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 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.

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.

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/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 represented the first consolidated attempt to address the identified needs across the three technologies of airborne acoustics, seismology and underwater acoustics.

Prior to start of this project, the capabilities for primary calibration across all three technologies was limited to low frequencies by the performance of available facilities and by the lack of scientific knowledge to extend them further. The project has overcome these limitations and gone beyond the state of the art by delivering new calibration capabilities in all three technologies (i.e. airborne acoustics, seismology and underwater acoustics) covering the targeted frequency ranges, with detailed uncertainty estimates, and each validated by intercomparisons. *(Objective 1)*

Further to this, laboratory based secondary calibration methods covering the same targeted frequency ranges and suitable for a wider range of sensors, have been developed by the project and validated in all three technologies. However, laboratory-based calibration capability represents only half of the solution, as field calibration, or so-called *on-site calibration* of sensors is necessary at periodic intervals to maintain traceability. Therefore, the project has identified suitable sensors compatible with the new laboratory calibration methods *and* suited to field use that can be used as transfer standards*. (Objective2).*

Methods for on-site calibration have also been evaluated by the project by using access to live monitoring stations. In the case of seismic sensing, the project has demonstrated this for the first time with a transfer standard sensor with traceable calibration. Furthermore, the impact of installation conditions and the operating environment have been studied by the project, including sensitivity to environmental parameters, ground-coupling and other installation influences on seismometer, as well as the effect of water depth on hydrophone performance. *(Objective 3)*

The high-level benefits of the technical developments are measurement traceability and new insight into measurement uncertainty. Both improve data quality and confidence in the information drawn from it. This project has gone beyond the state of the art by linking data from environmental monitoring activities to the SI, which demonstrates that it is physically meaningful, globally consistent, impartial and defendable. The project has also produced case studies which have successfully demonstrated the value of the new developments and highlighted further benefits including the ability to detect and correct for defects in sensor systems, and to optimise deployment strategy. *(Objective 4)*

Results

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.

In the case of microphones (which measure airborne sound) and hydrophones (measuring sound in water), absolute calibration methods 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 fully estimated measurement uncertainties. The project has developed unique and innovative facilities such as the carousel system for microphone calibration at partner PTB and the calculable pistonphone for hydrophone calibration at partner NPL, which are the world's first such capabilities.

For seismometers (which measure vibration in the ground), 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 now be used to calibrate seismometers in the frequency range from 10 mHz to 20 Hz (the target range for Objective 1).

Intercomparisons on primary calibration were conducted by the project for all three technologies (i.e. airborne acoustics, underwater acoustics and vibration (seismic) sensing systems). Notably, these intercomparisons include comparisons not only of capabilities in different laboratories, but sometimes between calibration methods using different physical principles. For microphones, the results were found to be generally consistent across the entire frequency range, with only a few isolated exceptions. The same was true for hydrophones, with the exception of 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.

The intercomparison of seismometers featured three models of differing designs. The intercomparison results revealed several difficulties with issues noted across the frequency range, limiting the extent of the analysis. At low frequency remanence of tilt influences were also observed. Results at mid-frequencies were generally 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. From these intercomparison results significant knowledge was learned that will inform such studies in the future.

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

Methods of primary calibration are often restricted by the types of sensors that can be calibrated. However, they can also provide the reference device for calibrating a wider range of sensors by comparison or secondary calibration methods. Indeed, secondary calibration is often the best economic solution for routine services. The project has developed laboratory-based secondary calibration facilities at partners PTB, LNE, DFM, CEA, NPL, TUBITAK operating in the same low frequency range as for primary calibration. The laboratory-based secondary calibration facilities can calibrate microphones and microbarometers, seismometers, hydrophones and ocean noise recording systems. One such facility (at partner PTB) is even capable of accommodating a complete measuring instrument such as a sound level meter within the infrasound field, as necessary for assessments of low frequency noise nuisance.

The calibration of microphones and microbarometers, and of hydrophones have also been 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.

In addition, the project has developed specifications for a class of sensor capable of operating effectively in both laboratory conditions and in the field; so-called transfer standards. 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 Comprehensive Nuclear Test Ban Treaty Organization (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. These seismometers were used extensively as references devices in the laboratory intercomparisons, too.

To support the measurement of potentially annoying or disturbing low-frequency environmental noise, the project created a document in which it has collected all existing national requirements and guidelines for infrasound measuring instruments; the first attempt anywhere to produce a global set of requirements. These initial findings on infrasound measuring instruments were presented to the committee responsible for standardisation in this area, IEC TC 29, prompting a request from IEC TC 29 for the project to further outline the requirements to progress the topic. Thus, the project produced a draft set of testing procedures, including both acoustic tests of the microphone and electrical tests of the signal processing features, have been prepared readiness.

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.

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. A series of case studies were formulated and carried out by the project at a station in Germany that was already active in infrasound and seismic monitoring. Equivalent studies in hydroacoustics, would necessitate ocean trials which were beyond the scope of the project, so case studies were restricted to modelling and feasibility assessment.

The practical 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 stakeholder CTBTO in testing its findings, in future trials of on-site calibration in the ocean.

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.

While the work in Objectives 1-3 evaluated 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 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.

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 International Monitoring System (IMS), it is these decisions that ultimately matter.

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 has been made available on the project website and describes the elements underpinning the recommendations and using the case studies mentioned above as illustration.

For another important application of infrasound measurement, the project carried out a case study at two wind energy generating sites in Germany. 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 (commonly used in general environmental noise assessment) and microbarometers (common in geophysical applications) for comparison. 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. The project's outcomes can now be used to inform end-users on matters such as specifying appropriate instrumentation and measurement protocols.

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=7ixPlWafEOU
- 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/lIllew1cTrc?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.

List of Publications

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

Project start date and duration:	01 Sep 2020, 40 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, Türkiye	External Funded Partners: 8. ASN, United Kingdom 9. BGR, Germany 10. CEA, France	Unfunded Partners: -
RMG: -		