EMPIR JOINT RESEARCH PROJECT December 2023

INFRAAUV News

NEWSLETTER NUMBER 4

CONTENTS

WELCOME

Dear Reader,

All good things must come to an end, and so it is with our joint research project. You have in front of you, the fourth and final Newsletter from the Infra-AUV project.

With a short extension to the original duration, our collaborative work has enjoyed a runtime of 40 month in total. However, since no piece of work is ever truly completed, I am confident that the partners will continue to collaborate and further develop the topics beyond the formal end of the project. The feedback we received on our work over the last period was so significant and encouraging, that we will surely proceed to implement and build upon the capabilities that are now in place, in further support of the traceability chain concept from primary calibration laboratories to the field measurements for very low frequency measurements. Whether this will happen in a new project or as individual informal collaborations is still an open question.

Within this newsletter, you will once again find a representative sample of our recent accomplishments covering most aspects within the scope of the project. To name a few, we will introduce several successfully implemented methods of primary acoustic and secondary hydro-acoustic calibration in the laboratory. We tell you about the influence of surface coupling in seismometer calibration, and the effective coverage area offered by a reference seismometer when used as a calibration reference at a seismic station. We venture into legal metrology in terms of type approval for sound level meters used for environmental noise and nuisance assessment, and into the field of measurement uncertainty of acoustic field quantities. Last but not least, we will give details of a comprehensive guidance document openly available from our website, that may help you to find out more.

We hope you find the news and related information in “the guide” as exciting as we found the joint research over the timeframe of the Infra-AUV project. Thank you for your interest and please feel free to contact us for more information any time.

- Thomas Bruns, project co-ordinator

THE CONSORTIUM

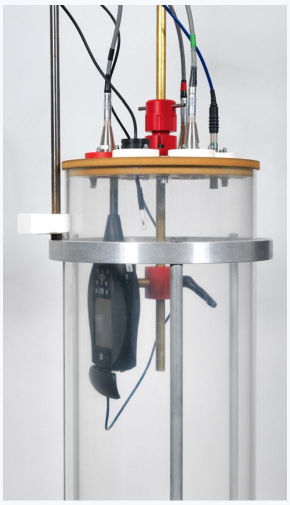
This consortium brings together a wide range of expertise and leading skills found within the partner organisations and comprises national metrology institutes (NMIs) and designated institutes (DIs) who are complemented by a number of research institutes and IMS station operators representing the expertise needed from the stakeholders.

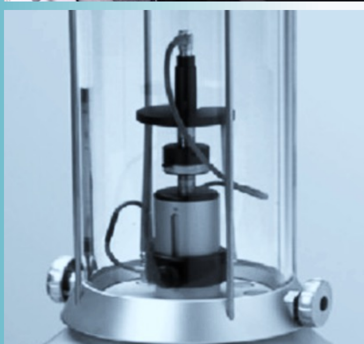
PTB, Germany
HBK, Denmark
CNAM, France
DFM, Denmark
LNE, France
NPL, United Kingdom
TUBITAK, Turkey
BGR, Germany
CEA, France
ASN, United Kingdom

NEWS IN BRIEF

NEW CALIBRATION CAPABILITIES

A high-level objective in the project was to develop new primary standards and calibration methods for their dissemination, across all three technologies. Several calibration facilities for infrasound sensors and sound level meters for low frequency environmental noise measurement have now been established. Primary measurement standards established at LNE, PTB and HBK cover the frequency range from 10 mHz to 20 Hz, which can be utilised directly for the calibration of microphones and barometers. These institutes also have new or improved secondary calibration methods suitable for a wider range of sensors including microbarometer. For hydroacoustics, a new primary standard at NPL based on a calculable pistonphone provides primary measurement standards from 0.5 Hz to 250 Hz and can be used directly for smaller hydrophone models. For larger devices including ocean noise recorders, a comparison coupler is available for secondary calibration against a reference hydrophone. Measurement systems for seismometer have also seen significant development and the launch of new calibration capabilities from 10 mHz to 20 Hz are planned for the near future.





SECONDARY HYDROACOUSTIC CALIBRATION

NPL has recently exploited the newly developed primary calibration capability for hydrophones based on a calculable pistonphone, to transform its secondary calibration methods. Of necessity, this has used a reference microphone in the past and was therefore traceable to measurement standards for *airborne* sound pressure. The microphone can now be replaced rightfully, with a reference hydrophone.

In generally, primary calibration of hydrophones, whether by calculable pistonphone or coupler reciprocity, is usually limited in the range of hydrophone designs that can be calibrated. Indeed it is often the case that coupler reciprocity is limited to the calibration of bespoke hydrophone designed specifically individual implementations of the method.

This creates difficulties when contemplating international key comparisons organised by the International Bureau of Weights and Measures (BIPM) to support the global measurement system, because no single hydrophone design is compatible with all the different realisations of primary calibration around the world. This issue was discussed at a recent meeting of the Consultative Committee for Acoustics, Ultrasound and Vibration (CCAUV), where it was recognised that secondary calibration methods have greater flexibility in the devices that can be calibrated. It was subsequently agreed that secondary calibration methods offer the best opportunity for future intercomparisons of calibration capability for hydroacoustics, a strategy partly informed by the Infra-AUV project.

SUMMARY OF INFRA-AUV PUBLICATIONS

Without exception, the scientific developments originating from Infra-AUV have been, or are in the process of being, published as journal papers and articles. The policy during the project has been to only submit to open-access journals, so that all published material is now freely available. So far, 10 journal papers have been published, with more in the pipeline. Details and links to the full publications are available on the project website, and will be updated as new papers are published.

We have also been active in presenting the work at several national and international conferences. Despite the hindrance of the Covid pandemic, over 40 papers have been presented at prominent conferences dedicated to acoustics and vibration technologies, and geophysical applications. Again, full details will remain available on the project website.

Follow this link to all Infra-AUV publications

RESEARCH HIGHLIGHTS

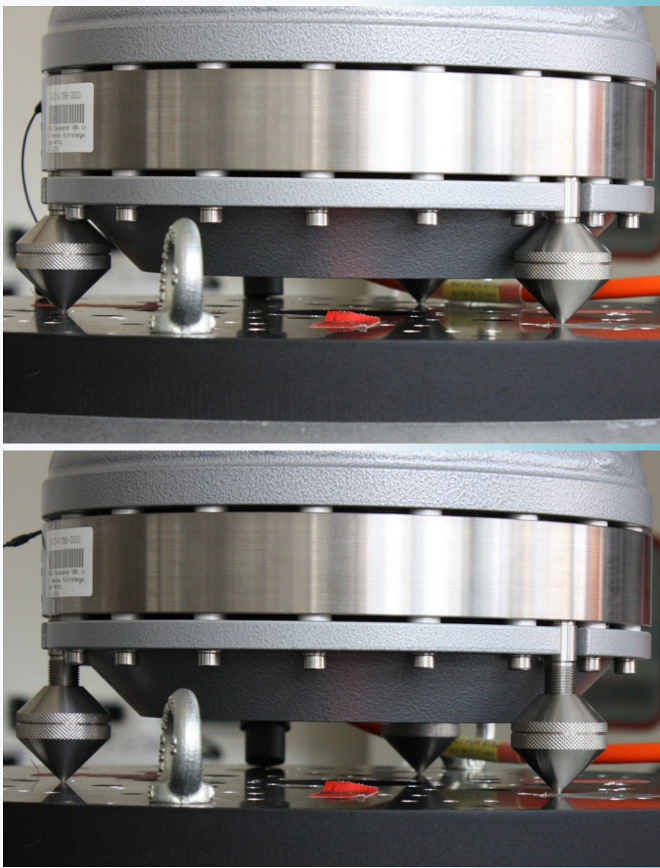
INFLUENCE OF THE FEET AND THE GROUND MATERIAL ON THE DYNAMIC BEHAVIOUR OF SEISMOMETERS

To analyse possible influences of feet height and of different ground materials on the dynamics of seismometers, several experiments have been carried out with one seismometer. The seismometer chosen for this purpose was a reference broadband seismometer Streckeisen STS 2.5. The frequency range of 1 Hz and 20 Hz was chosen, to focused on the the range where effects were expected.

The three adjustable feet of the seismometers were extended in 5 mm steps to analyse the behaviour. It was found that the sensitivity in the horizontal axes at higher frequencies increased compared to the expected levels. This effect became more profound, the further the feet were extended, yet the vertical measuring axis remained largely unaffected.

In a different experiment, the nut securing the feet from moving was not locked. This resulted in an even more profound increase in horizontal axis sensitivity, even when the feet were not extended. Again, the vertical axis was hardly affected.

This shows the importance of proper installation on site and is consistent with guidance in the manufacturer's user manual stating that the nuts should be locked and that the feet should only be extended as far as necessary for the levelling.



Mounting feet in 'factory' configuration (above) and fully extended (below).

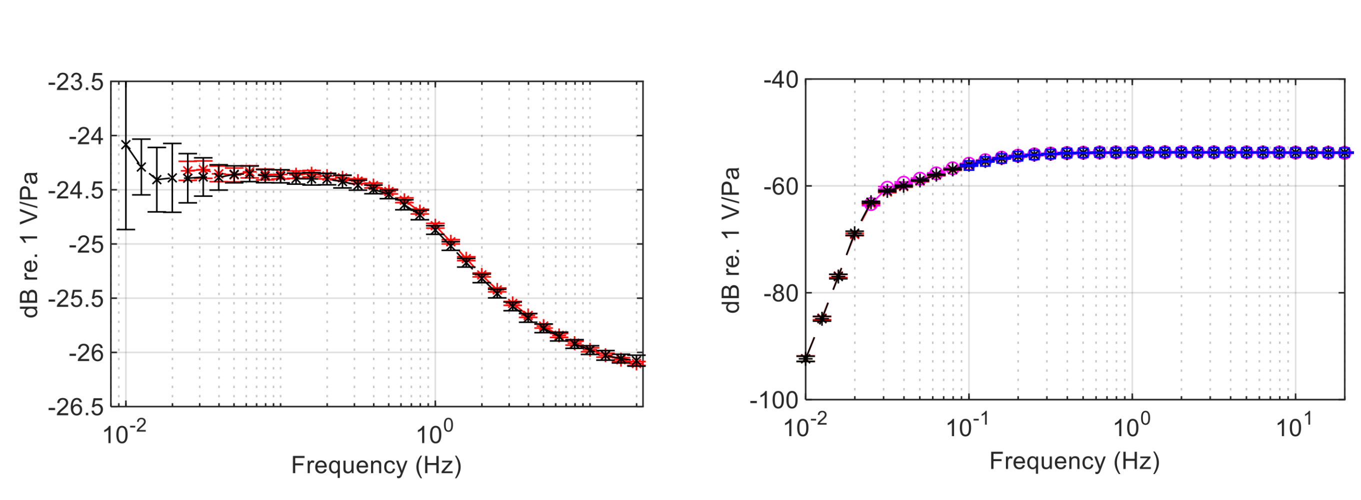
In a second step, the vibration exciter used for the calibration of seismometers was equipped with plates of different materials to analyse the influence of different ground stiffnesses. Five different materials were analysed: wood, aluminium, stainless steel, a glass plate placed on sand, and concrete. The wooden plate showed a significant increase in the sensitivity in all axes of measurement at the higher frequency, the glass plate was the second strongest increase (already only visible in the horizontal axes). The aluminium and the steel plate were very similar showing the smallest increase. The concrete seems to be a little more compliant than the metal plates, but still behaves very similar.

These results show that a calibration carried out on a metal plate can be transferred on site to a vault with rock or concrete floor without significant effects. Softer ground materials, however, can have significant effects which have to be taken into account.

AN INTERCOMPARISON OF INFRASOUND CALIBRATION CAPABILITY

One of the critical final stages in the project involves ensuring the validity of the calibration results provided by the various developed systems. For this purpose, two comparisons were organised in the infrasound field.

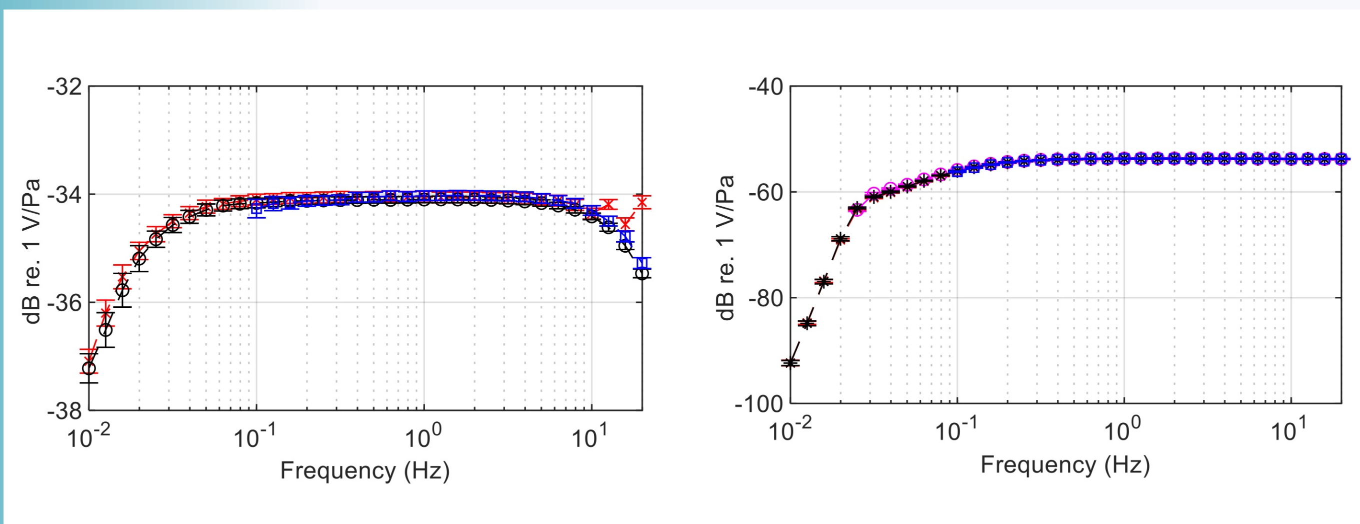
The first comparison, denoted INFRA-AUV_A.C1 concerned primary calibration methods. The participating laboratories were HBK-DPLA (Denmark), LNE (France) and PTB (Germany). The standards circulated among the laboratories were two B&K Type 4160 and two B&K Type 4193 microphones.



Left: *Open-circuit pressure sensitivity level (dB re. 1 V/Pa) and uncertainties (dB) of HBK-DPLA (red crosses) and LNE (black stars) for one B&K 4160 microphone.* ***Right***: *Pressure sensitivity level (dB re. 1 V/Pa) and uncertainties (dB) of LNE (black stars) and PTB (blue crosses) for one B&K 4193 microphone*

Due to technical limitations in calibration systems, HBK-DPLA provided results for the B&K 4160 microphones, PTB for the B&K 4193 microphones, and LNE for both type of microphones. Therefore, the comparison consisted finally in two bilateral comparisons. The plots above show examples of the collated results and uncertainties for the pressure sensitivity level (magnitude only, although phase was also determined)), from all participating laboratories. The reported sensitivities level and phase have been analysed using the normalized error as the performance criterion. In summary, with only a few isolated exceptions, the normalized errors consistently fall within the satisfactory range indicating a robust comparability between the laboratories and the calibration methods.

The second comparison, denoted INFRA-AUV_A.C2 was concerned with secondary calibration methods. The participating laboratories were CEA (France), HBK-DPLA (Denmark), LNE (France) and PTB (Germany). The standards circulated among the laboratories were two Martec Type MB2005 microbarometers and two B&K Type 4193 microphones. The plots below show an example of the collated results and uncertainties, from all participating laboratories. The reported sensitivities have been analysed using a least-squares technique. Apart from a few cases of observed inconsistencies, where reasons are understood, the measurements were shown to be consistent with the comparison reference values, indicating a robust comparability between the laboratories and the calibration methods.



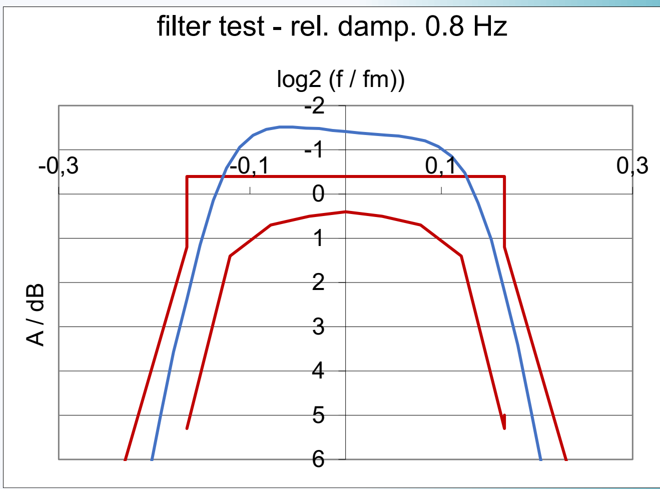
Left: *Pressure sensitivity level (dB re 1 V/Pa) and uncertainties (dB) of CEA (red crosses), LNE (black stars) and PTB (blue squares) for one MB2005 microbarometer.* ***Right***: *Pressure sensitivity level (dB re. 1 V/Pa) and uncertainties (dB) of CEA (red crosses), HBK-DPLA (magenta circles), LNE (black stars) and PTB (blue squares) for one B&K 4193 microphone.*

APPLICATION FOCUS

DEVELOPMENT OF TEST AND VERIFICATION METHODS FOR THE ELECTRICAL PROPERTIES OF SOUND LEVEL METERS AT FREQUENCIES FROM 1 Hz TO 20 Hz

The traceable and reliable measurement of sound in the infrasound frequency range is of increasing relevance. A very general and basic prerequisite of such a measurement is the availability of tested and approved devices fulfilling internationally accepted regulations and standards. Unfortunately, currently available type-approval methods, techniques, and regulations, developed for devices working in the audible frequency range cannot be simply transferred in the infrasound and low-frequency range. Thus, in the Infra-AUV project, first activities were made to develop a basis for the installation of a system of regulated and reliable device operation for on-site measurement.

After proposing requirements and specifications for sound measuring devices and their testing and type approval at low frequencies and infrasound, particular testing methods were developed and applied to microphones and sound level meters which are able to process acoustic input at infrasound frequencies.



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

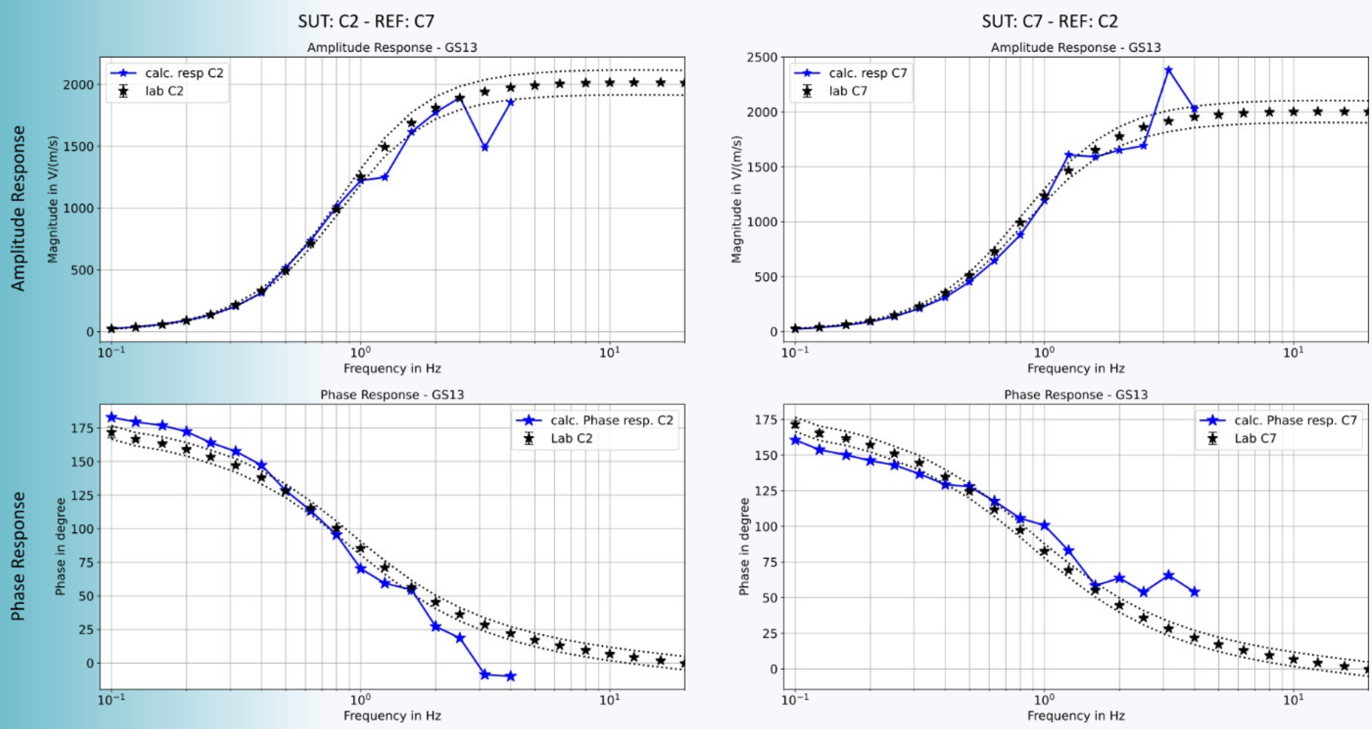
A first set of methods was developed for electrical measurements as one of the most important and time-consuming part of an approval. Six electrical issues, for example; the testing of the bandpass filters, the weighting functions, and the level linearity, were covered by the development of specific test methods. To investigate their validity and relevance they were applied to two devices which were generally able to handle infrasound frequencies. The plot above shows the measured filter damping of a third-octave band filter as an example. The plot clearly shows that the acceptance limits are exceeded, proving the relevance of the testing procedure. The results obtained for all electrical issues involved were analysed, and specifications and challenges of the newly developed methods have been compiled. These will be proposed as the basis for future development of international standards for the type approval of low frequency noise instrumentation.

ON-SITE CALIBRATION OF A SEISMOMETER ARRAY – OPTIMUM DEPLOYMENT OF REFERENCE SENSORS

The Gabrielson-Charbit method (see Newsletter 3) now provides the methodology for on-site calibration of two co-located broadband seismometers. However, seismometer stations are often array stations with more than one seismometer distributed over a given area. Therefore, experiments were carried out at the German IMS station PS19, to find out whether all these array seismometers need to be equipped with a reference sensor, or whether it will be possible to use the method to calibrate seismometers located at greater distances with a small number of distributed reference sensors.

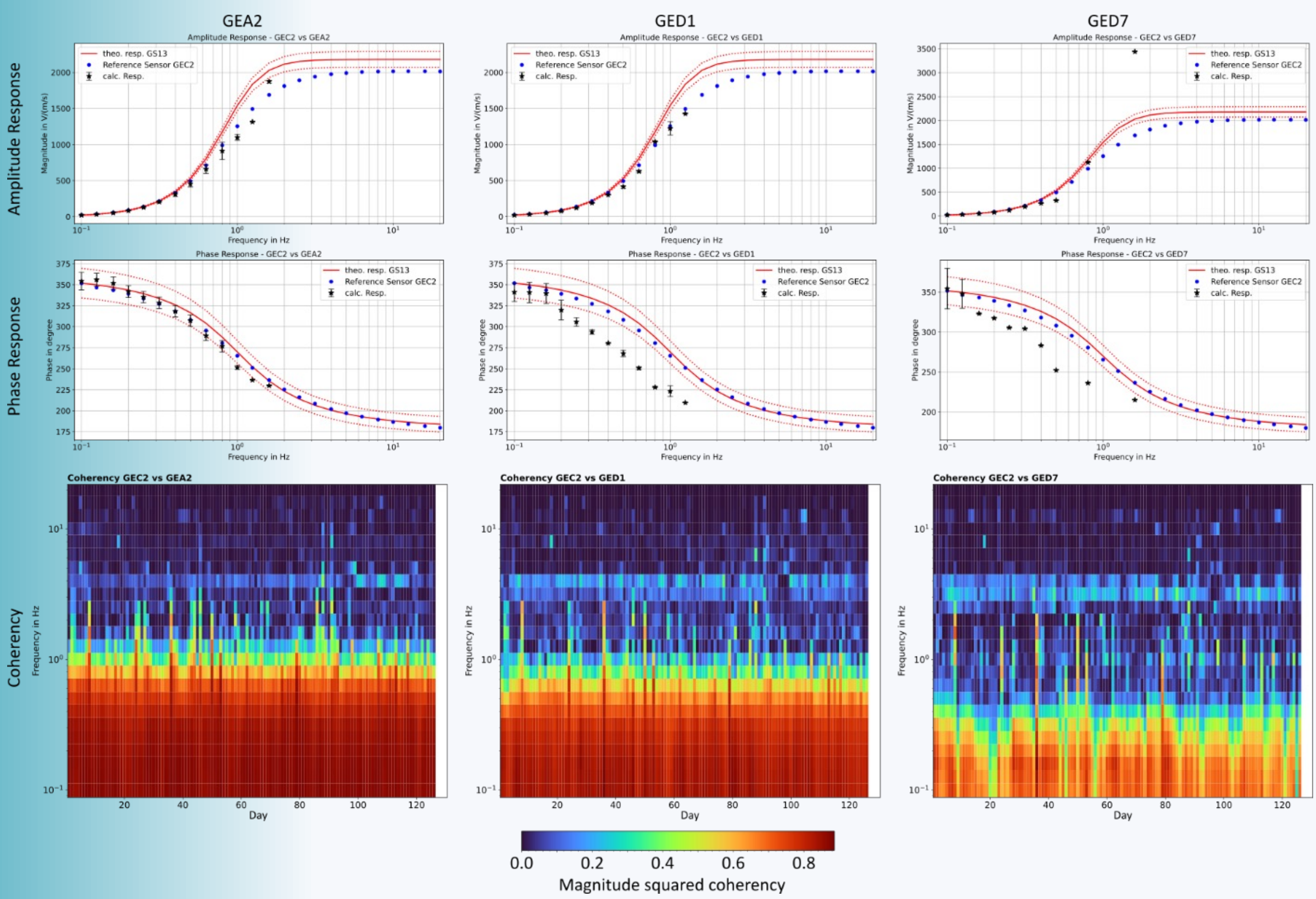
For the first experiment, two calibrated vertical short-period seismometers were installed at a distance of approximately 1400 m. Using one of these sensors as a reference and the other as the sensor under test (as well as the other way around), the plot below compares the amplitude and phase response obtained by the Gabrielson method (blue lines), with the laboratory values (black asterisks).

For frequencies below 1 Hz, the amplitude response values of the test sensor fit well with the laboratory values. However, there are deviations larger than 5°



observed for the phase response. Note that when the reference – test sensor pair are exchanged (right column), the phase deviations are mirrored. This indicates an influence of the travel time of the signal between the sensors.

Subsequently, the question of the maximum distance that the reference can be installed from the test sensor arose. In the next step, one of the calibrated sensors is used as reference for all other 25 array short period seismometers of the station PS19, Germany. Following the Gabrielson-Charbit method, the complex gain ratios and the corresponding amplitude and phase responses were determined and averaged for four days in 2023 that showed high cross-array coherency values. Note that on these days major earthquakes occurred.



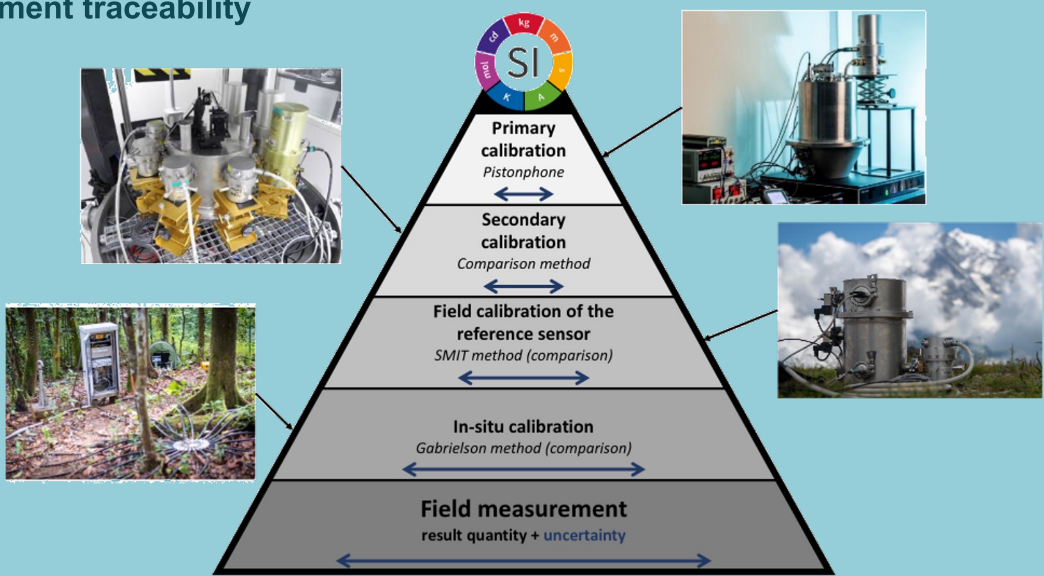
These plots show the results for three sensors (GEA2, GED1, GED7) in varying distances (722m, 1000m, 2900m) to the reference sensor. In the top and middle rows, the amplitude and phase responses are shown (black asterisks), respectively, and compared with the nominal values (red) and the reference sensor (blue dots). The bottom row shows the coherency for each given pair over a 130-day period.

These preliminary results show that for low frequencies (f ≤ 1Hz) promising results can be obtained, especially regarding the amplitude response. The phase response of one sensor lies within the expected range, whereas the other two sensors show large deviations from the expected values. This might be caused by the distance between the sensors. As the signals travel across the array, they are recorded by the sensors with a time shift relative to their distance, resulting in a phase shift in the response determination.

Regarding the requirement of signal similarity, there is a division into two parts when the coherency is considered. The low frequencies (0.1 – 1 Hz) are characterized by a high coherency (red colours) across the whole array, whereas frequencies greater than 1 Hz show very low coherency values (blue colours). This indicates that the local noise at the sensor dominates, and only little usable signal is observed within this higher frequency ranges across the array. The coherency is a good indicator of the distance between the field and reference sensors, as it decreases with distance. As a result, for the given array, the maximum distance range between reference and test sensor is approximately 1500 m. This means that, in all probability, there is no need for an individual reference for each seismometer, but an array station such as PS19 can be calibrated with a minimum of five reference sensors. Note that this number is both site as well as signal dependent and requires further investigation.

Ongoing investigations will look in more detail at the usage of certain signals or events that are distributed in all azimuthal directions to mitigate the effect of time delays and thereby phase shifts between the individual sensors. Furthermore, the travel times of signals between individual sensors may be corrected for the time delay to obtain more correlated and coherent signals for the analysis. Further challenges to overcome are the digitizers, which are currently not yet included in the calibration chain, therefore solely the nominal values are considered. Any deviation from that will be reflected in the obtained response values.

Measurement traceability



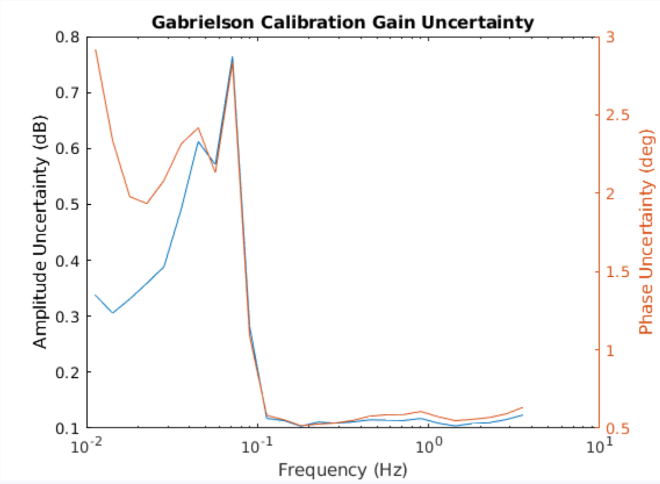
Traceability pyramid linking field measurements to the International System of Units (SI), thus showing how uncertainties in field measurements in inherited from each step, all the way up to the definition of the SI. The arrows represent the order of magnitude of the measurement uncertainties at each step.

This process is illustrated in the next article…

INFRASOUND UNCERTAINTY PROPAGATION: FROM THE LABORATORY TO THE FIELD

In order to make measurements in physically meaningful units, that is to say SI (Système Internationale) units, it is necessary to use instrumentation with calibrations that link to this system. In addition, parameters are sometimes derived indirectly from separate component measurements. A simple example of this would be speed, as it is typically measured by determining the time it takes to travel a distance. This is very similar to the methods used to measure the direction of an incoming infrasound wave, by measuring the differences in arrival time at several different sensors with known locations in an array.

Therefore, to determine the correct amplitudes in pascals, but also the correct speed and direction of arrival, it is necessary to have an unbroken calibration chain such as that shown in earlier panel (see above). In this case, primary and secondary calibrations of a microphone allow for a traceable standard to the field calibration of the reference sensor, for example using SMIT (Système de Métrologie Infrasonore de Terrain; in English: Field infrasound metrology system - see Newsletter 3). This calibrated reference sensor then provides a traceable calibration of the sensor-under-test via a comparison calibration using the so-called Gabrielson-Charbit method (see plot below). Once all of the sensors in the station array are calibrated in this manner, the corresponding calibration uncertainties are propagated to the horizontal velocity and back-azimuth outputs by using a Monte Carlo simulation.

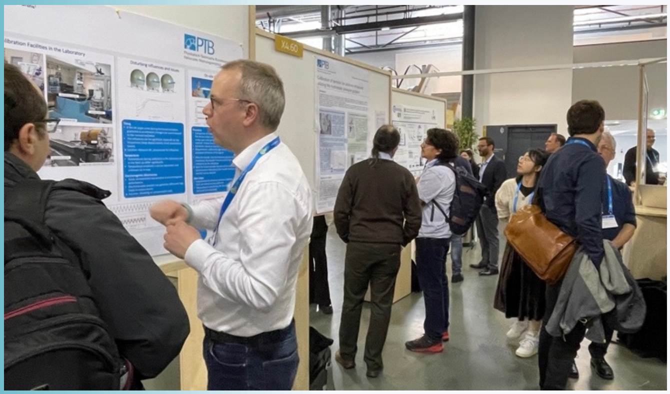


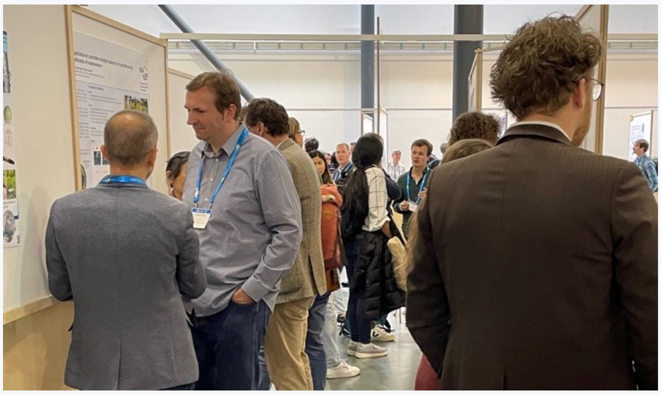
Gabrielson-Charbit calibration gain uncertainty for the sensor-under-test. The amplitude uncertainties (blue) are provided in dB relative to the total calibration response, and the phase uncertainties (orange) are provided in degrees.

STAKEHOLDER ENGAGEMENT

INFRA-AUV POSTERS FEATURE AT EGU2023

The Infra-AUV project team chose the European Geophysical Union General Assembly (EGU2023) to present a series of posters charting several project achievements from primary laboratory calibration through to field trials illustrating the application and benefits of on-site metrology. EGU2023 was held in Vienna from 23-28 April 2023 and attracted a staggering 15,000+ attendees. The poster presentations were part of a wider session on the International Monitoring System and On-site Verification for the CTBT, disaster risk reduction and Earth sciences.





EGU General Assembly 2023

The session at EGU 2023 was extremely popular with the collection of posters from the Infra-AUV project providing a focus for visitors on the various aspects of the project. Although the conference covered a diverse set of themes, there was significant interest in seismo-acoustic monitoring and the Infra-AUV related metrology and calibration approaches for these technologies, seeing a steady stream of visitors to the posters throughout the 2 hours designated to the session. For those who did not attend EGU2023, the posters are available on the Infra-AUV website.

THE INFRA-AUV TEAM AT THE CTBTO SCIENCE & TECHNOLOGY CONFERENCE 2023

The Comprehensive Nuclear-Test-Ban Treaty Organisation (CTBTO) regards quality assurance as a high priority in the global monitoring for signs of nuclear testing. Metrology is central to this initiative resulting in synergies between the CTBTO and the Infra-AUV project. Supported in part by the Infra-AUV project team, metrology featured strongly in the CTBTO Science and Technology Conference SnT2023, even at the highest levels. In his opening address CTBTO Executive Secretary, Dr Robert Floyd discussed at length the vital role of measurement and standards, not just in science and technology, but in nearly all aspects of life, commenting that "*There is no measurement without and agreed standards*…". What better vindication for the Infra-AUV project, that has developed the very standards needed for infrasound, hydro- acoustic and seismic measurements.

Then, an Expert Panel was assembled to discuss the topic "Operating the IMS in the Framework of the International System of Units", which was preceded by an invited talk by Dr Takashi Usuda, Executive Secretary of the International Committee on Weights and Measures (CIPM), entitled "International Equivalence – a Fundamental Backbone for the IMS".

Dr Usuda was joined in the panel by Infra-AUV project team members Dr Thomas Bruns and Dr Franck Larsonnier, and Dr Lind Gee and Dr Svetlana Nikolova representing network and station operators. Dr Richard Barham (also from Infra-AUV) was the panel moderator.

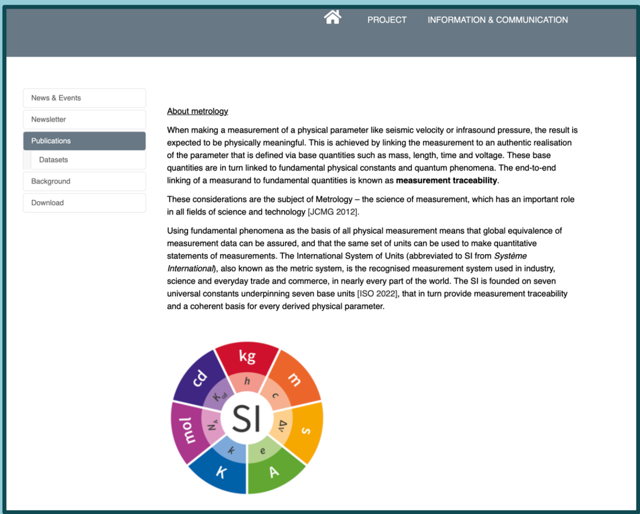
Project Workshop. Finally, SnT2023 was chosen as the host event for the project Workshop. Aimed principally at Station Operators, the workshop opened with coverage of basic metrology principles before presenting the achievements relating to the end-to-end calibration chain. Spread over two half-days, and with around 50 participants, a total of 10 presentations were made starting with primary and secondary laboratory calibration capabilities, and ending with on-site calibration developments, and the benefits of traceable calibration illustrated via the project case studies. Discussion opportunities were interspersed with the presentations and a selection of posters were on display to supplement the presentations.

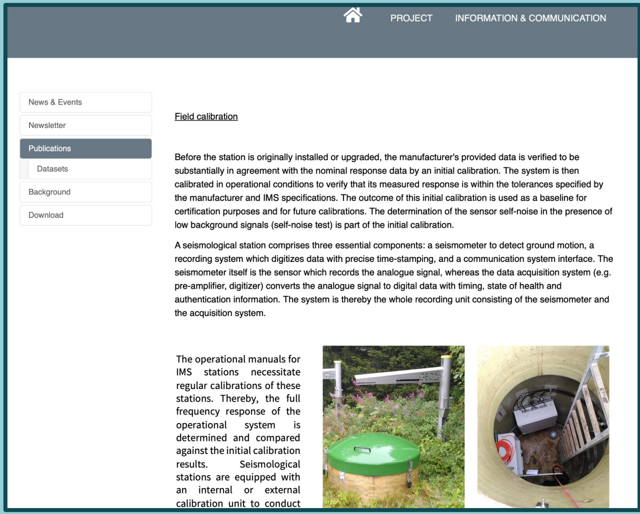
Watch the videos…
The SnT proceedings can be viewed on the CTBTO YouTube channel. You can view Dr Floyd's opening address here, Dr Usuda's presentation and the panel discussion here, or the workshop in its entirety here and here.

GOOD PRACTICE GUIDE

A Good Practice Guide has been prepared which aims to provide information for operators of the IMS and its stations, and by extension operators of other environmental measurement stations. The Guide collects all the technical developments from across the project, and provides a concise summary of each topic with links to the more detailed information for those that wish to access it.

Presented as a series of web pages, the Guide covers seismic, infrasound and hydroacoustic technologies individually, so that they can be navigated based on the needs and interests of the user.





Within each technology, there is information on primary and secondary laboratory calibration including newly available calibration capability. The project case studies have provided new insights into the possibilities for field calibration, and these are also featured strongly in the Guide. Throughout, references are provided to the body of open-access publications and presentation material arising from the project. Recommendations are then presented aimed at enhancing existing sensor system deployment practices and the associated underlying quality system.

The Guide can be accessed at the Infra-AUV website and will remain online for the foreseeable future.

TEAM MEMBER ‘BUSINESS CARD’

DFM

Danish National Metrology Institute

DFM is the Danish National Metrology Institute and contributes to the integrity, efficiency, and impartiality of the International Metrology System. DFM is also responsible for coordinating the Danish metrology infrastructure. DFM is a fully owned subsidiary of DTU, the Technical University of Denmark.

DFM’s scientific research results in new knowledge, measurement techniques and standards, which support the needs of Danish industry and authorities for accurate measurements. The services offered by DFM are high-level calibrations and reference materials traceable to National Primary or Reference standards, training courses related to metrology and consultancy services. DFM has a special role in developing measurement capabilities needed by small and medium sized high-tech companies in order for them to evolve and prosper. DFM works to ensure global confidence in Danish metrology services, which are critical for competing in the global marketplace.

Diversity, inclusion and a global outlook are important to DFM for expanding its strongholds in research. It is the view of DFM that diverse teams perform. DFM aims to ensure that metrology supports sustainability through new standards and regulations that guide the sustainable development of products, services and processes, via reliable and widely accepted measurements.

Concerning the field of Acoustics, there has DFM been an active participant in International Cooperation, both as a participant of Metrological coordination in Europe via EURAMET's Technical Committee for AUV, and in the international context at the International Bureau for Weights and Measures (BIPM), via the Consultative Committee in AUV (CCAUV). DFM has participated in several European projects related to Metrology for supporting audiometric measurements and hearing assessment, and another related to low-frequency calibration of hydrophones.

dfm.dk

le cnam Conservatoire national des arts et métiers

The Conservatoire national des arts et métiers (le cnam) is a French public institution of higher education and research with a scientific, cultural, and professional focus under the supervision of the Ministry of Higher Education. It was founded in 1794 by the Abbé Grégoire to promote the development of science and technology in France. Le cnam has three main missions:

- provide lifelong learning opportunities to all
- develop excellence in technological research and innovation
- disseminate scientific and technical knowledge

Le Cnam proposes study courses which are developed in close collaboration with companies and professional organizations to respond to their needs and to those of their employees.

In France, scientific and industrial metrology studies and research have historically been carried out by several laboratories belonging to different public or private bodies. Since 2005, the French government has entrusted LNE with the responsibility of managing and coordinating the network of laboratories that make up French metrology (Réseau National de la Métrologie Française - RNMF). This network comprises 10 laboratories: the French National Metrology Laboratory, LNE, and nine other Designated Institutes (DIs) at national and international level for specific fields. LNE-LCM at le CNAM is one of these laboratories. The LCM's metrological activities focus on four areas corresponding to the four basic units of the International System of Units (SI): kilogram and related quantities, meter, candela and kelvin.

In the scope of the project Infra-AUV, an innovative technique based on the use of a Fabry-Perot refractometer, where air density variations related to an acoustic wave can be tracked and determined by measuring the optical frequency variations of a laser locked onto a longitudinal mode of the Fabry-Perot cavity has been developed to measure acoustic pressure. In this project, CNAM has demonstrated the feasibility experiment for the primary calibration of infrasound sensors over a range from 40 mHz to 5 Hz using such a technique. Temperature variations induced by the acoustic process present a significant hindrance to the method. An analytical model has been developed to correct the effect of the acoustically induced temperature caused by the propagation of the sound wave. This correction works satisfactorily in both phase and amplitude, except in the transition between the quasi-isothermal and quasi-adiabatic regimes. A more detailed model accounting for the behaviour in the transition region is needed to improve accuracy of the measurement.

cnam.eu

InfraAUV

Metrology for low-frequency sound and vibration

September 2020 – December 2023

Thank you for your interest in the project

CONTACT US

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EMPIR EURAMET
The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States