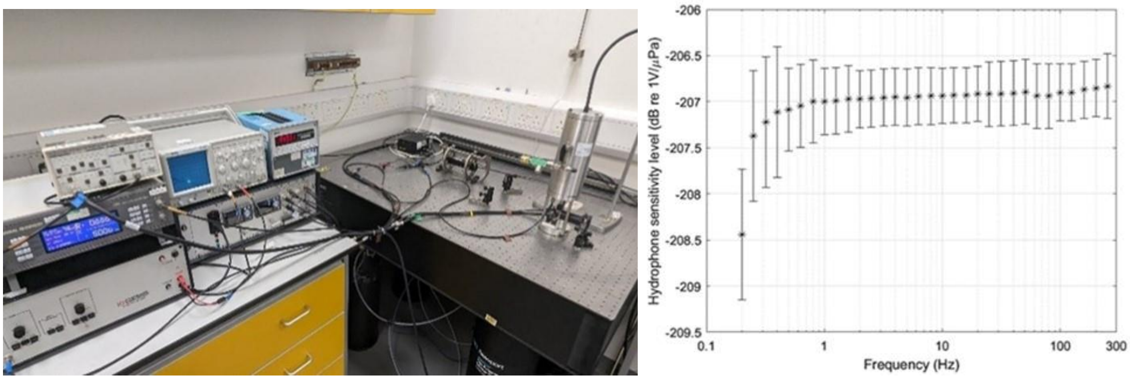

Figure 6 A photograph of the laser pistonphone set up at NPL and sensitivity level of a Brüel & Kjær (B&K) 8104 reference hydrophone.

Hydrophone calibration by coupler reciprocity

At NPL and TUBITAK extensive work was undertaken to establish the coupler reciprocity method in a water-filled chamber as a primary calibration method for hydrophones that can be operated over a range of simulated ocean conditions (elevated static pressure to simulate ocean depth, and over a range of temperatures). The facilities have been established and hydrophone calibrations have been obtained, however, significant technical challenges remain to be addressed before the method can be regarded as the primary standard for hydrophone calibration. The technical challenges that remain include excluding microscopic air bubbles from the water-filled chamber (which affect the acoustic compliance in unpredictable ways), and at NPL the performance of the reference transducers is sub-optimal at low frequencies.

At NPL and TUBITAK, the work to establish coupler reciprocity is foundational and will form the basis of future work to develop a primary standard for hydrophone calibration under national funding at NPL and TUBITAK (likely to be within the next 12 months as opposed to the > 4 years it would have taken without the outputs from this project).

4.1.2 Test of validity of novel primary calibration techniques

A primary calibration setup represents the absolute realisation of a unit and is the starting point for the dissemination of the complete chain of traceability. Thus, it affects the accuracy of all subsequent measurements that derive traceability from the primary standard.

It is therefore vital for the accuracy and reliability of the primary calibration setup to be carefully tested. During the development phase valuable communications about intermediate results and problems were maintained by the project's team which supported the various preliminary tests and comparisons that were made. At the end of the project the methods from sections 4.1.1.1-4.1.1.6 were involved in comparisons which allowed the direct and independent examination of the results obtained and a review of quality and reliability of the newly developed primary calibration methods.

4.1.2.1 Infrasound (primary) comparisons summary

An inter-laboratory comparison of the new calibration capabilities for infrasound were carried out between HBK, LNE and PTB using measurement microphones as reference devices. Since the different calibration facilities are compatible with different microphone designs, the comparison exercise consisted of two bilateral comparisons featuring different microphone models with LNE involved in both (i.e. HBK and LNE, and LNE and PTB).

Figure 7 shows an example of the collated results and uncertainties, from HBK, LNE and PTB. The reported sensitivity levels and phases were analysed using the normalised difference as the performance criterion.

Overall, with only a few isolated exceptions, the measured differences consistently fall within a satisfactory range indicating a robust comparability between the laboratories and the calibration methods. The comparison also provided comparable validation of the new primary calibration methods, which is a prerequisite for establishing new calibration techniques as services for end users.

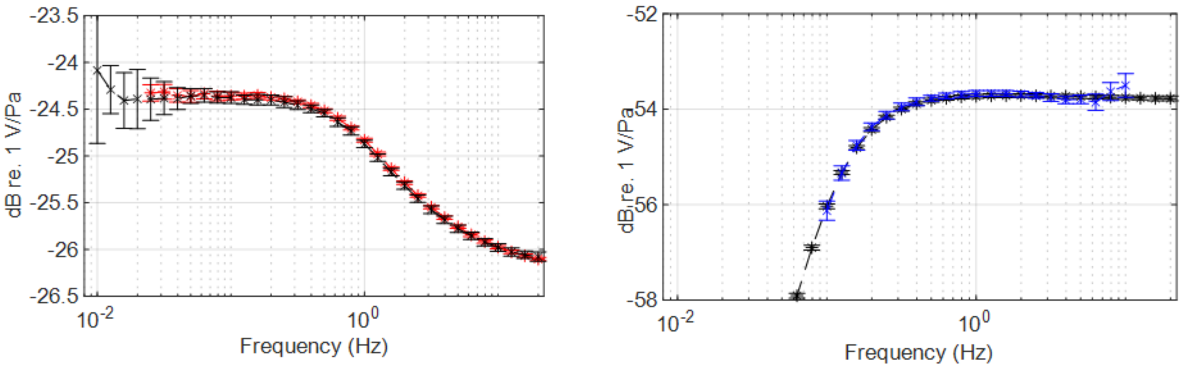

Figure 7: (Left) Open circuit pressure sensitivity level and uncertainties of HBK (red crosses) and LNE (black stars) for one reference microphone (B&K type 4160). (Right)_Pressure sensitivity level and uncertainties of LNE (black stars) and PTB (blue crosses) for one reference microphone (B&K type 4193).

4.1.2.2 Intercomparison of seismometer calibration

A similar process was followed for the primary calibration of seismometers and an intercomparison was arranged between PTB, HBK and CEA.

The 3 types of seismometers selected as *transfer standards* (see Objective 2, section 4.2.3) were used as reference devices. PTB, HBK and CEA were each required to measure the magnitude and phase of the velocity sensitivity, in each operating axis of the reference device, in the frequency range from 10 mHz to 20 Hz, and to estimate the associated measurement uncertainty.

Several limitations and challenges were seen during the comparison, i.e. PTB found problems with their data acquisition and needed to repeat several measurements, HBK only had a laboratory setup for horizontal excitation and found problems with the applied corrections for their data acquisition at the lowest frequencies (< 40 mHz) after completion of all measurements and CEA experienced unforeseen downtime limiting their measurements at the lowest frequencies.

Despite the above limitation and challenges, the outcome of the comparison proved to be a significant step towards achieving the much-needed new low frequency measurement capability. It made several technical aspects of the measurements evident and highlighted further work needed to fully understand the different influences seen during the primary calibration, e.g. tilting during calibration caused by imperfection of the excitation applied, ground coupling stiffness related mechanical setup, sensitivity of the transfer standards to transport and thereby overall stability etc.

4.1.2.3 Comparison of primary standard for underwater acoustics

The calculable laser pistonphone established at NPL (see section 4.1.1.6) was validated using microphones as transfer standard devices in the air-filled coupler, as the coupler was designed to operate with microphones as well as hydrophones. Comparisons of the primary methods were carried out by NPL (calculable pistonphone), DFM (coupler reciprocity) and LNE (independent calculable pistonphone) using air-filled calibration chambers.

The analysis showed that there is equivalence between the results of NPL and DFM across the frequency range from 3.15 Hz to 250 Hz, and that there is equivalence between the results of NPL and LNE across the frequency range from 1.6 Hz to 20 Hz. Across these frequency ranges, measurements were consistent, indicating comparability between the laboratories and the calibration methods. At the lowest frequencies (below 2 Hz), artefacts introduced by the performance of the microphones used as the reference device, increased the differences between calibrations.

4.1.3 Conclusions for objective 1

Objective 1 was fully achieved, and the project even went beyond its original targets.

Absolute calibration methods for microphones and hydrophones, based on five different physical principles have been under development by the project, and ten independent primary calibration facilities have consequently been established. While they typically cover different frequency ranges, these capabilities enable the sensitivity of a sensor to be determined in the frequency range from 10 mHz to 20 Hz for microphones (greater than the target of 40 mHz – 20 Hz) and 0.2 Hz to 250 Hz for hydrophones (better than the target of 0.5 Hz – 100 Hz*)*, with full measurement uncertainties. The project has developed unique and innovative facilities such as the carousel system for microphone calibration and the calculable pistonphone for hydrophone calibration, which are the world's first such capabilities.

For seismometers, three existing vibration calibration systems were upgraded by the project to handle large and heavy seismic sensors and also adapted for optimum low frequency performance. The project's initial experience of calibrating seismometers at low frequencies highlighted the influence of tilt (from an unwanted gravity component) on the calibration, but this was largely resolved. Each of the three vibration calibration systems can now be used to calibrate seismometers in the frequency range from 10 mHz to 20 Hz.

Intercomparisons on the developed primary calibrations were conducted by the project for all three technologies (i.e. airborne acoustics, underwater acoustics and vibration (seismic) sensing systems). These intercomparisons include comparisons not only of capabilities in different laboratories, but between calibration methods using different physical principles. For microphones, the results were generally consistent across the entire frequency range, with only a few isolated exceptions. The same was true for hydrophones, except for where limitations with the reference device restricted the validity of the comparison to frequencies above 1.6 Hz, requiring other available evidence to be drawn on to fully validate the capability. For seismometers, the intercomparison results revealed several difficulties with issues noted across the frequency range. At low frequency remanence of tilt influences were also observed. Results at mid-frequencies were good, except for one model of seismometer where its internal construction led to inherent instability. At high frequencies, observed differences have been attributed to the way the seismometer mounts to the test fixture, particularly the rigidity and height of the adjustable feet.

In summary, the capabilities and facilities developed by the project for (i) infrasound, (ii) vibration (seismic) and (iii) underwater sound have provided a fundamental basis for traceability at the European level, for the first time. This will significantly improve measurement reliability strengthening trust and acceptance of quantitative results for the widespread applications of low-frequency acoustic techniques worldwide.

4.2 Objective 2: To develop laboratory-based secondary calibration methods for airborne acoustics (40 mHz – 20 Hz), underwater acoustics (0.5 Hz – 100 Hz) and vibration (seismic) sensing systems (10 mHz – 20 Hz) as the first step in transferring new primary calibration capability to working standard devices.

4.2.1 Development of novel secondary calibration techniques

While primary standards are essential as the basis for measurement traceability, the methods are often limited to certain types of reference sensor, or even bespoke sensors unique to the calibration laboratory. Therefore, secondary calibration methods using sensors calibrated by primary methods as references but suited to a wider variety of sensors and measurement systems, are essential for the dissemination of traceability. Secondary calibration methods can also provide a more economical option for end user uptake.

4.2.1.1 Secondary calibration for airborne infrasound by pistonphone

LNE's laser pistonphone (Objective 1), which was constructed as a primary calibration facility, can also be used as secondary calibration facility, with either a microphone or a static pressure sensor as a calibrated reference device. The calibration device covers a frequency range from 10 mHz up to 20 Hz. The achievable measurement uncertainties for the best-performing sensors are 0.06 dB in amplitude and 0.4 degrees in phase at medium to high frequencies. These uncertainties rise to up to 0.3 dB for amplitude and 3 degrees for phase at 10 mHz. The laser pistonphone was operational during the early phases of the project, and thus it was often used for a validation of other techniques under development. Hence, this laser pistonphone was an essential component of technical discussion and cooperation between partners.

4.2.1.2 Secondary calibration for airborne infrasound by sound field in a tube

At PTB a sound tube apparatus was developed, which enables this transfer of measurement devices for airborne infrasound. This secondary calibration system can be used for a wide variety of currently available measurement microphones, sound level meters and even microbarometes with very different functioning principles and properties.

The sound tube consists of an acrylic tube which is sealed off by a lid at the top. A loudspeaker at the bottom provides a sinusoidal excitation signal, a device under test and a reference transducer can be mounted via the lid. Both the device under test and the reference transducer are subjected to the sound field created by the loudspeaker. The designed excitation configuration ensures a homogeneous sound field at the locations of the microphones and sound level meters. Mounting brackets (see Figure 8) in the lid allow positioning the venting holes of the reference microphones either inside or outside of the sound field, depending on the primary calibration method used and the addressed application.

The sound tube covers a frequency range from 0.2 Hz up to 100 Hz. For higher frequencies the sound field becomes more and more inhomogeneous and at frequencies below 0.2 Hz leakage occurs, which results in a limited excitation sound level. The uncertainty from the primary calibration of the reference microphone is currently the largest contribution to the uncertainty of the measurements in the sound tube. Excellent repeatability can be achieved.

Figure 8: Devices under test mounted in the sound tube.

4.2.1.3 Secondary calibration of hydrophones

As with airborne infrasound, the principle of secondary calibration of hydrophones is that of comparison with a reference device that has previously undergone an absolute calibration using the primary standard method. The hydrophone under test and a calibrated reference sensor (most commonly a reference hydrophone, but it is also possible to use a laboratory standard microphone) are subjected to the same sound field in a small coupler, and the hydrophone under test is calibrated by comparison with the reference device. The reference sensor and the hydrophone under test are either subjected to simultaneous excitation (both devices inserted into the coupler at the same time) or sequential excitation (each device inserted separately).

Sufficiently high sound pressure levels (and so a good signal-to-noise ratio) can be generated in sealed couplers, using pistons or loudspeakers as excitation sources (a loudspeaker cone may need to be coated to reduce leakage for very low frequency excitation). Alternatively, the coupler may be fluid-filled with piezoelectric transducer excitation. A fluid-filled chamber extends the upper frequency range of operation to around 1 kHz.

NPL and TUBITAK developed and improved their secondary calibration facilities for hydrophones. Figure 9 shows the facilities operated at NPL and TUBITAK. NPL operates their secondary calibration service for hydrophones over the frequency range from 2 Hz to 315 Hz with uncertainties ranging from of 0.5 dB at 2 Hz to 0.45 dB at 250 Hz. Currently, the service is accredited to ISO 17025 in the range from 20 Hz to 315 Hz, but an application will be made for an extension of accreditation to 2 Hz during 2024.

TUBITAK extended their capability for secondary calibration of hydrophones using a pressure comparison in a small chamber with a low frequency calibrated reference device (microphone) under laboratory conditions for the frequency range from 1 Hz to 100 Hz. The uncertainty at TUBITAK ranges from 0.3 dB at 100 Hz to 0.5 dB at 1 Hz.

Figure 9 Photographs showing the secondary calibration facilities at TUBITAK (left) and NPL (right).

For the comparison of the secondary calibration methods in underwater acoustics, both NPL and TUBITAK used a closed coupler with a reference hydrophone as a transfer device. The reported sensitivities were analysed using a pairwise degrees of equivalence approach. Results (shown in Figure 10) indicate an equivalence between the results of NPL and TUBITAK across the frequency range from 1 Hz to 100 Hz, with the maximum difference being less than 0.2 dB (uncertainties range from 0.45 dB to 0.7 dB). The measurements were shown to be highly consistent, indicating a robust comparability between NPL and TUBITAK and the calibration methods.

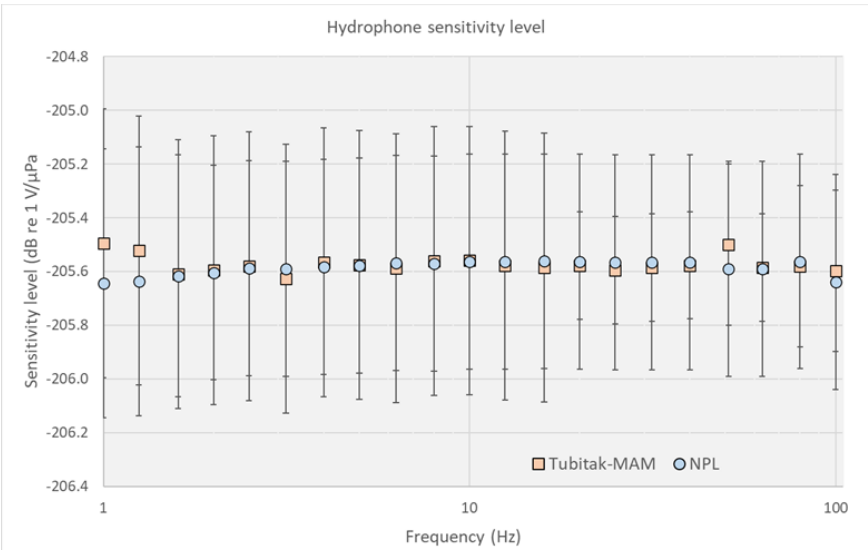

Figure 10 The results for NPL (circles) and TUBITAK (squares) plotted with uncertainties for the comparison of secondary calibrations of hydrophones.

4.2.2 Test of validity of novel secondary calibration techniques

This comparison was concerned with secondary infrasound calibration methods. As for the primary calibration techniques (section 4.1.2) a key comparison for the secondary calibration methods represents an indispensable element of review and assessment. The participating laboratories were CEA, HBK, LNE and PTB. The standards circulated among them were two microbarometers Martec Type MB2005 and two microphone units Brüel & Kjær (B&K) Type 4193. Figure 11 shows an example of the collated results and uncertainties, from the comparison. The reported sensitivities were analysed using a least-squares technique. Apart from a few cases of observed inconsistencies, where the reasons are understood, the measurements were shown to be consistent with the comparison reference values, indicating a robust comparability between

CEA, HBK, LNE and PTB. and the calibration methods. Therefore, the results support the reliability of the secondary infrasound calibration methods established and the results formed the basis for transferring the methods into measurement practise. Thus, LNE, HBK and PTB can now offer these secondary infrasound calibration services for customers. This includes, of course, potential calibrations for station operators of the International Monitoring System (IMS) where CEA is also active. Hence CEA also uses the facilities for on-site calibrations via their newly developed portable calibration service module.

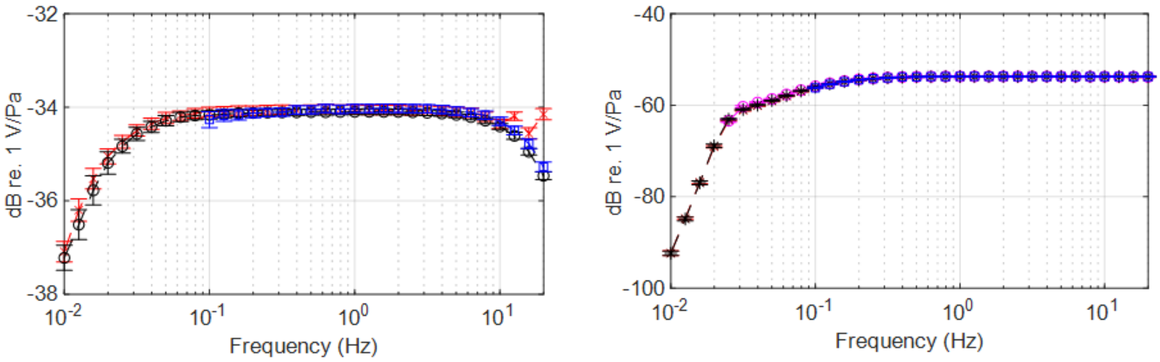

Figure 11: Pressure sensitivity level in dB re 1 V/Pa and uncertainties in dB of CEA (red crosses), LNE (black stars) and PTB (blue squares) for one microbarometer MB2005 (left chart). Pressure sensitivity level in dB re. 1 V/Pa and uncertainties in dB of CEA (red crosses), HBK (magenta circles), LNE (black stars) and PTB (blue squares) for one microphone units B&K 4193 (right chart).

4.2.3 Definition of transfer standards

Typically, calibration measurements are carried out in laboratories under controlled and well-defined conditions. However, the actual conditions of use for devices are often characterised by different operating and often challenging environmental conditions. To transfer the results from laboratory to onsite application with as low as possible loss, devices are needed that combine the ability for accurate calibration with stable and inert performance against disturbing factors of any kind. This is particularly true for the sensor stations of the IMS which are distributed all over the world and hence have a wide range of environmental and operating conditions. To allow to transfer of the project's newly achieved precision and reliability (from the developed primary or secondary standards (Objective 1 or 2) to the sensor stations of the IMS, suitable transfer standards were selected, reviewed, tested, and finally calibrated. Some of the transfer standards were then successfully applied in one of the IMS stations to additionally test the project's newly developed on-site calibration methods.

Transfer standards for infrasound

The chosen transfer standards for infrasound included the B&K LS1 microphone type 4160 for primary calibration, the B&K microphone-preamplifier set type 4193 L004 for calibration in both the laboratory and on-site, and the microbarometer Eolane MB2005 as a transfer standard for on-site calibration. The selection of the transfer standards was based on (i) their availability, (ii) previous use in monitoring stations, and (iii) the partners' familiarity with their performance. Two sensors of each type of transfer standard were selected for comparison calibrations between LNE, PTB, HBK and CEA. The results of the comparisons were satisfactory, demonstrating consistency between laboratories, with the except of the secondary comparison of calibration of microphones of type 4193 L 004 at frequencies below 0.2 Hz and a few other minor deviations. Thus, all the selected transfer standards were successfully calibrated and are ready for use in future on-site applications for infrasound measurements.

Transfer standards for underwater acoustics

For the transfer standards for underwater acoustics, a B&K 8104 hydrophone was chosen for the secondary comparison at ambient environmental conditions due to its stable and broadband response, with a flat frequency response to frequencies below 1 Hz. For the comparison of primary standards (Objective 1) with the calculable laser pistonphone (air-filled couplers), two microphone systems were chosen: a B&K 4134 fitted with a UA0825 adapter ring (NPL and DFM), and a B&K type 4134 microphone, a GRAS type 26AK preamplifier and Vinculum type E711 microphone power supply (NPL and LNE). For calibrations at simulated ocean conditions, a reason TC4033 hydrophone was chosen as it was more suitable due to its more stable performance with depth and temperature.

The results from the comparisons showed that transfer standard B&K8104 is an excellent choice for the most accurate primary and secondary calibrations under controlled conditions (at ambient pressure), with highly successful results obtained in the secondary comparison between NPL and TUBITAK, and for the primary calibrations at NPL. This device is likely to be chosen as the transfer standard in the future CIPM key comparison. However, for calibrations at simulated ocean conditions (where ocean depth is simulated by applying increased static pressure), a Reson TC4033 is more appropriate because of its better stability under such conditions.

For underwater acoustics, NPL summarised in a report their data on the stability of a variety of commercial hydrophones obtained by NPL from previous work using the Acoustic Pressure Vessel and the coupler reciprocity method. This summary provided a valuable resource as it compiles much of the known data on the topic.

Transfer standards for seismometers

The selection of transfer standards for seismometers calibration on-site was initially based on technical and operational criteria such as weight, dimensions, number of axes, bandwidth, power supply. Then the final selection was made considering (i) their availability, (ii) previous use in monitoring stations, and (iii) the partners' familiarity with their performance. Consequently, the STS2.5 (Streckeisen), the Trillium 360 (Nanometrics) and the GS13 (Geotech) were all chosen. One sensor of each type was selected and calibrated as part of the comparison between PTB, HBK and CEA.

The results from the comparisons showed that the force-feedback systems of the STS 2.5 and Trillium 360 were well suited for the use as transfer standard, while the passive system of the GS13 needed a re-adjustment of its internal damping after transport which may influence the frequency response of the instrument.

4.2.4 Conclusions for objective 2

Objective 2 was successfully achieved by the project. Secondary calibration methods and devices in the low frequency range for airborne acoustics (40 mHz – 20 Hz), underwater acoustics (0.5 Hz – 100 Hz) and vibration (seismic) sensing systems (10 mHz – 20 Hz) were developed and implemented. The laboratory based secondary calibration facilities can calibrate microphones and microbarometers, seismometers, hydrophones and ocean noise recording systems. The calibration of microphones and microbarometers, and of hydrophones were also the subject of intercomparison exercises by the project. The results were analysed using formal methods to demonstrate their equivalence, and thus contributed to the validation of the new laboratory-based secondary calibration facilities. Thus, several calibration setups were transferred into the regular service of project partners and are now offered to customers, as for example Comprehensive Nuclear Test Ban Treaty Organization (CTBTO) or consulting engineers and agencies engaged in environmental measurements.

Since laboratory calibration is carried out under controlled conditions, transfer devices were selected, tested and calibrated to transfer the calibration information into the different operating conditions, and often in extreme environments, of practical sensor sites. For airborne infrasound, several transfer standards were identified by the project, including two types of measurement microphone, a microbarometer and two types of static pressure sensor. The choices were verified through collaboration with experts at the CTBTO. For underwater acoustics, the demands on the sensors are made more extreme by the deep-sea environment in which they are deployed, where high static pressures and low temperatures prevail. Consequently, a document was prepared and made available on the project website, which contains a catalogue of the performance of the most popular models of hydrophones. For seismology, a critical evaluation of the performance parameters for eleven of the most commonly used seismometers was undertaken. The results of this have led to the selection of three candidate commercial seismometer devices to use as transfer standards.

4.3 Objective 3: To develop facilities and methods for the dissemination of traceability for airborne acoustics, underwater acoustics and vibration (seismic) sensing systems through specific methods for on-site calibrations. Improvements will be tested through a series of case studies with additional evaluation of stability, behaviour, positioning effects, installation conditions and sensitivity to the environment, leading to enhanced knowledge of system performance under operational conditions.

4.3.1 *Development of on-site calibration measurements*

4.3.1.1 Motivation

Measurements of seismic, infrasound and hydroacoustic activity are very important tools for the monitoring and analysis of extreme natural events such as volcanic eruptions, earthquakes, tsunamis or anthropic events like artificial explosions and in particular nuclear explosions. The introduction and operation of world-wide sensor networks using these technologies such as the IMS supports the Comprehensive Test Ban Treaty (CTBT) and has led to a wide range of new applications. Traceable calibrated sensors also offer many benefits: (i) the improvement of data quality and the associated enhanced confidence, (ii) increased trustworthiness and (iii) the credibility of the information contained in the data, hence leading to enhanced acceptance of the resulting data.

However, the main obstacles for further development and application of the IMS (prior to the start of this project) were (i) a lack of measurement traceability at low frequencies due to the absence of appropriate calibration methodology, techniques and infrastructure from the NMI community, and (ii) the lack of on-site traceability for when the sensor is initially installed and then during long term use. The remote locations of the monitoring stations and the safety-critical nature of the activity, requires the sensor systems to be operational 100 % of the time, which means that traditional return-to-base (laboratory) type calibrations are impractical. Therefore, on-site calibration of the sensors at periodic intervals, is necessary to maintain traceability.

For seismic sensors on-site calibration methods prior to the start of this project were restricted to the use of a built-in calibration coil in the case of electrodynamic sensors or to electrical checks between sensors. However, neither approach actually imparts traceability, and both approaches rely on assumptions of long-term stability of the sensor performance.

Taking advantage of access to test sites and access to one operational IMS station via partner BGR, novel and existing methods for on-site calibration were developed and/or evaluated in this project. These methods included natural excitation sources and controlled excitation ones for generating a testing, i.e. stimulating sound field. Therefore, measurements at a real example site could be made by the project and tested for further implementation in the IMS.

4.3.1.2 Potential field-calibration stimuli for on-site calibration

To begin, a comprehensive evaluation of natural, anthropogenic, and controlled sources of seismic, hydroacoustic, and infrasonic signals was completed in order to identify suitable excitation scenarios for on-site calibration procedures. The sources were evaluated for their (i) frequency bandwidth, (ii) signal characteristics and (iii) cost-effectiveness (Figure 12). Further to this, an important prerequisite for the implementation of an in-situ calibration procedure is the availability of adequate coherent excitation signals, which need to exceed the self-noise levels of the reference and sensors to be tested in the required frequency range.

In accordance with previous studies on in-situ calibration techniques of microbarometers and seismometers, earthquakes stand out across all three waveform technologies due to their suitable signal properties along with other natural sources. These include ambient noise recordings for both microbarometers and seismometers. Microseisms and microbaroms, naturally occurring and ever-present seismic and infrasound signals, allow a calibration at the lowermost end of the considered frequency range and have proven to be applicable in previous studies. Beyond these natural phenomena, most anthropogenic signal sources (e.g. cultural noise) evaluated met the necessary criteria.

In practice, multiple sources may be appropriate for a given situation. However, the utility of these sources is affected by various aspects, such as signal length, frequency content, and signal strength. It is not practical to rely solely on one form of excitation signal, because of the unpredictability of the repetition rates of earthquakes of a specific magnitude(s) or the restricted frequency ranges of individual sources, such as microbaroms. Therefore, to ensure comprehensive coverage of all relevant ground motions and pressure fluctuations, it is recommended to use all data recorded by the sensors and exclude signals that are not coherent for the sensor pair to be compared.

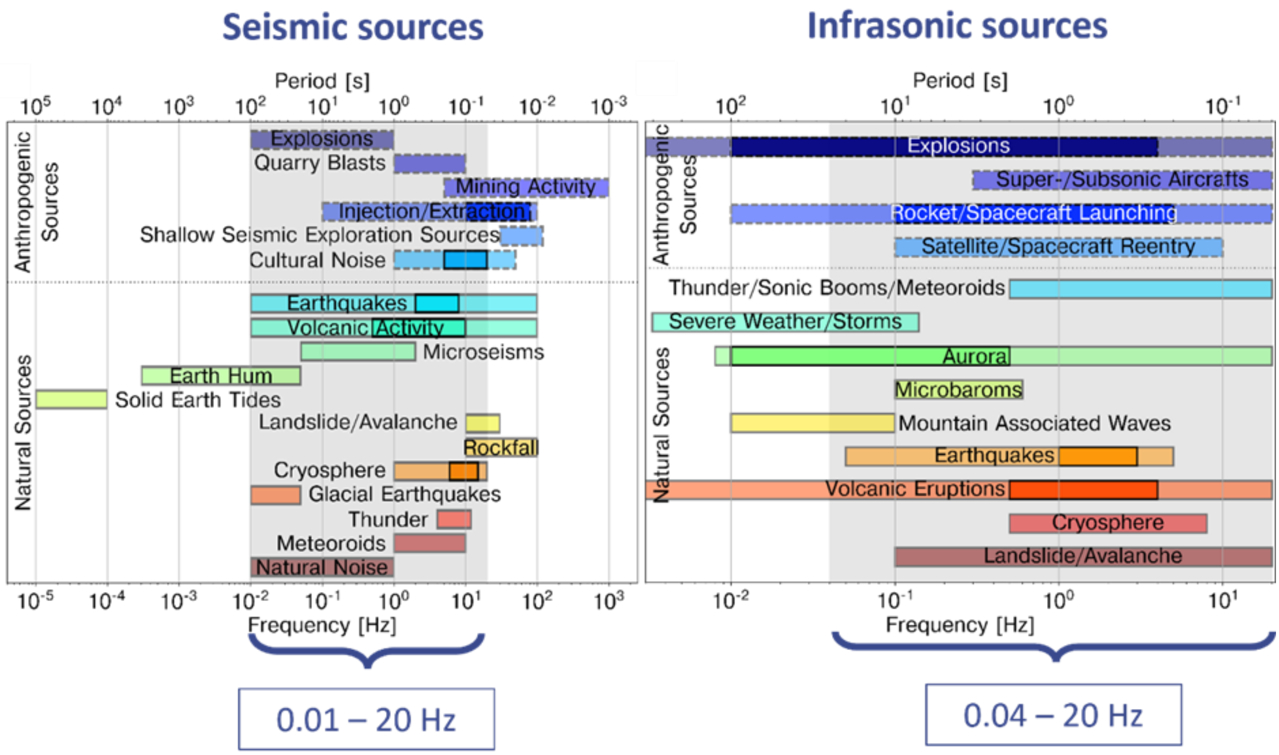

Figure 12: Observed frequency ranges for the evaluated seismic and infrasonic signals. Dashed-bordered boxes illustrate anthropogenic sources, solid-bordered boxes illustrate natural sources of each wave type. More saturated colours indicate commonly observed and dominant frequency ranges. The frequency ranges of interest are 0.01–20 Hz for seismic and 0.04–20 Hz for infrasonic signals; they are highlighted in grey. Note that only the most important and not all sources are included in the figure for reasons of clarity.

4.3.1.3 On-site calibration of infrasound detectors

An elegant method for the on-site calibration of infrasound detectors, known as the Gabrielson-Charbit method after the originator and subsequent developer of the concept was piloted by the project at IMS infrasound stations. The method allows the on-site calibration of infrasound measurement systems (a microbarometer including the wind-noise-reduction system (WNRS) consisting of a set of pipes arranged in a radial pattern around the microbarometer). The method is very interesting because (i) it requires no dismantling of the infrasound detector, (ii) is easy to install, (iii) is robust in terms of the environmental constrains and (iv) can be implemented via remote control means. Indeed, the sensor remains fully operational at all times, as it uses a reference sensor, usually another microbarometer, co-located and connected to the detector (Figure 13). The project developed a case study and applied the same principles to the on-site calibration of seismic sensors for the first time (see section 4.3.1.5).

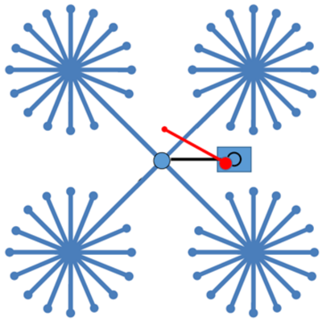

Figure 13: Operational infrasound detector composed of a WNRS and a microbarometer. The reference sensor is co-located and connected with a pipe to the microbarometer of the detector.

The response of the detector is determined relative to the reference microbarometer, which must itself be calibrated in advance in order to provide on-site traceability of the measurement produced by the infrasound measuring system. The innovative portable infrasound calibration system developed during the project called SMIT (see 4.3.1.4) was used to calibrate the reference microbarometer. Due to partial coherence of the wind noise at low frequency, a dip artefact was observed without being representative of the response of the detector. Gabrielson proposed a method to remove this artefact, and Green et al. proposed across-array coherence as an additional criterion to remove the wind-noise contributions. As the WNRS plays an important role in the operational infrasound measurement chain investigations of these methods to remove the dip artefact was carried out.

The investigations were designed to verify the modelled WNRS response for defective WNRS. They were performed on a test site and then on a real infrasound station over a sufficiently long period of time to benefit from (i) natural infrasound sources for stimulating signal, (ii) significant variations in ambient environmental conditions and (iii) to be able to implement several WNRS fault configurations. The Gabrielson-Charbit method without correcting for the dip artefact was successfully implemented, and calibration curves of the detector were obtained. By considering the statistics of the power spectral densities, the calibration response of the detector curves was obtained for each configuration, including the nominal.

4.3.1.4 Innovative infrasound field calibration system

CEA developed an innovative portable infrasound calibration system to bring traceability to the International System of Units (SI) in the field. This device, called *Système de Métrologie Infrasonore de Terrain* (SMIT), is composed of a portable infrasound dynamic pressure generator, a geophysical field digitizer, a calibrated HBK 4193 microphone as transfer standard, and the on-board electronics necessary for measurement and processing of the results (Figure 14). The signal-to-noise ratio is sufficient for such a microphone to be used as a transfer standard. SMIT weighs about 30 kg in its prototype version. Coupled with a laptop computer, the SMIT system allows the calibration of any type of geophysical infrasound sensor at the location where the measurement will be performed in the field, for the moment from 0.1 Hz to 100 Hz. The calibration method is a comparison method between the calibrated microphone, whose susceptibility to the environment is known and the infrasound sensor.

Figure 14: The SMIT system in its transport case.

SMIT has been tested at different locations, temperatures (from -2 °C to 40 °C) and altitudes (from 0 m to 4000 m) during the project, validating the method and the behaviour of the device in the field.

Notably, SMIT was deployed on the IS26 infrasound station (17 °C at that time, 900 hPa) to calibrate MB2005 and MB3 microbarometers. Now calibrated, these microbarometers have been used as reference sensors with the Gabrielson-Charbit method thus providing metrological traceability of the infrasound measurements to the SI units.

4.3.1.5 on-site seismometer calibration

The on-site calibration concept (Gabrielson-Charbit method) described in section 4.3.1.3 for infrasound detectors was adapted for seismometer field calibration. The adapted method divides the measured seismic signals from both the reference seismometer and the operational seismometers into small time sections for analysis. Metrics are then calculated that enable the signals from the two sensors to be compared, and the similarity in the signals tested mathematically. Sections where the signals are found to be coherent are then used for the calibration. The adapted method relies on two requirements: (i), the two sensors measure the same signal (as assessed by the mathematical test), which implies that they are in close proximity, and (ii), the response of the reference is known through traceable calibration. The sensitivity and frequency response of the operational sensor relative to the reference sensor can then be determined for those time intervals where the similarity measures exceed certain thresholds for accepting the data, and such results aggregated into a longer-term average sensitivity and frequency response.

This adapted method for seismometer field calibration was used as part of a field trial at a real network measurement station. Three calibrated seismometers (those selected as transfer standards in Objective 2 i.e. the STS2.5 (Streckeisen), the Trillium 360 (Nanometrics) and the GS13 (Geotech) were installed at the IMS seismic station PS19 in Germany in August 2022. The three calibrated seismometers were each co-located with one operational sensor of the IMS seismic station and provided continuous reference data for more than one year.

The field trial for seismometer calibration was comprised of four parts:

- Part 1. assessed the applicability and reliability of the Gabrielson-Charbit method for on-site seismometer calibration.
- Part 2. the full frequency response of one operational seismometer was determined with the Gabrielson-Charbit method.
- Part 3. the maximum distance between reference and operational sensor was estimated.
- Part 4. the applicability of controlled sources for on-site seismometer calibration purposes was evaluated.

The outcomes of the field trial outcomes were: (i) the proposed method for seismometer field calibration proved to be successful and reliable. (ii) Part 2 achieved good results for both magnitude and phase. A maximum distance of approximately 1500 m between reference and operational sensors was estimated. (iii) A benefit of the proposed method for seismometer field calibration was the option of using a single calibrated sensor as a reference for several operational sensors of an array of seismometers. (iv) The use of a controlled source improved the response estimation at higher frequencies.

4.3.1.6. In-situ calibration of deep ocean hydroacoustic sensors

For underwater acoustics, the approach successfully used by the project for the in-situ calibration of infrasound sensors, was proposed as an on-site calibration method for deep ocean hydrophones such as the stations of IMS. However, due to the locations of the IMS stations, access to them was not feasible within the project (and was prohibitively expensive). Therefore, a feasibility study was undertaken instead. The feasibility study investigated the use of natural ambient sound sources for calibration of the station hydrophones using a co-located calibrated hydrophone with real CTBTO hydroacoustic data for the simulations. The results were documented in a published NPL report titled “Study of the in-situ calibration of the hydroacoustic sensors”. The results of the feasibility study for the in-situ calibration of the hydroacoustic sensors demonstrated that the method of “Gabrielson-Charbit” with some extensions can indeed be used to provide calibrations of hydrophones in situ as long as the hydrophones are close enough for an extended period.

For future studies of the in-situ calibration of the hydroacoustic sensors the main difficulty remains the practical feasibility of achieving such a simultaneous exposure at such remote stations in hostile conditions (the most promising opportunity would be during routine periodic maintenance of the stations).

4.3.2 Application of novel infrasound calibration and measurement methods for environmental measurements

4.3.2.1 Definition of specifications for infrasound measuring devices

Infrasound emissions are increasing in commercial activities and everyday life. Noise measurements play an important role in the assessment of noise exposure and its impact on humans. Measurements must be legitimate, robust, accurate and defensible: hence the use of approved measurement devices is indispensable. Prior to the start of this project, sound level meters (SLM) were the instruments of choice for any noise measurement, however they are restricted to the audible frequency range. In addition, the available international documents for sound level meters or sound measurement procedures do not cover the full infrasound frequency range, and traceable and reliable measurements of sound in this frequency range have no sufficient rationale or widely accepted methodology.

To address this issue, the project produced a document defining the specifications and requirements which noise measurement devices need to comply with, when used in the frequency range of 1 Hz to 20 Hz. To produce the document, the project started by collating together the available national standards and documents with respect to regulations about the measurement of infrasound. This included the IEC 61672 Electroacoustics - Sound level meters series of standards (Part 1 Specifications, Part 2: Pattern evaluation tests, Part 3: Periodic tests) on the requirements of sound level meters. Based on this information the partners then deduced the necessary specifications for sound level meters that should be applied in the infrasound frequency range. This was accompanied with a discussion of the basic features and methods needed for the test of the specifications within (i) a type approval, (ii) regular testing or (iii) all-day tests. The document was disseminated to IEC TC 29 - Electroacoustics and is being used as input into their international standards.

4.3.2.2 Testing of sound level meters in the infrasound range

A necessary prerequisite for the reliable and traceable noise measurement at infrasound frequencies is the availability of tested and approved devices that can fulfil the requirements of internationally accepted regulations and standards. However, prior to the start of this project the available type approval methods, techniques, and regulations, developed for devices working in the audible frequency range could not be simply transferred in the infrasound and low-frequency range. Therefore, this project, sought to develop a basis for the installation of a system of regulated and reliable device operation for on-site measurement and testing of sound level meters in the infrasound range.

the project began by proposing the requirements and specifications needed for sound measuring devices and their testing and type approval at low frequencies and infrasound, in particular testing methods were developed and applied to microphones and sound level meters which are able to process acoustic input at infrasound frequencies. A first set of methods was then developed for electrical measurements as this is one of the most important and time-consuming parts of an approval.

Six electrical issues, e.g. the testing of the band filters, of the weighting functions, or the level linearity were each covered by specific test methods developed by the project. The project then investigated the validity and relevance of the test methods by applying them to two devices which could handle infrasound frequencies. As an example, Figure 15 shows the measured filter damping of a 3rd-octave band filter. It is obvious that the acceptance limits are exceeded proving the relevance of the testing procedure.

The results obtained for the electrical issues were analysed and the properties and challenges of the newly developed methods were compiled, in order to be able to draw conclusions for future development of the methods and for input to future international standardisation of a type approval.

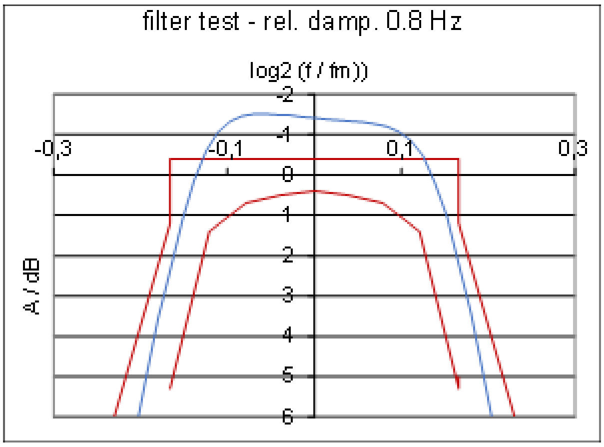

Figure 15: 3rd-octave band filter at 0.8 Hz plotted as relative damping over normalised frequency on a logarithmic scale and zoomed to the passband area. The filter response measured (in blue) exceeds the acceptance limits (in red).

4.3.2.3 Traceable measurements of low-frequency noise and infrasound near a wind park

The extension of the use of wind energy in order to promote the transition to renewable and sustainable energy production is currently hindered by serious questions concerning the noise emission and the resulting impact on people living in the vicinity of wind parks. In nearly all European countries the use of wind energy is the topic of serious and highly emotive debates. Such debates should be based on objective knowledge and proven and reliable quantitative data (especially for current exposure situations). Therefore, reliable and traceable measurements of infrasound power levels in the vicinity of a particular emitting source are vital for a successful implementation of wind energy and wind parks.

The aimed to address this issue by investigating the levels of infrasound emitted from a typical wind park, using the methods and developed by the project. This was done by partners BGR and PTB, who carried out traceable measurements of infrasound near a wind park located in Germany. Seven measurement stations equipped with microbarometers were placed by BGR in increasing distances to the wind park on a ground mainly covered with trees and closed bushes. The measurement stations continuously recorded the infrasound signals in the environment generated by any source. The measurements were accompanied by microphone measurements carried out by PTB at three of the stations (Figure 16). This was done in order to compare the results and to investigate properties of both measurement systems. The raw data of the microphone measurements were analysed by a procedure beyond the standardised methods (IEC 61400) to investigate the influence of wind and other environmental events. From the results, it could be shown that infrasound can be detected by both measurement techniques (microphones and microbarometers) and that results can be obtained which agree well within an acceptable and justifiable range. Wind, however, is an important factor and additional strategies are necessary to quantitatively describe its impact on the measured results. One aspect of the case study was to illustrate that the physical condition of the microphone must be given special attention. For example, a tiny perforation made in the membrane of one microphone was shown to be undetectable by the conventional use of a calibration-check device (a sound calibrator) operating at 1 kHz. However, this defect produced errors of over 20 dB (a factor of 10) in the infrasound region, where the microphone cannot currently be checked in the same way. Low frequency noise assessment is also a growing standardisation issue.

Figure 16: Figure of the setup for a measurement of sound pressure near a wind park, two microphones on tripods are seen under the umbrella, on the ground the microphone mounted on a board with additional extended wind screen.

4.3.3 Conclusions for objective 3

Objective 3 was fully achieved by the project completely A comprehensive evaluation of natural, anthropogenic, and controlled sources of seismic, hydroacoustic, and infrasonic signals was completed in order to identify suitable excitation scenarios for on-site calibration procedures. After ongoing discussions with the project's key stakeholder CTBTO, it became apparent that their established on-site calibration method for infrasound systems was very well developed and extremely effective. Therefore, it was more appropriate to add value to, rather than attempt to re-invent, the existing on-site calibration process for infrasound systems and instead to consider its applicability in the other technologies.

Multiple sources were identified, and methods were developed to apply them appropriately for a given situation. Several case studies were carried out including an extended measurement campaign using different technologies at a German IMS station located in the Bavarian Forest that was already active in infrasound and seismic monitoring. The case studies for infrasound and seismic monitoring investigated many facets of on-site calibration. For infrasound, a significant finding was that a calibration reference system was not only able to detect defects with the live sensor system, but also correct for it avoiding loss of data. For seismometers, the project's case studies provided the first practical experience of on-site calibration with a seismic stimulus. One case study evaluated the efficacy of different naturally occurring and actively generated excitation sources that were identified from an earlier extensive literature review. This work also led the project to produce guidance on several installation and operational issues for seismometers that currently impact their viability and precision. Most significantly, one case study investigated the effective coverage of the reference sensor and lead the project to the conclusion that one reference sensor can be used to calibrate several live seismometer sensors, and that a one-to-one deployment is not necessary.

For hydroacoustics, the calibration process was modelled and the influence of separation between the reference sensor and live sensor investigated. The modelling results indicated that the calibration method has potential application in the ocean environment but could be hampered by difficulties in ensuring that the sensors are co-located. This study has triggered interest by the CTBTO (outside of the project) in testing its findings, in future trials of on-site calibration in the ocean.

Valuable information about the stability and general behaviour of sensors and transfer standards was obtained by the project. The feasibility and quality of calibration was also investigated in detail by comparison of different methods. Here the newly developed SMIT-system was of particular value.

Finally, the development of novel calibration and testing methods for sound level measuring devices commonly used for environmental applications were successfully assessed and reviewed in a measurement study near a German wind park. The ability to make reliable low-frequency noise assessments is an important factor for the expansion of renewable energy infrastructure. The case study measurements were made using a measurement microphone and microbarometers for comparison. The project's outcomes can now be used to inform end-users on matters such as specifying appropriate instrumentation and measurement protocols.

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4.4 Objective 4: To evaluate the outcome and impact of improvements to current global acoustic, underwater and seismic sensor networks deployment strategies gained by introducing traceable calibration and the application of measurement uncertainty principles, and to propose optimised models and parameters in the applications, leading to increased confidence in measurements.

4.4.1 Impact of project results on performance of IMS

While the work described in Objectives 1-3 evaluated several practical aspects of on-site calibration, the all-important matter of measurement uncertainty was addressed in this Objective. Even primary calibrations have measurement uncertainty, and this propagates and builds at each stage in the calibration chain. Therefore, with the development of the elements of the chain completed in Objectives 1-3, a model was developed to estimate the measurement uncertainty in the on-site calibration process (Objective 3) as it inherits components from the laboratory calibrations (Objective 1) and performance of the transfer standard (Objective 2).

It should be highlighted that the calibration of the monitoring sensor systems was not the end goal for the project. The sensor networks are used to infer field parameters of interest for the given application. Therefore, the project developed another case study on an uncertainty propagation model to evaluate the influence of measurement uncertainty in the detection of infrasound and to estimate the location of its origin via the propagation speed and direction of arrival at the monitoring station. By having calibrated sensors with known levels of measurement uncertainty the project was able for the first time to use uncertainty information in the derived parameters of interest and systematically evaluate it from the underlying calibration data. This translates directly to confidence in the parameters and the source location details they yield; potentially vital information that has not been available until now. While the case study used an application in infrasound, however the findings are readily transferable to other technologies.

The project has generated significant amounts of new information derived from metrology considerations and created a strong rationale for ensuring that geophysical monitoring can utilise traceable measurements. Such data is intrinsically consistent with the SI system and linked to the global measurement system. This provides several useful benefits: (i) the system is universally recognised removing any doubt about transparency and impartiality of the data, and (ii) the associated measurement uncertainty enables the level of confidence and trustworthiness in the data to be quantified. These factors are important in considerations in quality and data management systems. At a practical level, confidence in the data translates into confidence in the decisions made based upon that data, whether that relates to fault diagnosis, the overall operational status of a monitoring station, or evidence of a detection. In the overall scheme of the IMS, it is these decisions that ultimately matter.

A series of case studies were undertaken to investigate and understand the stability, behaviour, installation conditions and sensitivity to the environment of the methods newly developed in Objections 1 to 3. Two such case studies and their outcomes and recommendations are outlined below to illustrate benefits derived from metrology considerations.

Case Study 1:

In August 2022, three seismometers (Figure 17, a 3-component Streckeisen STS2.5, and two vertical component Geotech GS13 devices), were re-installed at the IMS) seismic station PS19 in Germany, after having just been removed for laboratory calibration. The purpose of the case study was to demonstrate an on-site calibration procedure for these seismometers, and the benefits of using a calibrated sensor.

Figure 17: Seismometer models and their installation in the ground

The field (case) study evaluated the use of a modified version of the Gabrielson-Charbit method, originally developed for infrasound, for on-site calibration of seismometers (see section 4.3.1.5), with the additional feature of using a calibrated and traceable reference sensor. The calibration method gives the relative response of the two sensors (i.e. seismometer and reference sensor), so the calibration of the reference sensor enables measurement traceability to pass to the sensor under test (seismometer).

The first preliminary analysis focused on the magnitude of the vertical component (Figure 18). For each day, the gain ratio was calculated between a station sensor and the reference, which were co-located in neighbouring vaults at a distance of approx. 2 m. The relative response was calculated for time segments where two similarity conditions between both sensors (indicated by the mathematically - calculated coherence) were fulfilled.

In comparison with the theoretical response of the sensor (seismometer) given by the manufacturer, the estimated response shows a good fit with less than 5 % deviation compared to the theoretical value. However, obvious features were the significant fall-off at frequencies greater than 8 Hz, and the overall shift to smaller values (see Figure 18).

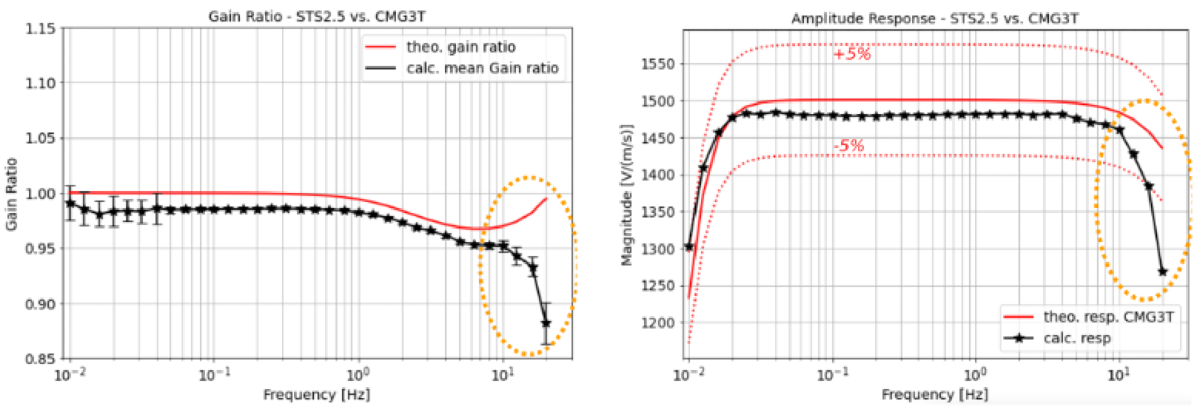

Figure 18: Sensor response estimated from on-site calibration compared with the manufacturer's specification

The case study went on to address the question of the maximum distance that the reference sensor can be installed from the sensor under test, and therefore whether a single calibrated sensor can be used as the reference sensor for several 'live' sensors. One of the calibrated sensors was used as reference for all 25 seismometers making up the array at the IMS station.

In Figure 19, the plots show selected results for three sensors (GEA2, GED1, GED7) at varying distances (722 m, 1000 m, 2900 m) from the reference sensor. The on-site calibration responses were determined and averaged for four selected days in 2023 that showed high cross-array coherency values. Note that on these days major earthquakes occurred.

In general, the results were variable, however they were sufficient to allow recommendations to be made on how best to deploy references sensors efficiently, and that in typically there is no need for an individual reference for each seismometer.

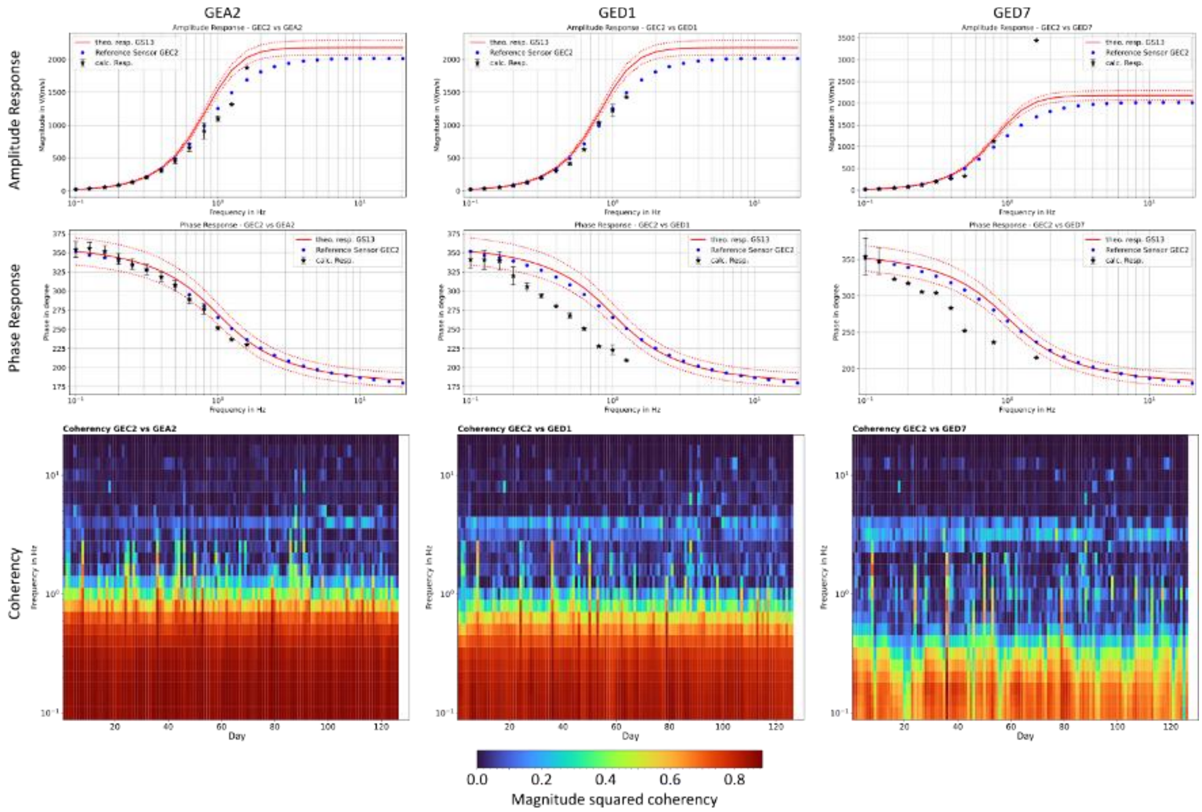

Figure 19 Estimated sensor response as a function of distance from the reference sensor

Case Study 2

A challenge of atmospheric infrasound measurements is the wind-generated turbulent noise. One method to reduce this noise is to use a pipe-array Wind-Noise Reduction System (WNRS). This system samples the pressure field over an array that is large compared to the size of the turbulent eddies (noise), but small compared to the wavelength of the infrasound in the frequency band of interest (0.01-4 Hz). Thus, the wind-noise is effectively averaged out, while the signal remains largely unaffected.

Although pipe-array WNRS work quite well, when defects such as blocked inlets or flooded pipes are present, the infrasound response of the system can be affected and result in errors in the observed signal.

The method to calibrate and monitor the status of pipe-array WNRS is to use a co-located reference sensor, which does not use a WNRS and so unfortunately suffers at time from wind-induced noise. Then by determining the relative response of the 'live' station sensor and the reference for times when the two signals are highly coherent (typically when there is no wind), the response of the 'live' sensor can be derived.

This procedure is typically used to monitor the status of the 'live' sensors at the station, however the project has been able to demonstrate that a calibrated reference sensor can also be used to correct the signal, such that the proper wave parameters, i.e. direction and speed of arrival, can be retrieved, even when the WNRS is defective.

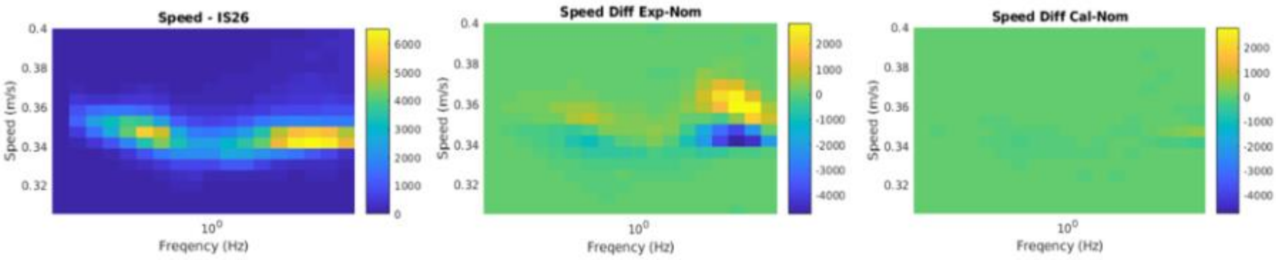

Figure 20 Illustration of the removal of field parameter anomalies using a calibrated reference sensor

A temporary WNRS was installed by the project alongside an existing sensor element at IMS station IS26 in Germany. Several different defects were then introduced to this temporary system, so that the effects of the different defective systems could be compared with the normally operating 'live' element. The project found that by determining the response of the defective system, and removing this response from the observed signal, that it was possible to retrieve the correct signal.

The left panel in Figure 20 shows the speed histogram as a function of the frequency using the 'normally' functioning IS26 array. The centre panel is the difference of the speed histogram between the defective system and the normally operating IS26 array. There is an apparent, but erroneous, increase in the velocity at high frequency due to the change of the detector response caused by the induced defects. When the signal is corrected, this error is noticeably eliminated (right panel). As can be seen, there is almost no difference between the signal correction and the normally operating detector, demonstrating that the signal was properly corrected using the calibration results.

The in-situ calibration was demonstrated by the project to allow the correction of signals when defects are present. This means that, when there are defects detected in sensors, but they cannot be fixed right away, the project's correction procedure could be used to correct the signals and retrieve the correct wave parameters. Hence helping to reduce the loss of data and improve measurement accuracy when defective detectors are identified in-situ.

4.4.2 Propagation and impact of uncertainties on sensor network output

4.4.2.1 Propagation of uncertainty in infrasound event evaluation

The calibration methods and facilities, and transfer calibration techniques developed in the project (Objectives 1-3) have inherent uncertainties that transfer into the on-site monitoring application. For example, at IMS stations, infrasound data is used to detect potential events based on determinations of the direction, magnitude, and speed of arrival of an incoming infrasound wave. But clearly the measurement uncertainty in these parameters has a large impact on the eventual certainty or confidence in the event detection. This uncertainty inherits components from all elements in the preceding calibration chain, from the laboratory calibrations (primary and secondary) to the field (SMIT and Gabrielson-Charbit) calibration methods. Therefore, models for the propagation of these uncertainties were used to estimate the confidence level of a potential measurement of these field parameters associated with an incoming infrasound signal

Although various impact factors (e.g. the relative sensor positions within the station, local environmental conditions, or the sensor susceptibilities to temperature and pressure) were considered, efforts were concentrated on determining the impact of sensor calibration uncertainties. For the case study, real data from an IMS station was used to focus on a field parameter representing the time delay of arrival (TDOA), as used widely in practice, in the analysis of IMS data for the localisation of events.

A mathematical uncertainty propagation model (Monte Carlo model) was created to examine the propagation of all identified components of measurement uncertainty, including those related to temperature, pressure, and the physical location of the sensors, through the algorithm used to calculate the TDOA and other field parameters that can be subsequently deduced. The model is extremely complex and considered over 100,000 permutations of variables in the calculations. Figure 21 shows these estimated uncertainties resulting from the mathematical uncertainty propagation model.

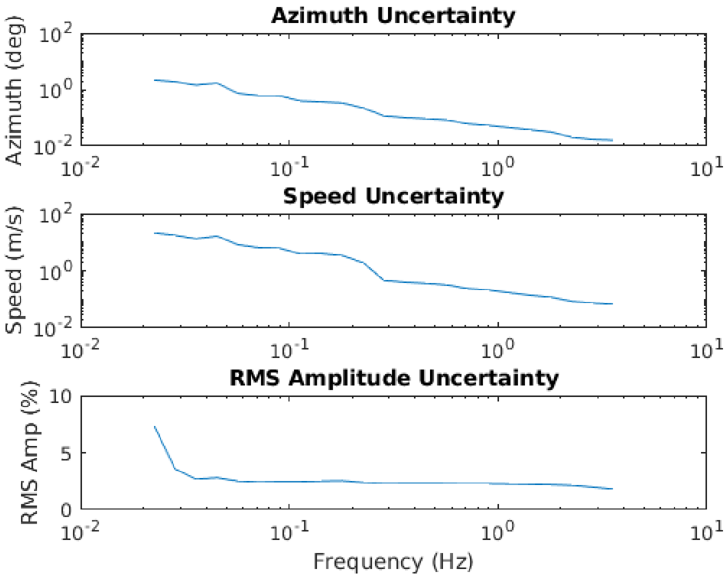

Figure 211 : TDOA azimuth (top), trace velocity (middle), and RMS amplitude (bottom) uncertainties.

The case study has demonstrated the importance of calibration and uncertainty principles in the context of atmospheric measurements of infrasound wave parameters. From the results it could be concluded that on-site calibration is the most important contributor to the overall uncertainty budget, and the reduction of noise remains the largest challenge in reducing the uncertainty further It should also be noted that the calibration phase uncertainties are by far (aside from the Signal to Noise Ration) the largest contributors to the uncertainty in the direction and speed of arrival parameters. Such information is invaluable for future improvements in the calibration and deployment of sensor systems.

4.4.2.2 The impact of traceability and uncertainty propagation for underwater event detection and the assessment of ocean noise

For underwater acoustics, the data recorded by a sensor operating in the field, possibly as part of a deployed sensor network, are used by different end-user communities for different purposes: event detection and attribution to derive temporal, spatial and amplitude information about the event, which can be anthropogenic or natural; ocean noise monitoring in which the data are used to derive metrics for noise maps for a given spatial region and time period; and environmental monitoring in which the data are used to derive long-term trends in sound pressure level and to correlate with sound sources. A case study on the propagation of uncertainties for hydrophones used in ocean noise monitoring was undertaken by NPL and published as an NPL report titled: "A Study of Uncertainty Propagation for an End-To-End Data Processing Pipeline for an Application in Underwater Acoustics". The study showed how uncertainty propagates through a data processing pipeline that starts with the raw data recorded by a hydrophone (the study used data from a real hydroacoustic sensor taken from the International Monitoring System of the CTBT) and finishes with advanced derived parameters which convey useful information about ocean noise., and its statistical distribution as derived from the raw data. Although these results are specific to the application, the approach taken in the investigation can be used as a template for other applications.

4.4.3 Output of the project for stakeholders, users and intended persons

A Good Practice Guide was prepared for use by CTBTO, its operators of International Monitoring System stations, and operators of other geophysical monitoring networks. The Good Practice Guide on 'On-site calibration methods for sound in air, underwater acoustics and seismic sensors of environmental measurement stations' collates together all the project's work on metrological aspects supporting the operation of such networks and presents a summary of the project's achievements and key outcomes. The Good Practice Guide is presented as a series of web pages that can be navigated based on the needs and interests of the end user. It is illustrated with diagrams and key results and includes references to the publications arising from the project. The project's case studies are used in the Good Practice Guide to illustrate the impact of the new research findings. The conclusion sections also include recommendations for enhancing existing sensor system deployment practices and the associated underlying quality system. The Good Practice Guide has been made available on the project website and is freely accessible for stakeholders.

https://www.ptb.de/empir2020/infra-auv/information-communication/publications/good-practice-guide/

4.4.4 Conclusions for objective 4

Objective 4 was successfully completely by the project. The outcome and impact of improvements to current global acoustic, underwater and seismic sensor networks deployment strategies was evaluated by practical case studies and by modelling. One of these investigated the impact of sensor stability, behaviour, installation conditions and sensitivity to the environment in a first-of-its-kind trial of on-site calibration of seismometers. Another case study developed an uncertainty propagation model to evaluate the influence of measurement uncertainty in the detection of infrasound and estimation of the location of its origin via the propagation speed and direction of arrival at the monitoring station. By having calibrated sensors with known levels of measurement uncertainty, the project was able for the first time to use uncertainty information in the derived parameters of intertest and systematically evaluate it from the underlying calibration data. This translates directly to confidence in the parameters and the source location details they yield; potentially vital information that has not been available until now. The case study used an application in infrasound however, the findings are readily transferrable to other technologies.

Using the project's results a Good Practice Guide has been produced on on-site calibration methods for sound in air, underwater acoustics and seismic sensors of environmental measurement stations including recommendations for improving the outcome from deployment strategies. The Good Practice Guide (GPG) is for use by CTBTO and operators of IMS stations, and operators of other geophysical monitoring networks. The Good Practice Guide includes the project‘s results on metrological aspects supporting the operation of such networks and presents a summary of the project's achievements and key outcomes. The Good Practice Guide has been made available on the project website.

5 Impact

The project has completed a comprehensive set of dissemination activities to promote the project including:

- a project website containing technical articles from the project and Newsletters;
- 13 published open-access publications;
- 61 presentations and posters delivered at conferences;
- a dedicated 'poster-corner' at the European Geophysical Union General Meeting (EGU2023), featuring 9 posters from the project team;
- a project workshop at the CTBTO Science and Technology Conference in 2023, with recordings at https://www.youtube.com/watch?v=kQkEwKHpUok https://www.youtube.com/watch?v=7ixPIWafEOU
- an online training webinar on low-frequency hydrophone calibration presented to the UK Acoustics Research Network a recording of which can be found at https://youtu.be/Illlew1cTrc?t=1551
- an online Good Practice Guide on Measurement traceability for seismo-acoustic and hydroacoustics sensor systems deployed in the International Monitoring System (Objective 4) aimed at operators of environmental monitoring networks, available on the project website at https://www.ptb.de/empir2020/infra-auv/information-communication/publications/good-practice-guide/

Impact on industrial and other user communities

A key stakeholder, the CTBTO have followed the project closely throughout and are already discussing how to take up the new calibration (Objectives 1 & 2) and data analysis capabilities produced by the project. In particular, traceability provision is currently impacting the revision of their quality assurance processes for seismic measurement systems, from device procurement to on-site calibration. For hydroacoustics, CTBTO are seeking opportunities for field trials of hydrophone calibration in the ocean, following the proof-of-concept modelling carried out in this project (Objective 3). Further to this, the project's software for the estimation and propagation of measurement uncertainty in geophysical field parameters (Objective 4) is potentially exploitable, e.g. by integrating with CTBTO software. Indeed the project has already discussed (2021) with CTBTO scientists the inclusion of the project's software in CTBTO's on-site calibration software CalXPy (Objective 3).

Similarly, the assessment of ocean noise pollution in response to international treaties (for example under the Oslo-Paris Agreement – OSPAR) and EU Directives such as the Marine Strategy Framework Directive can now benefit from the extended traceability at low frequency. Confidence can also improve in crucial acoustic measurements used to infer changes in the ocean temperature and polar ice coverage. Thus, other beneficiaries include the maritime transport community, where the environmental effect of ever-increasing ship traffic and the need to extend measurements to lower frequencies has been recognised by the International Maritime Organization.

The project's case study (Objective 4) illustrating the viability of reliable low-frequency community noise assessments is an important step for the renewable energy discussion. New understanding of the factors critical for a successful measurement, and the potential pitfalls, is ready for wider dissemination to regulatory authorities. This can assist in establishing assurances in environmental impact assessments, providing the first steps towards better-informed decision-making for stakeholders on both sides, e.g. in the fiercely debated environmental impact of wind farms near dwellings or in certain marine habitats. The impact also extends to environmental and industrial noise control in general, through developments in the verification of measuring instruments performance at low frequencies. Other industrial beneficiaries include mining and oil exploitation applications (including fracking), which rely on environmental measurements in their execution as well as for evidence of compliance with environmental regulations.

Further to this partner, HBK has marketed a commercial calibration device for microphones. The operating range of the device has been extended to 25 mHz using the new calibration capabilities developed in the project in Objective 1. In addition, CEA has developed a portable infrasound calibration system for use on-site (Objective 3), which has the potential to be used to develop calibration services or a commercial product.

Impact on the metrology and scientific communities

The project partners HBK, LNE, PTB and DFM have developed primary and/or secondary calibration capabilities (Objectives 1 & 2) that are now available to users, and already attracting enquiries. The services cover measurement microphones, and microbarometers used extensively in geophysical applications and static pressure sensors (where they have a limited dynamic response). The frequency range covered varies across the institutes depending on the method(s) implemented. The lowest frequency covered is 10 mHz, and capabilities extend beyond 20 Hz.

At both NPL and TÜBİTAK, calibration services for hydrophones under sea conditions, using secondary calibrations have been improved and extended in this project (Objective 2). At NPL, secondary calibrations are now traceable to the new primary standard provided by the project's calculable laser pistonphone. The capability for the service has been extended down from 25 Hz to 0.5 Hz. Before the end of 2023, NPL had already undertaken 30 hydrophone calibrations for customers at frequencies from 315 Hz down to 2 Hz. NPL will extend its accreditation to ISO 17025 to cover this extended low frequency range). At TUBITAK the developed secondary calibration facilities for hydrophone calibration are ready for an application and TUBITAK will start the process of transfer into a service for customers.

The project been promoted to the global acoustics and vibration measurement community, with interest from other metrology regions, some of which have been inspired to extending their own calibration capabilities. As examples of this dissemination to the metrology and scientific communities the project has:

- provided training to 60 students at the Technical University of Braunschweig on "Infrasound and airborne ultrasound perception and impact on humans".
- trained a guest worker from the Polish NMI GUM at NPL supported by the EURAMET Mentoring Programme, in methods of low frequency hydrophone calibration at NPL.
- presented results on "Application of infrasound in climate research" to the EURAMET EMN on Climate Change and Ocean.

The results of the project were disseminated to EURAMET TC-AUV (Acoustics, Ultrasound and Vibration), and BIPM and CIPM CCAUV (Acoustics, Ultrasound and Vibration). Presentation of the project was met with keen interest by CCAUV, which is the principal forum of the global metrology community in this field. Partners in the project are now working towards formal registration of their new Calibration and Measurement Capabilities (CMCs) through CCAUV. In addition, the scope for new key comparisons, underpinning measurement capability in all three technologies (infrasound, underwater acoustics and seismic vibration), has also been expanded through the project's input to both CCAUV and EURAMET TC-AUV.

In the wider scientific community, the new measurement standards developed by the project could benefit studies of the atmosphere and improved confidence in weather forecasting. Traceable low frequency measurement can also improve the representation of gravity waves in the stratosphere and estimation of wind speed and temperature in the thermosphere, ultimately improving existing models for these upper-atmosphere regions. These benefits also impact monitoring of climate-related phenomena such as thunderstorms, and stratospheric warming.

Impact on relevant standards

With IEC TC 29 Electroacoustics, the project has provided input to IEC TR 61094-10:2022. Electroacoustics - Measurement microphones - Part 2: Primary method for pressure calibration of laboratory standard microphones by the reciprocity technique and Part 10: Absolute pressure calibration of microphones at low frequencies using calculable pistonphones. For IEC TR 61094-10:2022 Part 2 the method of primary calibration was extended to cover the infrasound frequency range, with the introduction of the new model for the acoustic behaviour at very low frequencies. Another new standard Part 10 describing the use of calculable pistonphones for infrasound calibration, as developed in the project, was also approved and published. Both documents were prepared almost entirely with input from the project team. New understanding of the instrumentation requirements for low-frequency noise measurement were also disseminated to IEC TC 29.

For underwater acoustics, reports from the project were provided to committees developing standards for the calibration of hydrophones (IEC TC 87 Ultrasonics) and for monitoring of noise in the ocean (ISO TC 43 Acoustics SC 3 Underwater Acoustics). Within ISO TC 43 the project provided input to ISO 17208 Underwater acoustics — Quantities and procedures for description and measurement of underwater sound from ships — Part 3: Requirements for measurements in shallow water, ISO 7605 Underwater acoustics — measurement of underwater ambient sound and ISO 7447 Underwater acoustics — Measurement of radiated underwater sound from percussive pile driving — In-situ determination of the insertion loss of barrier control measures underwater. ISO TC 43 strongly supports the implementation of the EU Marine Strategy Framework Directive, where this project has provided the much-needed research in the low frequency range, in extending the assessment noise from shipping to much lower frequency.

For vibration, the project has highlighted the need for new standards within the scope of ISO TC 108 Mechanical vibration, shock and condition monitoring WG34 Calibration of vibration and shock transducers. New seismometer calibration capability arising from the project has made it possible to consider a new standard on this topic, including coverage of the low frequency range. A need for on-site calibration methods, was also identified by the project and international interest and a desire to cooperate on this has already been expressed by other stakeholders.

In addition to this, the project has provided input to DKE NA 001-01-03 GA Sound measuring devices.

Longer-term economic, social and environmental impacts

The project has provided for the first time, a robust metrology infrastructure for low frequency measurements for environmental monitoring. In airborne acoustics and vibration, there is a delicate balance between urban development and increased noise and vibration exposure of the population, for example due to road and high-speed rail developments, which are always heavily contested on environmental grounds, and where low frequency noise and vibration is a significant contributing factor. In such cases an improved ability to measure accurately and with known levels of confidence, will lead to improved future debates. and help to overcome social resistance to the technologies necessary to deliver the European Green Deal objectives on greenhouse emissions.

In underwater acoustics, the field of metrology for environmental noise is relatively immature and it has struggled to keep pace with the rapidly evolving legislative framework. This project's calibrations and new capabilities provide improved ocean noise measurements and will help to ensure that environmental decisions are underpinned by metrology. This is turn will support future environmental protection of the oceans without unnecessary barriers to developments and will support the required monitoring in existing and future Directives.

Often, environmental impacts also have a social component. For example, a reduction in environmental noise and vibration has well-documented health and wellbeing benefits to citizens, in terms of learning ability, sleep disturbance, mental health and hypertension (associated with heart disease and stroke). Less obvious, but perhaps higher profile in recent times, is the level of protection offered to society by the accurate monitoring of unlawful nuclear testing and the consequent international efforts to condemn and prevent further nuclear proliferation. Other social impacts are the use of accurate and robust environmental monitoring data for other forms of natural disasters and for climate change studies.

6 List of publications

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This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

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