Publishable Summary for 19ENV03 Infra-AUV
Metrology for low-frequency sound and vibration

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 are well-established, but their calibration requires further development, and currently lacks traceability to international system of units (SI). This project aims to establish both the first primary measurement standards for low frequency sound and vibration, over the frequency range of the applications, and a structure for effective and targeted dissemination of traceability. New calibration capabilities will primarily support the operation of global networks for environmental monitoring and research in areas such as climate change and non-proliferation of nuclear weapons. New measurement services will be launched, based on methods that will be subsequently embodied in international standards, and a series of case studies will introduce key metrology concepts such as traceability and measurement uncertainty into these applications for the first time.

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 are not fully covered by primary or secondary measurement standards, compromising reliability, value and wide acceptance. Even the measurement of low-frequency noise nuisance lacks 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, has given this issue high strategic importance. The main need is for novel primary and secondary calibration methods and devices, 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 often in remote and inaccessible locations. The sensors must operate continually and cannot be taken out-of-service just for calibration, so there is a strong need for 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 set additional challenges in understanding how sensor performance is impacted by the environment.

Objectives

The overall objective of the project is to extend the frequency ranges for traceable environmental measurements in the field of infrasound, underwater acoustics and seismic vibration to lower frequencies. This includes 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 are:

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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 yet covered by global calibration capabilities.
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/WG34, 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.

Progress beyond the state of the art

This project represents the first consolidated attempt to address the identified needs across the three technologies of airborne acoustics, seismology, and underwater acoustics.

Primary calibration capability across all three technologies is currently limited at low frequencies by the capability of available facilities or by scientific knowledge required for their implementation. Therefore, new research is being undertaken to overcome these limitations, in parallel with the development of novel calibration methods exploiting alternative physical principles for quantifying the sound pressure while avoiding such limitations altogether.

Laboratory based secondary calibration methods suitable for a wider range of sensors are also being developed for airborne and underwater acoustics. However, laboratory-based calibration capability provides only half of a solution, as field calibration, or so-called *on-site calibration* of sensors is necessary at periodic intervals to maintain traceability. Therefore, suitable sensors to act as transfer standards are being specified.

Then, through access to live monitoring stations operated by the partners in the project, methods for on-site calibration are under evaluation, building on the provision of traceability offered by the calibrated reference sensors. The use of actively generated test stimuli, and passive methods using naturally occurring ambient excitation are being considered. The impact of the operating environment on the performance of sensors will also be characterised, including the effects of temperature, humidity, and static pressure, as well as sensor-specific parameters such as the influence of water depth on hydrophone performance.

The technical developments flowing from the laboratory to the field use of the sensor systems are primarily targeted at improving data quality and therefore confidence in the information drawn from it. Improvements in data quality will be evaluated in a series of case studies designed to assess and demonstrate the impact of the metrological aspects developed in the project.

Results

Primary calibration

In the case of microphones (which measure airborne sound) and hydrophones (measuring sound in water), five absolute calibration methods are in development, exploiting different physical principles to determine the infrasound pressure used as the calibration stimulus. Ten independent primary calibration facilities have been established, for microphone and/or hydrophone calibration, with further plans to include microbarometers, the type of sensor used extensively at infrasound monitoring stations. The newly developed absolute calibration methods now supplement the mainstream primary calibration methods (known as reciprocity calibration) for both sound in air and in water, where progress has also been made in extending to significantly lower frequencies. Several of the calibration systems in development have produced new results in the targeted low frequency ranges, in some cases exceeding performance expectations, in readiness for a planned intercomparison that will validate the performance of each system.

For seismometers (which measure vibration in the ground), three existing vibration calibration systems have been upgraded to handle large and heavy seismic sensors. The operating ranges have also been extended to lower frequencies, e.g. one system has implemented a novel infrared laser-based technique. Elsewhere, the influence of a magnetic field inherent in the vibration exciters on the sensor under test, has been evaluated and a solution is being tested. First calibration results are also being completed, ahead of a planned series of comparisons across these systems to validate their performance.

Secondary calibration

Many of the infrasound generators developed for absolute calibration of microphones and hydrophones also facilitate calibration by comparison with a reference sensor. This is necessary when the sensor under test is incompatible with absolute calibration. Therefore, most secondary calibration facilities are now established, with some pending to provision of a reference transducer from the primary calibration application, while others are complete and potentially available for use. This includes one such facilities capable of accommodating a complete measuring instrument such as a sound level meter within the infrasound field, as necessary for the assessments of low frequency noise nuisance.

Studies has been completed leading to specifications for reference sensors for transferring traceability to the field. For airborne infrasound, the need for two types of referenced sensor, a laboratory standard microphone and a microbarometer, was identified and verified through collaboration with experts at CTBTO. For underwater acoustics, the demands on the sensor 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 has been prepared and made available on the project website, cataloguing the performance of the most popular models of hydrophones. For seismology, a critical evaluation of performance parameters for eleven of the most commonly used seismometers has led to the selection of three candidate reference sensors. The selected sensors will now be used to compare the performance of the newly developed calibration facilities.

To support the measurement of potentially annoying or disturbing low-frequency environmental noise, another document has been published (and available on the project website), collecting existing national requirements and guidelines for infrasound measuring instruments. This is the first attempt anywhere to produce a global set of requirements. The report was presented at a meeting of the IEC Technical Committee on Electroacoustics (IEC/TC 29) and has initiated standardisation discussions on this topic.

On-site calibration

After ongoing in-depth discussions with a key stakeholder CTBTO it has become apparent that their established on-site calibration method is very well developed and extremely effective. A decision was therefore made to add value to, rather than attempt to re-invent, this existing process. The potential to use different naturally occurring and actively generated excitation sources as calibration stimuli is very relevant in this context and has been studied extensively. A report of the results has been compiled and the core outcomes will be condensed in a peer reviewed paper in the near future. An ongoing dialogue with stakeholders examines what might be viable in practice, particularly for hydrophones deployed in the ocean where the operational environmental presents particular problems, and a review paper presenting the findings is in preparation. However, the strongest contribution to the existing CTBTO process is on the addition of measurement traceability and uncertainty. Active collaboration has been initiated to introduce the project’s calibration developments into CTBTO’s software and data platforms.

The influence of the prevailing environment on the performance of sensors and the consequential impact on the information derived for their data are being evaluated through the analysis of historical data. These formative studies will be developed into full case studies in due course.

Evaluation of outcome improvements

As technical developments flow from the laboratory to the use of sensors in the field, case studies from airborne acoustics, underwater acoustics and semiology will be formulated to illustrate the impact of traceable calibration, the estimation of measurement uncertainty and the propagation of uncertainty through the whole measurement process.

The first case study has been completed. Infrasound measurements have been carried out at two wind energy generating sites in Germany. The ability to make reliable low-frequency noise assessments is an important step for the renewable energy discussion. Measurements were made using microphone systems and microbarometers for comparison. One aspect of the study was to illustrate that the condition of the microphone needs special attention. A tiny perforation made in the membrane of one of the microphones was shown to have no consequence at regular frequencies and was not detected by the usual pre-assessment checks with a calibration device operating at 1 kHz. However, the same defect produced errors of over 20 dB (a factor of 10) in the infrasound region.

Another case study is evaluating the influence of measurement uncertainty in the detection of infrasound, specifically the propagation speed and direction of arrival at the monitoring station. An uncertainty propagation model is under development and preliminary results in some of the benchmark conditions look promising. The model will be refined as details of further influencing factors become available.

At least two further case studies are being formulated.

Impact

A project website has been established and includes news and technical highlights, details of the project and consortium, information on upcoming events and presentations, and links to the project newsletters. Contributions have been made to several conferences across a range of stakeholder communities (e.g. European Geophysical Union, CTBTO Science & Technology Workshop, Underwater Acoustic Conference and Exhibition, etc.). These include invited and contributed presentations, chaired sessions and participation in an expert panel discussion. On online training webinar on low-frequency hydrophone calibration was also presented. The project was presented to the Strategic Planning Working Group of the CCAUV where it directly addresses an identified strategic goal. It also featured in the meeting of EURAMET TC-AUV where new information on instrumentation requirements for low frequency environmental noise measurement were presented. Notably, the project made several important contributions in the area international standards development. In IEC/TC 29 on Electroacoustics, project outputs have initiated new strategic discussions on infrasound measurement and driven progress on two IEC standards which should see publication this year. In ISO TC 43/SC 3 on Underwater Acoustics, the new work items have begun on standards for measuring ship noise, ocean ambient sound and the effectiveness noise abatement for offshore windfarm construction – all of which will require traceable calibrations in the frequency range from a few hertz to 200 Hz where traceability and metrology is weakest.

The stakeholder engagement strategy includes the formation of a Stakeholder Advisory Group who provide a link to the wider stakeholder community. Eminent experts have accepted invitations to this group. A stakeholder mapping exercise has identified more than 60 stakeholders across the three technologies, that the project aims to engage with at some level.

There have been several online meetings and a training workshop with representatives of CTBTO, particularly their experts in infrasound and hydro-acoustics. Other engagement includes discussions with NASA, various academic departments specialising in sound and vibration, national professional bodies, national measurement institutes outside of Europe and with the EU-funded JOMOPANS project on noise monitoring in the North Sea. Some of these interactions have revealed new applications where Infra-AUV may create impact, e.g., in the calibration of motion sensors used in measuring sea-surface waves in climate studies.

Impact on industrial and other user communities

Operators of the CTBT monitoring system will be an early adopter of new calibration capability, offering measurement traceability for the first time, with consequent impact on data quality and enhanced credibility. To this end the project is collaborating with CTBTO to integrate traceability and measurement uncertainty aspects into their calibration software and processes. 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 will benefit. Confidence will improve in crucial acoustic measurements used to infer changes in the ocean temperature and polar ice coverage. Other beneficiaries include the maritime transport community, where the environmental effect of ever-increasing ship traffic has been recognised by the International Maritime Organization. The first project case study illustrating the viability of reliable low-frequency noise assessments is an important step for the renewable energy discussion. Understanding the factors critical for a successful measurement, and the potential pitfalls provides vital assurances in environmental impact assessments, leading to better-informed decision-making for stakeholders on both sides, e.g. in the fiercely contested debates over the environmental impact of wind farms near dwellings or in certain marine habitats. Environmental and industrial noise control in general will be improved by developments in the verification of measuring instruments performance at low frequencies, benefiting the general public and the workforce. 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.

Impact on the metrology and scientific communities

The project is being closely monitored in the global acoustics and vibration measurement community, with interest from the measurement institute in Japan (NMI-J) in a parallel development of a calibration method. Further uptake of new calibration methods is expected once publications are available, followed by new international measurement comparisons for validating and formalising the measurement capabilities. The project will establish the Europe measurement institutes as world leaders and innovators in these technologies.

In the wider scientific community, expected benefits include better scientific understanding of the atmosphere and improved accuracy in weather forecasting. Traceable low frequency measurement will 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. The benefits also spread to monitoring of climate-related phenomena such as severe weather, thunderstorms, and stratospheric warming, providing for improved evaluation of long-term trends.

Impact on relevant standards

The outcomes of the research will feed into current and future international standards for primary and secondary calibration in the fields of sound in air, underwater acoustics and vibration at low frequencies. Already, the project has made significant input to the work of IEC/TC 29, where proposals have been presented on extending the testing of sound level meters (the devices used for practical noise measurement), initiating strategic discussions in the relevant working groups. Two further draft IEC publications on the low-frequency calibration of microphones, prepared almost entirely with input from the project team, are expected to be published in 2022. For underwater acoustics, awareness of the project has been raised with the committees developing standards for the calibration of hydrophones (IEC/TC 87) and for monitoring of noise in the ocean (ISO/TC 43/SC 3). The latter strongly supports the implementation of the EU Marine Strategy Framework Directive, where this project provides much-needed research in the low frequency range. For vibration, input will be provided to a series of international standards (for example, TC 108 for the ISO 16063), to cover lower frequencies and fields of application. For example, there is a strong need for a new draft document concerning on-site calibration methods, where international interest and a desire to cooperate on this has already been expressed.

Longer-term economic, social, and environmental impacts

New capability to calibrate sensors and provide traceability adds significantly to the performance of sensors. Introduction of robust uncertainty estimation improves usability. These features foster a greater uptake and wider use of sensors and monitoring systems, improving sales of such systems which are predominantly developed and produced in Europe. The improved calibration methods will enable manufacturers of monitoring systems and sensors as well as of calibration equipment to more readily demonstrate that their performance meets the application requirements for the instrumentation. In terms of CTBT monitoring, enhancements to the data represents a greater return on the financial investment in establishing and operating the global monitoring system and provides stronger justification for the multi-national investment.

The project will provide 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 all cases an improved ability to measure accurately and with confidence adds scientifically robust factual details to the debate. The project therefore supports the development of strategies and local action plans for monitoring and control thereby contributing to the long-term EU goals for “Living well within the limits of our planet”.

In underwater acoustics, the field of metrology for environmental noise is relatively immature and struggles to keep pace with the rapidly evolving legislative framework. Improved ocean noise measurements will ensure that decisions are informed and underpinned by metrology, that the environment is protected without unnecessary barriers to developments, and that existing Directives requiring monitoring can be implemented in a scientifically robust manner, with appropriately calibrated instrumentation.

Often, environmental impacts also have a social impact component. For example, reduction in annoyance caused by environmental noise and vibration has well-documented impacts on the health and wellbeing of citizens, especially in terms of learning ability, sleep disturbance, mental health and hypertension, where there are known associations with heart disease, stroke and dementia. Even at the less severe end of the spectrum, improvements in quality of life are easy to appreciate. Less obvious is the level of protection offered to society by the monitoring of illegitimate nuclear testing and the consequent international efforts to condemn and prevent further nuclear proliferation. A secondary social benefit is the use of the data for monitoring other forms of natural disaster and for climate change studies, all of which have profound social impact.

List of Publications

[**1**] Kling C., Koch C., Rust M., Barham R., Rodrigues D., Barrera Figueroa S. and Sandermann Olsen E., "Specifications and testing strategies for measurement devices for noise exposure determination in the infrasound frequency range", 2021. Physikalisch-Technische Bundesanstalt (PTB). https://doi.org/10.7795/EMPIR.19ENV03.RE.20210609

[**2**] Ford B, Robinson S and Ablitt J, A Study of the stability exhibited by hydrophones when exposed to variations in temperature and hydrostatic pressure, Proc. Mtgs. Acoust. 44, 070024 (2021); https://doi.org/10.1121/2.0001491

[**3**] Bruns T, "Efficient very low frequency primary calibration method for accelerometers", Measurement Sensors 18 (2021). https://doi.org/10.1016/j.measen.2021.100156

[4]Winther J H, "Progress in the realisation of ultra- low frequency vibration calibrations", Measurement Sensors 18 (2021), https://doi.org/10.1016/j.measen.2021.100350.

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

Project start date and duration:		01 Sep 2020, 36 months
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Internal Funded Partners: 1. PTB, Germany 2. HBK, Denmark 3. CNAM, France 4. DFM, Denmark 5. LNE, France 6. NPL, United Kingdom 7. TUBITAK, Turkey	External Funded Partners: 8. ASN, United Kingdom 9. BGR, Germany 10. CEA, France	Unfunded Partners: -
RMG: -		