
Strategy Document for Rolling Programme Development for 2013 to 2023

The Consultative Committee for Acoustics, Ultrasound and Vibration

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1. General Information on CCAUV:

The Consultative Committee for Acoustics, Ultrasound and Vibration;
Established in 1999;
17 members and 14 observers;
46 participants at last meeting (invited and experts included);
3 working groups;
CCAUV meetings every 2 y;
Last meeting held 13 -14 June 2012;
CCAUV President Prof. Joachím Valdés, National University of San Martín UNSAM, (2000).
12 CC-KCs and 22 RMO-KCs carried out from 1999 to 2012;
1 Pilot Study carried out from 1999 to 2012.
There are 51 types of CMCs. 1031 CMC entries are published in KCDB of which 707 are linked to a Key Comparison supported by the CCAUV.

2. Terms of Reference

To:

- endow traceability by international collaboration and coordination;
- identify, plan and execute key comparisons of national measurement standards;
- harmonize contacts between RMOs and survey questions related to CMCs (cf. RMOWG);
- identify advances in physics and engineering that directly influence metrology in acoustics, vibration ultrasound and underwater acoustics;
- 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 (description status of activities and achievements up to and including 2012)

The CCAUV was created in 1999: 9 CIPM key comparisons have been completed since, 3 are still running, another 3 are in the planning process; 22 RMO key comparisons have been carried out, of which some are still running, 1 RMO comparison is planned. Two key comparisons are regionally complete, i.e. all active RMOs are linked within these areas (cf. Appendix 1). The CCAUV has now reached the stage where repeats of KCs are carried out.

The CCAUV plenary session meetings are usually preceded by meetings of each of its three working groups: the Strategic Planning Working Group (SPWG), Regional Metrology Organization Working Group (RMOWG) and the Key Comparison Working Group (KCWG). Strategic planning is not a new concept for the CCAUV, and the SPWG is in charge of revising its strategy and associated documents on a regular basis. The RMOWG is active and has amongst other things worked to facilitate CMC reviews in several aspects. A KCWG was constituted in 2011 whose task is to review protocols and reports of CIPM KCs, RMO KCs and also SCs, in order to assure the quality of published data.

The CCAUV meets on a regular basis every two years. The meetings are formatted to include issues covered by the ToR. They also provide an opportunity for scientific exchange and thematic presentations on current leading-edge acoustical metrology topics. Such sessions have become a feature of the meetings.

The CCAUV follows with interest the interactions with other adjacent fields and applications, such as the work on the new definition of the kelvin and in particular materials metrology. It has also 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 Committee.

The CCAUV covers four main disciplines: Airborne sound (A), ultrasound (U), vibration (V) and underwater acoustics (W). The different fields have deliberately been more or less separated in the following sections to facilitate the identification of each.

4. Stakeholders (who they are and their level of involvement)

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

Stakeholder	**Application**
Metrological bodies	High precision metrology Precursor to other stakeholders
Health	Hearing assessment Objective audiology Diagnostics (imaging) Therapy (e.g. drug delivery in cancer and Alzheimer therapies, treatment enhancement of CVAs) Cleaning and materials processing
Industry	Industrial design Equipment manufacturers Automotive Aerospace Testing (e.g. bulk materials and surfaces) Health and safety Cleaning procedures
Trade	Added value in performance of products
Environment	Marine noise pollution Climat change monitoring Air-borne environmental noise Earth quake monitoring Carbon capture and storage
Society	Environmental protection Psychological influence and human health
Energy	Offshore energy Marine renewable energy Biofuel production
Defense	Mine detection Stealth applications Anti-submarine applications Harbor security Weapons systems
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 (2013-2023)

5.A Airborne Sound (sound in air)

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 of 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 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 four 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, 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.

5.A.1 Metrology infrastructure, sensors and instrumentation

A common situation is to find that 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 develop ahead of these drivers, 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, provide a 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.

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 to 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 and for underpinning traceability chains and quality management requirements.

5.A.2 Hearing assessment and conservation

Hearing is one of our most vital senses and 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 programmes invest heavily in both hearing diagnostics (through screening programmes) 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. 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 programmes 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 oto-acoustic emission and evoked brainstem response. The provision of suitable measurement standards, reference devices (ear simulators) and calibration methods needs to build 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 behavioural 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.

5.A.3 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.

5.A.4 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.

5.U Ultrasound

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

5.U.1 Medical applications of ultrasound

Ultrasound has become one of the most frequently used diagnostic tools 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 last 15 years has seen a dramatic increase in quality and complexity of medical applications with modalities such as the early, routine cancer screening through elastographic or shear-wave imaging methods, showing particular promise. A number of these applications involve generating higher acoustic output.

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 of both existing and emerging 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*, supporting 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. For manufacturers, micro-bubbles coupled with therapeutics will drive developments of the next wave of ultrasound technology into clinical practice over the next 5 to 10 years. 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 demanding 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, 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 in order 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 elastrographic imaging techniques, there may also be a requirement to develop standardized methods of determining Young’s modulus and shear acoustic properties of tissue-like materials.

5.U.2 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 the 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 for 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 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, so there will be significant activity in developing 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.V Vibration

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
- Shock acceleration measurements in the range up to 10^5 m/s² (and beyond) are apparently required in many fields and various NMIs have setup new facilities to respond to this demand
- New approaches concerning the measurement of transient excitations based on deconvolution techniques generate the demand for adapted methods in calibration and dissemination.

- The emerging metrological activity in the field of dynamic measurement of mechanical quantities, like force and torque, has set up a whole new area where acceleration and angular acceleration becomes a base quantity for traceability of the derived quantities.
- Low-frequency vibration transducers are widely used for monitoring earthquakes but also in oil exploration and control of building vibrations. The demand has increased of earth quake 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 0.5 Hz, even to 0.008Hz. Low-frequency vibration key comparison down to 0.1 Hz for traceability is one of the future actions to support this field.

5.W Underwater Acoustics

Acoustic techniques are the methods of choice for most marine applications requiring remote imaging, communication or mapping in sea water, where techniques based on electromagnetic waves suffer from limited range due to high levels of absorption. Such acoustic applications are important in a number of sectors: (i) offshore energy (including oil and gas and marine renewable energy); (ii) environment (marine noise pollution, climate change monitoring and carbon capture and storage); (iii) defense and security (including mine hunting, stealth applications, anti-submarine applications, and harbor/port security); (iv) ocean science (including the study of ocean processes, hydrographic mapping, etc). Technical applications include positioning, navigation, communications, sonar, echo-sounding, geophysical surveying, weapons systems, and tomographic measurements of ocean currents and temperature. Civil offshore activities 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 harbors from mines and potential terrorist threats.

Key drivers in the future are the increasing legislation with regard to assessing and mitigating the exposure of marine life to noise pollution. This is already subject to regulation (for example, EU Marine Strategy Framework Directive, and the EU Habitats Directive). This is increasing the need for absolute acoustic measurements in the ocean, and placing more stringent requirements on the underpinning metrology, both with regard to characterizing sound sources, and undertaking long-term monitoring. The sources of man-made noise causing most concern are construction noise (offshore oil & gas and marine renewable energy developments), geophysical surveying for oil and gas exploration, military sonar, and increased shipping traffic (where deep ocean measurements have reported a 3 dB increase per decade). A major barrier to the planned massive European expansion in offshore renewable energy (wind, wave and tidal) is the impact of the radiated noise. Climate change studies provide another driver, where acoustics may be used as a tool to probe the oceans, for example for changes in acidification and detection of methane seepage. With the move toward increased Carbon Capture and Storage (CCS) using subsea storage, absolute acoustic techniques provide the potential for monitoring CO2 leakage. It should also be remembered that there is a substantial underwater acoustics industry supporting off-shore applications. In oil and gas, there is a clear 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. In particular, hydrophones and materials are required with consistent acoustic performance over a range of different water temperatures and depths.

6. Rationale for various activities (2013-2023)

6.A Airborne Sound (sound in air)

Airborne sound pressure standards based on the electroacoustic reciprocity principle are 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). Presently, a Key Comparison combining the audio and low frequency ranges is underway (CCAUV.A-K5).

It is likely that a Key Comparison similar to CCAUV.A-K5 will be carried out for Laboratory Standard Microphones of other types. A repetition of the K5 comparison should also be expected in the next 5-10 year period.

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 Realization of the acoustic pascal in a diffuse field is also a potential subject subject of work.

6.U 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-K1) is 15 MHz, and it is anticipated that this will be extended up to at least 40 MHz, possibly through an intermediate Supplementary Comparison. 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-K1). Anticipating a potential routine clinical take-up of HIFU or HITU related technologies, there will be a need to employ new focused transducers capable of generating sufficiently high time-average acoustics powers. Again this might best be expedited through a Supplementary Comparison.

6.V Vibration

The traditional areas of vibration metrology 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. s

In the field of shock calibration (especially in the area of high intensity shocks) the established primary calibration procedures (ISO 16063-13) are not adequate to perform comparisons. New procedures are under development and these have to be tested and ultimately employed to provide the means for the dissemination.

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.W 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 only Key Comparison in this field so far was CCAUV.W-K1, completed in 2003. This covered free-field standards in the range 1 kHz to 500 kHz. In spite of large frequency range, the range 500 kHz to 1 MHz remained uncovered (and was not covered by the ultrasound Key Comparison CCAUV.U-K1). The time is right for new free-field Key Comparison to repeat the initial exercise, but also to allow several NMIs with newly-established capabilities to participate. It would be advisable to try to extend the frequency range of this comparison upward to 1 MHz to cover the applications such as short-range imaging, sediment and current profilers, and down to at least 500 Hz to cover the range of some of the powerful low frequencies noise sources. However, not all NMIs will have the capability to cover all frequencies. In addition, a Key Comparison of pressure calibrations is required to cover the important low frequency range down to a few hertz. This is likely to present more of a challenge because there will be fewer NMIs and DIs with sufficient capability. Another area where a Key Comparison might be desirable is in the area of characterization of the acoustic properties of materials for use in underwater acoustics.

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). This places limitations on the ability to disseminate accurate standards. For the most demanding industrial applications, the accuracy requirement can push the boundaries of the primary standard accuracy. The grand challenge for underwater acoustic metrology is perhaps the requirement for the next generation of primary standards of improved accuracy, with optical techniques providing possibilities for improved realization of the acoustic pascal. There is already research being undertaken into such techniques, and in the next ten years these will begin to feed into Key Comparisons as these methods are adopted by some of the NMIs (most likely at higher frequencies at first: 100 kHz to 1 MHz).

7. Required Key comparisons and pilot studies 2013-2023 with indicative repeat frequency

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.A Airborne Sound (sound in air)

Sub-area/ Reference No.	Description	Rationale	How far the light shines	Expected start
Airborne sound	Comparison of Laboratory Standard Microphones type LS2	Repeat of CCAUV.A-K3 and extending frequency range	Pressure sensitivity in the frequency range 2 Hz to 30 kHz	2015
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	2017
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	2018
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	2020
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	2020
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	2023

7.U Ultrasound

Sub-area/ Reference No.	**Description**	**Rationale**	**How far the light shines**	**Expected start**
Ultrasound	Comparison of reference hydrophone calibrations	Repeat of CCAUV.U-K2	End-of-cable loaded hydrophone sensitivity, in nV/Pa, over the frequency range 2 to 20 MHz	2013
Ultrasound	Ultrasonic power	Extension of CCAUV.U-K1 (Pilot Study)	Transducer electro-acoustic radiation conductance and transducer ultrasonic output power, 20 – 300W+	2017
Ultrasound	Comparison of reference hydrophone calibrations	Extension in frequency of CCAUV.U-K2 (Pilot Study)	End-of-cable loaded hydrophone sensitivity, in nV/Pa, over the frequency range 20 to 40 MHz	2018
Ultrasound	Ultrasonic power	Repeat of CCAUV.U-K1	Transducer electro-acoustic radiation conductance and transducer ultrasonic output power, 0.01 – 15 W¶	2020
Ultrasound	Comparison of reference hydrophone calibrations	Repeat of CCAUV.U-K2	End-of-cable loaded hydrophone sensitivity, in nV/Pa, over the frequency range 2 to 20 MHz¶	2023

Ɉ Parameters defining the Key Comparisons such as frequency range and ultrasound power levels, may be the subject of the results of the previous Supplementary Comparisons.

7.V Vibration

Sub-area/ Reference No.	Description	Rationale	How far the light shines	Expected start
Vibration sine-excitation	Comparison of primary calibration in magnitude and phase	Coverage of traditional calibration services in acceleration	0.1 Hz to 200 Hz This will be a regular KC to be repeated in 8 y intervals (subject to discussion)	2013/14
Vibration sine-excitation	Comparison of primary calibration of magnitude and phase	Coverage of traditional calibration services in acceleration	40 Hz to 10 kHz This will be a regular KC to be repeated in 8 y intervals (subject to discussion)	2013/14 2021/22
Vibration: Shock excitation	Primary calibration with parameter identification	Increasing number of NMIs with the capability and demand for CMCs	100 m/s² to 10^5m/s² This will ultimately be a regular KC to be repeated in an 8 year interval. The precondition is a validated procedure and possibly a pilot study: This area may be split into high intensity shock and low intensity shock	2014/15 2021/2022
Vibration: angular vibration	Primary calibration of magnitude	Increasing number of NMIs with the capability and demand for CMCs	Depending on the global demand this may become a regular KC	2015/16

7.W Underwater Acoustics

Sub-area/ Reference No.	Description	Rationale	How far the light shines	Expected start
Underwater Acoustics	Comparison of free-field calibrations of hydrophones	Repeat of CCAUV.W-K1	Free-field hydrophone sensitivity in V/Pa over the frequency range ~500 Hz to 1 MHz	2013
Underwater Acoustics	Comparison of pressure calibration of hydrophones	Extension of CCAUV.W-K1 to low frequencies	Free-field hydrophone sensitivity in V/Pa over the frequency range 20 Hz to 1 kHz	2015
Underwater Acoustics	Comparison of measurements of sound speed and attenuation	New comparison for materials properties	Transmission loss, insertion loss, sound speed, absorption Frequency range 1 kHz to 100 kHz	2016
Underwater Acoustics	Comparison of free-field calibrations of hydrophones	Repeat of CCAUV.W-K1	Free-field hydrophone sensitivity in V/Pa over the frequency range ~500 Hz to 1 MHz	2020
Underwater Acoustics	Comparison of pressure calibration of hydrophones	Extension of CCAUV.W-K1 to low frequencies	Free-field hydrophone sensitivity in V/Pa over the frequency range 20 Hz to 1 kHz	2023

8. Resource implications for laboratories for piloting comparisons

The resources employed for some of the CCAUV Key Comparisons that already have been completed are depicted in the diagram of Fig. 1. An estimation of the employed resources for piloting comparisons already carried out is given in the sections below for each AUV area. On this basis, it is possible to estimate future costs and how to make them more cost effective based of former experience.

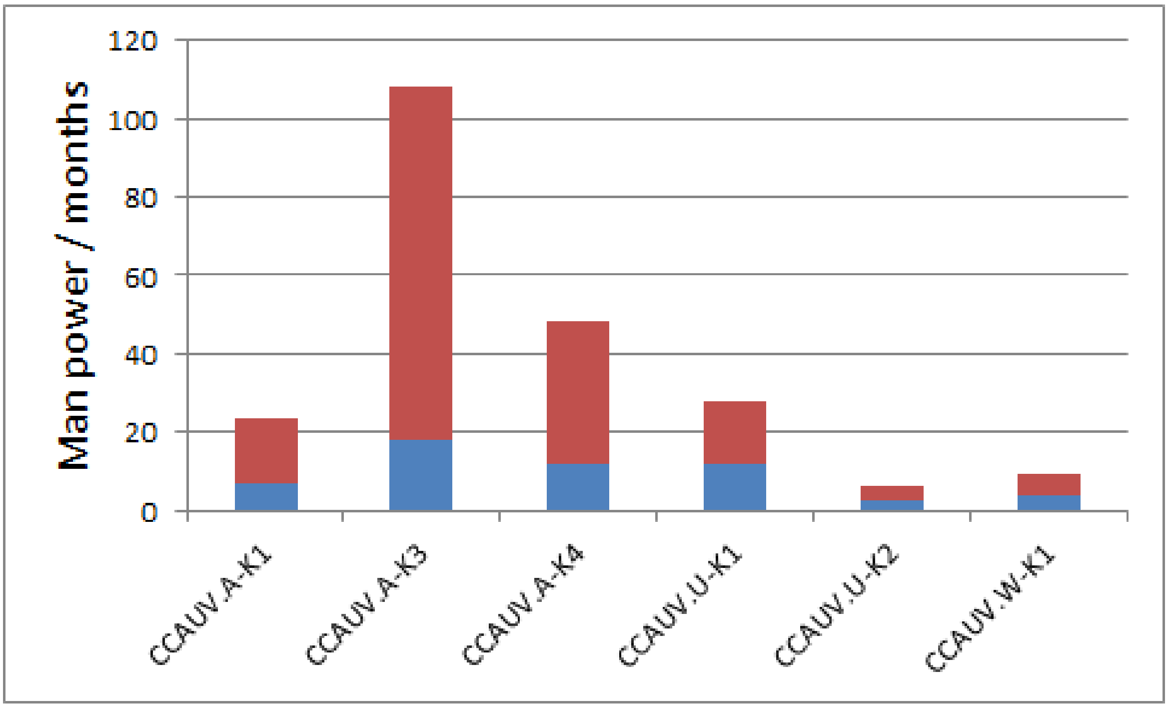


Fig. 1. Resources employed for some of the Key Comparisons that already have been carried is depicted as a histogram. The blue areas correspond to the manpower in terms of months, while the red areas correspond to the total time invested by all participant laboratories.

8.A Airborne Sound (sound in air)

Sub-area/ Reference No.	Description	Rationale	Resource estimates	Pilot Laboratories
Airborne sound (2015)	Comparison of Laboratory Standard Microphones type LS2	Repeat of CCAUV.A-K3 and extending frequency range	14 PM	TBC (LNE, NPL)
Airborne sound (2017)	Comparison of Laboratory Standard Microphones type LS2	Repeat of CCAUV.A-K4	12 PM	TBC (DFM)
Airborne sound (2020)	Comparison of Laboratory Standard Microphones type LS1	Repeat of CCAUV.A-K5	14 PM	TBC (NPL)
Airborne sound (2020)	Comparison of Working Standard Microphones type WS3 (Pilot study)	Extension of the frequency range up to 150 kHz	12 PM	TBC (DFM)
Airborne sound (2020)	Comparison of Laboratory Standard Microphones type LS1/LS2 (pilot study)	Calibration in a diffuse field	8 PM	TBC (DFM, NPL)
Airborne sound (2023)	Calibration of LS1/LS2/WS3 microphones (pilot study)	Calibration using optical techniques	8 PM	TBC (NPL)

8.U Ultrasound

Sub-area/ Reference No.	**Description**	**Rationale**	**Resource estimates**	**Pilot Laboratories**
Ultrasound (2013)	Comparison of reference hydrophone calibrations	Repeat of CCAUV.U-K2	6 PM	NPL
Ultrasound (2017)	Ultrasonic power	Extension of CCAUV.U-K1 (Pilot Study)	3 PM	TBC
Ultrasound (2018)	Comparison of reference hydrophone calibrations	Extension in frequency of CCAUV.U-K2 (Pilot Study)	3 PM	TBC
Ultrasound (2020)	Ultrasonic power	Repeat of CCAUV.U-K1	14 PM	PTB
Ultrasound (2023)	Comparison of reference hydrophone calibrations	Repeat of CCAUV.U-K2	7 PM	NPL

8.V Vibration

Sub-area/ Reference No.	**Description**	**Rationale**	**Resource estimates**	**Pilot Laboratories**
Vibration: CCAUV.V-K3	Primary Sinusoidal accelerometer calibration for low frequency	Extension of frequency range	10 PM	To be discussed

8.W Underwater Acoustics

Sub-area/ Reference No.	Description	Rationale	Resource estimates	Pilot Laboratories
Underwater Acoustics	Comparison of free-field calibrations of hydrophones	Repeat of CCAUV.W-K1	8 PM	NPL
Underwater Acoustics	Comparison of pressure calibration of hydrophones	Extension of CCAUV.W-K1 to low frequencies	6 PM	TBC
Underwater Acoustics	Comparison of measurements of sound speed and attenuation	New comparison for materials properties	5 PM	NPL or NIST-USRD
Underwater Acoustics	Comparison of free-field calibrations of hydrophones	Repeat of CCAUV.W-K1	6 PM	NPL
Underwater Acoustics	Comparison of pressure calibration of hydrophones	Extension of CCAUV.W-K1 to low frequencies	7 PM	TBC

9. Summary table of comparisons, dates, required resources and the laboratories already having institutional agreement to pilot particular comparisons

Since its inception in 1999, nine CIPM Key Comparisons have been completed covering the four disciplines: Airborne Sound, Ultrasound, Underwater Acoustics and Vibration. The metrology for these technical fields have various degrees of maturity. Sound-in-Air is by far the most mature area, and this is reflected in the number of NMIs participating Key Comparisons, the consequent resource implications for piloting Key Comparisons (Figure 1) and the number of CMC entries supported over the various disciplines (Figure 2). In comparison, metrology within the Ultrasound is relatively new and this is 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 here, considerably more metrology has been invisible as it has been within the defense sector.

There are a number of challenges facing the CCAUV and other CCs with regard to ensuring that the level of the NMI resource, committed to the rolling programme of Key Comparisons, is appropriate and minimized. These will be briefly covered below.

Repeat period for Key Comparisons

We are only now seeing 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 – 7 years 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.

In Appendix 2, a table is given where the completed, still running and planned KCs are listed. On “How far does the light shine?” the number of CMC entries directly linked to the particular KC is indicated. However, in figure 2 are depicted the number of CMCs that is traceable to a CC KC.

It may 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. In this figure are included measurements and analysis, but also reporting. Each participant laboratory spends in most cases 1-2 months on the comparison.

In U and W, the number of KC participants is limited to half a dozen, while for A and V a dozen of NMIs are on average registered to participate. For the case of A and V, 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 are not too 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.

Meeting emerging metrology requirements for the future

The CCAUV has structured a limited and optimized KC-set to concentrate and prioritize its activities, still covering a broad range of needs in society. It is clear from the earlier Sections of this Strategic Plan 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 A, U, V and W, and the need to underpin calibration beyond the regions currently covered by Key Comparisons, are likely to become more important. The challenge here is to meet 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.

Refer to Appendix 2??

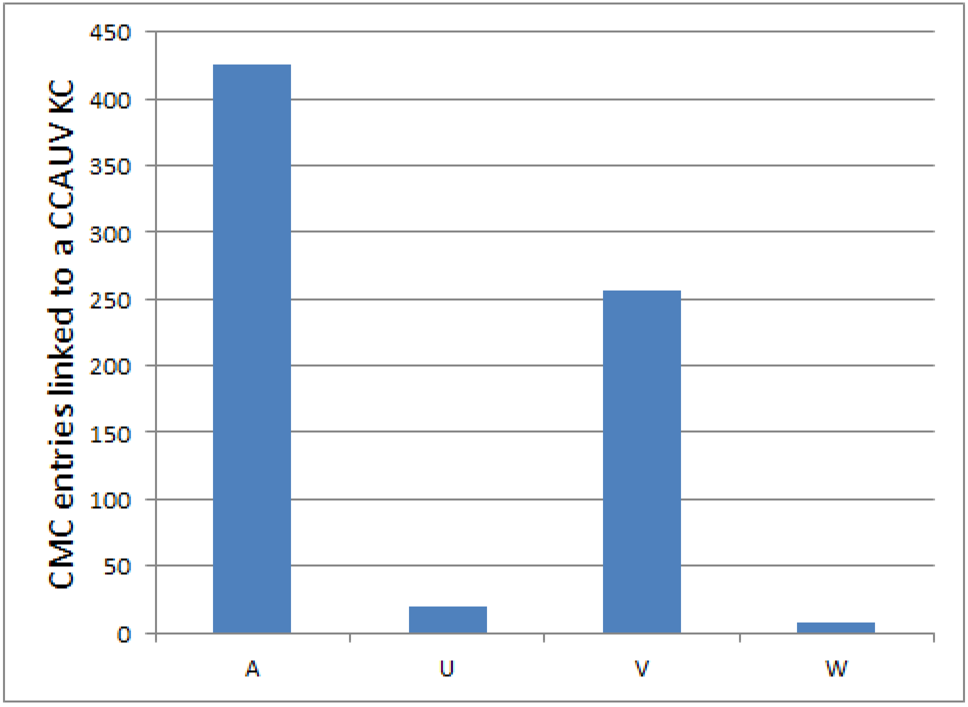


Fig. 2. Number of CMC entries for Airborne sound, ultrasound, vibration and underwater acoustics that are traceable to a CCAUV KC.

10. Document Revision Schedule

2 year updating of all lists
4 year major revision with extension of period covered by rolling **programme**

APPENDIX 1

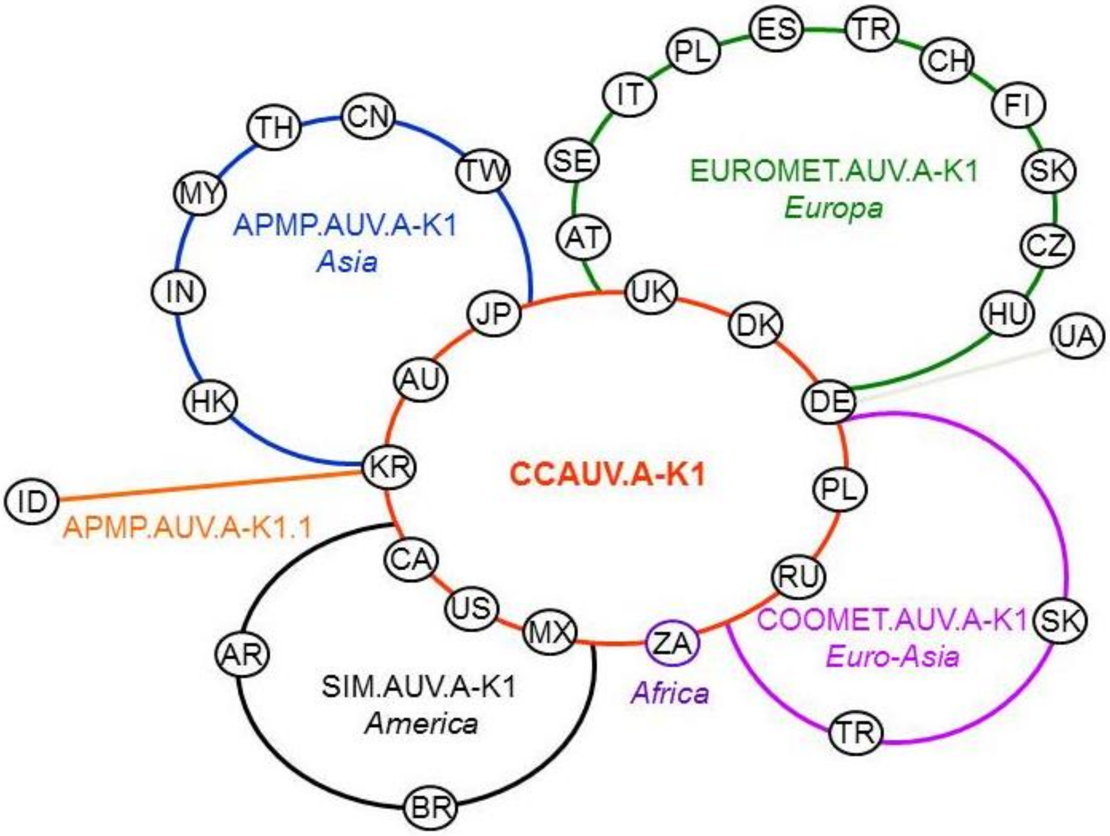


Fig.A-1. Symbolic scheme of the CCAUV.A-K1 comparison to which all active RMOs are linked. This particular comparison concerns the pressure sensitivity level of laboratory standard microphones (LS1P) over the frequency range 63 Hz to 8 kHz.

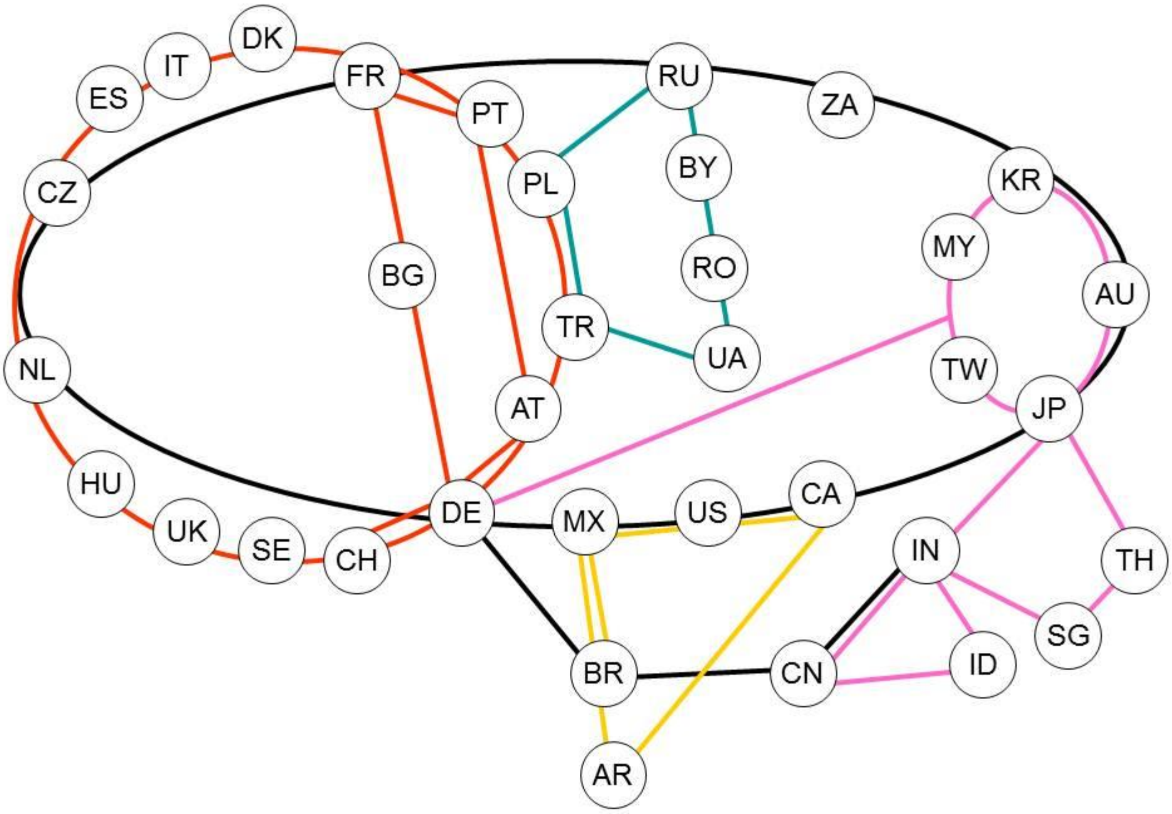
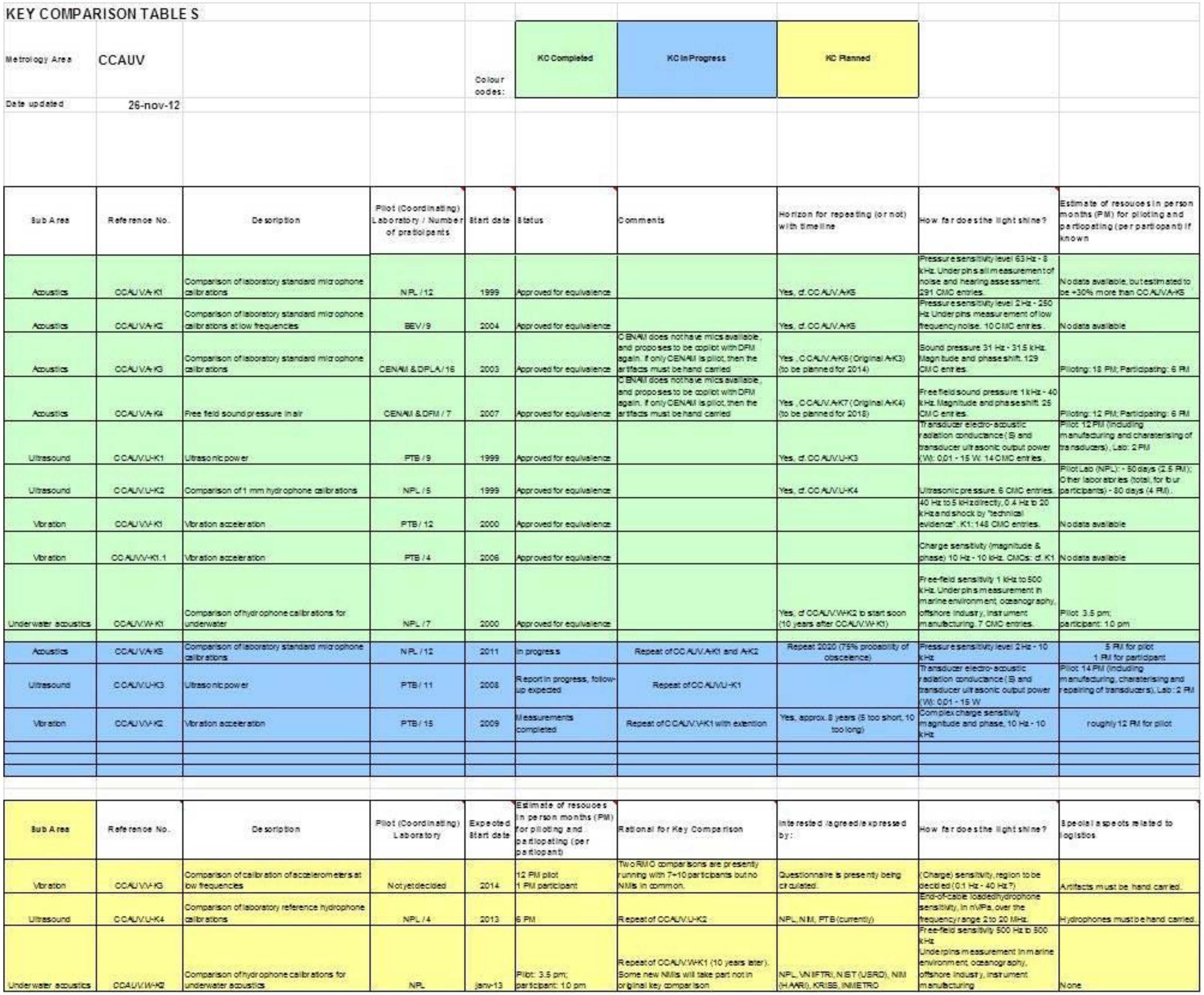


Fig.A-2. Symbolic scheme of the CCAUV.V-K1 comparison to which all active RMOs are linked. The black oval represents the CCAUV.V-K1 comparison; red – EURAMET; green – COOMET; pink – APMP; yellow – SIM. For this particular comparison, links between RMOs have been established which enhances the robustness of the KCRV. This particular comparison concerns the charge sensitivity of back-to-back and single-ended frequency range 40 Hz to 5 kHz.

APPENDIX 2



KEY COMPARISON TABLE S

Metrology Area: CCAUV

Date updated: 26-nov-12

Colour codes: 🟩 KC Completed; 🟦 KC In Progress; 🟨 KC Planned

Sub Area	Reference No.	Description	Pilot (Coordinating) Laboratory / Number of participants	Start date	Status	Comments	Horizon for repeating (or not) with timeline	How far does the light shine?	Estimate of resouces in person months (PM) for piloting and participating (per participant) if known
Acoustics	CCAUV.A-K1	Comparison of laboratory standard microphone calibrations	NPL / 12	1999	Approved for equivalence		Yes, cf. CCAUV.A-K5	Pressure sensitivity level 63 Hz - 8 kHz. Underpins all measurement of noise and hearing assessment. 291 CMC entries.	No data available, but estimated to be +30% more than CCAUV.A-K5
Acoustics	CCAUV.A-K2	Comparison of laboratory standard microphone calibrations at low frequencies	BEV / 9	2004	Approved for equivalence		Yes, cf. CCAUV.A-K5	Pressure sensitivity level 2 Hz - 250 Hz Underpins measurement of low frequency noise. 10 CMC entries.	No data available
Acoustics	CCAUV.A-K3	Comparison of laboratory standard microphone calibrations	CENAM & DPLA / 16	2003	Approved for equivalence	CENAM does not have mics available, and proposes to be copilot with DFM again. If only CENAM is pilot, then the artifacts must be hand carried	Yes , CCAUV.A-K6 (Original A-K3) (to be planned for 2014)	Sound pressure 31 Hz - 31.5 kHz. Magnitude and phase shift. 129 CMC entries.	Piloting: 18 PM; Participating: 6 PM
Acoustics	CCAUV.A-K4	Free field sound pressure in air	CENAM & DFM / 7	2007	Approved for equivalence	CENAM does not have mics available, and proposes to be copilot with DFM again. If only CENAM is pilot, then the artifacts must be hand carried	Yes , CCAUV.A-K7 (Original A-K4) (to be planned for 2018)	Free field sound pressure 1 kHz - 40 kHz. Magnitude and phase shift. 25 CMC entries.	Piloting: 12 PM; Participating: 6 PM
Ultrasound	CCAUV.U-K1	Ultrasonic power	PTB / 9	1999	Approved for equivalence		Yes, cf. CCAUV.U-K3	Transducer electro-acoustic radiation conductance (S) and transducer ultrasonic output power (W): 0.01 - 15 W. 14 CMC entries.	Pilot: 12 PM (including manufacturing and charaterising of transducers), Lab: 2 PM
Ultrasound	CCAUV.U-K2	Comparison of 1 mm hydrophone calibrations	NPL / 5	1999	Approved for equivalence		Yes, cf. CCAUV.U-K4	Ultrasonic pressure. 6 CMC entries.	Pilot Lab (NPL): - 50 days (2.5 PM); Other laboratories (total, for four participants) - 80 days (4 PM).
Vibration	CCAUV.V-K1	Vibration acceleration	PTB / 12	2000	Approved for equivalence			40 Hz to 5 kHz directly, 0.4 Hz to 20 kHz and shock by "technical evidence". K1: 148 CMC entries.	No data available
Vibration	CCAUV.V-K1.1	Vibration acceleration	PTB / 4	2006	Approved for equivalence			Charge sensitivity (magnitude & phase) 10 Hz - 10 kHz. CMCs: cf. K1	No data available
Underwater acoustics	CCAUV.W-K1	Comparison of hydrophone calibrations for underwater	NPL / 7	2000	Approved for equivalence		Yes, cf CCAUV.W-K2 to start soon (10 years after CCAUV.W-K1)	Free-field sensitivity 1 kHz to 500 kHz. Underpins measurement in marine environment, oceanography, offshore industry, instrument manufacturing. 7 CMC entries.	Pilot: 3.5 pm; participant: 1.0 pm
Acoustics	CCAUV.A-K5	Comparison of laboratory standard microphone calibrations	NPL / 12	2011	In progress	Repeat of CCAUV.A-K1 and A-K2	Repeat 2020 (75% probability of obscelence)	Pressure sensitivity level 2 Hz - 10 kHz	5 PM for pilot 1 PM for participant
Ultrasound	CCAUV.U-K3	Ultrasonic power	PTB / 11	2008	Report in progress, follow-up expected	Repeat of CCAUV.U-K1		Transducer electro-acoustic radiation conductance (S) and transducer ultrasonic output power (W): 0.01 - 15 W	Pilot: 14 PM (including manufacturing, charaterising and repairing of transducers), Lab: 2 PM
Vibration	CCAUV.V-K2	Vibration acceleration	PTB / 15	2009	Measurements completed	Repeat of CCAUV.V-K1 with extention	Yes, approx. 8 years (5 too short, 10 too long)	Complex charge sensitivity magnitude and phase, 10 Hz - 10 kHz	roughly 12 PM for pilot

Sub Area	Reference No.	Description	Pilot (Coordinating) Laboratory	Expected Start date	Estimate of resouces in person months (PM) for piloting and participating (per participant)	Rational for Key Comparison	Interested /agreed/expressed by:	How far does the light shine?	Special aspects related to logistics
Vibration	CCAUV.V-K3	Comparison of calibration of accelerometers at low frequencies	Not yet decided	2014	12 PM pilot 1 PM participant	Two RMO comparisons are presently running with 7÷10 participants but no NMIs in common.	Questionnaire is presently being circulated.	(Charge) sensitivity, region to be decided (0.1 Hz - 40 Hz ?)	Artifacts must be hand carried.
Ultrasound	CCAUV.U-K4	Comparison of laboratory reference hydrophone calibrations	NPL / 4	2013	6 PM	Repeat of CCAUV.U-K2	NPL, NIM, PTB (currently)	End-of-cable loaded hydrophone sensitivity, in nV/Pa, over the frequency range 2 to 20 MHz.	Hydrophones must be hand carried.
Underwater acoustics	CCAUV.W-K2	Comparison of hydrophone calibrations for underwater acoustics	NPL	janv-13	Pilot: 3.5 pm; participant: 1.0 pm	Repeat of CCAUV.W-K1 (10 years later). Some new NMIs will take part not in original key comparison	NPL, VNIIFTRI, NIST (USRD), NIM (HAARI), KRISS, INMETRO	Free-field sensitivity 500 Hz to 500 kHz Underpins measurement in marine environment, oceanography, offshore industry, instrument manufacturing	None