Bureau International des Poids et Mesures

Consultative Committee for Acoustics, Ultrasound, and Vibration (CCAUV)

Strategy 2021 - 2031

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Strategy Document

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Executive Summary

The Consultative Committee for Acoustics, Ultrasound, and Vibration was established in 1999 to ensure that the quantities relevant to sound and acceleration metrology are realized and disseminated worldwide in a uniform and appropriate manner. Though the measurement units that the CCAUV supports are not base units of the International System of Units (SI), they have a direct relationship to public safety, health, and national security. The CCAUV carries out key comparisons to support measurements related to sound in air and water, ultrasound, and acceleration based on sinusoidal and shock excitation. Member laboratories also carry out comparisons at the regional level and through participation in and reporting on bilateral comparisons between laboratories.

The CCAUV has no excessive work in progress for reviewing current CMCs but plans to pursue a risk-based assessment approach towards reviewing them in the future. The planning process for consultative committee-level key comparisons (CCKCs) involves careful deliberation to optimize resource requirements needed to respond to the needs of its stakeholders. Some mature key comparisons (KCs) have now reached the stage where repeats of CCKCs, normally in a 10-year cycle, are being conducted to assess them as well as to extend their calibration range. Efforts to catch up the calibration capabilities emerging NMIs are underway, however, their calibration capabilities must first be confirmed by regional metrology organization (RMO). Before proposing new CCKCs, the CCAUV's approach is to hold pilot comparisons to review their feasibility, the adequacy of the technical protocol, and the calculation process used to determine the reference value.

As stakeholders of the CCAUV are diverse, traceability to end users can be guaranteed only if the secondary calibrations at the level of accredited and non-accredited calibration and testing laboratories and measurement protocols at user level are adequately followed. Guide documents, available from the IEC and ISO, are referred to in our KC protocols to be followed by our stakeholders and users. Thus, the CCAUV keeps close interaction with the relevant technical committees (TCs) in the IEC and ISO, as well as with regulators for occupational safety, environmental safety, traffic authorities, as well as others as needs arise.

1. General Information on CCAUV

1.1 Administrative Information

- Consultative Committee for Acoustics, Ultrasound, and Vibration (CCAUV)
- Established in 1999
- President: Dr. Hector Laiz (INTI), since 2019
- 18 members, 12 observers, and 3 liaisons
- CCAUV meets every 2 years
- Last meeting was held 24 to 27 September 2019
- 51 participants at last meeting (experts included)
- 17 CC-KCs and 24 RMO-KCs carried out from 1999 to 2021
- 4 Pilot Studies were carried out from 1999 to 2021
- 1299 CMC entries are published in KCDB of which 205 from the last CCAUV meeting.

1.2 Working Groups

The CCAUV has 3 Working Groups (WGs) that typically meet every two years, in conjunction with the CCAUV plenary meeting.

- CCAUV Working Group on Strategic Planning (CCAUV-SPWG)
- CCAUV Working Group for RMO Coordination (CCAUV-RMO)
- CCAUV Working Group for Key Comparisons (CCAUV-KCWG)

1.3 Key Comparisons

The CCAUV has carried out 17 key comparisons (KCs), three repeats of KCs, and two are in progress. *Table 1* below shows a listing of them as well as a summary description. More information can be found on the online Key Comparisons Database (KCDB).

Table 1. Listing of Key Comparisons with links to the CCAUV key comparison database carried out and in progress since the inception of the CCAUV

Key Comparison	Description	Date
CCAUV.A-K1	Comparison of laboratory standard microphone calibrations, 63 Hz to 8 kHz	1999 - 2001
CCAUV.A-K2	Comparison of laboratory standard microphone calibrations at low frequencies, 2 Hz to 250 Hz	2004 - 2005
CCAUV.A-K3	Comparison of laboratory standard microphone calibrations, 31.5 Hz to 31.5 kHz	2003 - 2006
CCAUV.A-K4	Free field sound pressure in air, 1 kHz to 40 kHz	2007 - 2008
CCAUV.A-K5	Comparison of laboratory standard microphone calibrations, 2 Hz – 10 kHz	2011 - 2012
CCAUV.A-K6	Primary pressure calibration of laboratory standard microphones LS2P, 20 Hz - 25 kHz	2019 - 2022
CCAUV.U-K1	Ultrasonic power, 1.9 MHz, 6.3 MHz and 10.5 MHz at 10 mW, 100 mW, 1 W, 10 W and 15 W	1999 - 2002
CCAUV.U-K2	Comparison of 1 mm hydrophone calibrations, 1 MHz to 15 MHz	1999 - 2003
CCAUV.U-K3	Ultrasonic power, 2 MHz to 15 MHz at 10 mW to 15 W	2008 - 2012
CCAUV.U-K3.1	Ultrasonic power, 2 MHz to 15 MHz at 10 mW to 15 W	2014 - 2015

Key Comparison	Description	Date
CCAUV.U-K4	Comparison of 1 mm hydrophone calibrations, 0.5 MHz to 20 MHz	2014 - 2016
CCAUV.V-K1	Vibration acceleration, 40 Hz to 5 kHz	2000 - 2001
CCAUV.V-K1.1	Vibration acceleration, 40 Hz to 5 kHz	2006 - 2007
CCAUV.V-K2	Vibration acceleration, 10 Hz to 10 kHz	2009 - 2012
CCAUV.V-K3	Acceleration complex sensitivity, 0.1 Hz to 40 Hz with specified acceleration amplitudes	2013 - 2015
CCAUV.V-S1	Angular acceleration, 0.4 Hz to 1 kHz	2012 - 2013
CCAUV.W-K1	Comparison of hydrophone calibrations for underwater acoustics, 1 kHz to 500 kHz	2000 - 2003
CCAUV.W-K2	Comparison of free-field hydrophone calibrations in water, 250 Hz to 500 kHz	2016 - 2021
CCAUV.V-K4	Accelerometer shock calibration, 500 m/s^2 to 5000 m/s^2	2016 - 2019
CCAUV.V-K5	Primary calibration of magnitude and phase of the complex sensitivity of accelerometers from 10 Hz to 20 kHz	2017 – 2021

1.4 CMCs

There is a total of 39 countries offering Calibration Measurement Capabilities (CMCs) adding up to a total of 1299 CMC entries published on the online CMC database (KCDB).

All 39 of the National Measurement Institutes are listed as offering airborne sound calibrations, most of which include LS1P and LS2P standard microphone, pistonphone, and sound calibrator calibrations. Three NMIs are listed as offering hydrophone calibration capabilities. Nine NMIs are listed as offering ultrasound calibrations related with ultrasonic power. Thirty-one NMIs offer vibration-based accelerometer sensitivity calibrations; four are listed as offering shock calibrations.

2. Terms of Reference

The CCAUV ensures that the quantities relevant to sound and acceleration metrology are realized and disseminated worldwide in a uniform and appropriate manner to establish and maintain global compatibility of such measurements through promotion of traceability to the SI. Sound and acceleration metrology include airborne sound, underwater acoustics, ultrasound, sinusoidal acceleration and shock acceleration, as well as inertial acceleration. Towards these ends, the CCAUV works to:

- Endow traceability by international collaboration and coordination;
- Identify, plan and execute key comparisons of national measurement standards;
- Harmonize contacts between Regional Metrology Organizations (RMOs) and survey issues related to CMCs in the framework CIPM MRA (cf. RMOWG);
- Identify advances in physics and engineering that directly influence AUV metrology;
- Provide a vision for short- and long-term strategy (cf. SPWG);
- Provide expertise to maintain AUV metrology at its highest level (cf. KCWG);
- Prepare recommendations for discussion at the CIPM.

3. Baseline (up to and including 2021)

The CCAUV was created in 1999. At the writing of this report 17 CIPM key comparisons (KCs) have been completed, 3 have been repeated, and 1 is in progress. In addition to this, 36 Regional Metrology Organization (RMO) key comparisons have been carried out. Two key comparisons are regionally complete, i.e. all active RMOs are linked within these areas. The CCAUV has now reached the stage where repeats of KCs are being carried out in addition to considering new ones.

The AUV designation signifies Acoustics (A), Ultrasound (U), and Vibration (V). The designation (A) for Acoustics refers to Airborne Sound. The designation (U) refers Ultrasound and Underwater Acoustics. The designation (V) refers to acceleration measurements, which are inclusive of Sinusoidal Acceleration and Shock Acceleration, as well as Inertial Acceleration.

Table 2. Sub-fields covered by the categories A-U-V

(A)	**Acoustics**	
	Airborne Sound	Airborne sound is sound that is transmitted through the air.
(U)	**Ultrasound and Underwater Acoustics**	
	Ultrasound	Ultrasound is sonic energy at a frequency above the human hearing range (20 kHz) whose applications are both in industrial and medical applications.
	Underwater Acoustics	Underwater acoustics is the study of the propagation of sound in aquatic environments.
(V)	**Vibration**	
	Sinusoidal Acceleration	Acceleration measurements using sinusoidal steady state mechanical vibrations (rectilinear and angular).
	Shock Acceleration	Acceleration measurements using transient impact.
	Inertial Acceleration (under consideration)	Acceleration measurements by static positioning in the gravitational field or held at continuous rotation rate.

The CCAUV plenary session is preceded by meetings of each of its three working groups: the Strategic Planning Working Group (SPWG), the Regional Metrology Organization Working Group (RMOWG) and the Key Comparison Working Group (KCWG) [1]. The SPWG oversees revising the CCAUV strategy and associated documents on a regular basis. The RMOWG, among other things, works to resolve inter-RMO CMC review obstacles and to harmonize intra-RMO CMC review processes. The KCWG reviews protocols, reports of international key comparisons and coordinates with the RMO key and supplementary comparisons in order to assure the quality of the published data.

The CCAUV meets every two years. The meetings are formatted to include issues covered by the Terms of Reference (ToR). The meetings also provide an opportunity for scientific exchange and thematic presentations on current leading-edge AUV metrology topics, which have become a feature of the meetings.

The CCAUV follows the interactions with other adjacent fields and applications, such as the work on the new definition of the kelvin and materials metrology. It also has close interaction with the Technical Committees of the International Electrotechnical Commission (IEC) and the International Organization for Standardization (ISO), both of which have an observer status within the Consultative Committee.

The CCAUV's Key Comparisons (KCs) are listed with the suffixes A, U, V, and W, which cover the topics of: Acoustics (A), Ultrasound (U), and Vibration (V) and underwater acoustics (W).

Acceleration calibrations were initially only supported using vibration-based (sinusoidal) methods, hence the designation of V assigned to refer to acceleration and shock, as well as inertial acceleration.

4. Stakeholders

The stakeholders and applications of AUV activities cover a large range of interest groups. Below, examples of some major actors and implications are listed.

Table 3. Stakeholders of the CCAUV

Stakeholder	**Application**
Metrological bodies	High precision metrology Precursor to other stakeholders
Health	Hearing assessment Objective audiology Diagnostics (imaging) Therapy Cleaning and materials processing Occupational safety Patient safety Human body comfort (vibration)
Industry	Industrial design Equipment manufacturers Automotive Aerospace Testing Health and occupational safety Cleaning procedures Robotics and machine tool Secondary calibration and testing laboratories
Consumer Electronics	Mobile devices Fitness tracking
Trade	Added value in performance of products
Environment	Marine noise pollution Climate change monitoring Airborne environmental noise Earthquake monitoring Carbon capture and storage Public transportation Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) International Monitoring System (IMS)
Society	Environmental protection Psychological influence and human health Music and entertainment
Academia	Universities Research Institutes
Energy	Offshore oil and gas Marine renewable energy Biofuel production Wind
Standardization Organizations	ISO, IEC, Regional and National Bodies
Legal Metrology	Regulators and Administration, OIML
Defense	Defense and security

Ocean science and marine applications	Ocean processes (e.g. currents and temperature) Hydrographic mapping Positioning, Navigation Communication Sonar Echo-sounding Geophysical survey

5. Future Scan (10 years)

The CCAUV identifies, develops, and supports key comparisons in acoustics, ultrasound, and vibration measurements. The future scan reviews the evolving needs associated with its existing services and emerging needs that arise in this field of metrology. The CCAUV has expanded its measurement support, completing a key comparison for underwater acoustics in 2014, and has carried out a new key comparison for shock acceleration, which was completed in 2019.

Since the previous edition of this document, the new topic of inertial acceleration has been added, motivated by a growing significant global market for inertial sensors based on Microelectromechanical Systems (MEMS).

5.1 Acoustics

5.1.1 Airborne Sound

Future development for the metrology for airborne sound (sound in air) can be encompassed along four main lines with emerging technologies: a) Metrology infrastructure, sensors and instrumentation, b) Hearing assessment and conservation, c) Product and machinery noise, d) Environmental noise assessment. In all these areas, the common denominator is to better understand and mitigate the impact of noise on humans, and their environment.

Although the requirements from each line of development can be described separately, a number of synergies and common elements among them naturally occur. It is, for instance almost a matter of common sense that the generation of a robust metrological infrastructure will underpin all the other lines. Overlap among the lines dealing with noise is also expected.

Each line of development has a strong impact on the population, and on industrial activities, industrial design, urban planning, health, safety, security, and environmental protection; positive applications of sound and strategies for the mitigation of noise are intertwined in several cases. Most important is the fact that benefits extend across all society, from urban to rural populations, and across all stages of life, from birth (in the form of neonatal screening) into old age (hearing conservation). It also identifies the investments needed now, that will produce benefits for generations to come. The four lines are described below.

Metrology infrastructure, sensors and instrumentation

Novel, emerging applications for acoustic measurement are often pushing the limits of frequency and dynamic range at which measurement traceability can currently be provided. Primary standards need to continue developing ahead of these drivers, also by developing alternative realizations of the acoustic SI units, supporting a comprehensive range of practical and affordable calibration services for working devices. Here the focus is on extending capability, for example, to enable the measurement of airborne ultrasound and infrasound, develop further the direct realization of sound power, or link with standards for dynamic pressure where levels are substantially higher. Furthermore, the pursuit of optical methods to provide a direct basis for traceability and move away from an artifact-based primary standard, is already underway in some NMIs [2-4] and may be increased.

Additionally, the impact of Acoustic Metrology in the further development of the SI, for instance, on the realization of the Boltzmann constant via Acoustic Thermometry should be pursued further and emphasized as a strong part of an interdisciplinary approach for supporting the new SI. Another interdisciplinary line is the metrological support of applications related with food safety and air pollution such as Acoustic Spectroscopy for particle size measurement and Photoacoustic Spectroscopy in trace gas monitoring.

Sensors, and the instrumentation used to produce meaningful outputs from them, underpin all acoustic measurement, starting with the realization and dissemination of the primary standard and finishing with hearing assessment, noise measurement or a description of sound quality. In many cases, the drivers for developments in acoustic instrumentation can be addressed through innovation in sensors and instrumentation. In this respect, there is great potential to exploit synergies with the consumer product sector, where the demand for microphones now exceeds 2 billion units per annum. These markets are generating the basic components to enable the development of low-cost robust sensor systems capable of wireless, autonomous and intelligent operation, possibly combining multi-parameter sensing within a single device or network of devices. Such features will dramatically extend the role of acoustic measurement across the health, environment, industry and energy sectors. However, the deployment of such systems needs to be underpinned by new metrology (e.g. remote self-calibration, data fusion in network systems and uncertainty analysis) to support reliable and safe operation (including the use of digital sensors) and for underpinning traceability chains and quality management requirements. Further along in the digital agenda, the digital distribution of calibration data, whether on-the-cloud storage or locally at the instrumentation, should be a relevant line of work.

Hearing assessment and conservation

Hearing impairment can lead to severe degradation in quality of life. Hearing loss leads to social isolation, family tensions and employment challenges for adults. In children, it effects communication ability, literacy, educational achievement, and social and psychological development. Consequently, national healthcare programs invest heavily in both hearing diagnostics (through screening programs) and rehabilitation (hearing aids). Aside from disease and inherent disability, hearing is put at risk, most commonly, from excessive noise exposure. Noise induced hearing loss is one of the most prevalent occupational diseases. Aside from any ethical perspectives, the high economic burden that accompanies hearing loss makes it more important to develop preventative approaches to hearing conservation, this is particularly relevant because recent data also indicates that younger segments of the population may also suffer some degree of hearing loss induced by “voluntary” exposition to high sound levels. Measurement of noise dose is currently a sampling exercise, though usually limited to work premises. Widespread screening of a work-force, or 24-hour personal noise dose monitoring needs new approaches and innovative instrumentation.

As a result of initiatives to capitalize on the benefits of early diagnosis and treatment of hearing disorders in neonates and children, newborn screening programs using objective methods of audiology are now in place in many countries. Metrology underpinning hearing screening has not kept pace with modern audiological practices where there is a movement towards objective methods such as otoacoustic emission and evoked brainstem response. The provision of suitable measurement standards, reference devices (ear simulators) and calibration methods are in progress and need to continue building momentum to firstly catch up and then keep pace with rapidly developing clinical practices. The metrological underpinning of objective audiology is a vital prerequisite for the extended use of this technology which has the potential of becoming the standard diagnostic technology in audiology in future. Improved methods for the determination of reference values of the ear as hearing thresholds requires new calibration methods traceable to national standards and the investigation of the relationship to behavioral hearing thresholds which have to be determined for the new earphones.

Alongside these developments, further generic science is needed to better understand and model the human auditory process, particular regarding hair cell damage by very high frequency sound, and the bone conduction mechanism. This underpins the basic science needed to establish hearing threshold data for transient and mixed stimuli, for bone conduction and for ultrasound and infrasound exposure.

Many sound sources arising from new technologies such as wind turbines, heat pumps, or sonochemical reactors emit sound in the infra- or ultrasound ranges. The perception mechanism of this non-audible noise is currently unclear, but it can be harmful or annoying. The well-established measurement and exposure determination of common noise assessment strategies extends only in the hearing frequency range and methodology outside of this are completely missing. This results in the situation that an assessment of this global threat is not possible to date. Investigation of the perception mechanisms and the development of measurement methodology for exposure will lead to a rational basis for an assessment of this non-audible sound which is currently not possible. This will support an assessment of potential health hazards and underpin the development of appropriate safety regulations and guidelines.

Product and machinery noise

Increasingly, the acoustic performance of products becomes a distinguishing added-value feature. Examples include luxury cars, laptop computers, and domestic products such as vacuum cleaners, fans, washing machines, lawn mowers etc. The first measurement consideration has been the sound power produced by the product, but acoustic considerations have now evolved and engineering the sound produced by a product to improve its perceived quality is becoming increasingly important. Such positive uses of sound are rather unusual and create the demand for alternative metric types relevant to perception.

With the proliferation in low-cost sensors, there is now scope for active management of the acoustic performance of sophisticated items. For example, condition monitoring of machinery, vehicles, rail infrastructure and even domestic appliances could be implemented to maintain the acoustic performance designed into such products, optimizing operating efficiency or simply monitoring the level of noise produced. These applications demand new metrology such as acoustic signature recognition, decision making based on multi-parameter and/or distributed input data, in-situ calibration of sensor and sensor networks, and associated uncertainty and confidence considerations.

Environmental noise assessment

Noise produced by a variety of sources is detrimental to the environment. These sources include transportation (road, rail, air), industrial plant and wind farms, neighborhood noise, sports and entertainment venues, and should be considered as extending to both outdoor and indoor environments.

Many processes described in noise directives (such as the EU directives) are repeated every 5 years providing scope for ongoing improvement in its mandates. One criticism is that its results bear little resemblance to the noise levels experienced at a given location at any particular time. It has further been criticized for relying totally on prediction, with no requirement for validation by actual measurement, because this would be “prohibitively expensive” through employing existing technology. New metrology for cost-effective widespread distributed noise measurement is needed to redress this deficiency.

A further aspect to be considered is the monitoring of highly dynamical events such as seismic activity and controlled explosions such as mining, demolition of man-made structures or weapon testing. Besides the impact on the environment, some of these sound sources may be have a vital importance for global security. In this context, a subset of the environmental monitoring which has relevant applications for supporting the monitoring of the international treaties for banning nuclear testing requires establishing acoustic traceability to very low frequencies down to 0.02 Hz.

5.2 Ultrasound and Underwater Acoustics

5.2.1 Ultrasound

Applications of ultrasound may be broadly divided into two areas: medical and industrial.

Medical applications of ultrasound

After X-rays, ultrasound is the second most commonly used imaging tool in medicine. World-wide, there are 250,000 diagnostic ultrasound instruments and 250 million examinations per year. Within the developed world, most foetuses will be the subject of at least two obstetric examinations during normal pregnancy. Safety-sensitive diagnostic applications will drive the continued development of improved metrological tools and prediction models. In particular, the past decades have seen a dramatic increase in quality and complexity of medical applications with modalities such as the early, routine cancer screening through elastographic [5] or shear-wave imaging methods, showing particular promise. A number of these applications involve generating higher acoustic output. Photoacoustics [6] is an emerging imaging modality which involves the application of light to a tissue, with an ultrasonic transducer array used to detect acoustic waves generated by optical absorption. The technique is used for pre-clinical imaging but is also starting to be applied for the diagnosis of breast disease. The technique combines the enhances optical absorption of tissues with acoustic beam-forming capability. Lung sonography [7] is a novel imaging diagnosis which is the method for getting clinical features of pulmonary lesion such as pneumonia from artefacts and pleural movement. The technique is used as the early screening for being able to carry out safely and repeatedly at the bedside. The technique has attracted a lot of attention during COVID-19 pandemic. Quantitative imaging, where intrinsic properties of tissue are determined with robust uncertainty estimates, is likely to be of growing importance for medical diagnosis. To improve the reliability of any individual investigation all results need to be traceable to national standards including the development of methods for a dedicated quality ensuring management. This covers the whole process from manufacturing of devices till the applications in clinics and medical centers. One basic element are test data sets or test objects which are proven by NMIs, calibration and measurement laboratories, or health agencies and which can be applied to investigate the accuracy and reliability of a device under test.

The complex nature of many medical interrelations, the high benefit to patients and the potential high economical outcome will dramatically promote the development of artificial intelligence in medical applications in future. This currently extensively developing process increasingly requires clear and dedicated rules and the development of a quality infrastructure. Test data sets for validating learning data and for an investigation of performance are required. This includes the development of a strategy for approval of software based on learning principles with respect for example to Medical Device Regulation (MDR) in Europe or other regulations in the world.

Novel therapeutic applications of ultrasound will continue to emerge, supporting drug delivery concepts based on high-power ultrasound or cavitation and more extensive use of High Intensity Focused Ultrasound (HIFU) or High Intensity Therapeutic Ultrasound (HITU). Exploitation of the clinical potential of these methods requires the development of metrology for both existing and emerging dosimetric quantities. To unlock the potential of therapeutic ultrasound and to better assess safety in diagnostic applications, metrology is particularly essential to develop and validate methods for determining *ultrasound dose*. This will support treatment planning and risk assessments. Such advances require concepts of thermal ultrasound dose to firstly be developed, underpinned by validated measurement, and this will be a major thrust area for activity over the next decade. It is highly likely that future ultrasound therapies will increasingly move away from being ablation (temperature) based but will involve the use of micro-bubbles which respond to an applied ultrasound field. Even in the absence of micro-bubbles, ultrasound is being applied transcranially for the treatment of brain disorders (essential tremor) and neurostimulation. This is essentially at lower acoustic frequencies (100's of kHz) to overcome the high acoustic absorption of the skull. For manufacturers, micro-bubbles coupled with therapeutics will drive developments of the next wave of ultrasound technology into clinical practice. Microbubble-based drug/gene delivery vehicles for cancer and Alzheimer therapies promise significant advances in treatment. Applications involving the spatially and temporally-controlled application of ultrasound-induced heating or acoustic cavitation, high-frequency imaging or micro-machined transducers will come into use and bring with it a demand for underpinning metrology at various stages of instrumentation development and application.

Key factors in assessing the safety of medical ultrasound applications lie in methods of estimating *in-vivo* ultrasound levels to support treatment planning, and its implications in terms of bio-effects. Validated methods of determining the acoustic properties of materials over a wide frequency range, 20 kHz – 50 MHz, are required to enable reliable estimates to be made. These properties include absorption, attenuation, scattering, speed of sound and nonlinearity parameter. The ability to make such measurements over a wide-bandwidth, and use this to characterize liquid composition, is likely to find increasing application, for example in the evaluation of protein solutions, or assessment of nano-particles, where the requirement may be for acoustic frequencies in excess of 100 MHz. To support the development of quantitative elastographic imaging techniques, there will be a requirement to develop standardized methods of determining Young's modulus and shear acoustic properties of tissue-like materials and to disseminate these to the user community.

Industrial applications of ultrasound

Industrial applications of ultrasound are extensive, where it is commonly applied as a means of bringing about macroscopic changes in materials, either within the bulk or at surfaces. One key phenomenon driving these changes is acoustic cavitation: the generation of bubbles in a liquid medium through application of sound, whose eventual collapse creates the hostile conditions required to generate free-radicals, emit light, catalyze chemical reactions or clean surfaces. Ultrasonic cleaning is the most widespread application of industrial ultrasound, and such vessels are used for the cleaning of surgical and dental instruments. The equipment generates complex *acoustic pressure* distributions, leading to 'hot-spots' and 'cold-spots' in generated cavitation activity. Recent industrial developments are targeting higher frequency (>500 kHz) systems employed for fine-cleaning applications required for optical component and microelectronics manufacture, where understanding cavitation severity and type are crucial to minimizing unwanted surface damage. There is therefore a need for broadband measurement methods capable of resolving non-uniformity in acoustic field distributions, providing information on the spatially-varying degree of cavitation. Cavitation activity has been shown to be strongly related to process efficiency, and it is anticipated there will be significant activity within the standardization community to develop appropriate metrological tools for determining this quantity, at laboratory and user levels. This will lead to a better understanding of factors affecting the application of cavitation, optimizing its use and enabling high power ultrasound to be further applied in an economically viable way, over a wide range of technical fields such as food (crystallization control, pasteurization), pharmaceuticals (particle size control) and biofuel production industries.

5.2.2 Underwater Acoustics

The ultimate aim of underwater acoustic metrology is the protection of the marine environment commensurate with the sustainable exploitation of the oceans for applications in energy, environment and security. Oceans cover 72% of the surface of our planet and constitute more than 95% of the biosphere [8]. The oceans nurtured the beginnings of life and continue to support all life today by generating oxygen, absorbing carbon dioxide, recycling nutrients and regulating global climate and temperature. Oceans provide a substantial portion of the global population with food and livelihoods and are the means of transport for 80% of global trade. The seabed currently provides around 30% of the global supply of hydrocarbons with exploration expanding. Advancing technologies are opening new frontiers of marine resource development from bio-prospecting to the mining of seabed mineral resources [9]. The sea also offers vast potential for renewable “blue energy” production from wind, wave, tidal, thermal and biomass sources, and the maritime environment continues to form a key part of national and international defense and security initiatives [10].

Acoustic techniques underpin key maritime applications and the blue economy (which globally has a Gross Value Added of $1.5t). Acoustic technology continues to provide the primary imaging and communication modalities for the exploration and exploitation of the ocean. Acoustic techniques are the methods of choice for most marine applications requiring remote imaging, communication or mapping in the ocean, where techniques based on electromagnetic waves suffer from limited range due to high levels of absorption in sea water. Such acoustic applications are important in a number of sectors: (i) offshore energy (including oil and gas, but also the emerging field of marine renewable energy); (ii) environment (marine noise pollution, climate change monitoring, carbon capture and storage); (iii) defense and security; (iv) ocean science (including the study of ocean processes, hydrographic mapping, etc.).

The marine technology industry continues to innovate with advances in technical applications including positioning, navigation, communications, sonar, echo-sounding, geophysical surveying, weapons systems, and tomographic measurements of ocean currents and temperature. Civil offshore activities in support of energy extraction are heavily dependent on underwater acoustic technology, which is a crucial underpinning technology. In oceanographic science, acoustic methods are used for sea-bed mapping, ocean acoustic tomography, and the study of marine life. Deep ocean studies increasingly utilize Autonomous Underwater Vehicles (AUVs) which are heavily dependent on acoustic systems. In shallow water, acoustic techniques are used in the study of sediment transport processes, important for assessment of coastal erosion, and for systems used for protection of ports and harbours from mines and potential terrorist threats. Traceability is increasingly required for calibration and performance testing of underwater acoustic transducers, materials and systems. There is particular need to respond to a range of innovations in technology for sensors and materials, challenges provided by measurements in harsh conditions (e.g. deeper water), requirements for increased accuracy, and the increasing requirement for extracting quantitative information about the ocean environment and seabed. Calibration of digital systems such as autonomous recorders provides challenges (currently, no standards exist to govern their calibration) because the sensor is typically contained within a black-box which includes ADC and DSP stages.

Marine environmental noise pollution

Human development activities have seriously tested the resilience of marine resources. Data from the United Nations indicates that 87% of global fish stocks are fully or over exploited, and increasing pollution contributes to the loss of biodiversity, ecological function and the decline in provision of environmental services [8]. The impact of acoustic noise emanating from human activities poses unprecedented risks for the sustainability of key marine species, biodiversity, ecosystems and overall ocean health, and the increasing concern has led to regulation. A European example is the EU Marine Strategy Framework

Directive (MSFD) [11], and in the USA, NOAA has published recent guidance (for example, the US Ocean Noise Strategy Roadmap). This has led to an increasing the need for absolute acoustic measurements in the ocean. At present, legislation requires absolute measurement of in-situ underwater sound, but in many cases no standards exist to govern the methodology for specific sources. The whole field of underwater noise metrology (and impact assessment) is relatively immature, and there is a strong requirement to improve metrology infrastructure, both with regard to characterizing sound sources and undertaking long-term monitoring, such that the metrology for offshore noise measurement catches up with the rapidly evolving legislative framework. Noise-generating activities include geophysical surveying for offshore oil and gas exploration (which utilize air gun arrays as high-amplitude sound sources), construction of offshore structures such as marine renewable energy developments (where marine pile driving is commonplace and where noise impact is a major barrier to the planned expansion in the industry), dredging and aggregate extraction, naval sonars, explosive decommissioning of offshore developments, and disposal of munitions and ordnance. In addition, the rapid increase in commercial shipping traffic also has the potential to increase the background level of sound in the ocean [12]. Many of the above sound sources radiate most of their sound energy in the frequency range between 10 Hz and 1 kHz. However, it is in this frequency range where traceability is weakest, with much of the historic demand being for testing of active systems being at kilohertz frequencies. There is a technology push provided by the development and increasing commercial availability of new instrumentation, specifically autonomous sound recorders which combine hydrophones and acquisition and data storage capabilities. There is increasing need to measure particle motion with regard to ocean sound. All fish species and invertebrates detect particle motion whereas only a limited number of fish detect sound pressure. Thus, to consider effects of sound on such animals, we must be able to measure the particle velocity (or acceleration) in the acoustic field, especially where the particle velocity cannot be inferred from the sound pressure (close to boundaries and in the acoustic nearfield). This requires appropriate sensors, and measurement standards, to be developed.

Climate studies and oceanographic science

Climate change threatens to remove broad swathes of coastal development whilst rising atmospheric CO_2 levels are undermining fundamental aspects of many marine ecosystems through ocean acidification, changing ocean chemistry at a speed faster than at any time in the last 300 million years [8-10]. Ocean studies related to climate change use acoustics as a tool to probe the oceans, for example in detection of changes in acidification, detection of methane hydrate dissociation and seepage, the study of CO_2 flux in atmosphere-ocean transfer, the study of changes in sea temperature using ocean acoustic thermometry, and the study of the melting polar ice caps. Acoustics is also used to detect CO_2 leakage from sub-seabed Carbon Capture and Storage (CCS) sites. There is also increasing interest in "quantitative imaging" with application to sonar, useful in seabed imaging for habitat mapping, seabed classification and object identification, where such system calibration would enable absolute comparison of images independent of sonar type or operator. The "calibration" of the overall transfer response of the imaging system uses a method employing a standard target. Increasingly, marine systems are becoming autonomous, which presents measurement challenges for the acoustic systems used in remote communication and navigation, and the handling of large data sets from sensor networks.

Marine energy

Marine renewable energy developments present a number of acoustic measurement challenges ranging from determination of water flow (often achieved using acoustic systems such as ADCPs), to mammal collision avoidance for underwater tidal turbines, and the validation of noise abatement systems for offshore construction of windfarms. In the offshore oil and gas industry, there is a continuing trend toward working in deeper water as the shallower coastal waters become heavily harvested. This is setting new challenges as acoustic systems are required to work at greater depths and over greater ranges. Digital transformation of sensors is providing challenges for calibration with systems such as autonomous recorders where the hydrophone sensor is contained within a digital system which includes digital signal processing stages.

Defense and security

Recently, in addition to the traditional deep-water applications, defense applications have focused on shallower coastal waters, for example for mine-hunting and harbor surveillance. This has led to an increased requirement for the performance of acoustic systems and the acoustic properties of materials to be determined over a range of different water temperatures and depths. Development of more sustainable methods for disposal of unexploded ordnance in the marine environment is a developing topic, requiring validated acoustic test methods.

There is an additional requirement for improved traceability by the Comprehensive Test Ban Treaty Organization whose deep-ocean hydroacoustic listening stations operate from frequencies of 1 Hz to 100 Hz, a frequency range for which there are few available NMIs and DIs with the capability to supply traceable calibrations appropriate for deep-ocean conditions, and where there is no Key Comparison to underpin CMCs.

5.3 Vibration

The topic of vibration refers to sinusoidal acceleration, shock acceleration, and inertial acceleration. The typical areas of vibration measurement with requirements for traceability and mutual recognition of measurement results originate from industry (e. g. automotive, aerospace, testing) and society (e. g. worker’s safety, human response to vibration). Emerging needs are arising from consumer electronics applications such as smart phones and tablets, as well as new automotive applications leading towards autonomous driving. There is also a shift of sensors in general, and accelerometers and microphones in particular, towards digital communications which we refer to as *digitization*.

Consumer Applications

Consumer applications for accelerometers include smartphones, tablet computers, smart watches, fitness trackers, cameras, and gaming consoles, exemplifying the largest application domain in terms of units manufactured and sold. These applications are driven by cost reduction while increasing performance and maintaining an acceptable reliability factor. Since these applications are not considered to be directly related to human safety, the industry has moved from testing and calibrating every device towards statistical sampling to reduce manufacturing costs while delivering statistically acceptable levels of performance and reliability.

Automotive Applications

MEMS accelerometers made their debut in the automotive application of crash sensing and airbag control. Here, the accelerometer continuously measures acceleration of the car. The acceleration curve is monitored to determine if a large change in velocity has occurred and if it exceeds a predetermined threshold the airbag is fired. The decision to fire the airbags must be made on the order of milliseconds yet the operation must be extremely reliable since errors can result in loss of life and limb. Electric vehicles and specifically the safety of the used battery packs led to requirements for rather long duration low intensity shocks in mechanical safety testing.

Autonomous Vehicles

The development of autonomous vehicles is rapidly advancing, with well-known companies such as Apple, Google, Tesla, and others pioneering their development as well as lobbying for government legislation. Autonomous vehicles are already operating on some public roads. Some states in the US, for example, allow fully autonomous self-driving car testing on public roads, including Arizona, California, Florida, Georgia, Michigan, North Carolina, and Ohio. Accelerometer specifications for inertial guidance of an autonomous vehicles will be the strictest compared to the other applications discussed above, since in the event that a GPS signal is lost the position of the vehicle must be determined by the inertial guidance system over a period of time that might span tens of minutes. The current designs for capacitive MEMS-based accelerometers and gyroscopes may not ever meet requirements for fully autonomous driving and may have to move towards optical based systems [13,14] instead of today's capacitive based systems.

Digitalization

Today, a majority of inertial sensor combos, as well as microphones, utilize digital data interface standards such as I2C or SPI. The CCAUV's key comparisons do not include the use of reference transducers with digital interfaces. Although in principal the testing of transducers with digital interface devices could follow a similar procedure as their analogue cousins, in practice interfacing with them is likely not straightforward. These digital sensors are not "plug and play," meaning that interfacing with each sensor requires some customized software and hardware. For example, sensors from different manufacturers might be equivalent, i.e. a one axis inertial accelerometer, and even follow the same communication protocol, i.e. I2C, but the data communications and control would not be the same, as well as the configuration of the socket might not be the same, requiring customization of the communications protocol and socketing in order to calibrate them.

In this age of digitalization, some NMIs have taken interest in developing capabilities for sensors to communicate not only their instantaneous measurements but to also communicate other information in parallel that would be useful for improving the reliability and performance of sensor networks, AI, and machine learning.

5.3.1 Sinusoidal Acceleration

The typical areas of vibration measurement with requirements for traceability and mutual recognition of measurement results originate from industry (e.g. automotive, aerospace, testing) and society (e.g. worker's safety, human response to vibration). These areas have not changed drastically over the last decade. However, within these stakeholder-groups new requirements are growing and already now some new demands can be predicted:

- Angular vibration in terms of angular rate measurement is becoming increasingly important in the field of automotive safety and autonomous driving.
- Low-frequency vibration transducers are widely used for monitoring earthquakes or nuclear weapon testing but also in oil exploration and control of building vibrations. The demand has increased of earthquake monitoring after major accidents due to seismic activity; special sensors provide traceability to thousands of seismometers and hundreds of observation stations in the Global Seismographic Network giving immediate alert to the population, needing calibration at ultra-low-frequencies below 0.1 Hz, even to 0.008 Hz [15].
- Recent R&D in integrated laser-optical sensors may lead to new approaches to primary traceability in the future [16].

5.3.2 Shock Acceleration

Requirements for traceability in shock acceleration measurements are generated in research, industry, medicine and military. The challenge is to cover the wide range of applications with a small number of efficient methods and calibration techniques.

The foundation of traceability is (still) the international standard ISO 16063-13 for primary shock calibration by laser interferometry and based on that ISO 16063-22 for secondary shock calibration by comparison to a reference accelerometer. It is well known in the community that the employed method of determining a peak ratio sensitivity has methodical shortcomings. An alternative method described in ISO 16063-43, resolves those shortcomings but is still far from common acceptance.

Existing and foreseeable requirements include:

- Primary and secondary shock calibration of accelerometers in the range from 50 m/s² to 10^6 m/s² with excitation durations from 150 ms to 10 µs, depending on the targeted field of application.
- Provision of model-based calibration results to allow for traceable measurements of transient signals with high mechanical bandwidth.
- New approaches concerning the measurement of transient excitations based on deconvolution techniques generate the demand for adapted methods in calibration and dissemination [17].
- Providing the base for international mutual recognition, i.e. the organization of key comparisons in the frame of the CIPM MRA.

5.3.3 Inertial Acceleration

The topic of inertial acceleration is included in this future scan, motivated by the significant global market for inertial sensors based on Microelectromechanical Systems (MEMS). Yole Development reported in 2016 [18] that the global market for MEMS-based inertial sensors was $3.4B and expected to continue to grow with a compound annual growth rate (CAGR) of 9.6% for inertial combos. Other market studies forecast even higher growth rates [19].

Manufacturers see value in a traceability chain to the national laboratories, however, the currently used reference accelerometers and testing protocols are not compatible with their requirements. They have different mounting requirements, use different testing and calibration protocols, and often use digital interfaces for data and communications.

These technologies include multi-axis accelerometers and gyroscopes called inertial combos, which are devices with a combination of accelerometers, gyroscopes, and or magnetometers. Inertial Measurement Units (IMUs) are a type of inertial combo integrating three-axis accelerometers, gyroscopes, and magnetometers into a single integrated package.

The accelerometers used in consumer electronics applications predominantly have a digital interface and their sensitivity is often specified in terms of the standard acceleration of gravity, g_n.* Present performance characteristics of accelerometers used in smartphones, for example [20], offer and acceleration range selectable from order ±20 to ±160 m/s^2, with a resolution of up to 14 or 16-bits, and resulting in a sensitivity of order $6x10^{-4}$ to $5x10^{-3}$ (m/s^2)/LSB, respectively. An example specification for accelerometers used in automotive applications for crash sensors can be found in [21], also exemplifying a digital communication interface with a user selectable range from order ±600 m/s^2 to ±4800 m/s^2.

Considerations by CCAUV regarding a possible pilot study or key comparison include the development of a standard testing protocol, preferably through ISO, its adoption by a sufficient number of NMIs, the inclusion of an uncertainty due to the gravitational acceleration as taught in ISO 16063-16 or by the development of CMCs for local gravitational acceleration at the NMIs, and other factors such as related to the primary determination of angular position in the earth’s gravitational field. Furthermore, a digital-based standard

* g_n refers to the average acceleration produced by gravity at the Earth’s surface (sea level), 9.80665 m/s^2 (value published by the Committee on Data for Science and Technology (CODATA) for international use)

reference transducer must also be developed, preferably one that is commercially available and not subject to international restrictions that would inhibit comparisons between countries.

6. Rationale for various activities (2021-2031)

A rationale for the research and development activities, measurement services and the selection basis for comparisons (including statements on ‘how far the light shines’) that are foreseen over the period, indicating the time periods when these different activities will be required.

6.1 Acoustics

6.1.1 Airborne Sound

Airborne sound pressure standards based on the electroacoustic reciprocity principle are still the main source of traceability for measurements of airborne sound. No changes in the form of new principles are expected to replace these techniques; however, efforts to extend the frequency range and the calibration levels are now a reality when low-frequency sound is concerned by calibrating microphones under uniform pressure conditions. Extension to high frequencies in the free-field reciprocity calibration of microphones is imminent too. In the past, Key Comparisons for the realization of the acoustic pascal under uniform pressure field have been completed in the conventional audio frequency range (CCAUV.A-K1, CCAUV.A-K3), and for low frequencies as well (CCAUV.A-K2); the realization of the acoustic pascal in a free field has been the subject of another Key Comparison (CCAUV.A-K4). A Key Comparison combining the audio and low frequency ranges was completed (CCAUV.A-K5) in 2014, the Key Comparison similar to CCAUV.A-K5 for LS2 microphones (CCAUV.A-K6) is currently in progress. A repetition of the CCAUV.A-K4 comparison should also be expected in the next 2-6 years period, while a repetition of CCAUV.A-K6 which is still underway is still early to be decided upon.

It is not unlikely that Key Comparisons or Pilot studies designed to test the extension of the frequency range in the realization of the *pascal* within a free field become an issue of discussion on realization of the acoustic pascal in a diffuse field is also a potential subject of work.

6.2 Ultrasound and Underwater Acoustics

6.2.1 Ultrasound

Ultrasound standards for pressure and power determined in *water* (a standardized medium whose properties show some similarities to biological tissue) form the basis of all metrology in this area and will continue to do so over the coming decade. Currently, two specific measurands are the subject of Key Comparisons: *ultrasound power*, specifically through measurement of the electro-acoustic radiation conductance of standard sources and *ultrasonic pressure*, through the determination of the free-field sensitivity of ultrasonic measurement hydrophones. It is anticipated that a significant extension in frequency and power application ranges will be required in the near future, driven by existing and emerging medical applications. For ultrasonic pressure, there will be a need to increase the frequency range. The current upper frequency range covered by the Key Comparison for hydrophone sensitivity (CCAUV.U-K4) is 20 MHz, and it is anticipated that this might be extended up to at least 40 MHz and may include phase response. The phase response is required for establishing deconvolution technique [22-23] for precise measurement of instantaneous acoustic pressure of broadband ultrasound. Similarly, for the measurement of ultrasound output power and driven by the increasing number of therapeutic applications of ultrasound, there may be a need to extend the upper applied power level of the Key Comparison to 300 W and potentially beyond, from the current 20 W limit (CCAUV.U-K3). Anticipating a potential routine clinical take-up of HIFU or HITU related technologies, there may be a need to employ new focused transducers capable of generating sufficiently high time-average acoustic powers.

6.2.2 Underwater Acoustics

Acoustic fields in water are most often characterized in terms of acoustic pressure, and primary standards are provided by a realization of the acoustic pascal in water. This is most often achieved somewhat indirectly through a calibration technique based on the principle of reciprocity, the transfer standard device being a hydrophone. Standards for hydrophone calibration are typically provided either under free-field conditions, or by a pressure calibration. Free-field calibrations require a volume of water (a tank or open-water facility) and are commonly undertaken at frequencies from a fraction of a kilohertz to 1 MHz (a larger water volume being required for lower frequencies). Pressure calibrations are undertaken in small chambers or couplers and can provide standards at frequencies from a few hertz to about 1 kHz.

The first Key Comparison in this field was CCAUV.W-K1, completed in 2003 (seven countries represented: UK, US, RU, CN, DE, ZA). This covered free-field standards in the range 1 kHz to 500 kHz. The range 500 kHz to 1 MHz was uncovered, though this has since been covered by the ultrasound Key Comparison CCAUV.U-K4 for miniature hydrophones used in medical ultrasound. A new free-field Key Comparison for underwater acoustics completed measurements in late 2020 and will report in late 2021: CCAUV.W-K2, covering the frequency range 250 Hz to 500 kHz (eight countries represented: UK, US, RU, CN, TR, ZA, BR, IN). Several of the NMIs and DIs participating have newly established capabilities, though not all have the capability to cover all the frequency range of CCAUV.W-K2.

In addition, a Key Comparison of pressure calibrations is required to cover the important low frequency range below 250 Hz down to a few hertz. This presents more of a challenge because there are fewer NMIs and DIs with sufficient capability. Another area where a future Key Comparison might be desirable is in the area of characterization of the acoustic properties of materials for use in underwater acoustics, and for the calibration of particle velocity sensors.

In general, in underwater acoustic metrology, there is a lack of “headroom” between the best measurement capability of national primary standards (free-field uncertainty approximately

0.4 dB) and the general capability in industry (typical uncertainty 1 dB), placing limitations on the dissemination of standards. For the most demanding industrial applications, the accuracy requirement can push the boundaries of the primary standard accuracy. A challenge for underwater acoustic metrology is development of the next generation of primary standards of improved accuracy, with optical techniques providing possibilities for improved realization of the acoustic pascal at high kilohertz frequencies. There is already research being undertaken into such techniques [24], and in the next ten years these will begin to feed into Key Comparisons as these methods are adopted by some of the NMIs and DIs (most likely at higher frequencies at first: 100 kHz to 1 MHz).

The requirement for measurement standards for particle motion sensing has already led to work within IEC and will lead to the establishment of primary standard capabilities within NMIs/DIs which must eventually be underpinned by suitable Key Comparisons. The characterization of the acoustic properties of materials in terms of transmission loss, insertion loss, sound speed, and absorption in the frequency range 1 kHz to 100 kHz may eventually also need to be underpinned by suitable Key Comparisons in the frequency range from 10 Hz to 10 kHz.

6.3 Vibration

In the area of vibration and shock acceleration an active liaison exists between CCAUV and ISO/TC 108/WG 34. The activities are based on mutual participation of experts in both committees. The standards written in the ISO community act as the foundation of the calibration procedures used in key comparisons and CMCs registered in the KCDB and are thus tested and applied within the community. Vice versa any demand of the community further standards is mirrored in the ISO TC and new standard developments are started wherever sensible.

6.3.1 Sinusoidal Acceleration

The traditional areas of vibration metrology are in the scope of CCAUV, i.e. sinusoidal acceleration and shock acceleration, despite the many years of development, still have to be considered under development in terms of the implementation of the CIPM MRA. Several reasons can be given in support of this judgment.

In the field of sinusoidal calibration, the demand for the frequency range covered and the measurement uncertainty provided at the NMI level are still increasing. With more NMIs building up capacity the feasibility and, in fact, the need for key comparisons increases.

New techniques employed in industries necessitate proper means of traceability in the area of angular vibration with all respective consequences (KCs, CMCs) in the framework of the CIPM MRA.

The emerging area of dynamic measurement of mechanical quantities is not yet allocated to a CC in terms of CIPM activity. As it is technically borderline work between working groups of CCM and CCAUV the implications arising from this field have to be discussed in CCAUV in the future.

6.3.2 Shock Acceleration

While the area of sinusoidal acceleration metrology rests on the sound foundation of internationally accepted Key Comparisons and the respective CMCs in the framework of the CIPM MRA, the existing standards for shock calibration, i.e. ISO 16063-13 and ISO 16063-22 are prone to lead to systematic errors and thus are inadequate for Key Comparisons at least for high intensity shock.

This situation has changed with the publication of ISO 16063-43 which complements the previously existing standards by the method of model parameter identification. With the implementation of this standard laboratories should be able to calibrate transducers independent of systematic influences of their specific calibration device. Hence, the application of the new standard now provides the opportunity to perform Key Comparisons for high intensity shock excitation.

From the customer's side an increasing request for internationally recognized, traceable calibration with intensities up to and beyond 10^6 m/s² calls for an extension of existing capabilities by at least one order of magnitude. In order to get such calibrations under the umbrella of mutual recognition appropriate key comparisons are necessary in order to establish the respective CMCs.

6.3.3 Digitization of Sensor Interfaces – MEMS

The vast majority of today's vibration sensor manufacturing is producing MEMS-sensors with digital interfaces. This implicitly includes autonomous and asynchronous sampling of the device in relation to any external calibration system. It also means a huge diversity in terms of data transmission protocols. Both implications pose substantial challenges to the traceable calibration.

Some NMIs have started to develop new (primary) calibration methods in research and development projects in order to deal with the specific needs of such systems. The gained insights need to be up taken by others with the goal of establishment of the respective global infrastructure. Furthermore, documentary standards incorporating the new methods have to be created or existing standards need to be adapted.

7. Required Key Comparisons and Pilot Studies (2021-2031)

A list and proposed dates of key comparisons has been established for each of the four AUV areas by applying the above rationale. Indicative repeat frequencies, and statements on 'how far the light shines' have been taken into account.

7.1 Acoustics

7.1.1 Airborne Sound

Sub-field	Description	Rationale	How far the light shines	Expected start
Airborne sound	Comparison of Laboratory Standard Microphones type LS2	Repeat of CCAUV.A-K4	Free-field sensitivity in the frequency range 1 kHz to 30 kHz	2022
Airborne sound	Comparison of Laboratory Standard Microphones type LS1	Repeat of CCAUV.A-K5	Pressure sensitivity in the frequency range 2 Hz to 20 kHz	2023/2024
Airborne sound	Comparison of Laboratory Standard Microphones type LS2	Repeat of CCAUV.A-K6	Pressure sensitivity in the frequency range 2 Hz to 25 kHz	2032 (TBA)
Airborne sound	Comparison of Working Standard Microphones type WS3 (Pilot study)	Extension of the frequency range up to 150 kHz	Free-field sensitivity in the frequency range 10 kHz to 150 kHz	2023
Airborne sound	Comparison of Laboratory Standard Microphones type LS1/LS2 (pilot study)	Calibration in a diffuse field	Diffuse-field sensitivity in the frequency range 2 Hz to 20 kHz	2023/2024
Airborne sound	Calibration of LS1/LS2/WS3 microphones (pilot study)	Calibration using optical techniques	Pressure and free-field sensitivity in the combined frequency range 1 Hz to 200 kHz	TBA

TBA: To be agreed

7.2 Ultrasound and Underwater Acoustics

7.2.1 Ultrasound

Sub-field	Description	Rationale	How far the light shines	Expected start
Ultrasound	Ultrasonic power	Repeat of CCAUV.U-K3	Transducer electro-acoustic radiation conductance and transducer ultrasonic output power, 0.01 W – 15 W*	2023
Ultrasound	Comparison of reference hydrophone calibrations	Repeat of CCAUV.U-K4	End-of-cable loaded hydrophone sensitivity, in nV/Pa, over the frequency range 0.5 MHz – 20 MHz*	2024

***** Parameters defining the Key Comparisons such as frequency range and ultrasound power levels will be agreed through discussion with participants and the CC. The range of frequencies (U-K4) and ultrasound powers (U-K3) given in the table may be regarded as “core”, and this scope may be extended to higher frequencies (possibly 40 MHz) and elevated, therapeutic-level powers (>300 W), subject to requirement and the availability of artifacts.

7.2.2 Underwater Acoustics

Sub-field	Description	Rationale	How far the light shines	Expected start
Underwater Acoustics	Comparison of pressure calibration of hydrophones	Extension of CCAUV.W-K2 to low frequencies	Free-field hydrophone sensitivity in V/Pa over the frequency range 1 Hz to 1 kHz	2023
Underwater Acoustics	Comparison of free-field calibrations vector sensors (pilot study)	Comparison of particle velocity standards	Free-field sensitivity in V/(m s^{-1}) over the frequency range 20 Hz to 10 kHz	2025
Underwater Acoustics	Comparison of free-field calibrations of hydrophones	Repeat of CCAUV.W-K2	Free-field hydrophone sensitivity in V/Pa over the frequency range ~250 Hz to 1 MHz	2026
Underwater Acoustics	Comparison of pressure calibration of hydrophones	Extension of CCAUV.W-K2 to low frequencies	Hydrophone pressure sensitivity in V/Pa over the frequency range 2 Hz to 1 kHz	2028

7.3 Vibration

7.3.1 Sinusoidal Acceleration

Sub-field	Description	Rationale	How far the light shines	Expected start
Sine-excitation	Comparison of primary calibration in magnitude and phase	Coverage of traditional calibration services in acceleration CCAUV.V-K3	0.1 Hz to 40 Hz This will be a regular KC to be repeated in 10-year intervals	2025
Sine-excitation	Comparison of primary calibration of magnitude and phase	Coverage of traditional calibration services in acceleration CCAUV.V-K5	10 Hz to 20 kHz This will be a regular KC to be repeated in 10-year intervals	2027

7.3.2 Shock

Sub-field	Description	Rationale	How far the light shines	Expected start
Shock excitation	Primary calibration according to ISO 16063-13 (peak ratio)	Increasing number of NMIs with the capability and demand for CMCs CCAUV.V-K4	500 m/s^2 to 5000 m/s^2 This will ultimately be a regular KC to be repeated in a 10-year interval.	2026

8. Resource implications for laboratories for piloting comparisons

The resource estimates for pilot laboratories for future CCAUV Key Comparisons (KCs) are compiled in the figure below. These estimates are based on experience from previous KCs and include efficiencies gained from lessons learned. Past experience is used to improve the experimental protocols and to optimize the frequency of the KC repeat cycle.

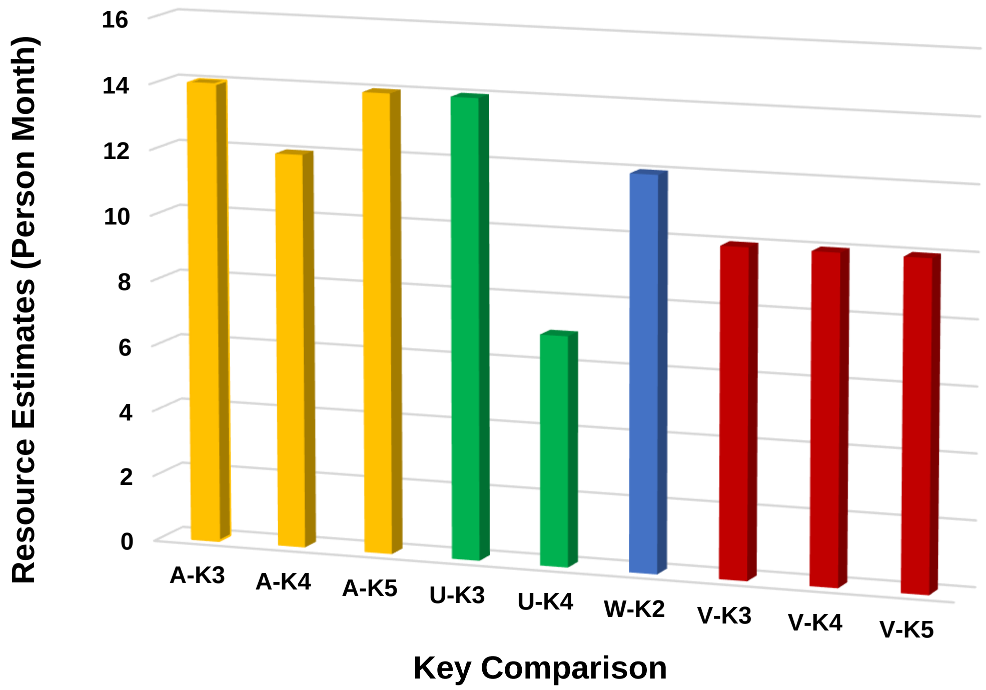

Fig. 1. Resources estimates for pilot laboratories for future CCAUV Key Comparisons

8.1 Acoustics

8.1.1 Airborne Sound

Sub-field/ Reference No.	Description	Rationale	Resource estimates	Pilot Laboratory
Airborne Sound CCAUV.A-K4 (2022)	Comparison of Laboratory Standard Microphones type LS2	Repeat cycle	12 PM	DFM
Airborne Sound CCAUV.A-K5 (2023/2024)	Comparison of Laboratory Standard Microphones type LS1	Repeat cycle	14 PM	LNE
Airborne Sound Pilot Study (2023 TBC)	Comparison of Working Standard Microphones type WS3	Extension of the frequency range up to 150 kHz	12 PM	DFM (TBC)
Airborne Sound Pilot Study (2023/2024 TBC)	Comparison of Laboratory Standard Microphones type LS1/LS2 (pilot study)	Calibration in a diffuse field	8 PM	DFM (TBC)
Airborne Sound Pilot Study (TBD)	Calibration of LS1/LS2/WS3 microphones (pilot study)	Calibration using optical techniques	8 PM	TBD

TBC : To Be Confirmed
TBD : To Be Determined
PM : Person Months

8.2 Ultrasound and Underwater Acoustics

8.1.1 Ultrasound

Sub-field/ Reference No.	Description	Rationale	Resource estimates	Pilot Laboratory
Ultrasound (2023)	Ultrasonic power	Repeat cycle	14 PM	TBD
Ultrasound (2024)	Comparison of reference hydrophone calibrations	Repeat cycle	7 PM	NPL

TBD : To Be Determined
PM : Person Months

8.2.2 Underwater Acoustics

Sub-area/ Reference No.	Description	Rationale	Resource estimates	Pilot Laboratories
Underwater Acoustics (2023)	Comparison of pressure calibration of hydrophones	Extension to low frequencies	7 PM	TBC (NIST-USRD or NPL)
Underwater Acoustics (2025)	Comparison of free-field calibrations vector sensors (pilot study)	Comparison of particle velocity standards	7 PM	TBC (NPL or NIST-USRD, other NMI)
Underwater Acoustics (2026)	Comparison of free-field calibrations of hydrophones	Repeat cycle	12 PM	NPL
Underwater Acoustics (2028)	Comparison of pressure calibration of hydrophones	Extension to low frequencies	8 PM	TBD

TBC : To Be Confirmed
TBD : To Be Determined
PM : Person Months

8.3 Vibration

8.3.1 Sinusoidal Acceleration

Sub-area/ Reference No.	Description	Rationale	Resource estimates	Pilot Laboratories
Vibration (2025)	Primary Sinusoidal accelerometer calibration for low frequency	Repeat Cycle	10 PM	TBD
Vibration (2027)	Primary calibration of magnitude and phase of the complex sensitivity of accelerometers	Repeat Cycle	10 PM	TBD

TBD : To Be Determined
PM : Person Months

8.3.2 Shock Acceleration

Sub-area/ Reference No.	Description	Rationale	Resource estimates	Pilot Laboratories
Shock excitation (2026)	Primary calibration according to ISO 16063-13 (peak ratio)	Increasing number of NMIs with the capability and demand for CMCs	10 PM	TBD

TBD : To Be Determined
PM : Person Months

9. Summary

Since its inception in 1999, 16 CIPM Key Comparisons have been completed covering the four disciplines: Airborne Sound, Ultrasound, Underwater Acoustics and Vibration. The metrology for these technical fields has various degrees of maturity. Sound-in-Air has by far the greatest participation among the NMIs, reflected by the number of NMIs participating Key Comparisons.

Estimating the resource implications for piloting Key Comparisons and in participation in them is carried out using past experience, exemplified in Figure 1. The number of CMC entries supported over the various disciplines is 1299. Metrology within Ultrasound is relatively new, reflected in the limited number of NMIs involved within the technical field for the two relevant Key Comparisons. Within Underwater Acoustics, there is a similar story although there could be metrological work that has been invisible since it lies within the defense sector.

The CCAUV recognizes that participating laboratories may change their priorities over the period of the 10 years that are covered in this strategy document and therefore the pilot laboratories identified in future key comparisons may be subject to change. There are a number of other challenges facing the CCAUV and other CCs with regard to ensuring that the level of the NMI resource, committed to the rolling program of Key Comparisons, is appropriate and minimized. These are briefly covered below.

Repeat period for Key Comparisons

We are only now seeing second repeats of the first Key Comparisons undertaken, so *de facto*, the repeat period for comparisons is currently in excess of 10 years. This is already significantly longer than the original 5 to 7-year interval suggested early within the early life-time of the CCs. With experience in completing Key Comparisons it is anticipated the process will be more streamlined with lower resource requirements, although these gains will probably be less significant the longer the intervening time period is, as it becomes more likely that it will involve new personnel and the need to address a learning curve.

It should be noted that information on resource estimates has in some cases not been possible to obtain for the simple reason that the staff piloting these comparisons are no longer accessible.

The workload to pilot a KC varies depending on the number of participants and the measurement process involved. The very few data available indicate 1-2 months spent per participant in Airborne sound and Vibration comparisons, as for Ultrasound and Underwater acoustics the time dedicated to one participant is limited to 0.5-1 months. Each participant laboratory spends in most cases 1-2 months on a comparison.

In Ultrasound and Underwater Acoustics, the number of KC participants is limited to half a dozen, while for Acoustics and Vibration a dozen of NMIs are on average registered to participate. For the case of Acoustics and Vibration, all RMOs are hence represented.

Extension of the NMI community

As the number of NMIs within the CCAUV increases and more want to participate within Key Comparisons, there will be a need to ensure that the resource implications for the pilot laboratories do not become onerous, through appropriate linkages through RMO Key comparisons. The CCAUV must play a key role in ensuring that resource implications of Key Comparisons are appropriate.

The CCAUV has structured a limited and optimized KC-set to concentrate and prioritize its activities, while still covering a broad range of needs in society. It is clear from the earlier Sections of this document that the work of the CCAUV touches a range of areas affecting the health and well-being of individual, the environment and industry. Sections 5 and 6 demonstrate that there are also exciting developments in physics and engineering which may have implications for metrology over the four technical disciplines. Additionally, emerging applications of Acoustics and Underwater Acoustics, Ultrasound, and Vibration and Shock, as well as Inertial sensors, and the need to underpin calibration beyond what is currently covered by Key Comparisons, are likely to become more important. The challenge faced is meeting these requirements with an appropriate commitment of NMI resource. This should be done with an assessment of the driver or market pull for these new developments, as well as the availability of standard calibration protocols and NMI interest and capabilities for participation that starts with participation in bilateral comparisons.

10. Document Revision Schedule

The revision schedule is on a 2-year period for updating of all lists and a 4 year period for major revision with an extension of the period covered by a rolling program.

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