SnT 2023

CTBT: SCIENCE AND TECHNOLOGY CONFERENCE

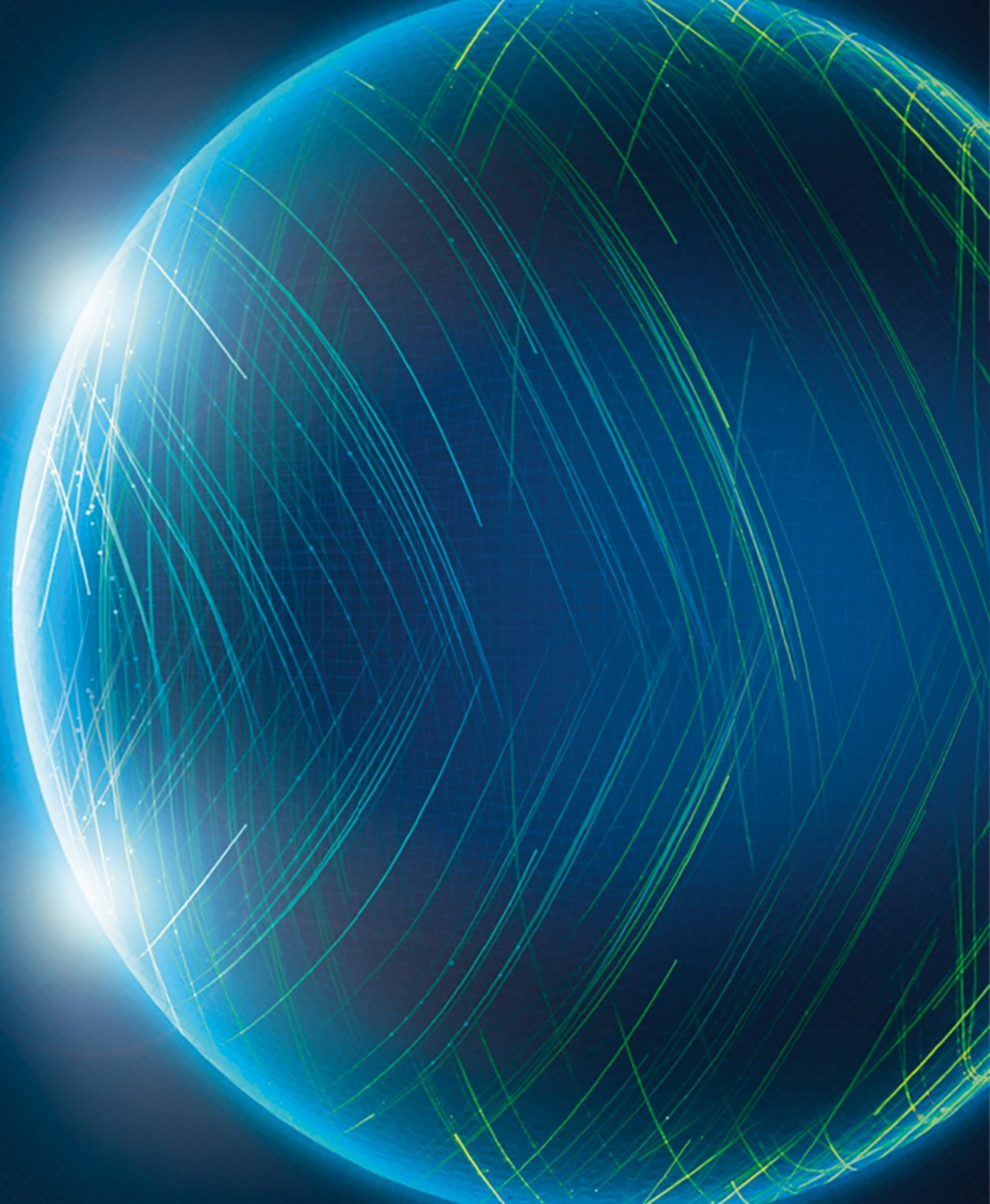
HOFBURG PALACE - Vienna and Online

19 TO 23 JUNE

Workshop on Metrology for the IMS

Welcome

Richard Barham



InfraAUV

Introduction of the Infra-AUV project

Acoustic and seismic monitoring are key technologies in many geophysical applications including CTBT activities, however;

- In the frequency range of interest there is little or no provision of measurement traceability to enable measurement data to be physically meaningful
- While sensor calibration methods are implemented both in the laboratory and in the field, they cannot yet be linked to a primary measurement standard
- The performance of infrasound sensors, hydro-acoustic sensors and seismometers needs to be characterised over the wide range of environmental conditions found in operational conditions

The Infra-AUV project was formulated to address these measurement needs

A-U-V is an acronym frequently used in metrology circles. In Infra-AUV it denotes Acoustics, Underwater acoustic and Vibration

Infra-AUV Objectives

1. To develop primary and secondary calibration methods in the low frequency range
2. To specify devices suitable for transferring measurement traceability to sensor deployed in the field, e.g. at IMS monitoring stations
3. To develop new methods or augment existing methods of on-site calibration, incorporating full measurement traceability
4. To illustrate the impact of metrology considerations, such as traceability and measurement uncertainty, in AUV monitoring
5. To maximise impact by engaging widely with stakeholders
   - station operators and other scientific users of data
   - sensor manufacturers
   - standardisation committees

A mix of

- National Measurement Institutes providing leading-edge input on metrology, standardisation and sensors
- Station operators providing application-specific knowledge and insight into operational requirements and issues
- A scientific consultant managing stakeholder engagement

PTB (Germany) is the project co-ordinator

Workshop

Day 1

Focus on

Laboratory Calibration

Day 2

Focus on

Field Calibration

Agenda Day 1

<u>Background</u>

Traceability to the SI – what does it mean, what are the benefits and how does it work on the global scale? - Thomas Bruns

<u>Fundamental realization of quantities at National Metrology Institutes (NMIs)</u>

Methods of absolute calibration of microphones and microbarometers at low frequencies - Dominique Rodrigues

Measurement standards for hydroacoustics - Stephen Robinson

Calibration of seismometers by laser-interferometry - Thomas Bruns

<u>Comparison calibration methods for working standard sensors</u>

Secondary methods of microphone and microbarometer calibration - Marvin Rust

Hydrophone calibration in the laboratory and at simulated ocean conditions - Stephen Robinson

Laboratory calibration of seismometers at low frequencies by comparison - Jacob Winther

Agenda Day 2

Delivering the SI to IMS stations through on-site calibration*

Practical implementation of traceable initial calibration and ongoing on-site calibration at infrasound stations using the CalxPy software.
Benoit Doury, CTBTO and Samuel Kristoffersen

Concepts of traceable on-site calibration of deployed hydroacoustic sensors. - Stephen Robinson

Considerations for installing and utilizing traceable reference sensors for seismic monitoring - Michaela Schwardt

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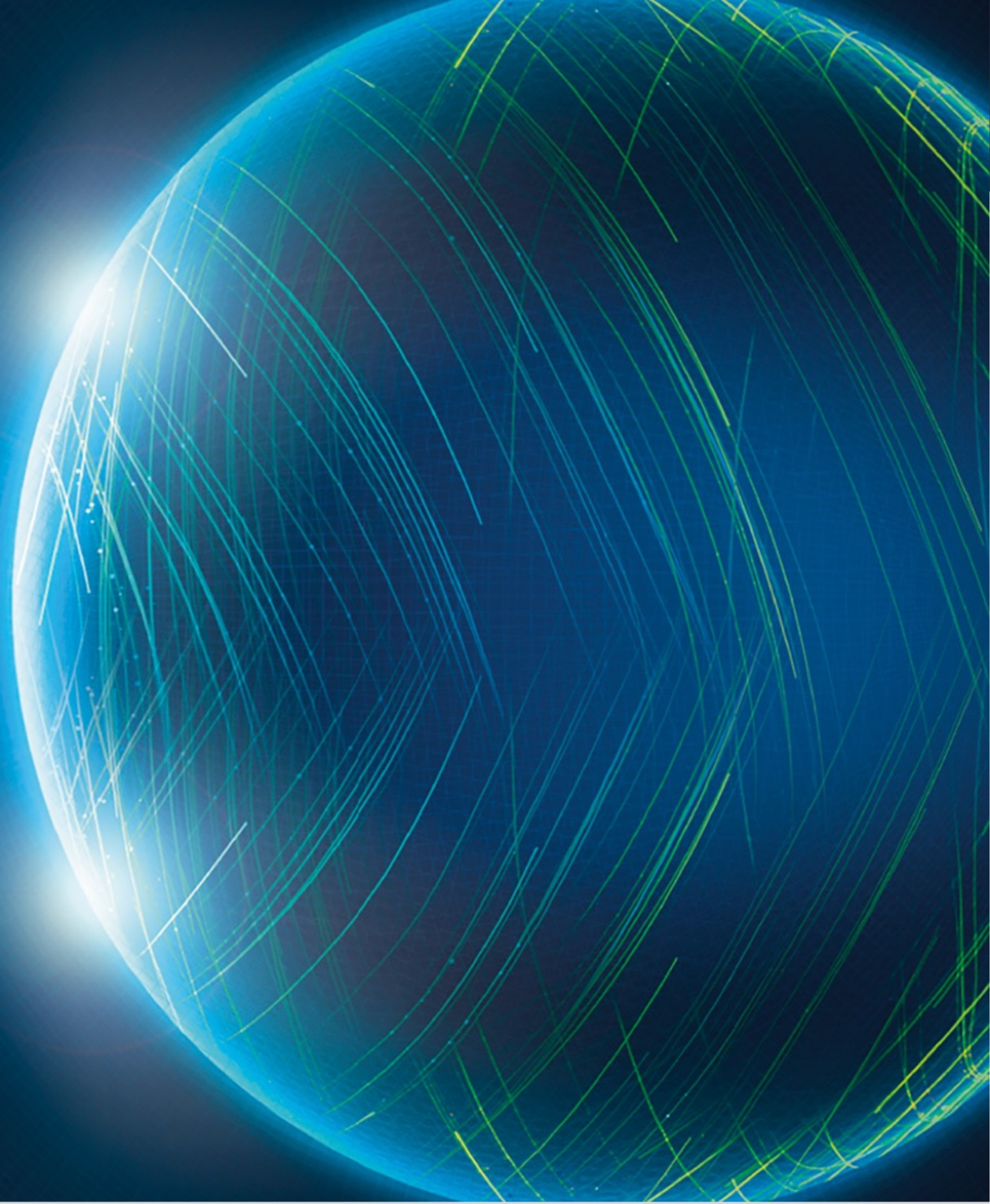
Traceability to the SI: what does it mean, how does it work on the global scale?

Thomas Bruns

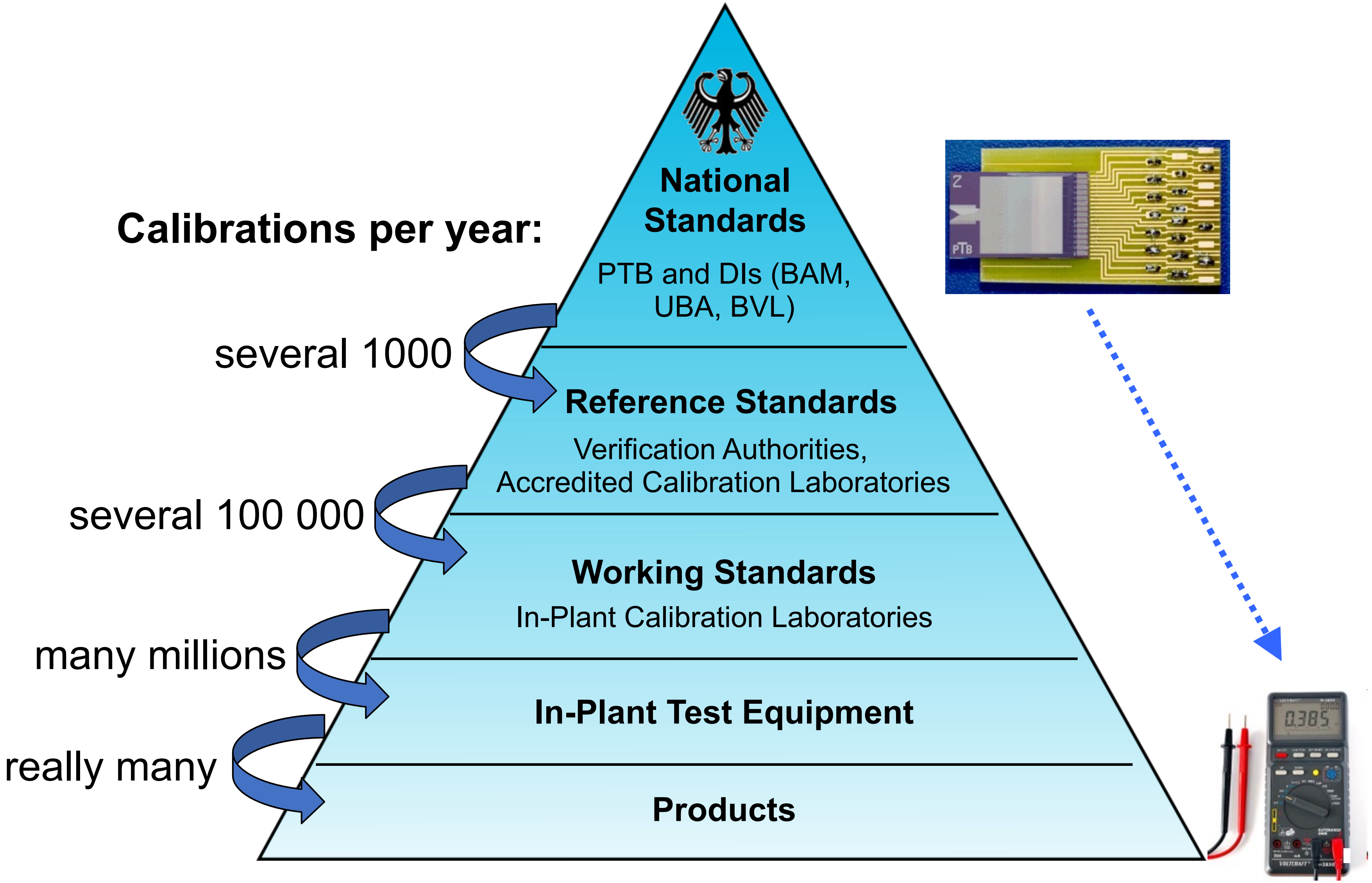
Physikalisch-Technische Bundesanstalt

Germany

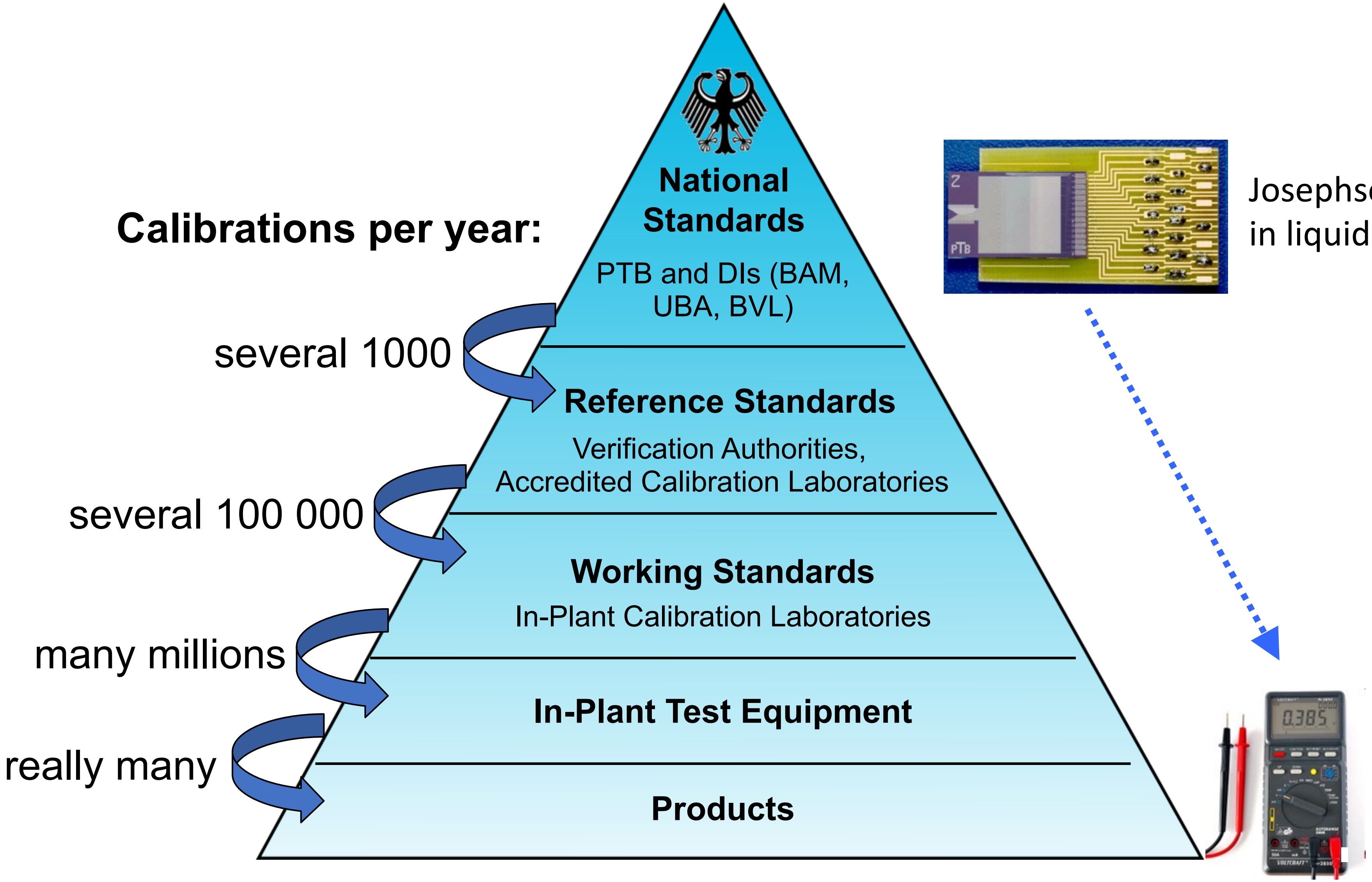
InfraAUV



The National Traceability Pyramid

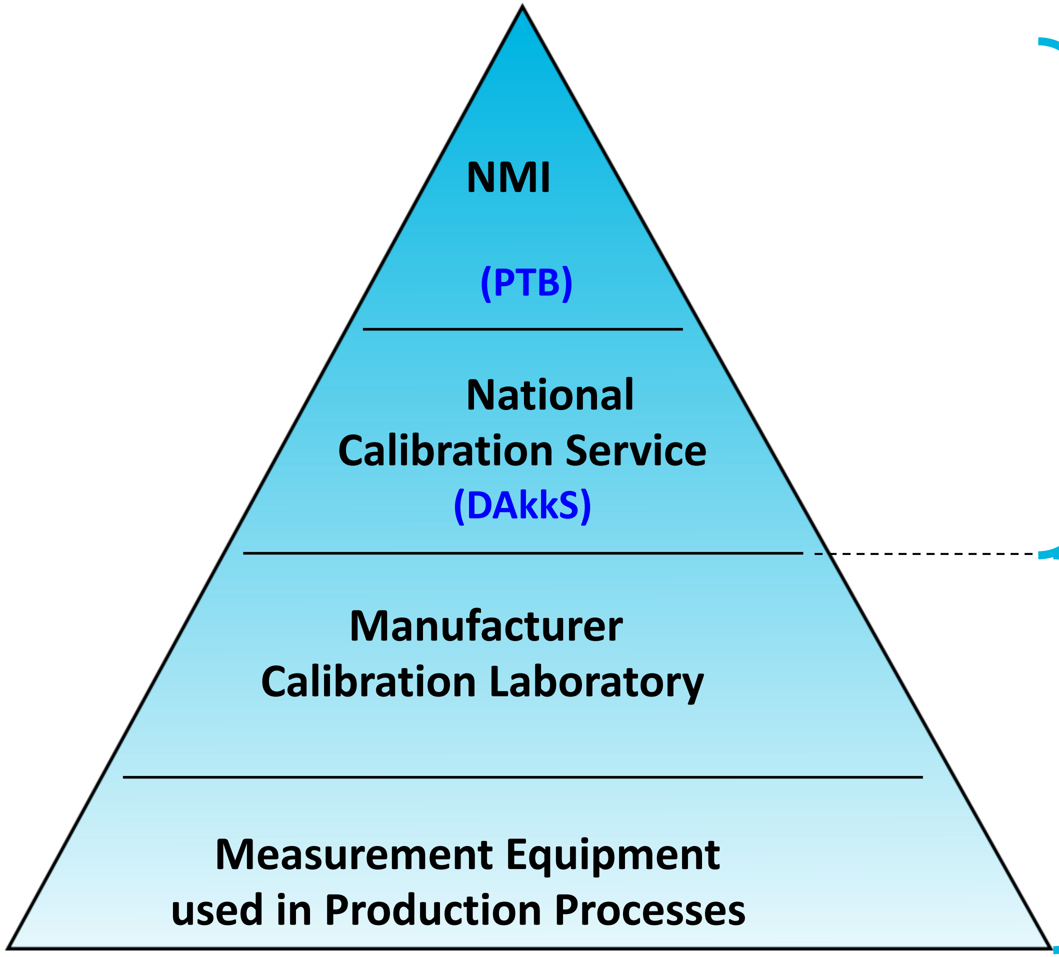


The National Traceability Pyramid



Josephson Junction Array in liquid Helium

Multimeter in bare hands

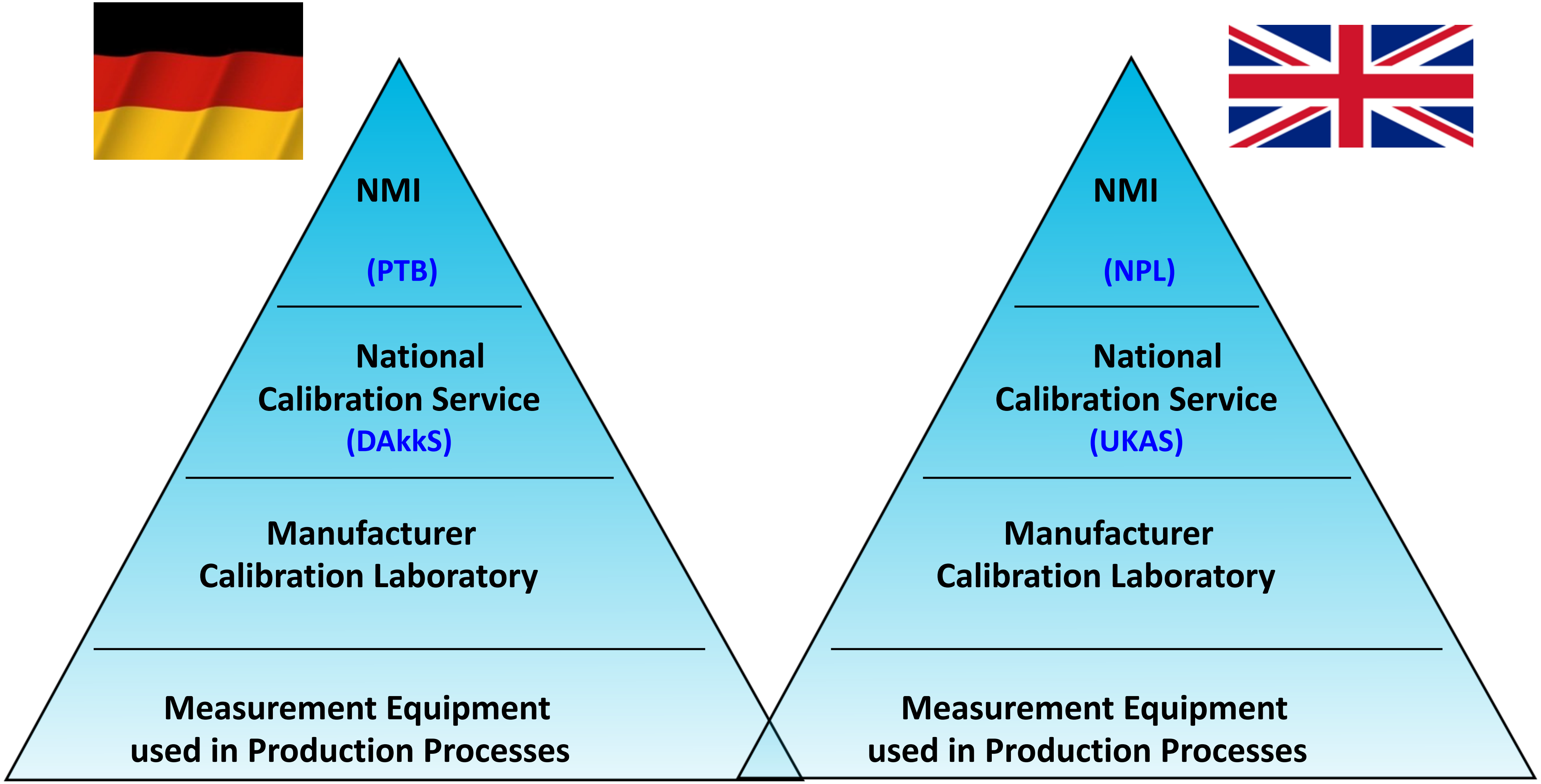


covered by international and national written standards

- ISO/IEC 17025:2005
- ISO 16063-xx (for vibration measurement)
- DKD-R 3-1 part 1 to 4 (national)
- validated methods

defined in the manufacturers internal Quality Management System

International Implementation of the SI



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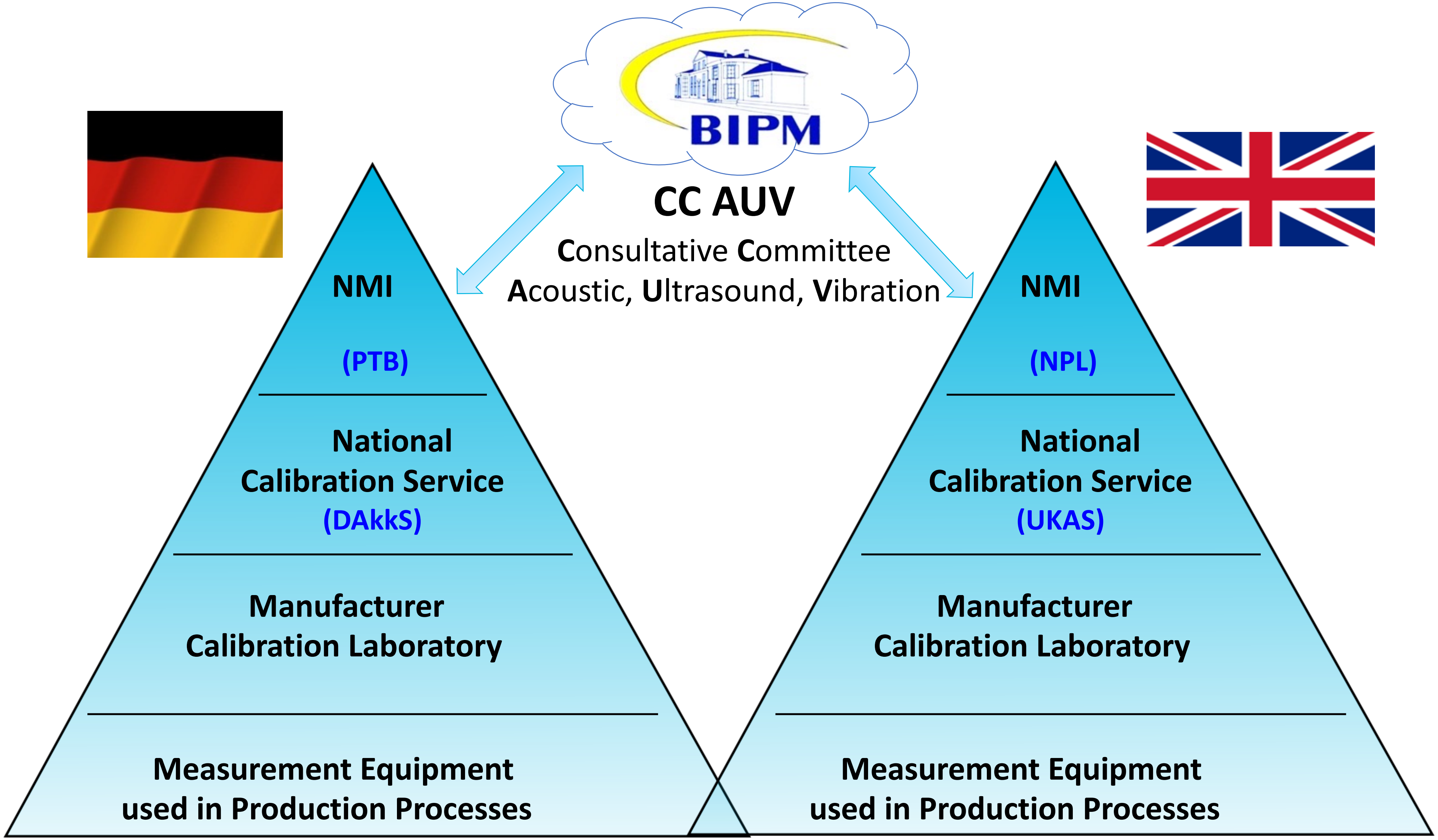
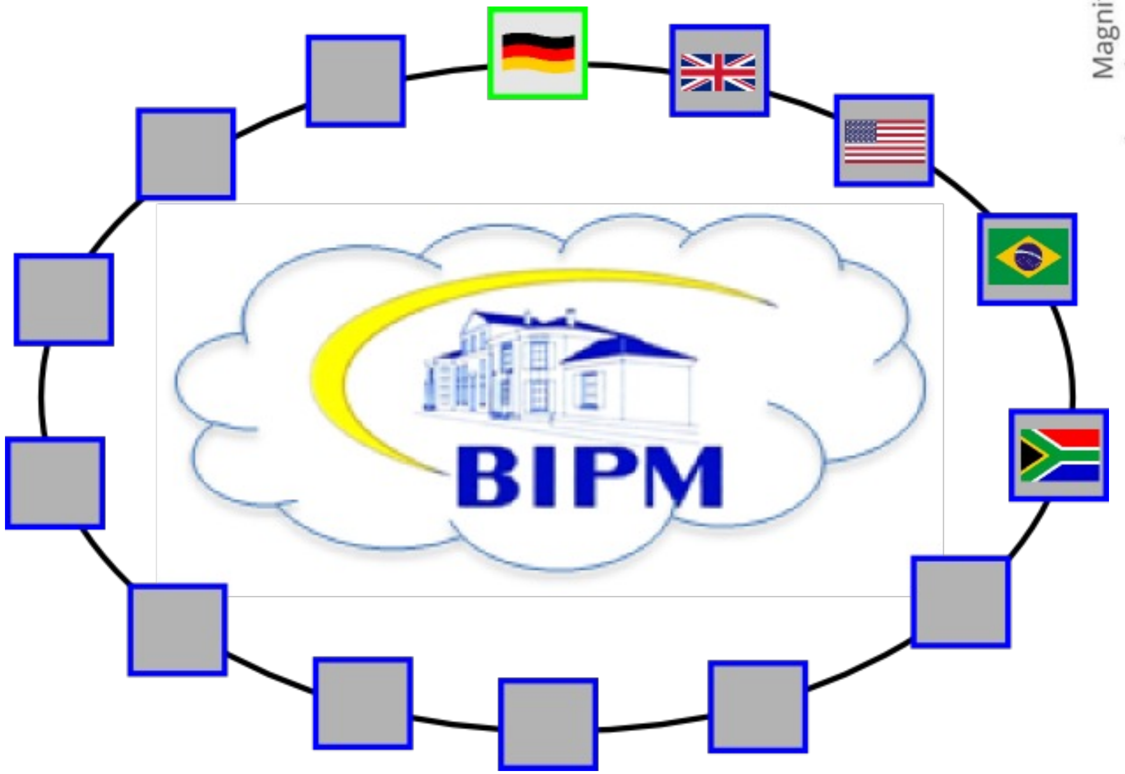
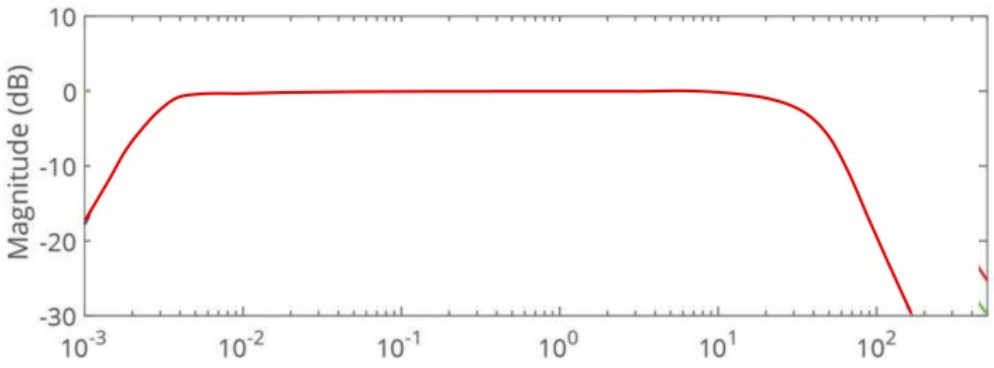


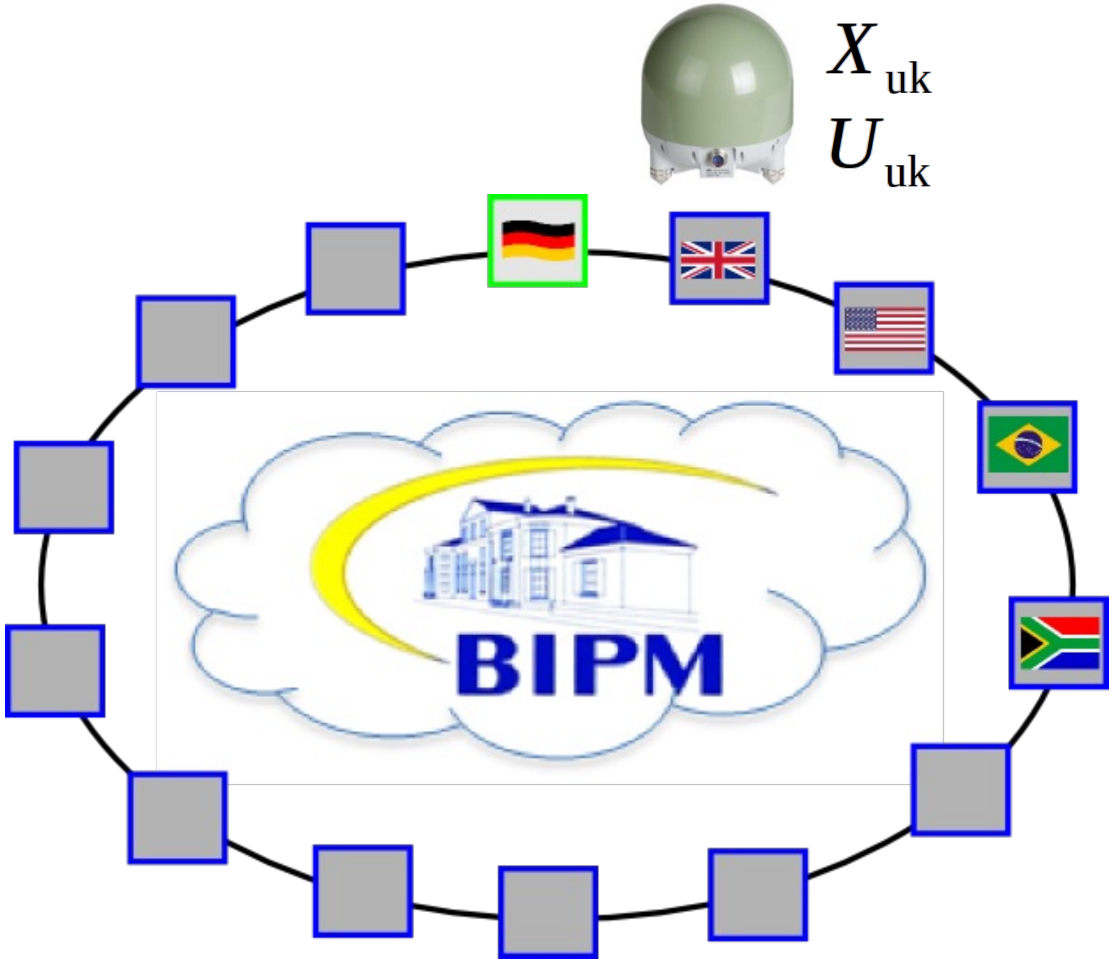
“Equivalence“: Building a Network of Trust

X_{de}
U_{de}



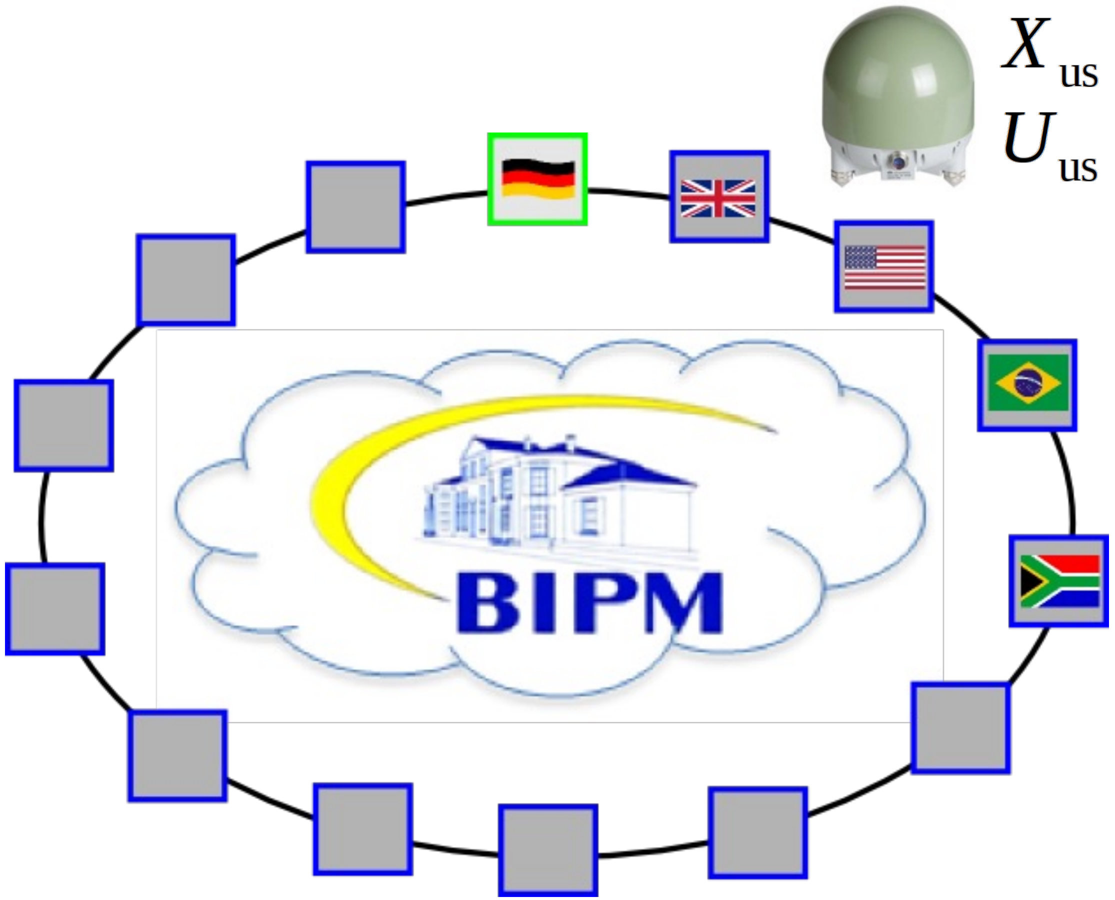


"Equivalence": Building a Network of Trust



Workshop on Metrology for the IMS

“Equivalence“: Building a Network of Trust

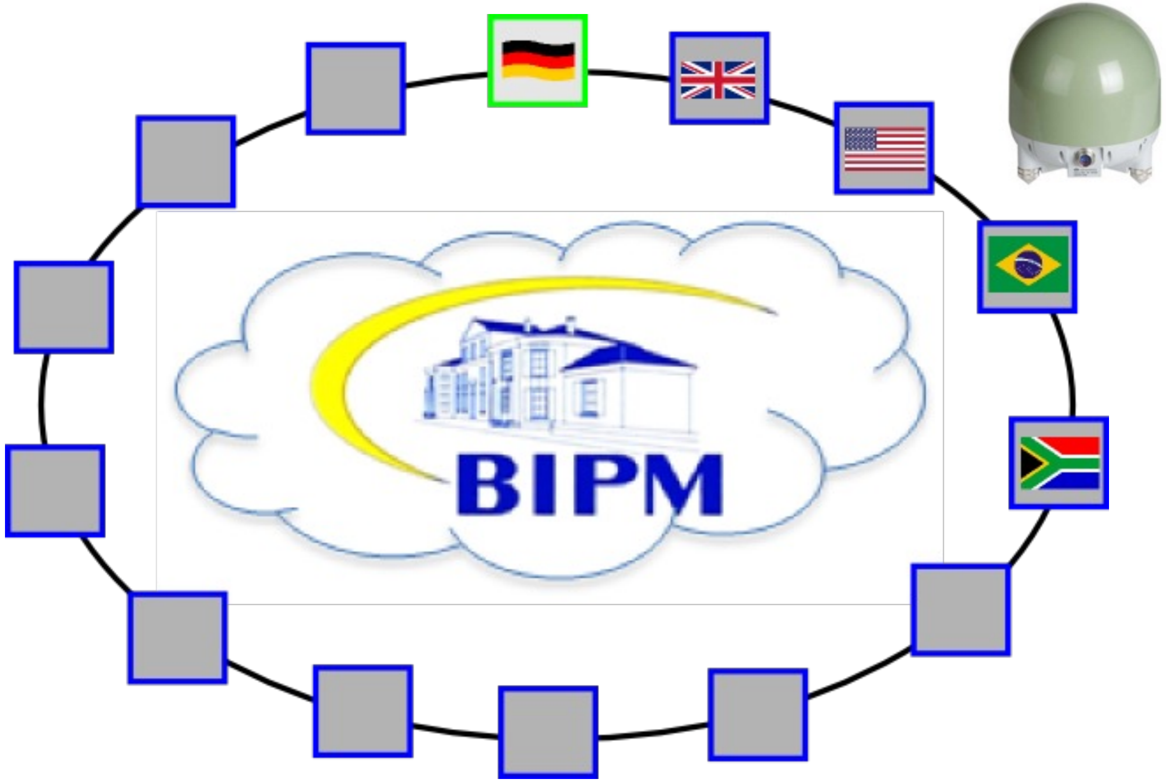


X_{us}

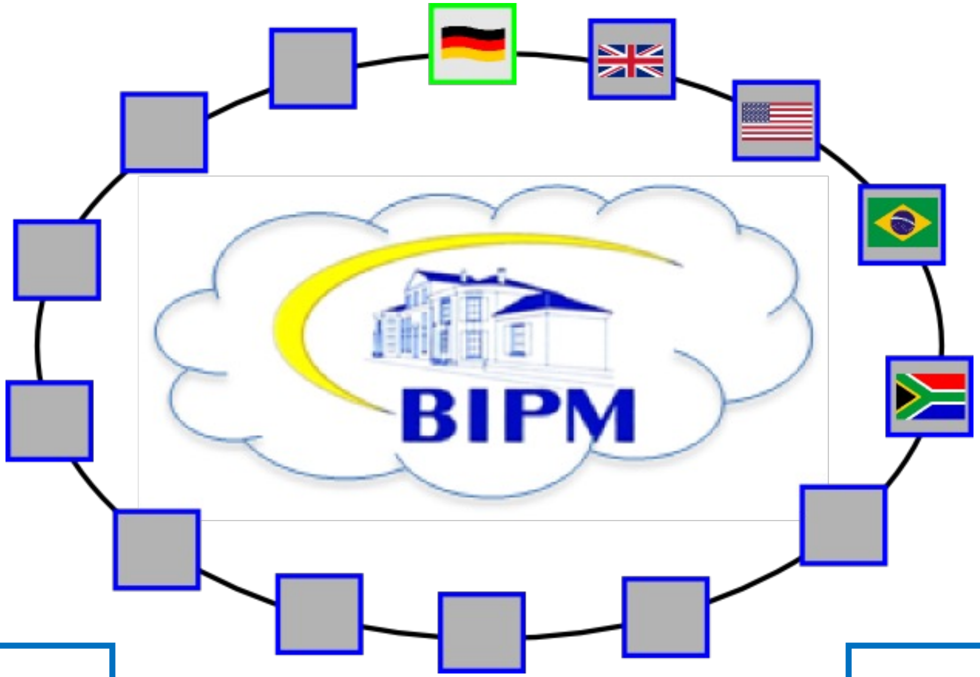
U_{us}

Workshop on Metrology for the IMS

“Equivalence“: Building a Network of Trust



X_{us}
U_{us}



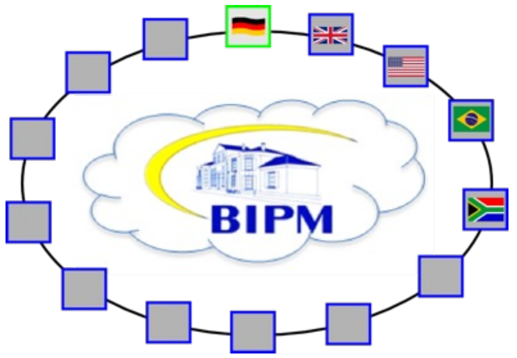
Reference Value

$$X_{ref} = \frac{\sum \frac{x_i}{u_i^2}}{\sum \frac{1}{u_i^2}}$$

Combined Uncertainty

$$u_{X_{ref}} = \sqrt{\frac{1}{\sum \frac{1}{u_i^2}}}$$

"CMC": Calibration and Measurement Capability



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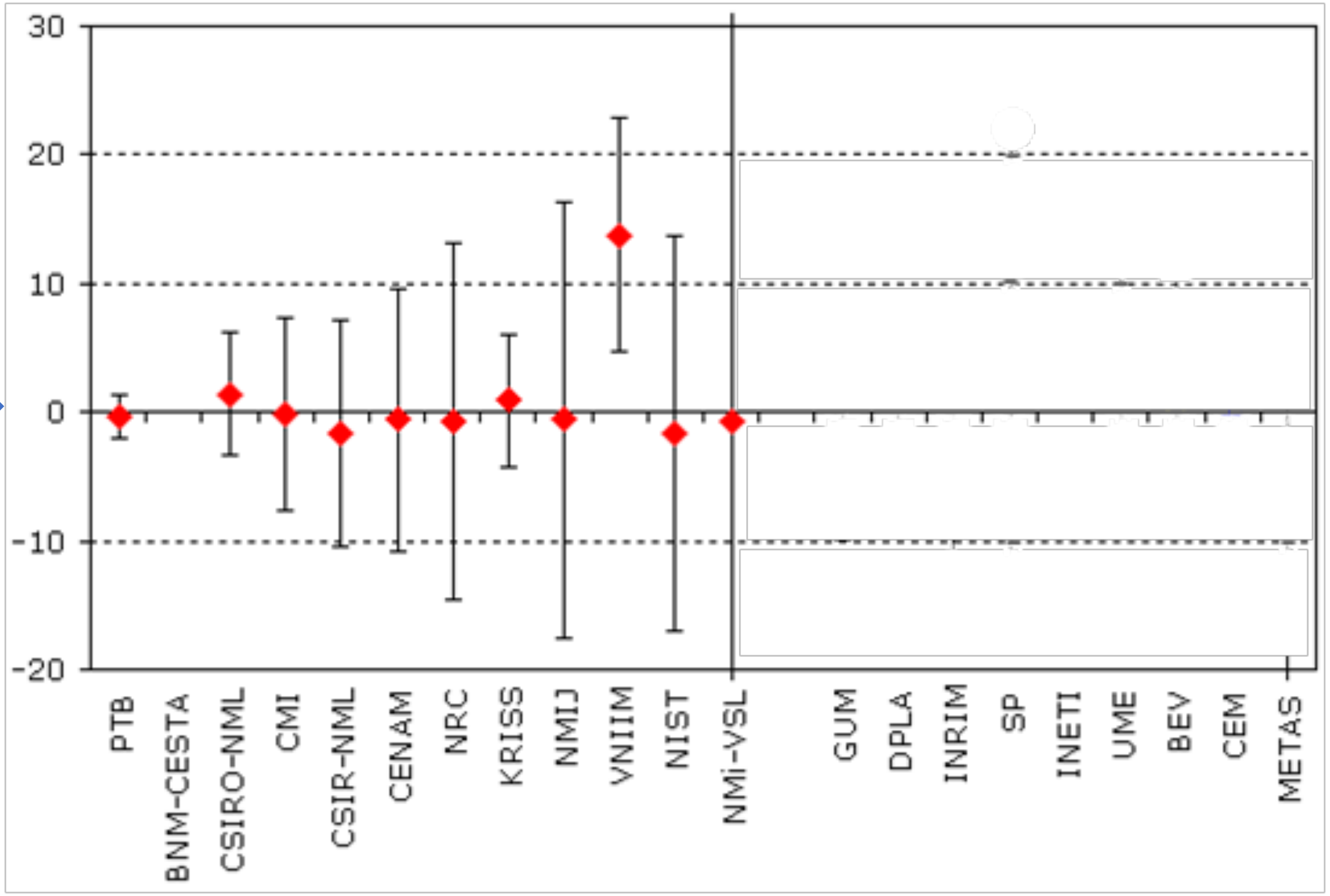
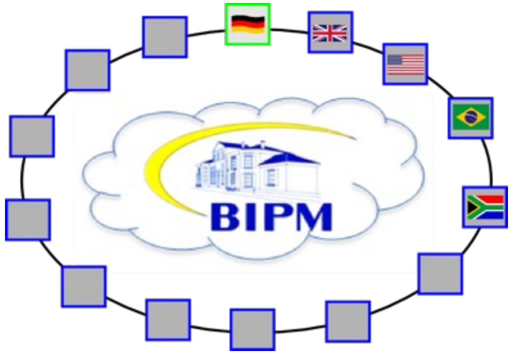


"CMC": Calibration and Measurement Capability



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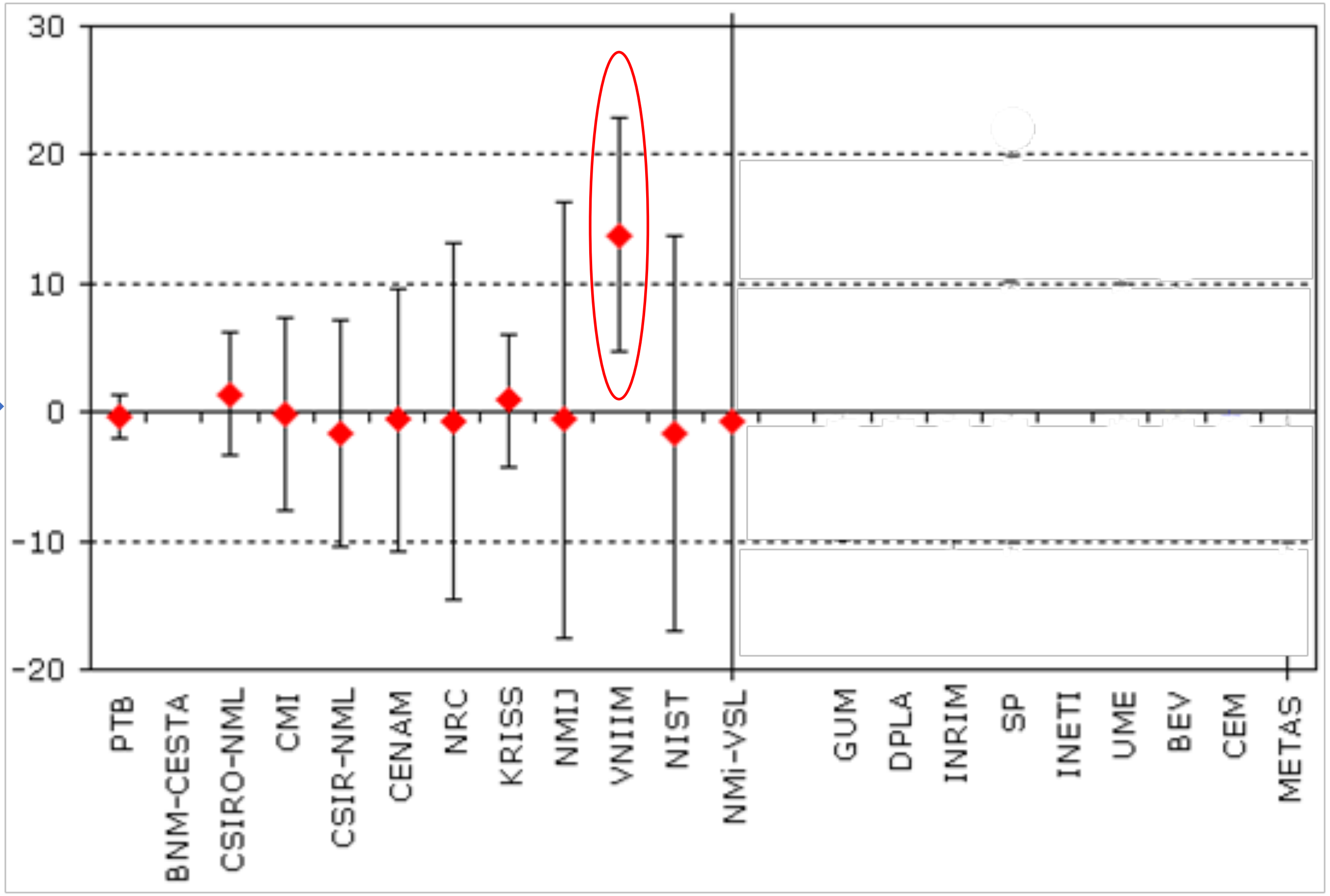

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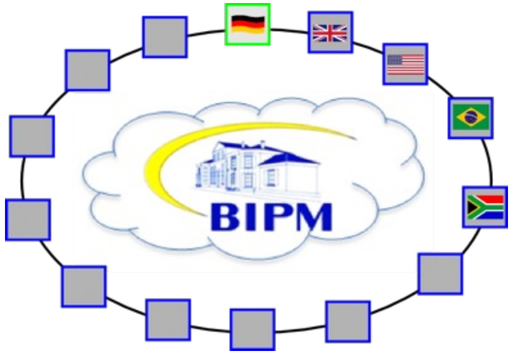
"CMC": Calibration and Measurement Capability



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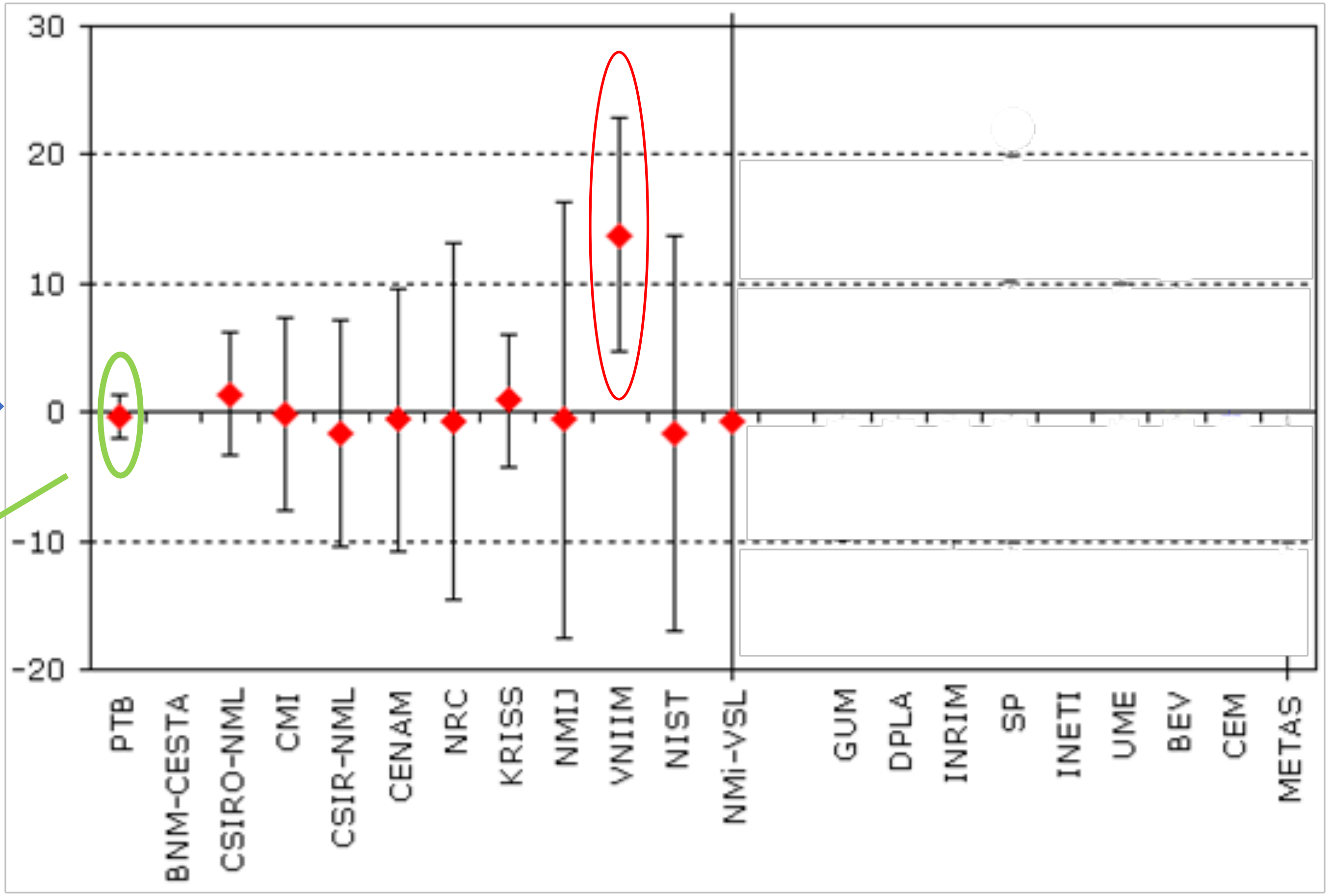
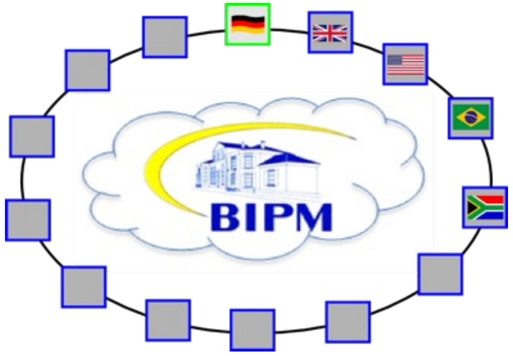


CMC confirmed

X_{de}

U_{de}



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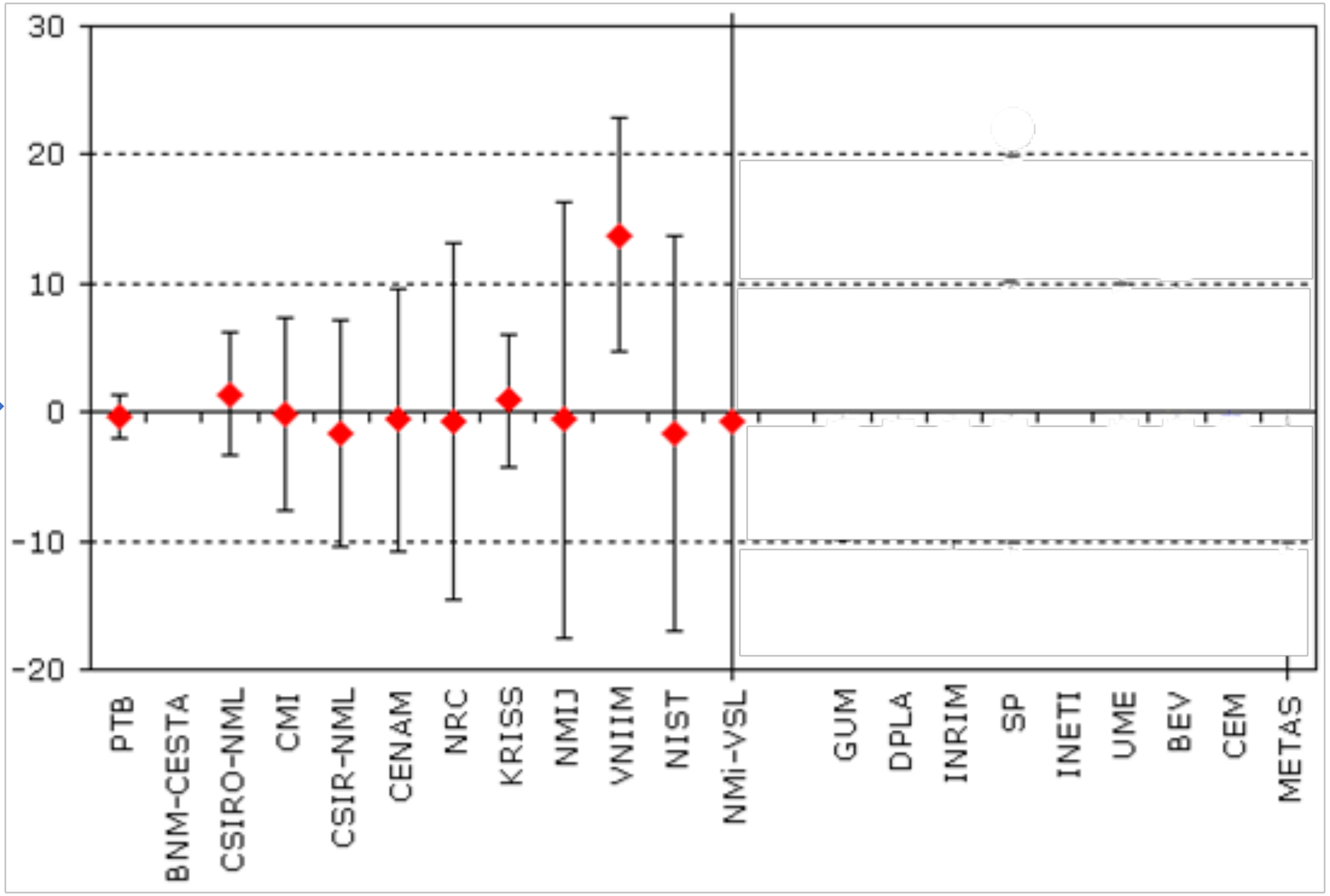

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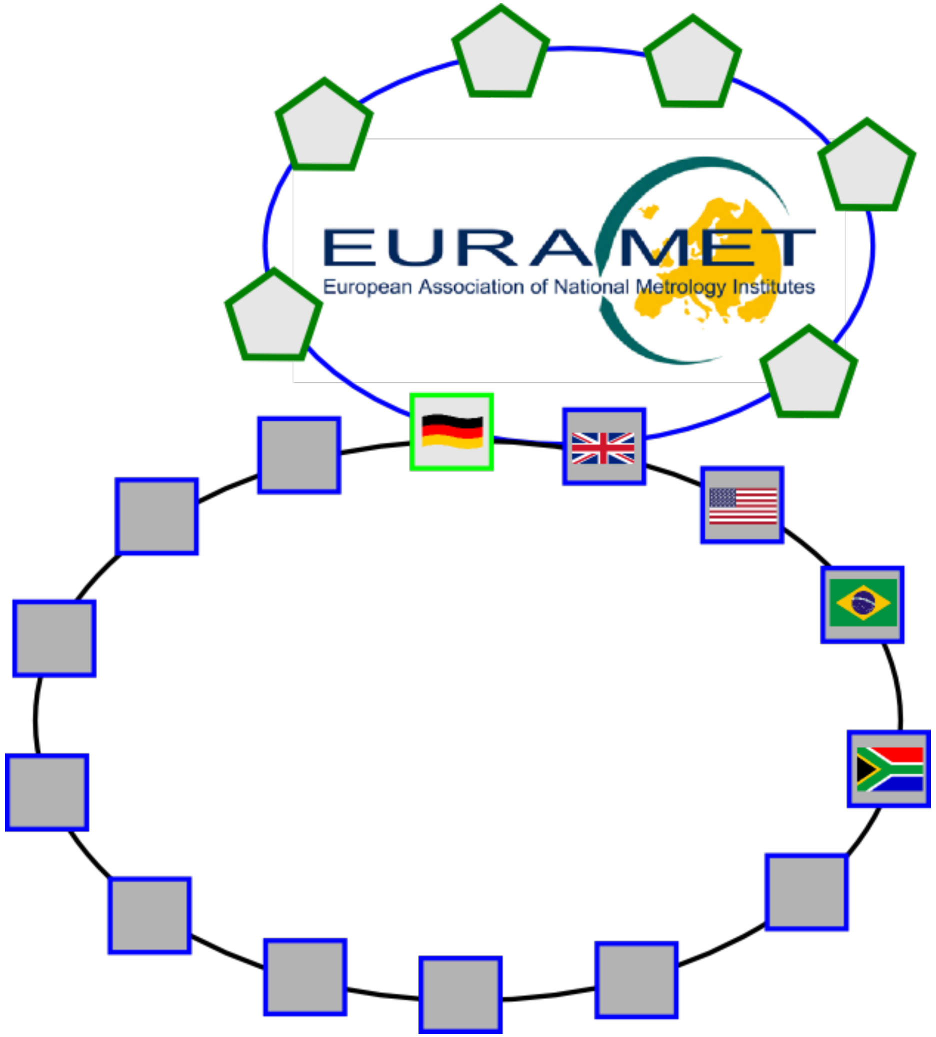
From Global to Regional – “no one left behind“



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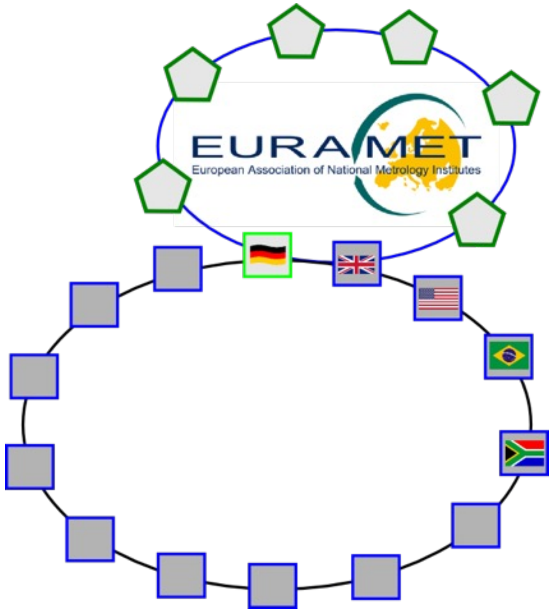

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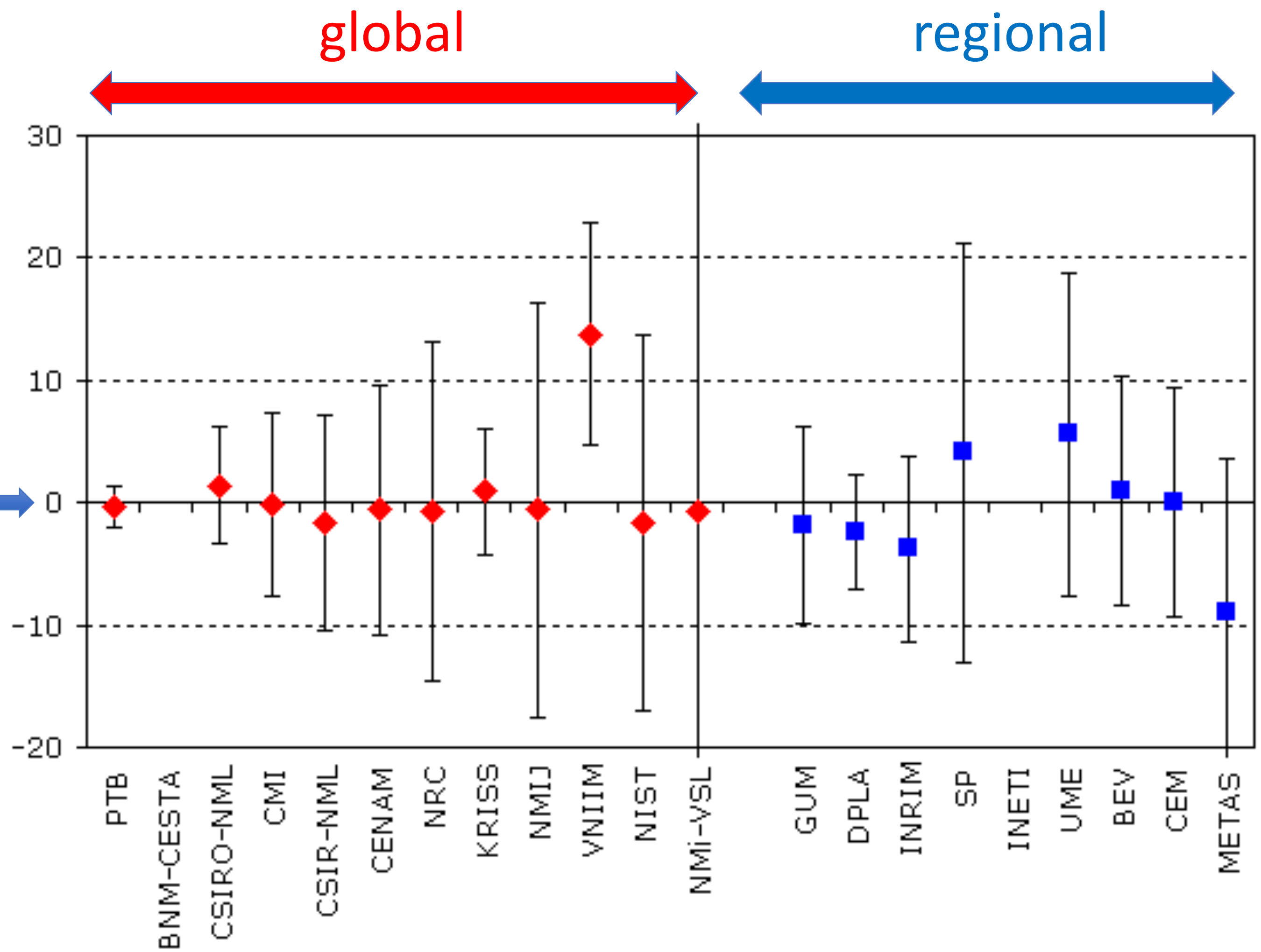

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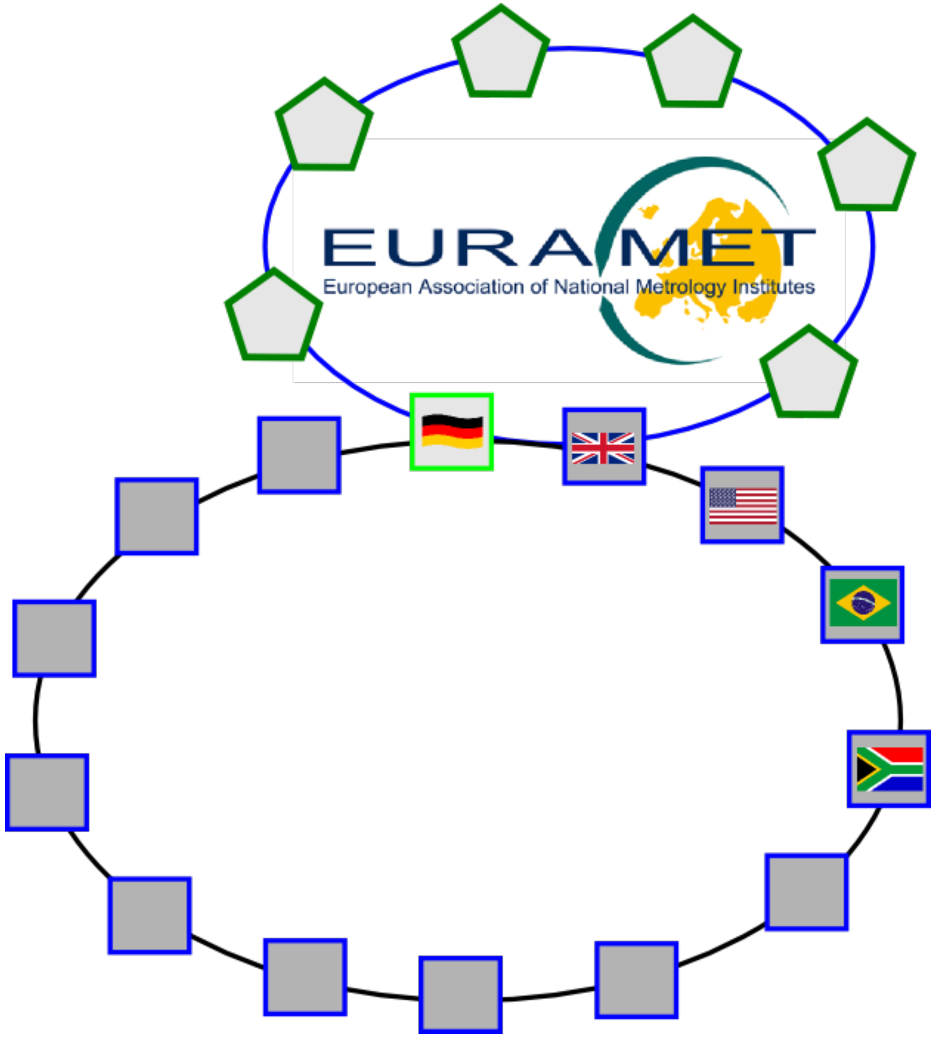

SIM SISTEMA INTERAMERICANO DE METROLOGIA — **Americas**

ASIA PACIFIC METROLOGY PROGRAMME · APMP · — **Asia/Australia**

AFRIMETS Intra-Africa Metrology System Système Intra-Africain de Métrologie — **Africa**

COOMET — **Several former soviet members plus some others**

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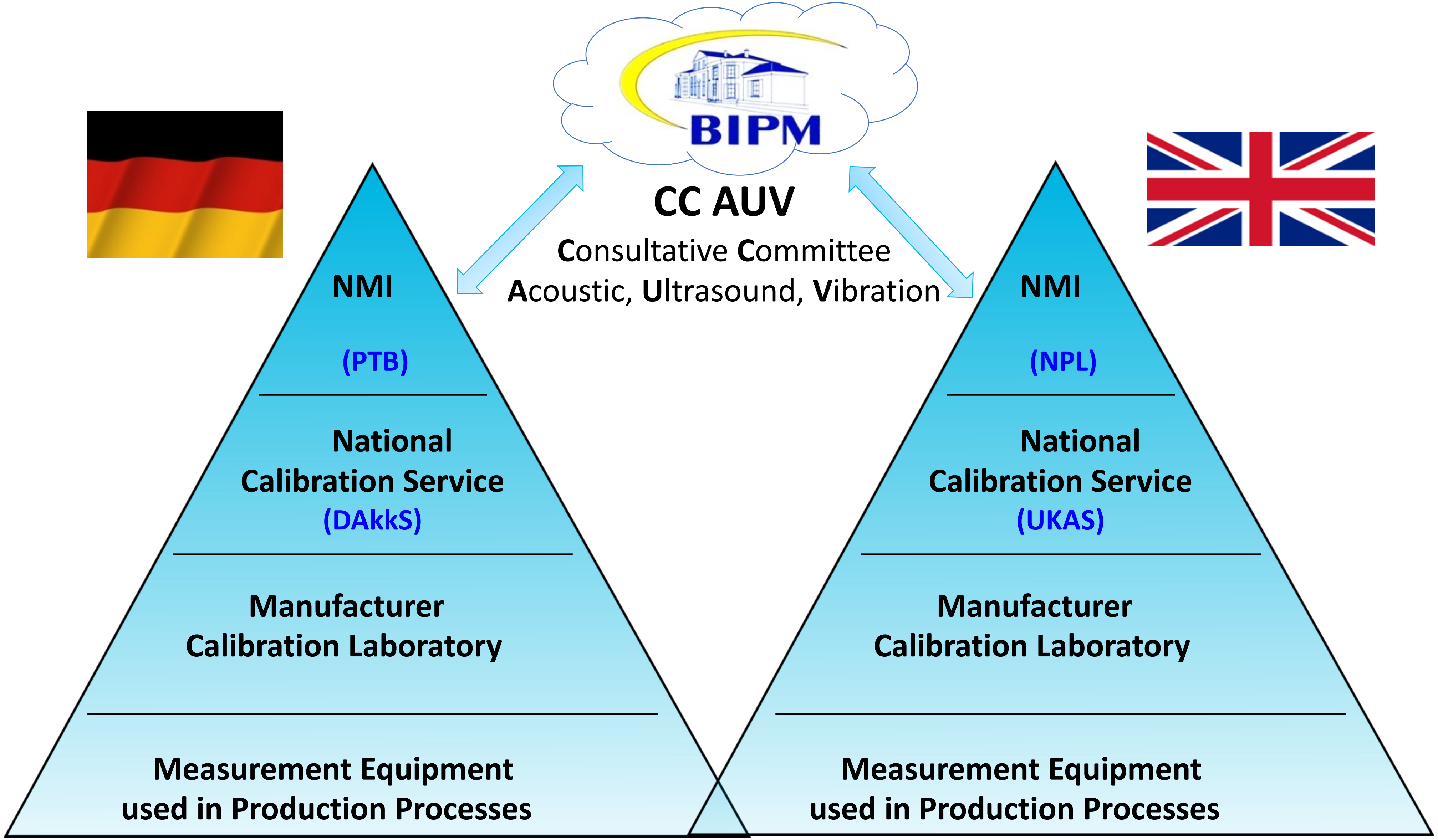
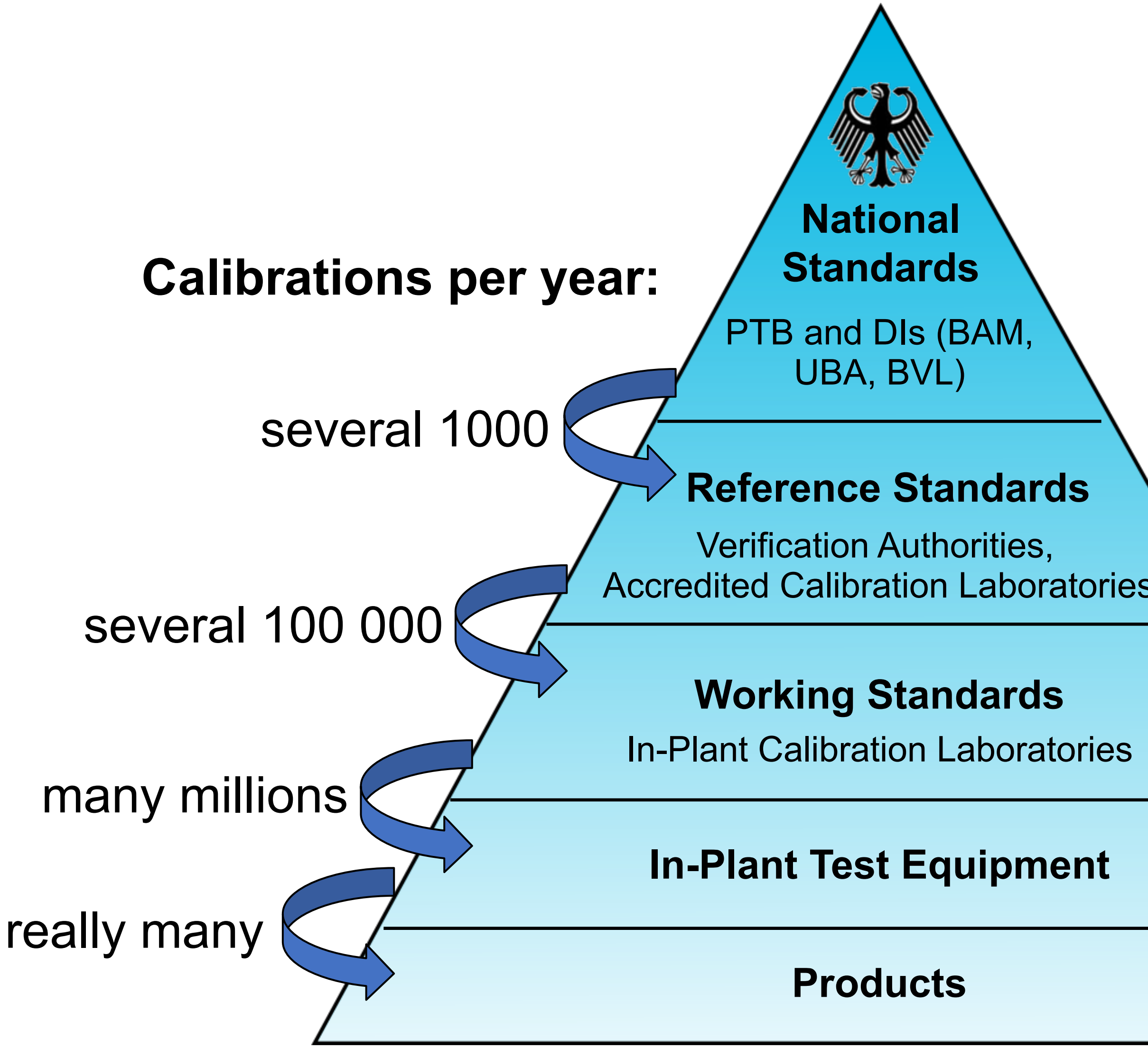
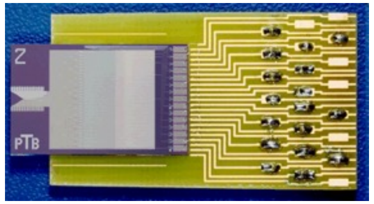
International Implementation of the SI



From Global to National – “closing the circle“





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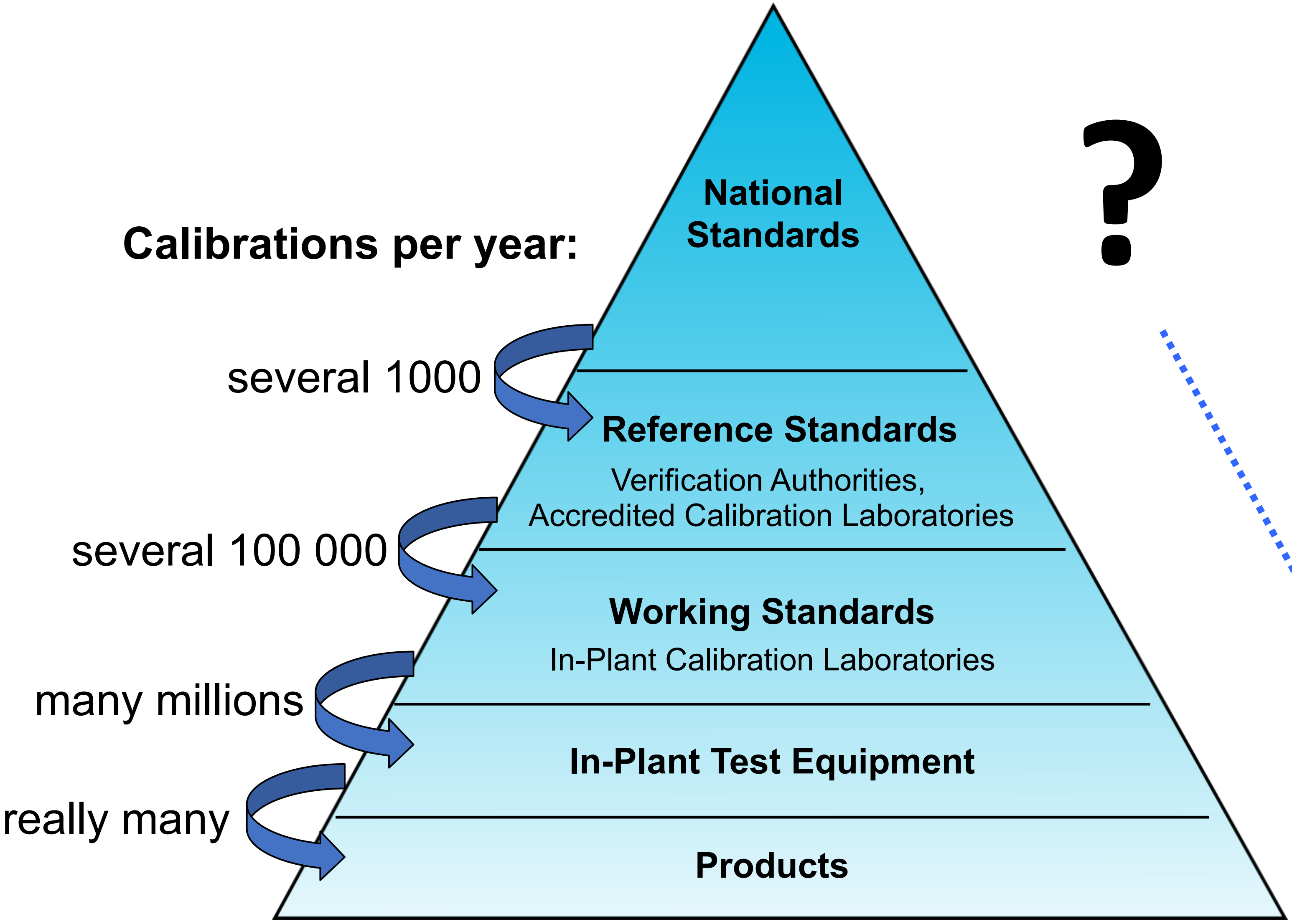

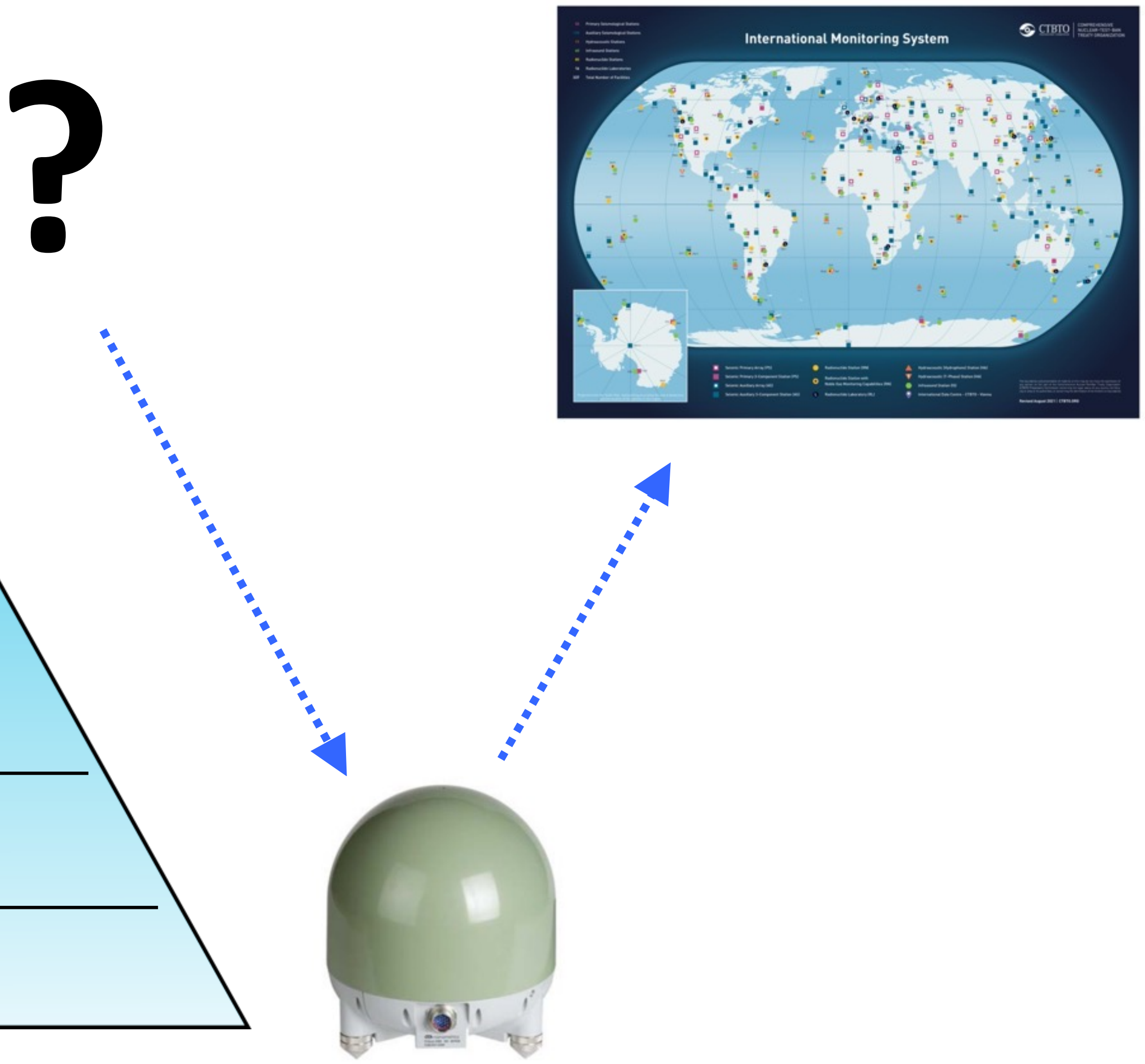

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Methods of absolute calibration of microphones and microbarometers at low frequencies

D. Rodrigues[1], R. Barham[2], S. B. Figueroa[3], M. Rust[4], E. Sandermann Olsen[5], Z. Silvestri[6]

[1]LNE – France, [2]ASN – UK, [3]DFM – Denmark, [4]PTB – Germany, [5]HBK – Denmark, [6]CNAM - France

GENERAL OVERVIEW

National Metrology Institutes
Primary reference standard

Accredited / Expert Laboratories
Working standard

One site calibration laboratories
Travelling standard

Final user
Measuring equipment

Established using a **primary method** of measurement

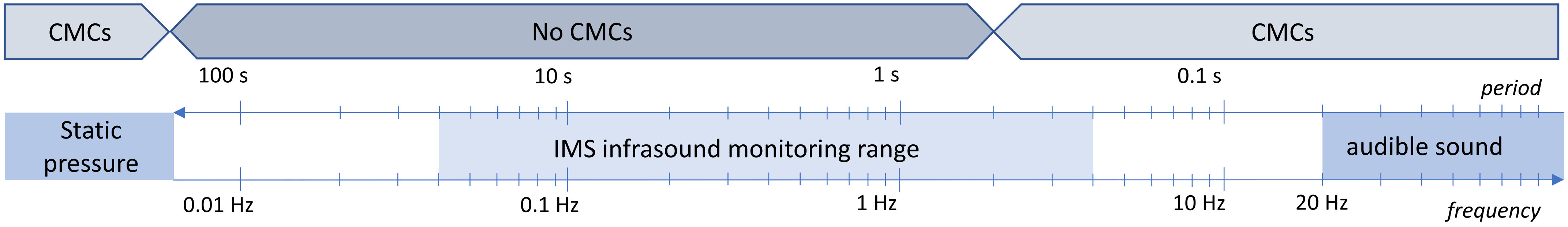
The **Primary method** of measurement provides the essential first link in the chain of traceability from the definition of a unit of the International System of Units (SI)

Metrological traceability

Property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty.

STATE OF THE ART ON INFRASOUND MEASUREMENTS

- For conventional acoustic measurements, the primary reference standard is established by the reciprocity method IEC 61094-2:2009.
- The BIPM Key Comparison Data Base (KCDB) provides the best Calibration and Measurement Capabilities (CMCs) of the NMIs demonstrating the traceability of the measurements to the SI.
- Current CMCs in primary standards for sound pressure have a lower limiting frequency of 2 Hz.



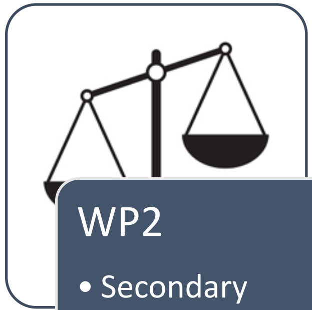
Need for a primary reference standard covering the lack of traceability at DC - 2 Hz

INFRA-AUV STRUCTURE & OBJECTIVES

- Establish the necessary calibration procedures and methods, to provide traceability to the SI for AUV measurements at very low frequencies.
- Demonstrate the implementation and the resulting benefits of improved data quality.

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

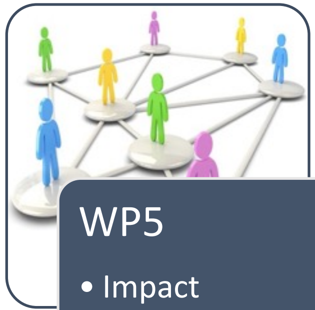
WP1
- Primary calibration



WP2
- Secondary calibration

WP3
- On-Site calibration

WP4
- Consequences & improve data quality



WP5
- Impact

Task 1.1: Development of five independent methods and facilities for calibration of infrasound sensors

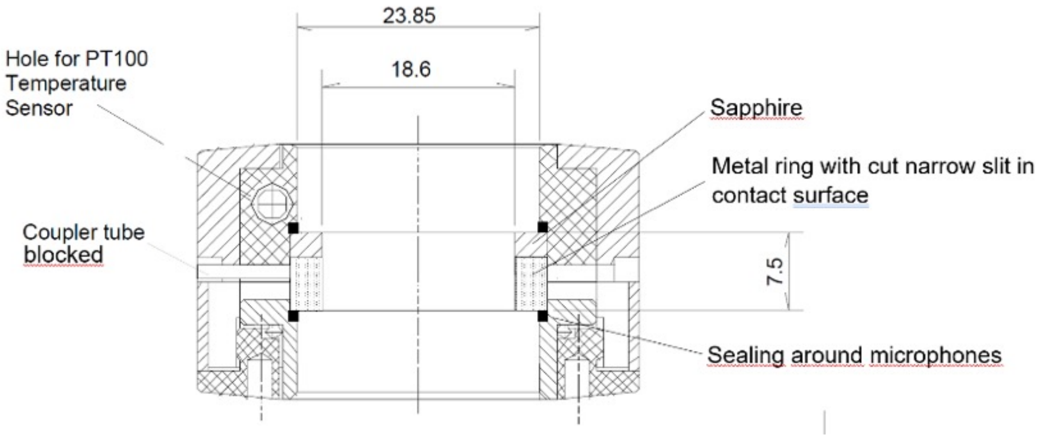
PTB
DFM Danish National Metrology Institu
HBK HOTTINGER BRÜEL & KJÆR
le cnam
LNE

EXTENSION OF RECIPROCITY CALIBRATION (HBK)

- Reciprocity calibration is a well established primary method – Standardized in IEC 61094-2
- Rely on calculation of acoustical transfer admittance
  - The calculation methods have been improved in recent years
- Single method covers range from low frequency limit of method to 10 kHz (LS1 microphones)
- Validated down to 2 Hz in International key comparisons CCAUV.A-K5 and CCAUV.A-K6
- Challenges in lowering the lower frequency limit with present couplers
  - Leakage between coupler and microphone surfaces too large and not sufficiently reproducible
  - Full sealing gives instable measurements, possibly due to thermal fluctuations
- Prototype couplers for reciprocity calibration at infrasound frequencies
  - Coupler cavity is made from sandwich of sapphire ring and metal ring
  - Coupler tube normally used for pressure equalization is blocked
  - Sealing around microphones
  - Pressure equalization is established with cut narrow slit in contact surface of metal ring
  - Time constant of cavity in range 50 s to 100 s, verified with model fit before each measurement

HBK HOTTINGER BRÜEL & KJÆR

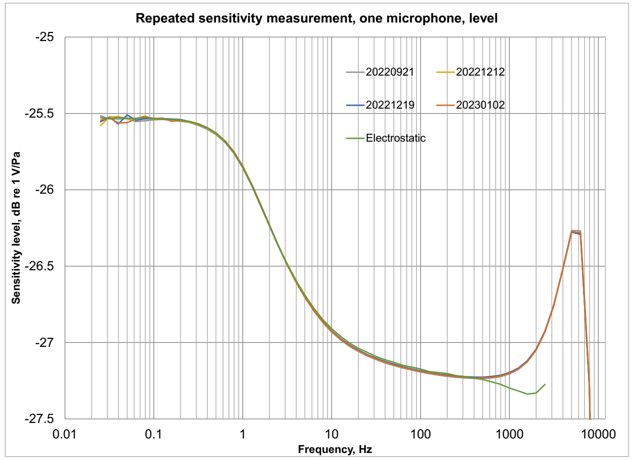
LS1 microphone
Brüel & Kjær Type 4160

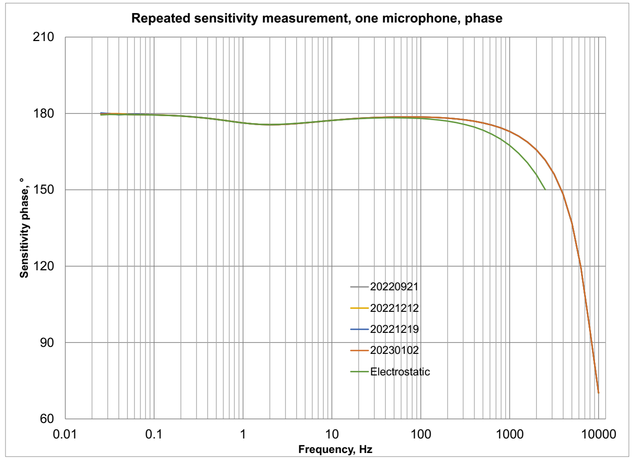


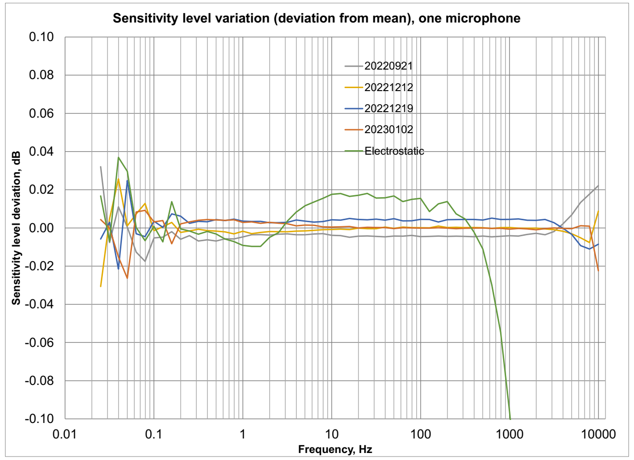
EXTENSION OF RECIPROCITY CALIBRATION (HBK)

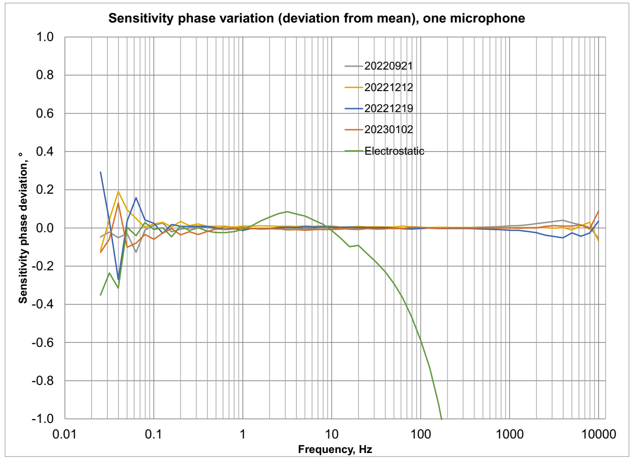
HBK HOTTINGER BRÜEL & KJÆR

- Reproducibility is satisfactory from 25mHz, it may be possible to extend the method further
- Results are consistent with measurements with electrostatic excitation of the diaphragm
- The upper graphs show sensitivity level and phase of a microphone measured 4 times over a period of 5 months and the result of a measurement with electrostatic excitation
- The electrostatic excitation differs from reciprocity calibration towards higher frequencies due to air mass load of the diaphragm
- The lower graphs show the same results relative to the average of the four reciprocity calibration results – note the scales



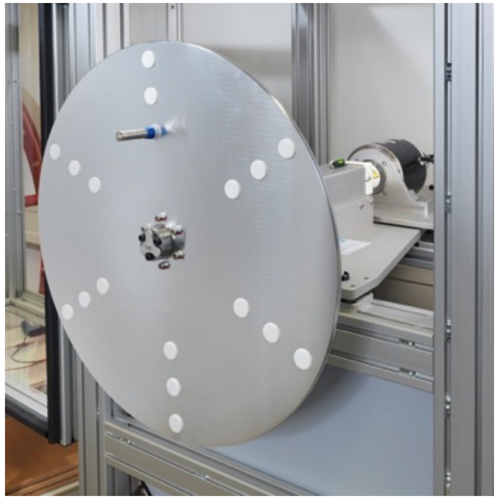


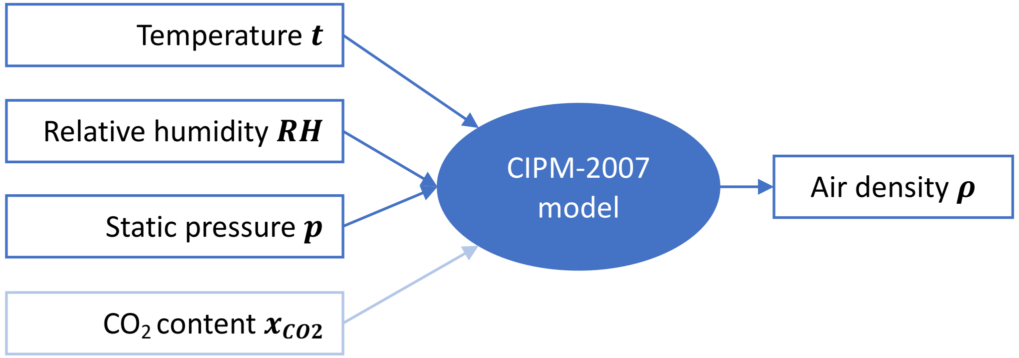




MICROPHONE CAROUSEL – WORKING PRINCIPLE (PTB)

- Stimulus: Vertical gradient of the ambient pressure
- Subject a DUT to an alternating pressure by periodically changing its altitude
- Amplitude $\boldsymbol{\Delta p}$ of the alternating pressure depends on the air density $\boldsymbol{\rho}$, gravity $\boldsymbol{g}$ and altitude change $\boldsymbol{\Delta h}$:
- $\boldsymbol{\Delta p = -\rho \cdot g \cdot \Delta h}$
- Altitude change $\boldsymbol{\Delta h}$: Defined by the measurement setup
- Gravity $\boldsymbol{g}$: Known at PTB with high accuracy
- Air density $\boldsymbol{\rho}$: Determined from climate measurements using the CIPM-2007 model (density of moist air)

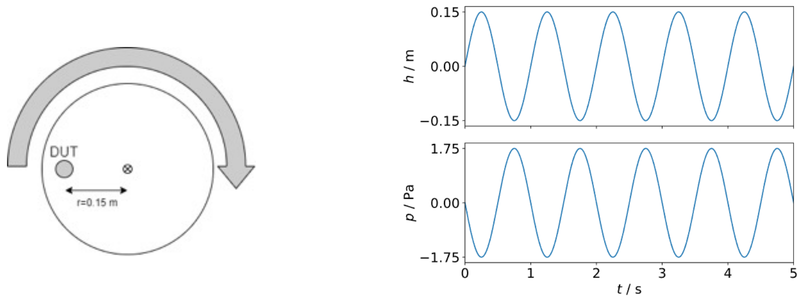


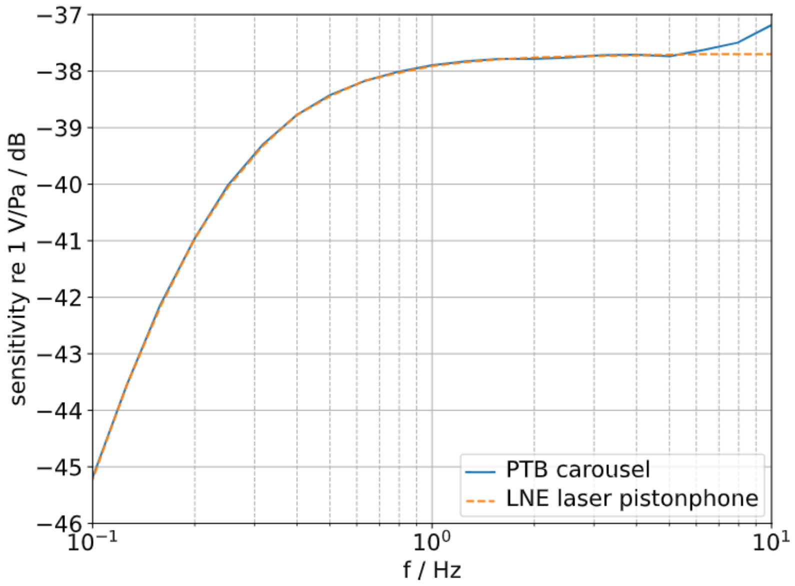


MICROPHONE CAROUSEL – MEASUREMENT SETUP (PTB)

- DUT mounted eccentrically on a vertically rotating disk
- Constant rotating speed → sinusoidal alternating pressure
- Altitude change of $\boldsymbol{\Delta h}$=±$\mathbf{15}$ cm → $\boldsymbol{L_{Zeq}}$≈$\mathbf{96}$ dB
- Working frequency range: 0.1 Hz to 5 Hz
  - Extension to 10 Hz is planned
- Measurement uncertainty ≤0.07 dB
- Challenges:
  - Low signal-to-noise ratio at frequencies below 0.5 Hz
  - Wind-induced noise at frequencies above 5 Hz

Details see poster
P3.1-646



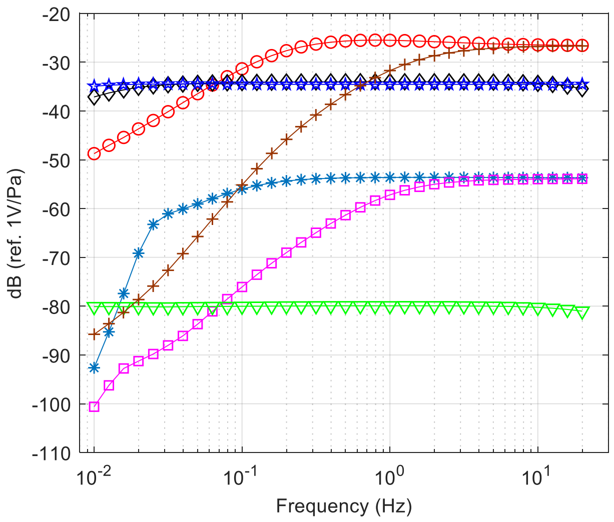


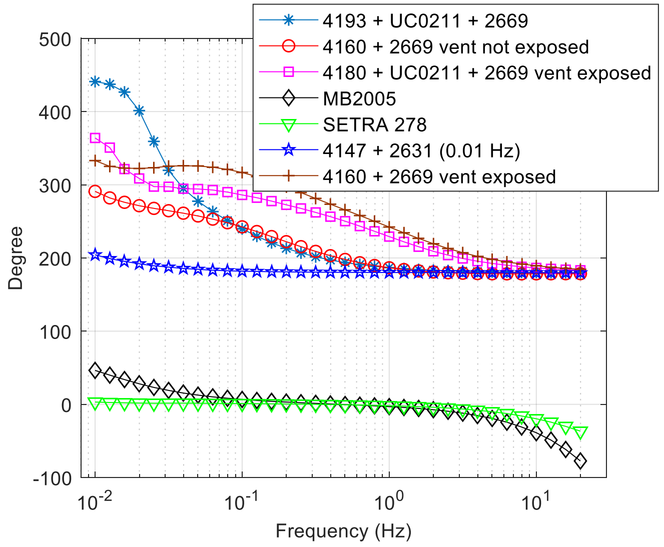
LASER PISTONPHONE (LNE)

- The infrasound sensor to be calibrated is exposed to a calculable sound pressure produced in a coupler by a piston.
- The sound pressure is calculated from the acoustic impedance of the coupler and the measurement of the volume velocity of the piston.

$$P_c = Z_T \int_S v_p ds$$

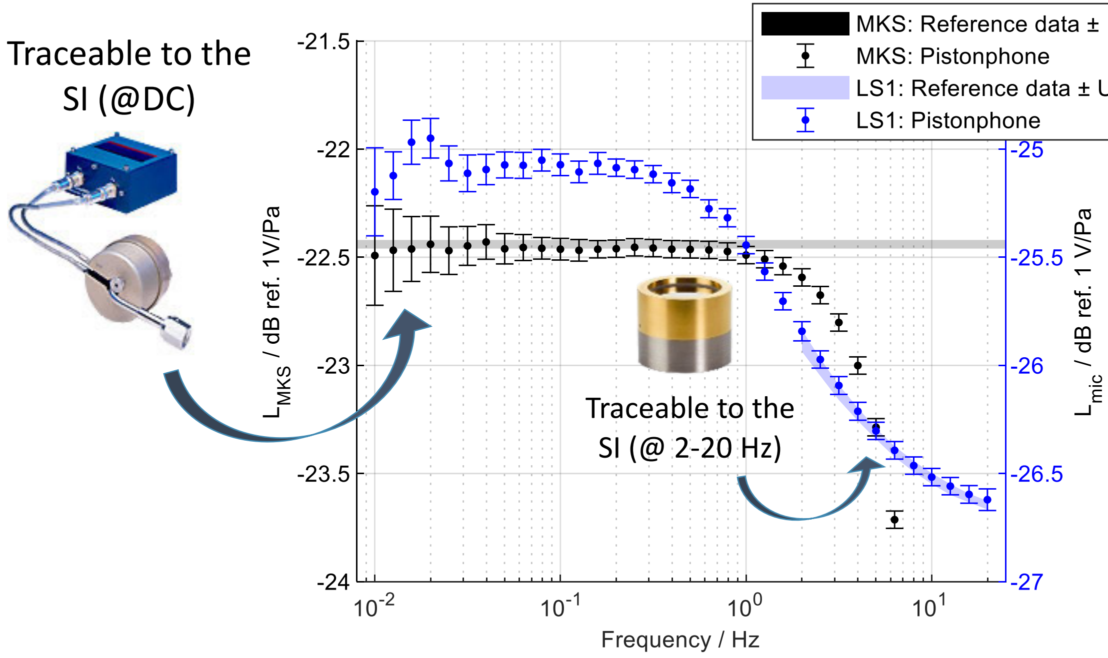
- Example of calibrations (10 mHz – 20 Hz) :

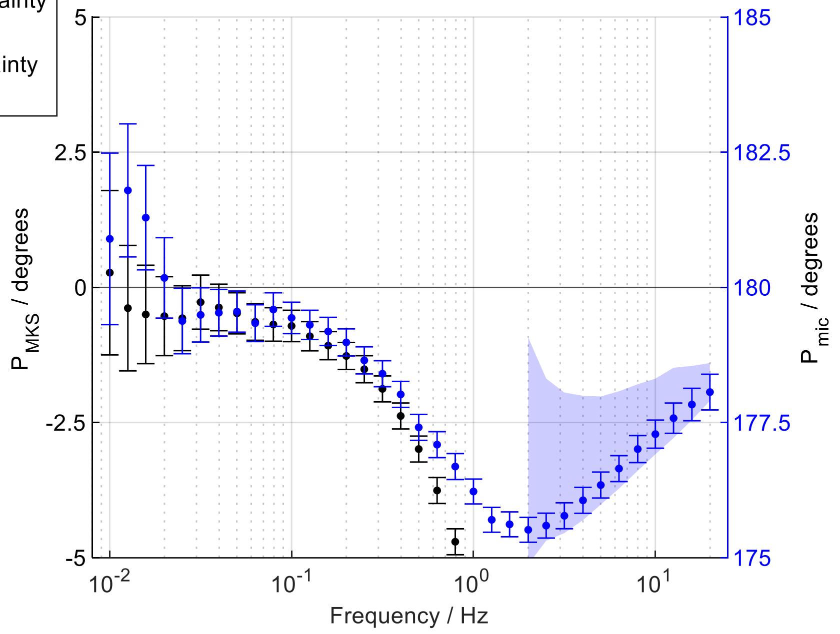




Laser Pistonphone (LNE)

- Metrological performance (comparisons with other validated methods)





- Uncertainty (typical): 0.03 dB @ 1 Hz

Details: See D. Rodrigues et al 2023 Metrologia 60 015004

MANOMETRIC METHOD: THE DYNAMIC REALIZATION (DFM)

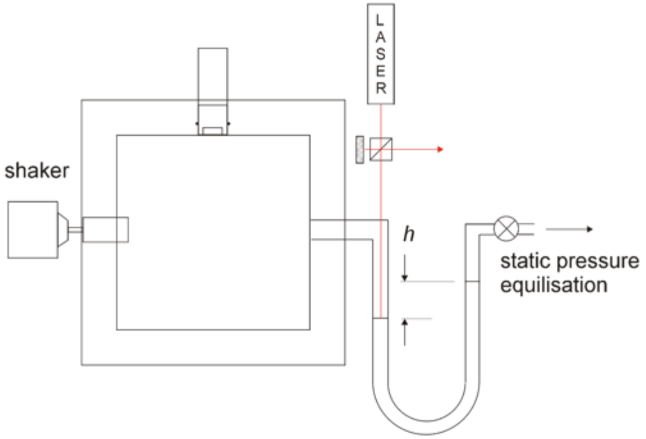
- Vari-static methods
  - The pressure to be measured is applied to one side of the tube producing a movement of liquid in the tube.
  - The applied sound pressure can be calculated from the measurement of the water column height as:

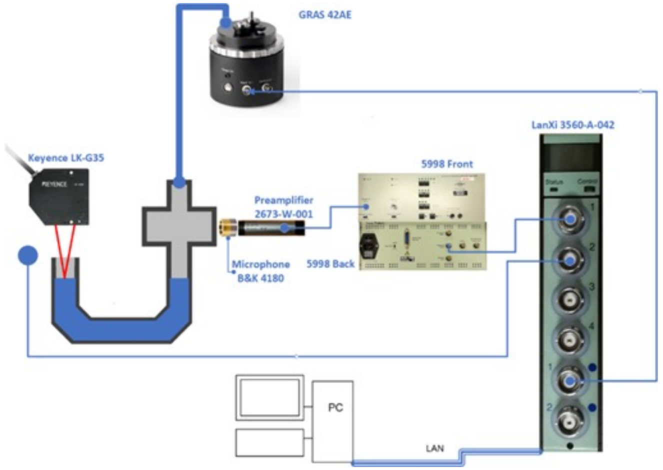
$$p = \rho\, g\, h_0 \sin(\omega t)$$

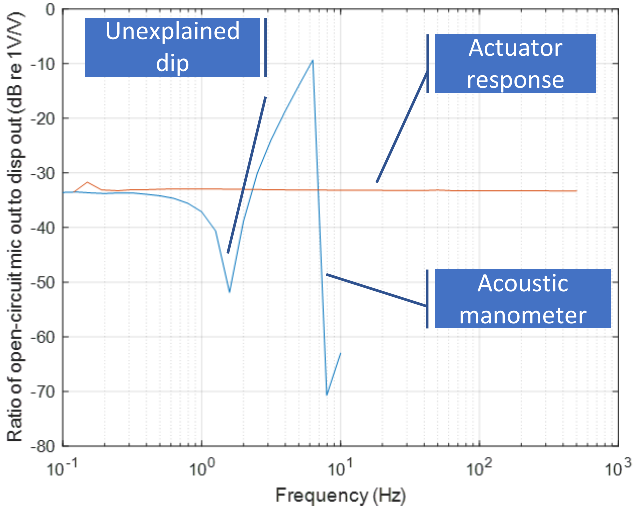
  - Changes in water column height required to produce 1 Pa (RMS):

$$h = \frac{1}{\sqrt{2}\rho g}$$

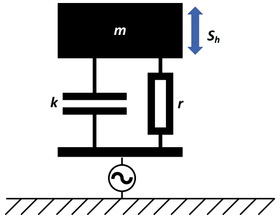
1 Pa (94 dB)-- 0.0721 mm.
10 Pa (114 dB) -- 0.721 mm
100 Pa (134 dB) -- 7.21 mm





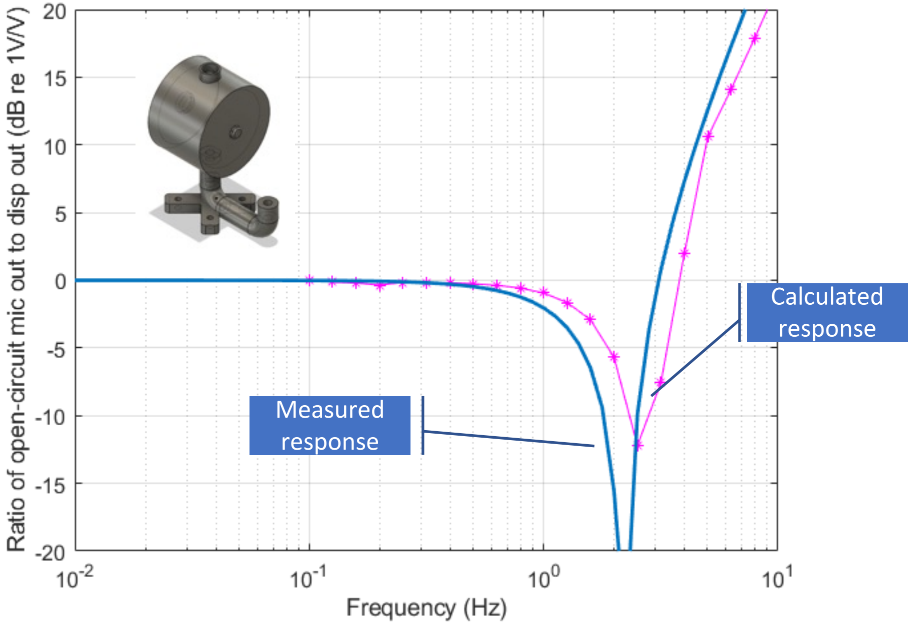


MANOMETRIC METHOD: THE DYNAMIC REALIZATION (DFM)



- In reality, the coupled system is rather a dynamic system
- The 'pressure response' (i.e. the pressure causing a specific displacement of the water column) of the U-tube is

$$\frac{F}{Sh} = \frac{1}{S}(k - \omega^2 m) = \left(\frac{\gamma P_0 S}{V}\right) - \omega^2 \rho L$$



The next iteration

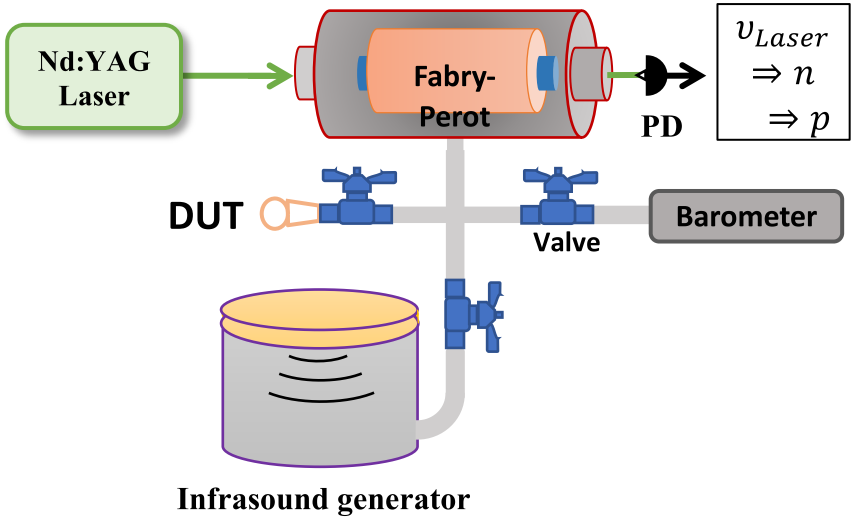
- Smaller acoustic cavity – u-tube combo
- Challenges to solve:
  - Measurement of the water column height
    - Confocal displacement sensor?
    - Other interferometric methods?
  - Isolation from LF background noise/vibration
  - Stopping leakage

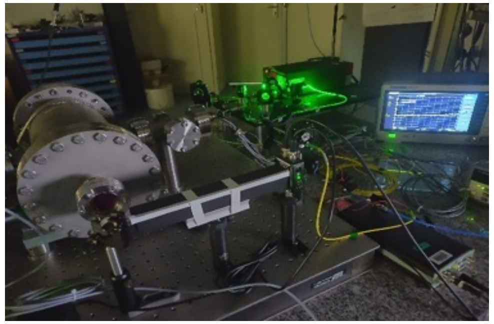
Refractometry technique using Fabry-Perot cavity (CNAM)

- Development of an optical technique to measure the infrasound acoustic pressure (40 mHz – 5 Hz).
- A Fabry-Pérot interferometer features an optical cavity with parallel reflecting surfaces
- Only light with a wavelength in resonance (coherent with the mirror spacing) can pass through the cavity
- Optical wavelength is a well-known function of refractive index
- The revised Edlen's formula derived from the Lorentz-Lorenz equation, links air refractivity index with atmospheric parameters (temperature and pressure)

$$(n-1)_{tp} = \frac{(n-1)_x \cdot p}{93214.6} \times \frac{1 + 10^{-8} \cdot (0.5953 - 0.009876 \cdot t) \cdot p}{1 + 0.003661 \cdot t}$$

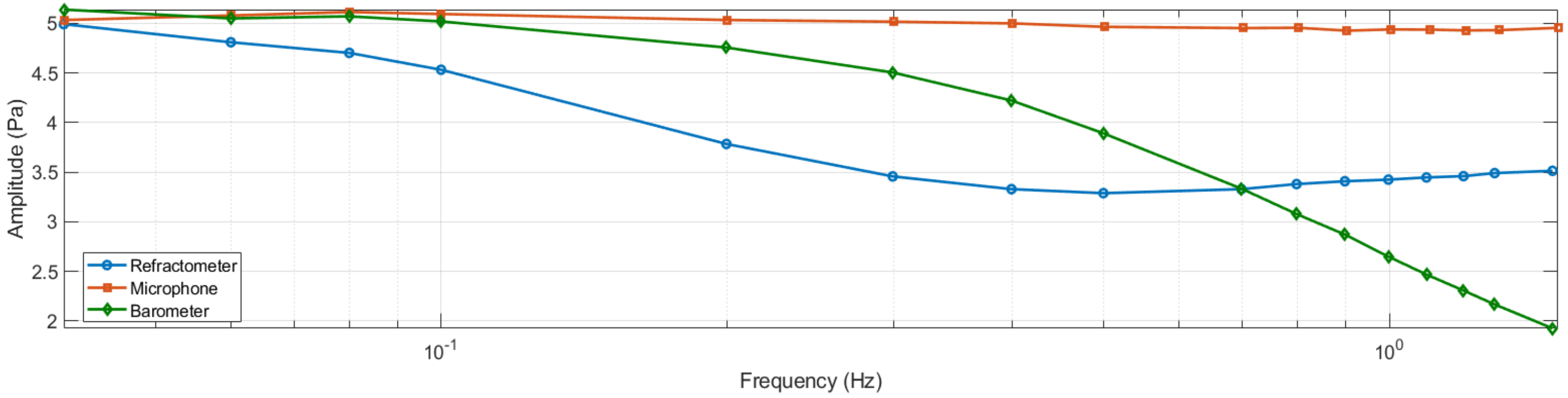
Experimental set-up

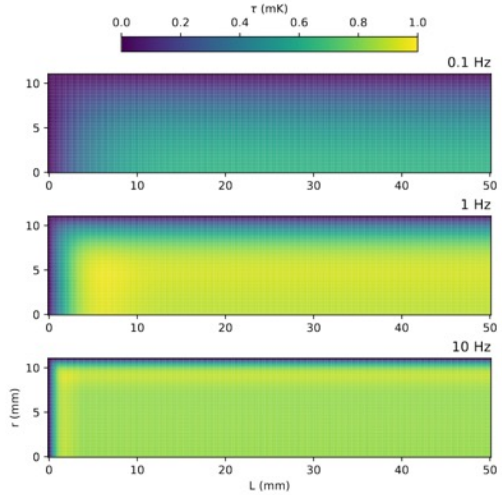




REFRACTOMETRY TECHNIQUE USING FABRY-PEROT CAVITY (CNAM)

- Experimental results





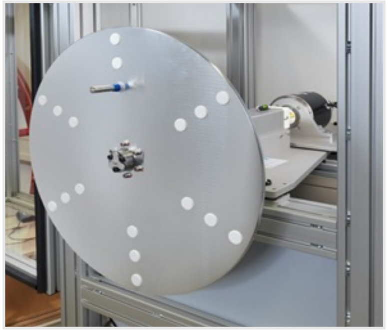
- Demonstration of the feasibility to use Fabry-Perot refractometer to measure infrasonic pressure (40 mHz – 5 Hz). However, demonstrated accuracy insufficient, further works required.
- Ongoing work:
  - Finalize the treatment of the transition from quasi-isothermal to quasi-adiabatic regime
  - Characterization and minimization of the acoustic temperature variation (modeling and geometrical optimization of the refractometer)

RESPECTIVE BENEFITS

Reciprocity

- Freq. : 25 mHz–10kHz
- Internationally standardised
- Relies on heat conduction model
- Suitable for LS microphones
- Validated performance down to 2 Hz

Carousel

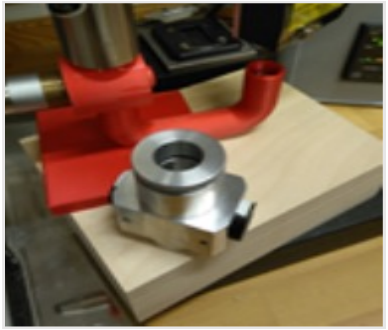


- Freq. : 0.1 Hz–5 Hz
- Conceptually simple
- Independent of heat conduction model
- Suitable for microphones
- Poor SNR at lower frequencies
- Control of airflow noise needed
- Validated performance

Laser pistonphone

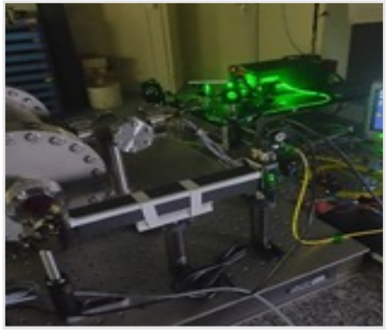
- Freq. : 10 mHz–20 Hz
- Relies on heat conduction model
- Suitable for a large variety of sensors
- Validated performance

Manometric method



- Freq. : 10 mHz–5 Hz
- Conceptually simple
- Independent of heat conduction model
- Suitable for a large variety of sensors
- Demonstrated accuracy insufficient
- Further works required

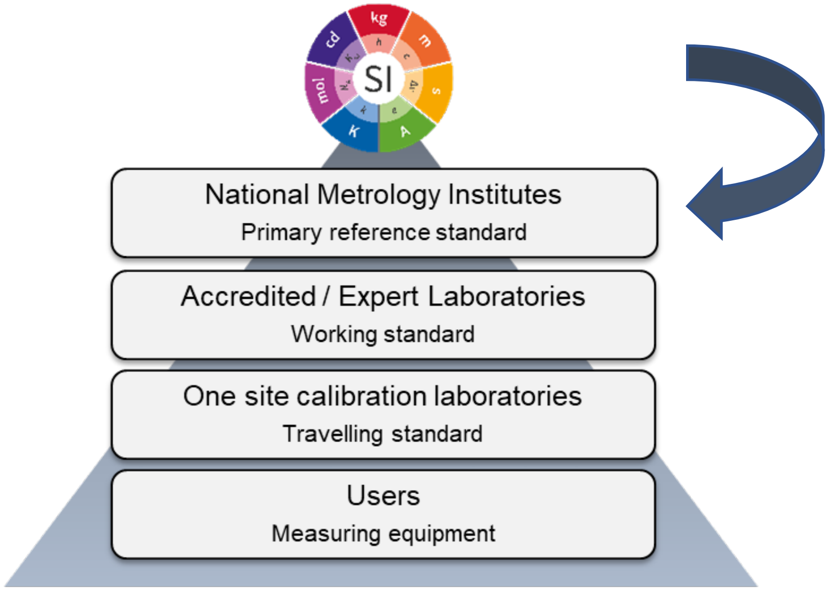
Refractometry



- Freq. : 40 mHz – 5 Hz
- Relies on heat conduction model
- Suitable for a large variety of sensors
- Demonstrated accuracy insufficient
- Further works required

CONCLUSION AND NEXT STEPS

- Having several independent absolute calibration methods provides:
  - Excellent opportunity to cross-compare for consistency
  - A high degree of confidence in measurement standards arising from demonstrated consistency
  - Coverage of the low frequency range with a combination of optimally suited calibration methods
  - Matching of most appropriate calibration method to the type of sensor under test



- The metrological performances are now demonstrated for some methods, bringing the first link in the chain of traceability in the full frequency range of interest for infrasound measurements of the IMS
- Some methods are being used in an intercomparison exercise
- Traceable calibration services expected
- New IEC standard expected to provide international recognition

SnT 2023

CTBT: SCIENCE AND TECHNOLOGY CONFERENCE

HOFBURG PALACE - Vienna and Online

19 TO 23 JUNE

Workshop on Metrology for the IMS

Measurement standards for hydroacoustics

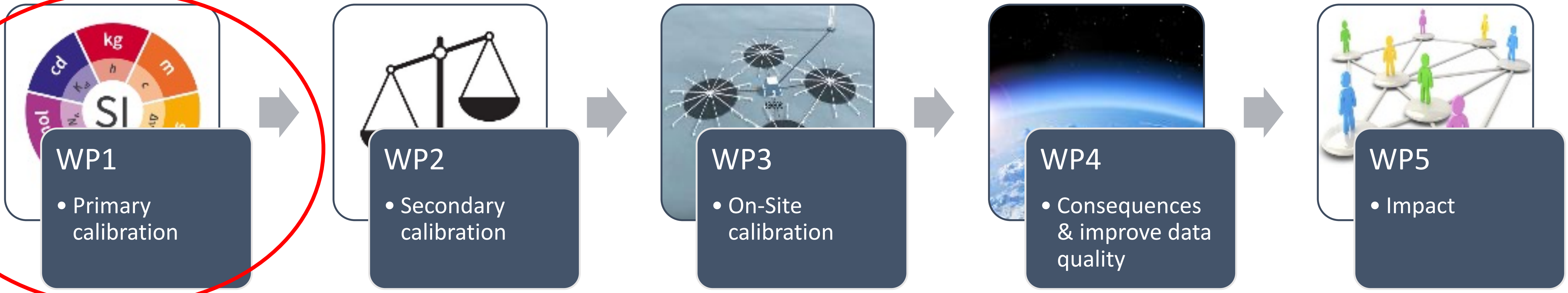
Stephen Robinson[1], Ben Ford[1], Freya Malcher[1], Sei-Him Cheong[1], Justin Ablitt[1], Lian Wang[1], Peter Harris[1], Richard Barham[2], Can Coracki[3], Alper Biber[3]

[1]NPL, UK; [2]ASN, UK; [3]Tubitak-MAM, TK

INFRA-AUV STRUCTURE & OBJECTIVES

- Establish the necessary calibration procedures and methods, to provide traceability to the SI for AUV measurements at very low frequencies.
- Demonstrate the implementation and the resulting benefits of improved data quality.

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



Task 1.3: Development and evaluation of primary calibration methods in underwater acoustics in a frequency range from 0.5 Hz to 100 Hz

NPL
TÜBİTAK
DFM Danish National Metrology Institute
acoustic sensor networks

GENERAL OVERVIEW

National Metrology Institutes
Primary reference standard

Accredited / Expert Laboratories
Working standard

One site calibration laboratories
Travelling standard

Final user
Measuring equipment

Established using a **primary method** of measurement

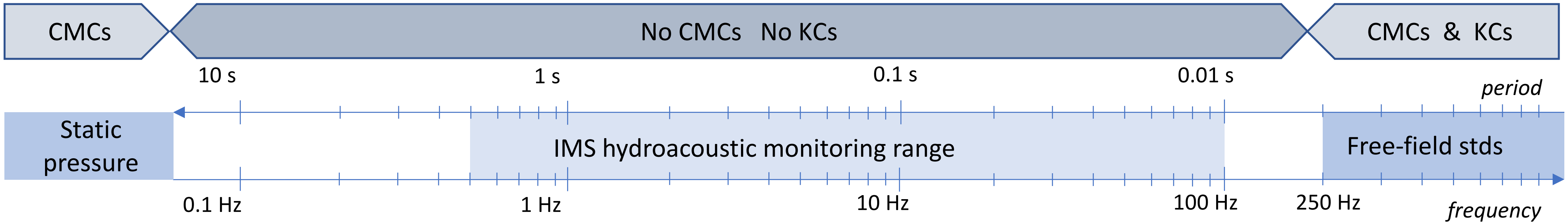
The **Primary method** of measurement provides the essential first link in the chain of traceability from the definition of a unit of the International System of Units (SI)

Metrological traceability

Property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty.

STATE OF THE ART FOR LOW FREQUENCY HYDROACOUSTIC STANDARDS

- For conventional free-field acoustic measurements, the primary standard is established over the range 250 Hz to 500 kHz by the free-field reciprocity method IEC 60565-1:2020.
- For low frequency pressure calibrations, a number of primary standard methods are available in the range 0.1 Hz to 250 Hz – described in IEC 60565-2:2019.
- **However:** the BIPM Key Comparison Data Base (KCDB) contains only one best Calibration and Measurement Capabilities (CMCs) for an NMIs in the low frequency (NPL: 25 Hz to 400 Hz)
- Current CMCs in primary standards for sound pressure have a lower limiting frequency of 25 Hz
- There are no Key Comparisons underpinning calibration standards below 250 Hz, or for any pressure calibrations



Need for a validated primary standards covering the 0.5 Hz – 250 Hz

Primary Method 1: Hydrophone calibration by pistonphone

- small chamber is driven by a piston
- filled with air
- pressure depends on compliance and volume change
  - compliance may be calculated
  - volume change measured (optical measurement of piston displacement using laser interferometer)

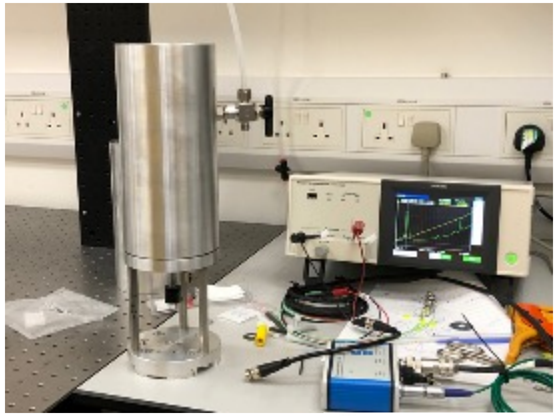
- piston driven by piezo stack
- can provide phase as well as magnitude
- established in air acoustics for microphones

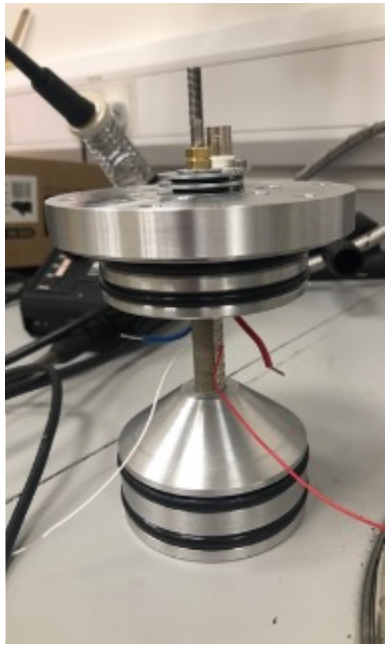
- frequency range: 0.5 Hz - 250 Hz

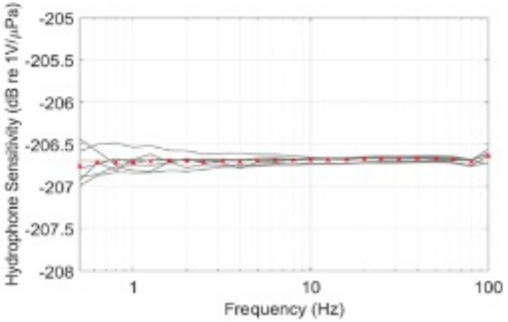
$$p = j\omega V_{\mathrm{D}} \frac{1}{j\omega C_{\mathrm{M}}} = \frac{V_{\mathrm{D}}}{C_{\mathrm{M}}}$$

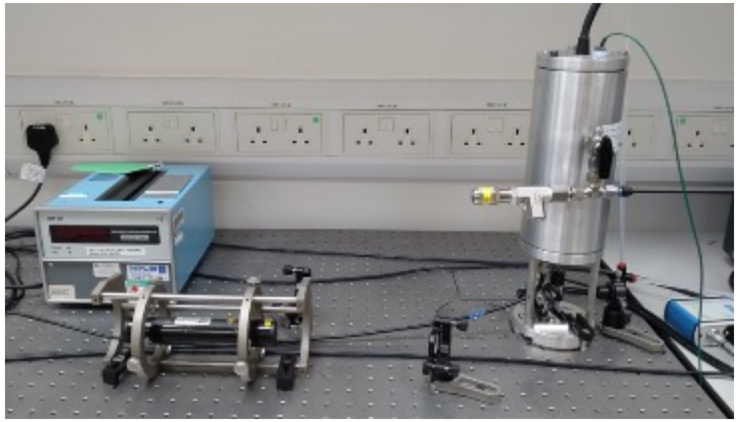
$$C_{\mathrm{M}} = \frac{V_0}{\gamma p_0}$$

$$M_{\mathrm{p}} = \frac{U_{\mathrm{H}}}{p}$$



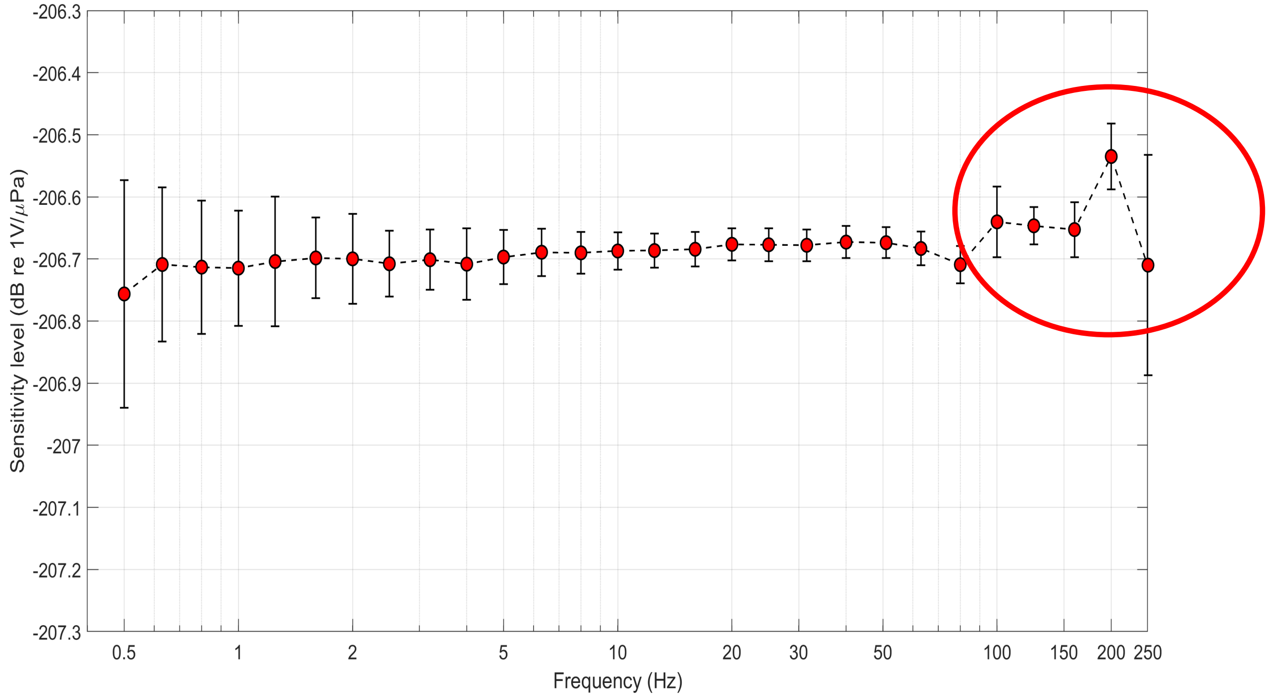






Primary Method 1: Hydrophone calibration by pistonphone

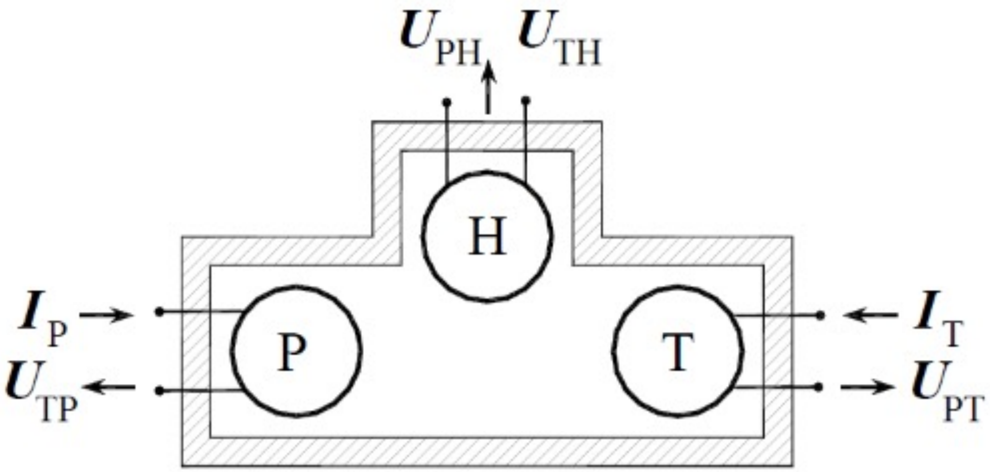
- corrections required for non-adiabatic conditions (heat correction)
- electrical impedance of hydrophone
  - causes difficulty at low frequencies
  - “insert voltage” correction required to account for preamplifier loading
- sensitivity of piezo hydrophone should be invariant witl frequency to very low frequencies (<0.5 Hz)
- results shown for B&K8104 hydrophone
- comparison underway with independent methods
  - static pressure sensor – provides link with DC standards
  - microphone calibration
  - possible link to manometric method



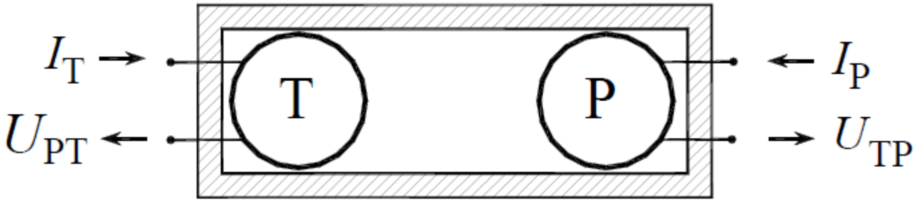
- microphone can also be calibrated
- comparison undertaken with LNE for microphone calibration
- initial results show good agreement

Coupler reciprocity calibration (method)

- Three hydrophones (one reciprocal)
- Hydrophones inserted into small chamber
- Compliance of the chamber is a crucial parameter to be determined
- Fluid filled
- May be pressurised to simulate depth
- Frequency range typically ~1 Hz to 2 kHz
- Can provide phase as well as magnitude



- Reference-transfer method
  - reference transducers used in two-port coupler
  - no need to know hydrophone compliance

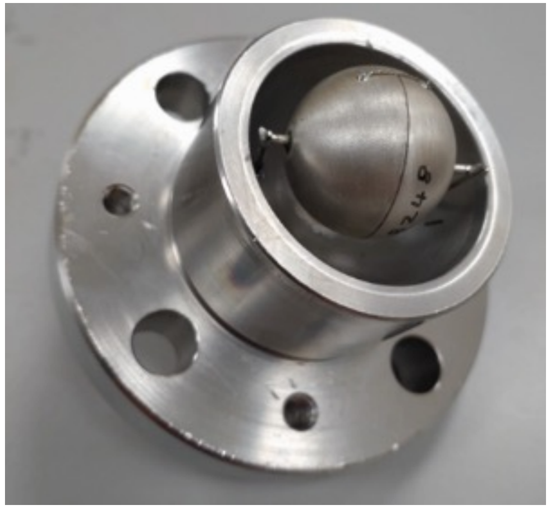


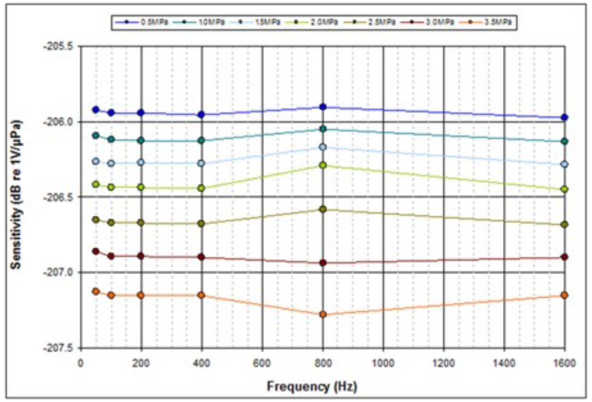
$$M_H^2 = \omega C'_t \frac{|Z'_{PH}||Z'_{TH}|}{|Z'_{PT}|}$$

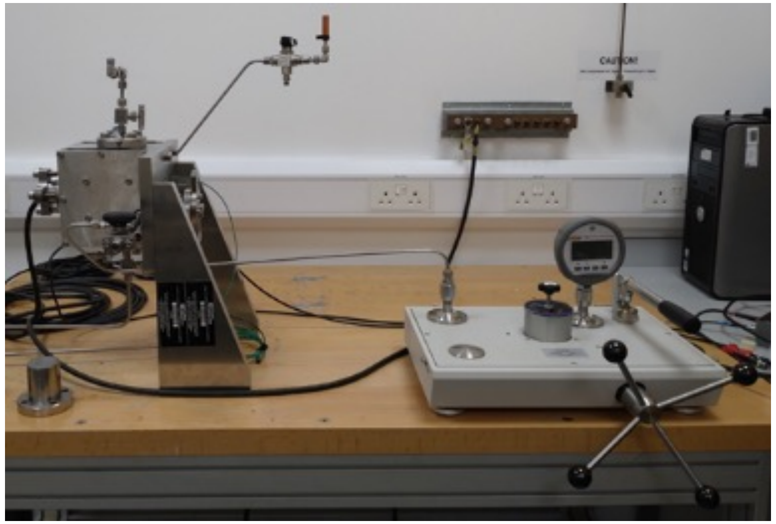
$$C_t = V_f / \rho_f c_f^2$$

Primary Method 2: Coupler reciprocity (NPL)

- Reference – Transfer method established by NPL
    - fluid filled with deionised degassed water
- Reference transducers are spherical transducers
    - no compliant material
    - compliance of reference chamber only required
- Lock-in amplifiers used for signal detection
- Problems with lowest frequencies
    - repeatability must be improved
    - very high electrical impedance of transducers
    - must prevent any electrical conductance through water
- Hydrostatic pressure: up to 7 MPa (~700 m depth)
    - difficult to operate at ambient pressure(trapped air)
- Temperature control (water jacket):

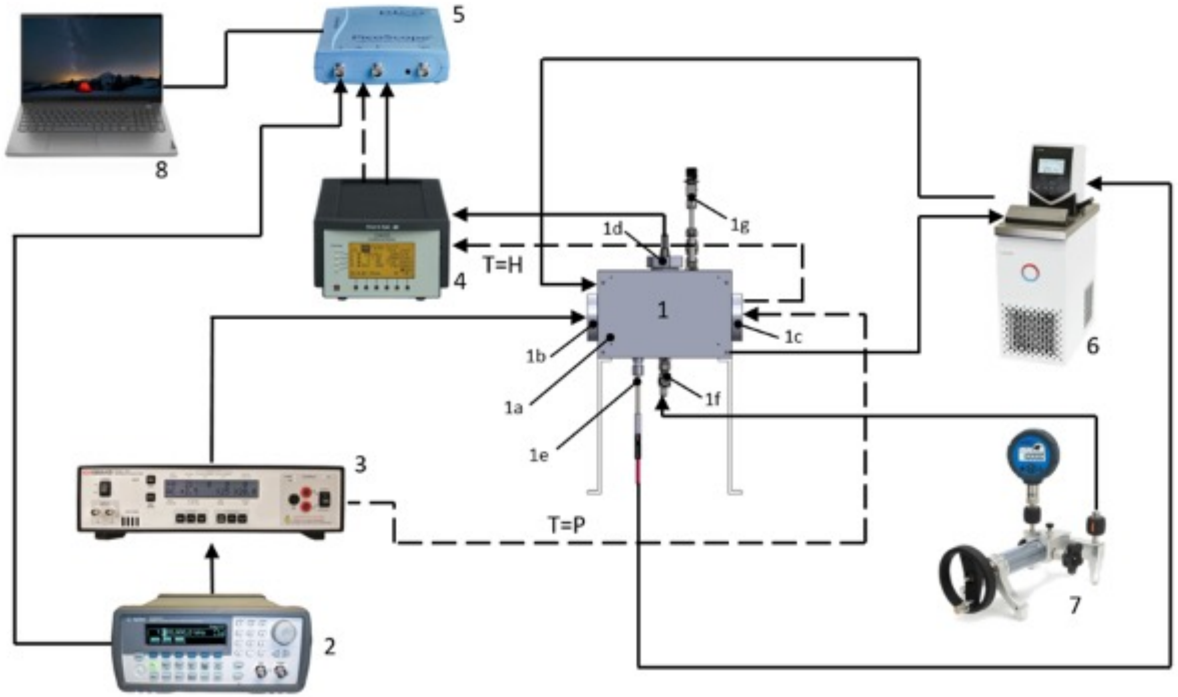


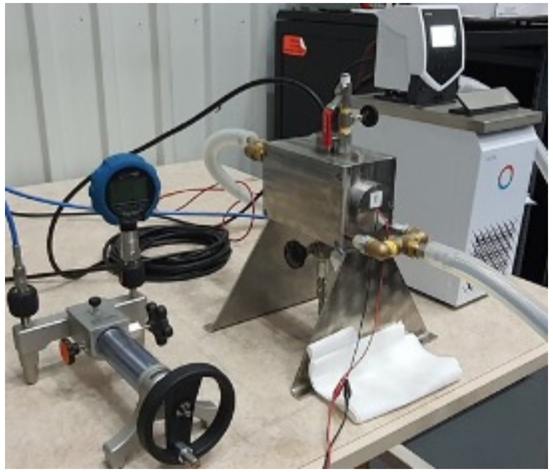


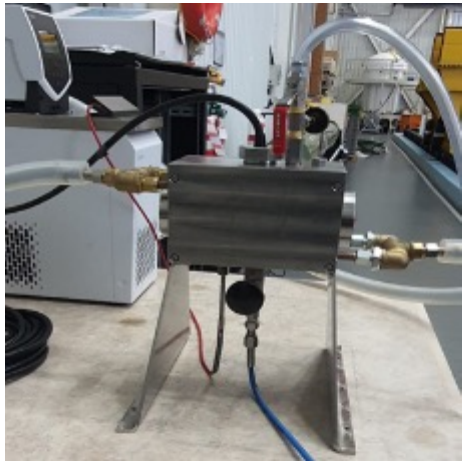


Primary Method 2: Coupler reciprocity (Tubitak-MAM)

- Similar configuration to NPL
- Reference transducers are spherical transducers
  - no compliant material
  - compliance of reference chamber only required
- Comparisons planned between NPL and Tubitak-MAM for late summer 2023

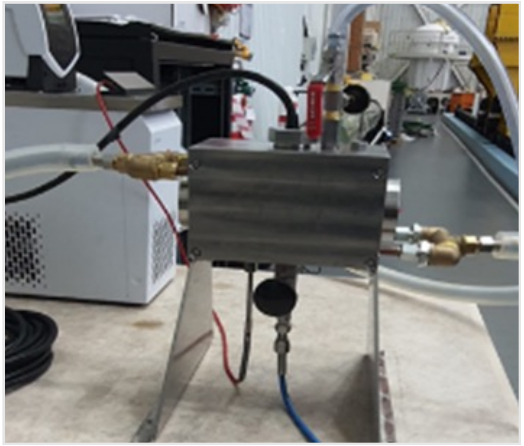






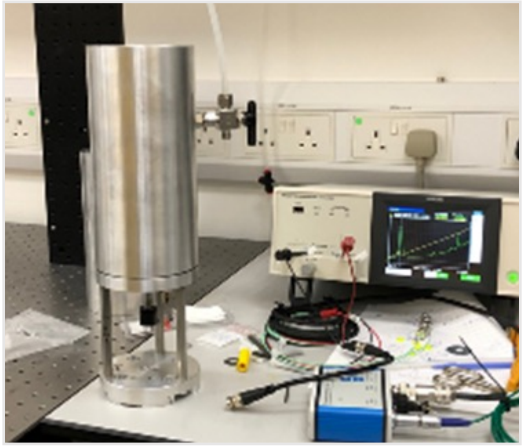
Method comparison

Reciprocity



- Freq: few Hz – 2 kHz
- Described in IEC 60565-2
- Can pressurize to simulate depth (fluid filled)
- Restricted to reference hydrophones

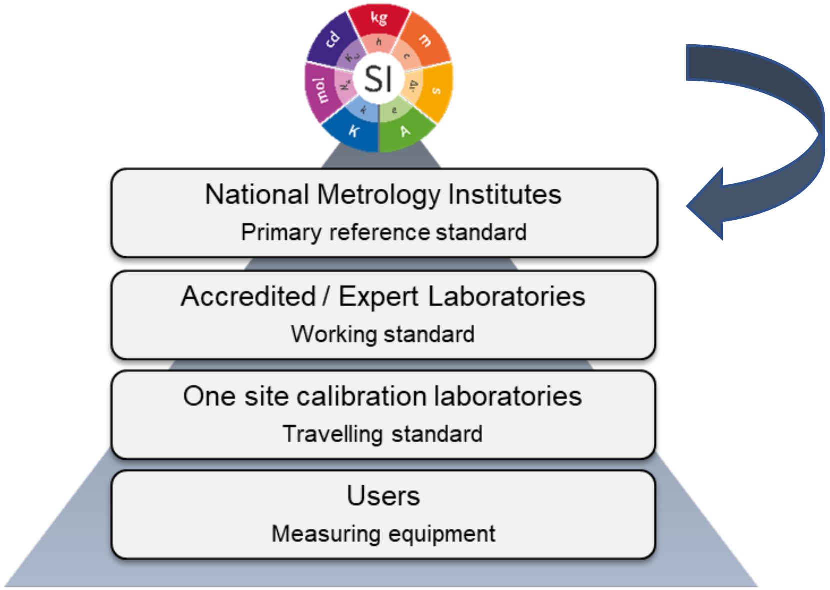
Laser pistonphone



- Freq. : 0.5 Hz - 100 Hz
- Described in IEC 60565-2
- Cannot pressurise (ambient pressure only)
- Air-filled
- Greater range of hydrophone types (but still limited)
- Validated performance – highest accuracy?

CONCLUSION AND NEXT STEPS

- More than one independent absolute calibration methods provides:
  - Opportunity to cross-compare for consistency
  - Greater confidence in measurement standards arising from demonstrated consistency
  - Better coverage of the low frequency range than proviously
  - Coupler reciprocity enables primary calibrations to be undertaken as function of depth (and temperature)



- metrological performances are now demonstrated for some methods
- primary link in the chain of traceability in the full frequency range of interest for infrasound measurements of the IMS
- methods now being used in an intercomparison exercise
- traceable calibration services eventually expected
- updates to IEC standard to reflect new implementations

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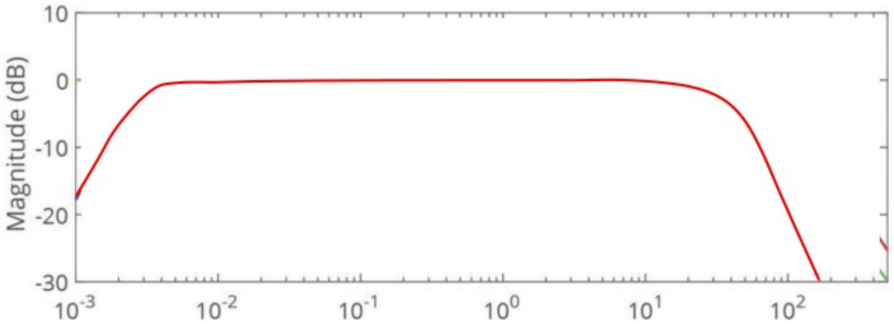
Workshop on Metrology for the IMS

Primary calibration of Seismometers by Laser-Interferometry

Thomas Bruns
Physikalisch-Technische Bundesanstalt
Germany

InfraAUV

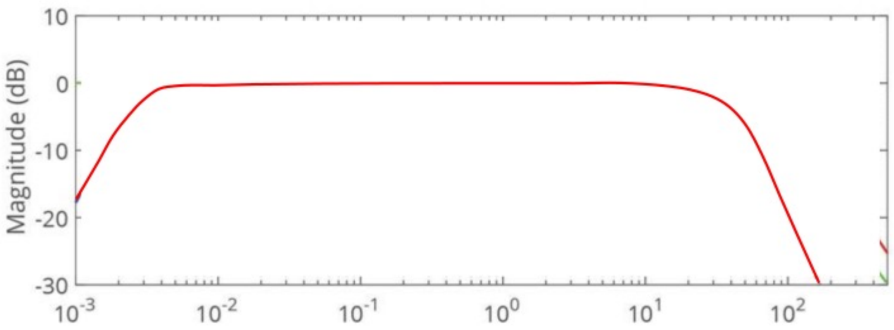
What Parts of the SI do we Need?



Magnitude of Sensitivity:

$$\frac{\text{Volts}}{\frac{\text{Meter}}{\text{Second}}}$$

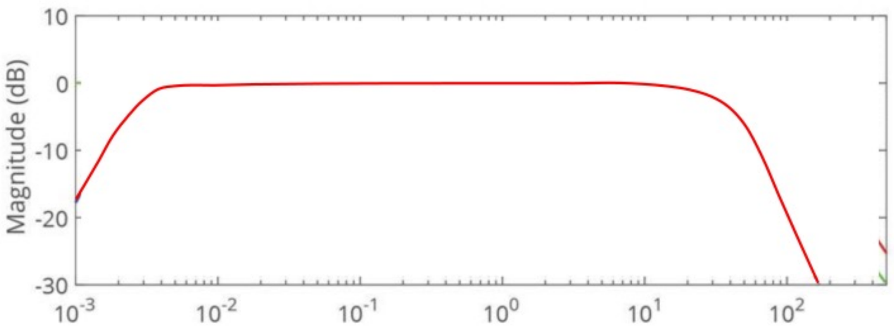
Time is simple (well, for us at least)



Magnitude of Sensitivity:

$$\frac{\text{Volts}}{\text{Meter}\ \boxed{\text{Second}}}$$

Time is simple (well, for us at least)



Magnitude of Sensitivity:

$$\frac{\text{Volts}}{\frac{\text{Meter}}{\boxed{\text{Second}}}}$$

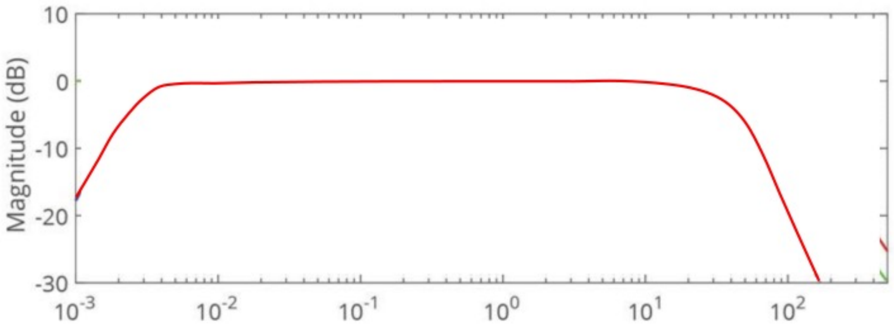
Cesium Atomic Fountain Clock

rel. stdev. 10^{-17}
1s in 3 bil. years

10 MHz ref. clock

Synchronized sample clock

Voltage needs some transfer & traceability



Magnitude of Sensitivity:

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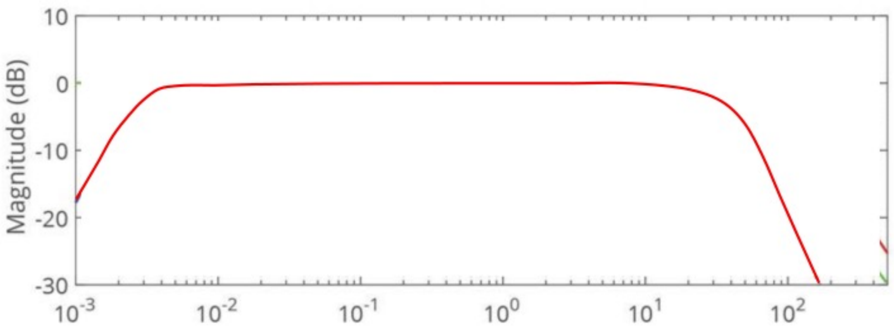
Voltage needs some transfer & traceability



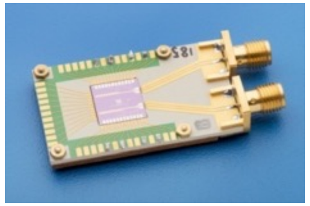
Magnitude of Sensitivity:

$$\frac{\text{Volts}}{\dfrac{\text{Meter}}{\text{Second}}}$$

Atomic Clock

75 GHz

Josephson AWG



rel. stdev. 10^{-8}

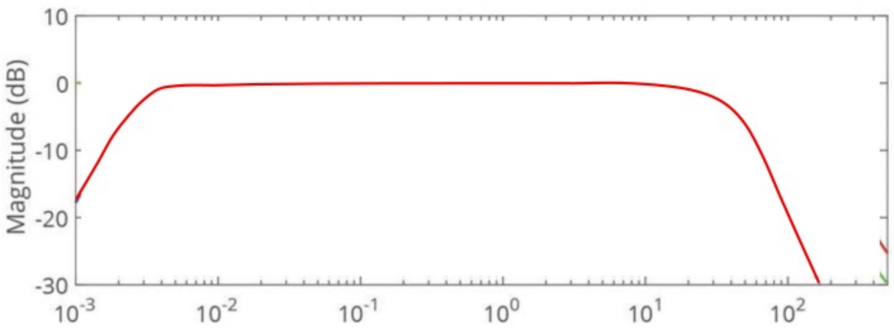
8.5 digit Multimeter (~28-bit)

rel. stdev. $\sim 10^{-6}$

18-bit ADC

rel. stdev. $\sim 5 \cdot 10^{-5}$

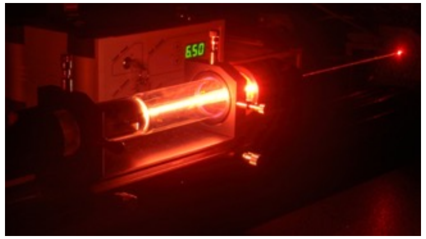
Length is most interesting

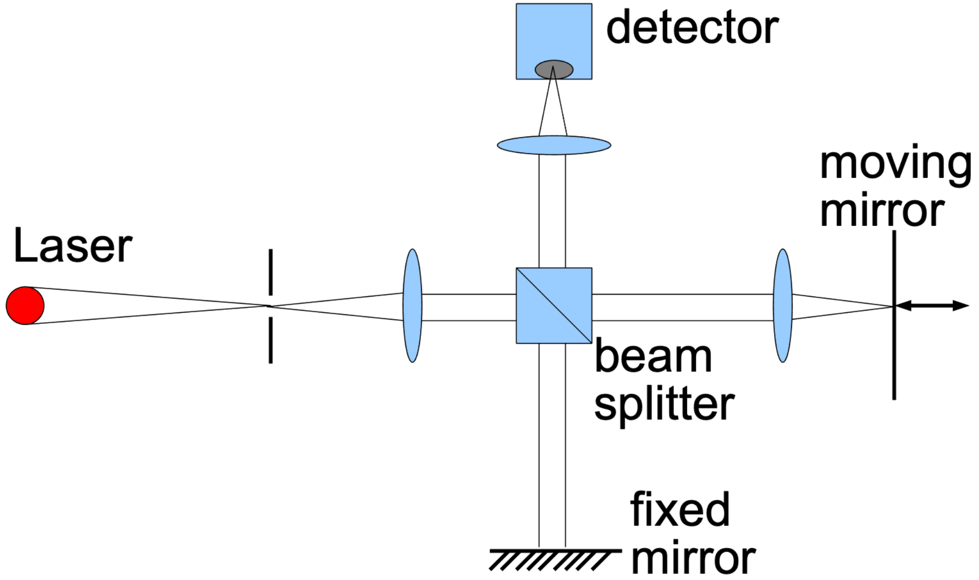


Magnitude of Sensitivity:

$$\frac{\text{Volts}}{\frac{\boxed{\text{Meter}}}{\text{Second}}}$$

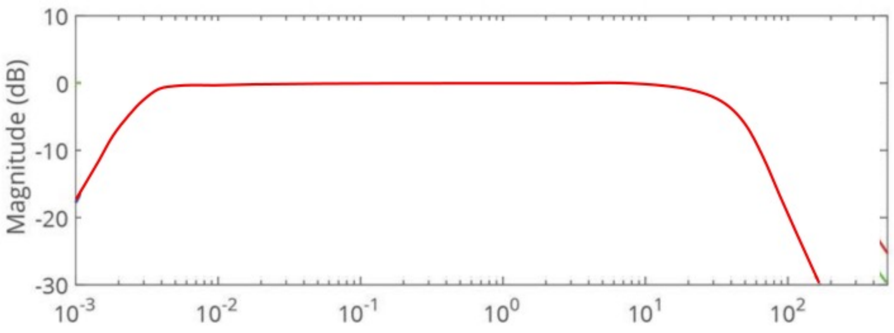
Laser





Workshop on Metrology for the IMS

What Parts of the SI do we Need?



Magnitude of Sensitivity:

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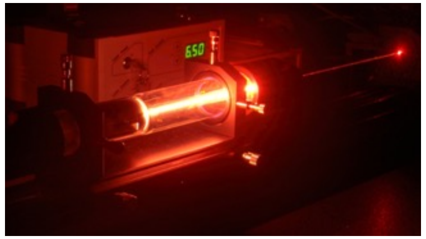
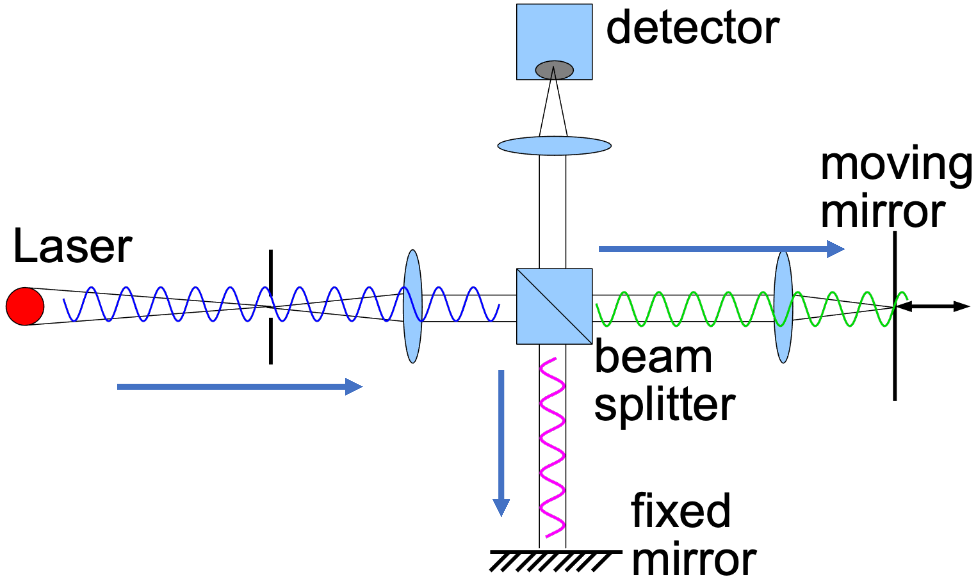
Laser





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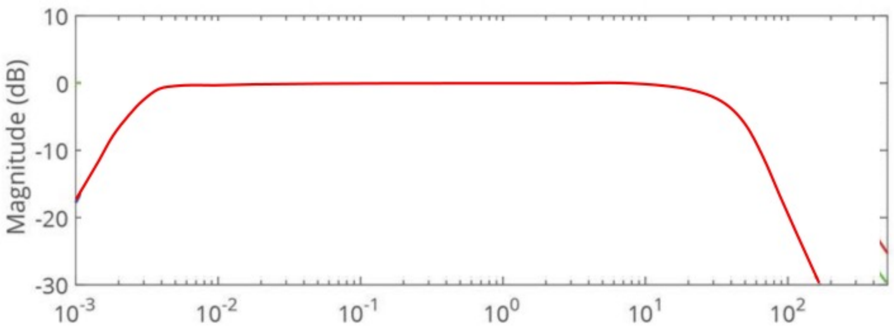
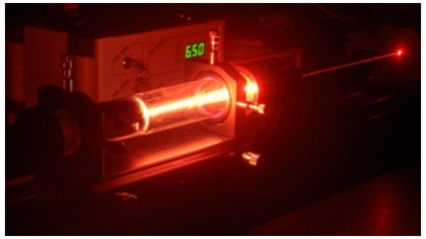
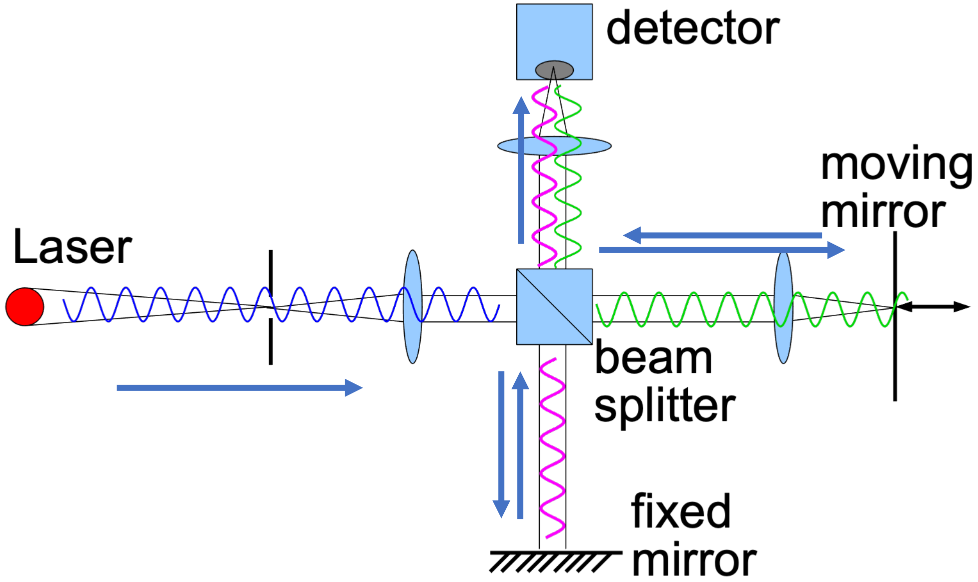


Magnitude of Sensitivity:

$$\frac{\text{Volts}}{\frac{\boxed{\text{Meter}}}{\text{Second}}}$$

Laser





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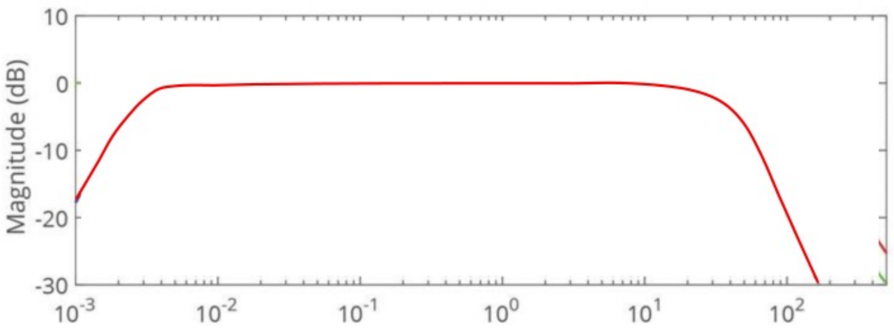
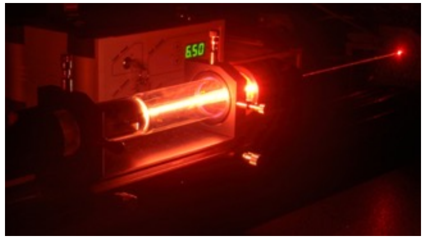
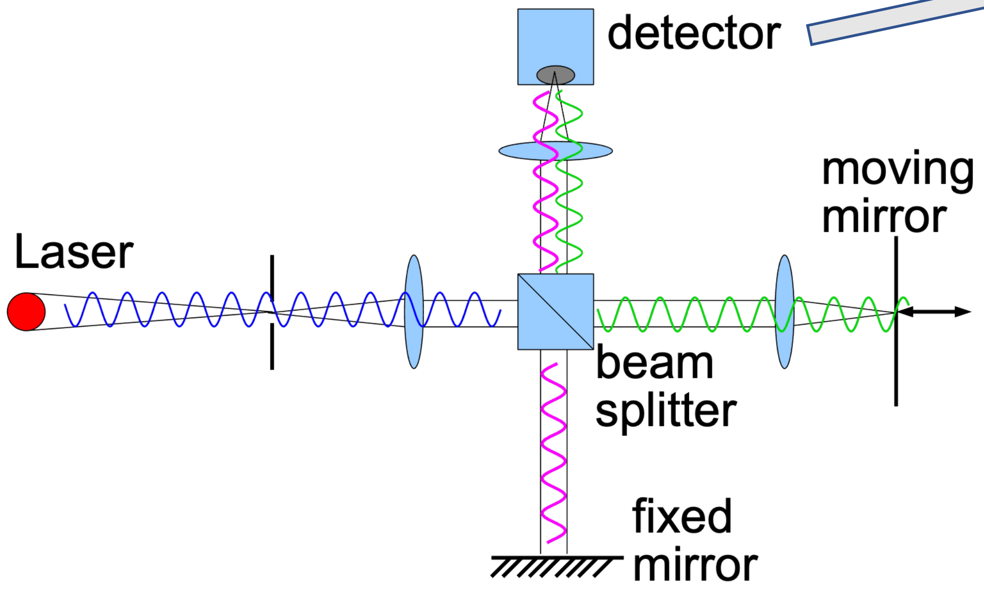


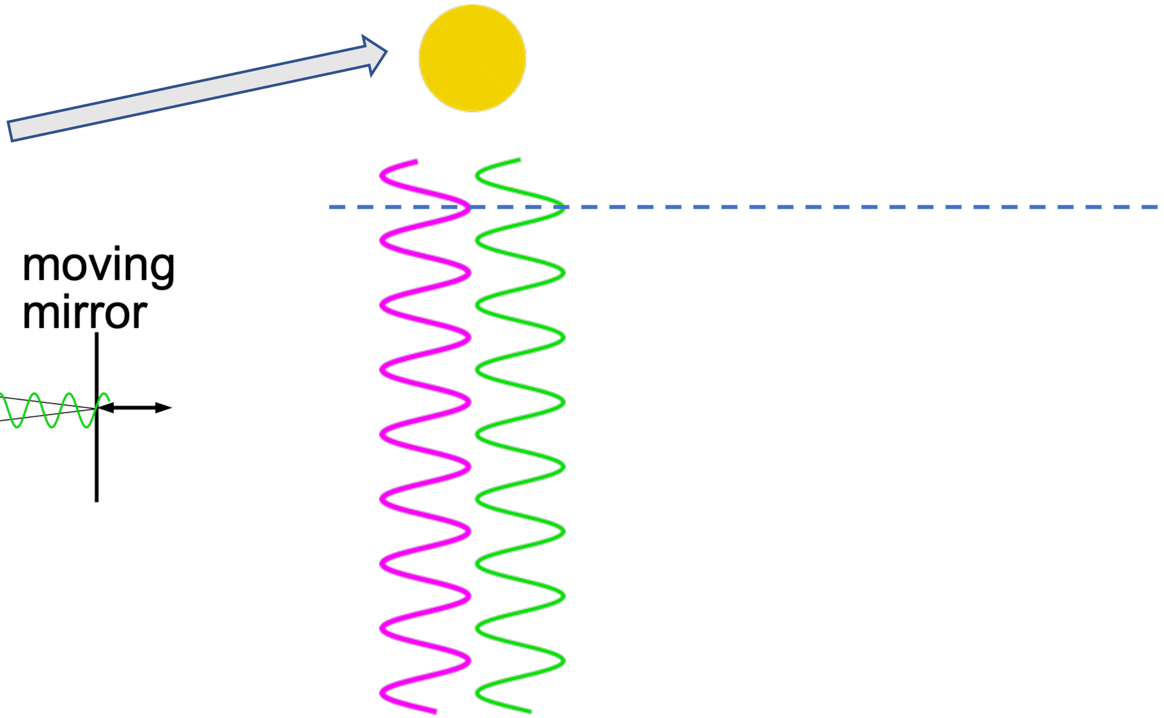
Magnitude of Sensitivity:

$$\frac{\text{Volts}}{\frac{\boxed{\text{Meter}}}{\text{Second}}}$$

Laser

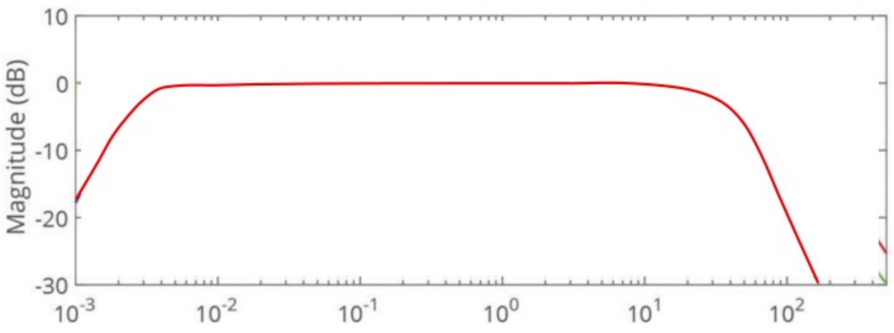






Workshop on Metrology for the IMS

What Parts of the SI do we Need?



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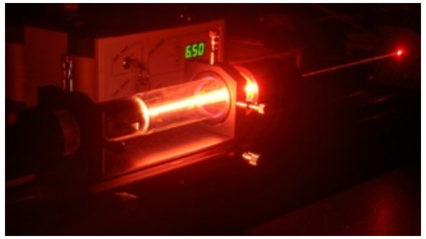

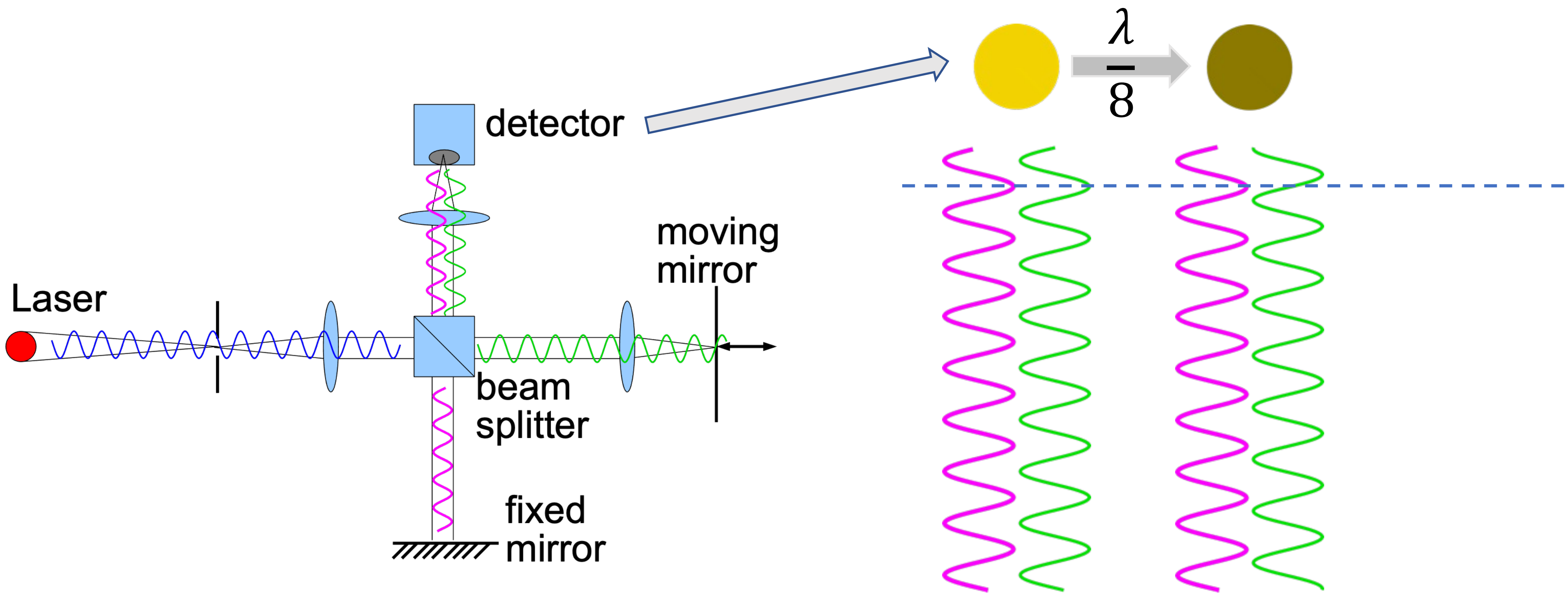

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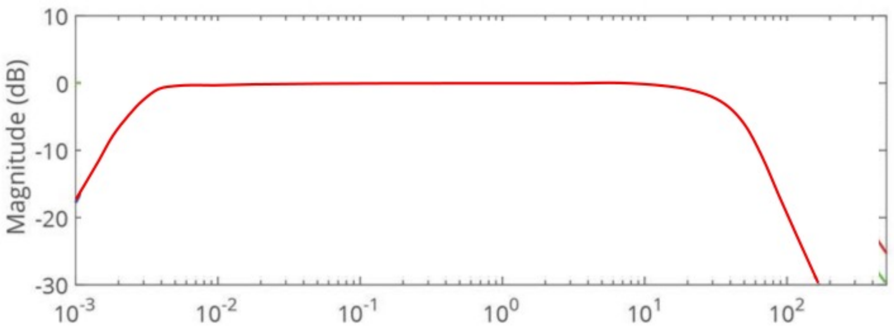

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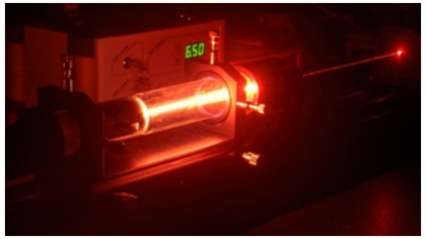

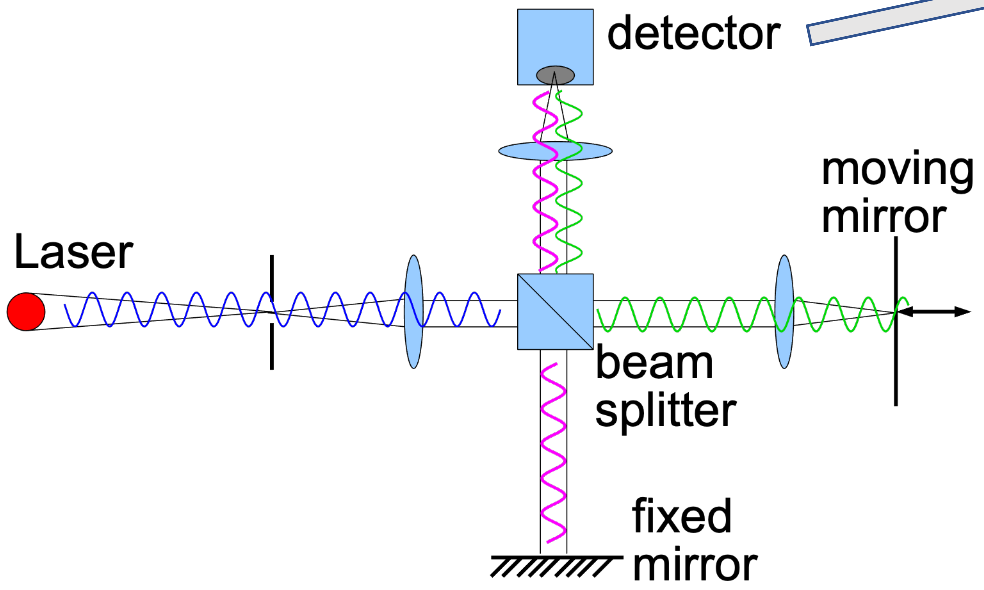

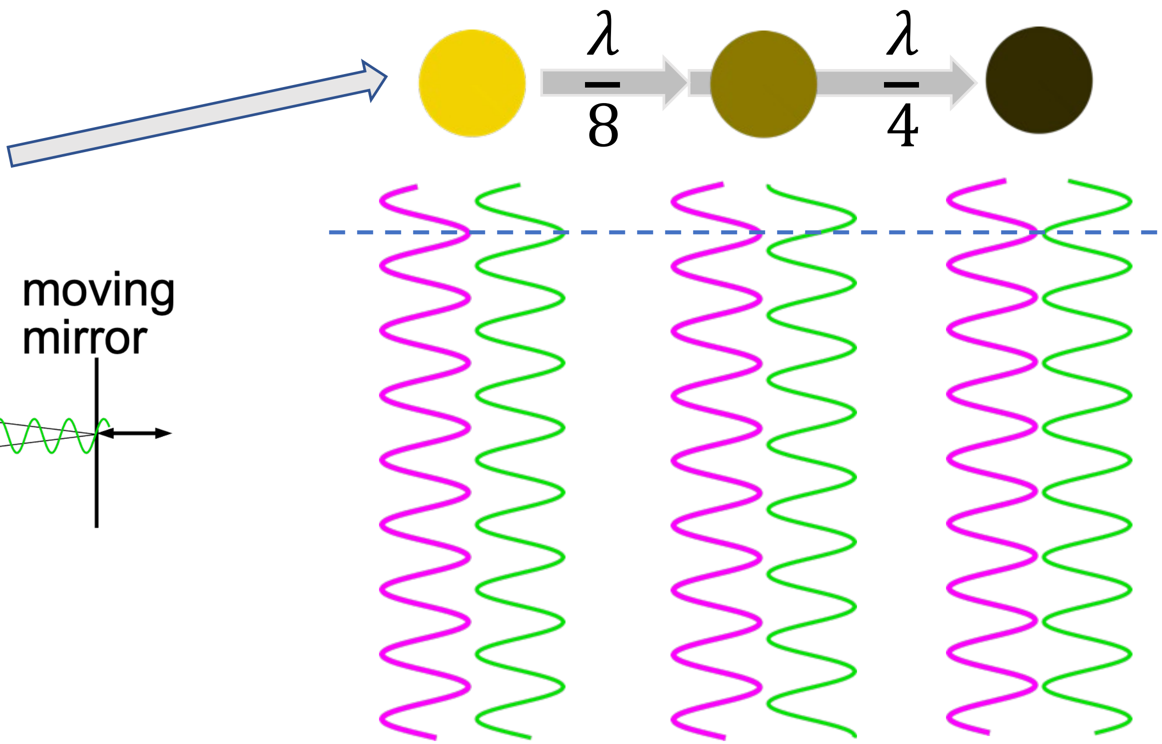

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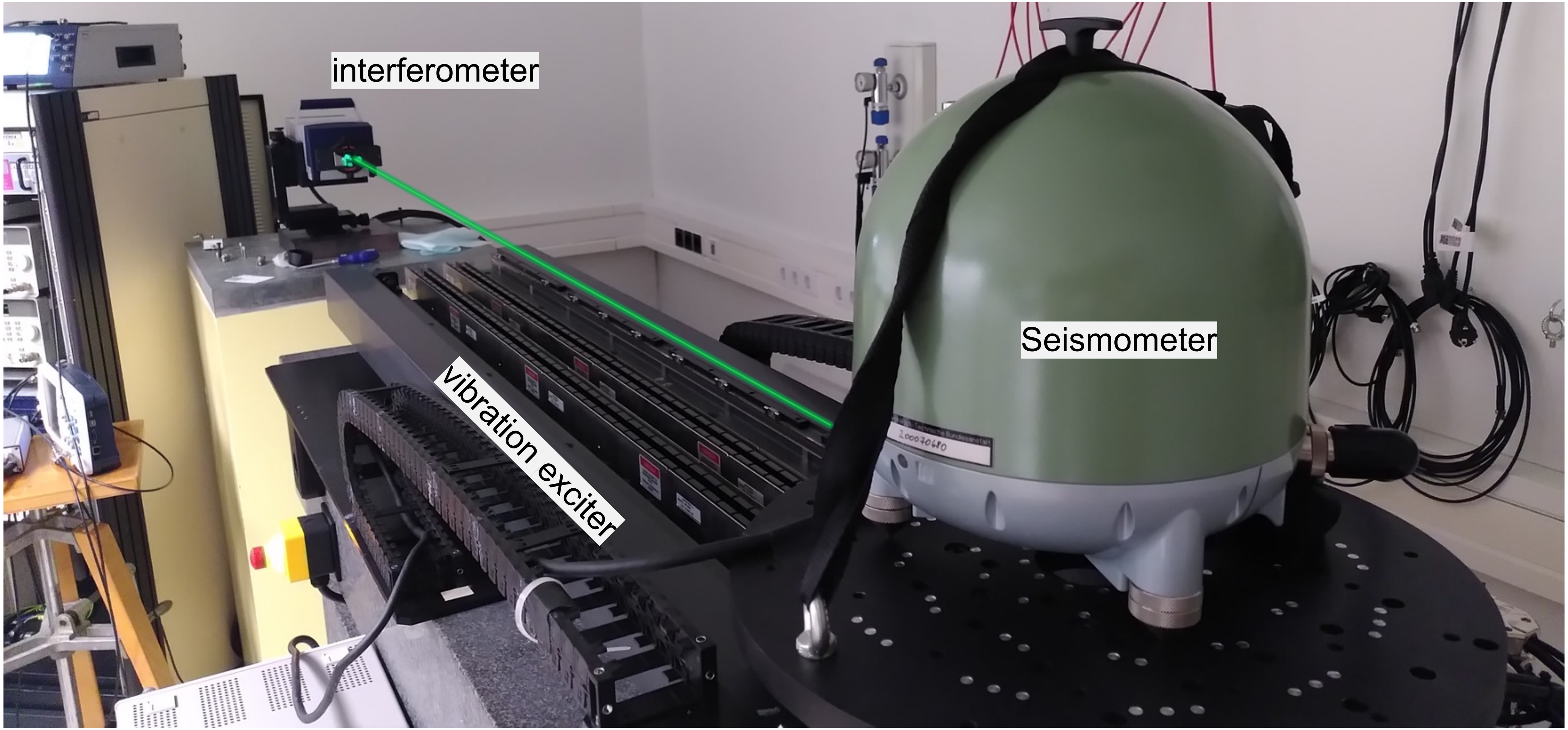

What Parts of the SI do we Need?

- Single- or multi-sine vibration excitation
- Heterodyne Interferometry, digital arctangens demodulation
- Sine approximation to the sampled time-series of velocity and voltage

$$v(t) = a\sin(wt) + b\cos(wt) + c$$

$$v_i = \sqrt{a^2 + b^2}$$

$$\varphi = \operatorname{atan}\left(\frac{b}{a}\right)$$

- Magnitude = Voltage / Velocity (amplitudes)
- Phase (delay) = $\varphi(Voltage) - \varphi$(velocity)

What can go wrong?

Measurement uncertainty issues:

- Electrical uncertainty ≤ 10^{-4} (relative)
- Time/Sampling uncertainty ≤ 10^{-8} (relative)
- (Wave-) Length uncertainty ≤ 10^{-4} (relative)
- Mechanics, Geometry ≤ 10^{-2} (relative)
  - Tilt during movement
  - Orientation of sensor to motion axis (Laser)
  - Ambient vibrations
  - Mounting conditions
  - relative motion (mirror to reference surface)
  - …

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Workshop on Metrology for the IMS

Secondary methods of microphone and microbarometer calibration

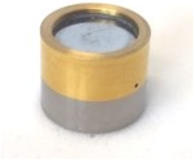
M. Rust[1], D. Rodrigues[2], P. Vincent[3],
S. B. Figueroa[4], E. Sandermann Olsen[5]

[1]PTB (Germany), [2]LNE (France), [3]CEA (France),
[4]DFM (Denmark), [5]HBK (Denmark)

InfraAUV

Motivation

Laboratory



Field

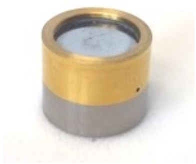
Primary standard	Field device
Laboratory standard microphone	Microbarometer, sound level meter
Long-term stability, suitability for the primary method	Ruggedness, reliability in the field
Controlled laboratory climate conditions	Rough climate conditions
Designed for primary calibration	Designed for field use

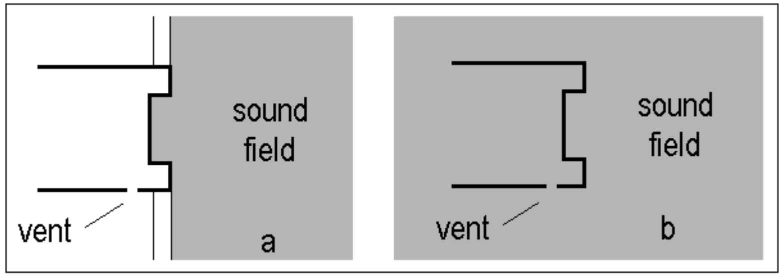
→ Different sensor types for different applications

Motivation: Limitations of pressure reciprocity method

Example: Pressure reciprocity method

- At low frequencies (below 10 Hz) only applicable for one specialized type of microphone
  - Membrane without protection grid

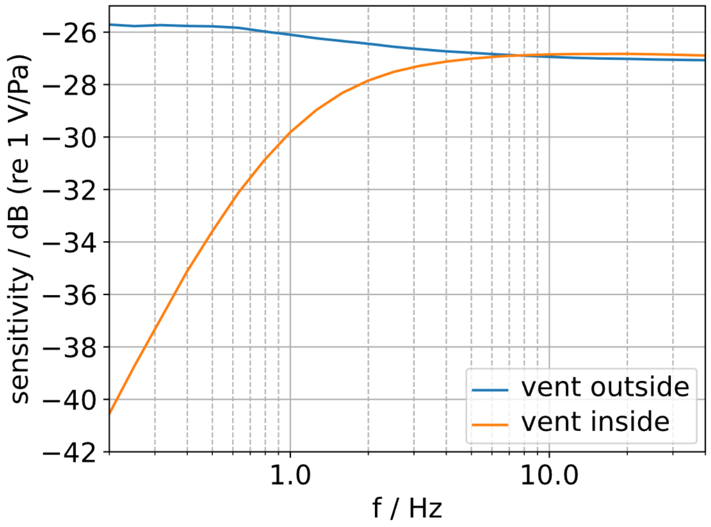




Low frequency calibration of measurement microphones - Scientific Figure on ResearchGate. Available from: https://www.researchgate.net/figure/Measurement-microphone-with-the-equalization-vent-a-not-facing-the-sound-field-and-b_fig1_322343504

- Equalization vent not subjected to the sound field
  - Low-frequency response heavily depends on the vent location

➢ Not directly applicable in the field



Secondary Calibration: Basics of Comparison

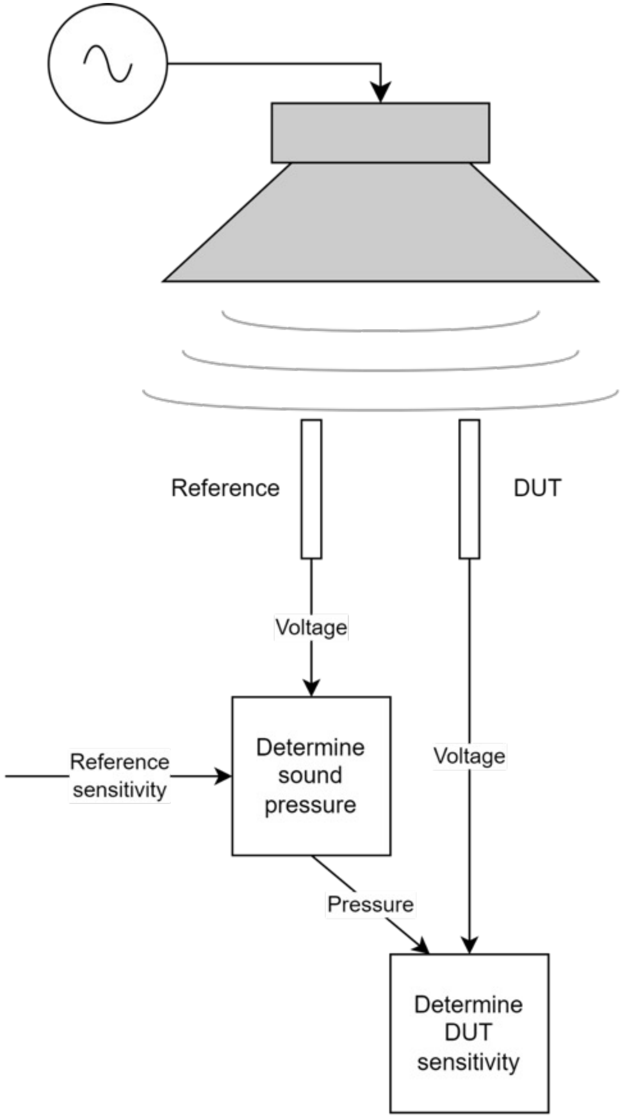
Objective: Transfer the calibration onto field devices
Main method: Comparison

1. Subject Reference and device under test (DUT) to the same excitation signal (sound pressure)

2. Determine the amplitude of the sound pressure from the voltage at the reference and the (known) reference sensitivity

3. Determine the sensitivity of the DUT from the voltage at the DUT and the amplitude of the sound pressure

- Two major methods: simultaneous and sequential excitation

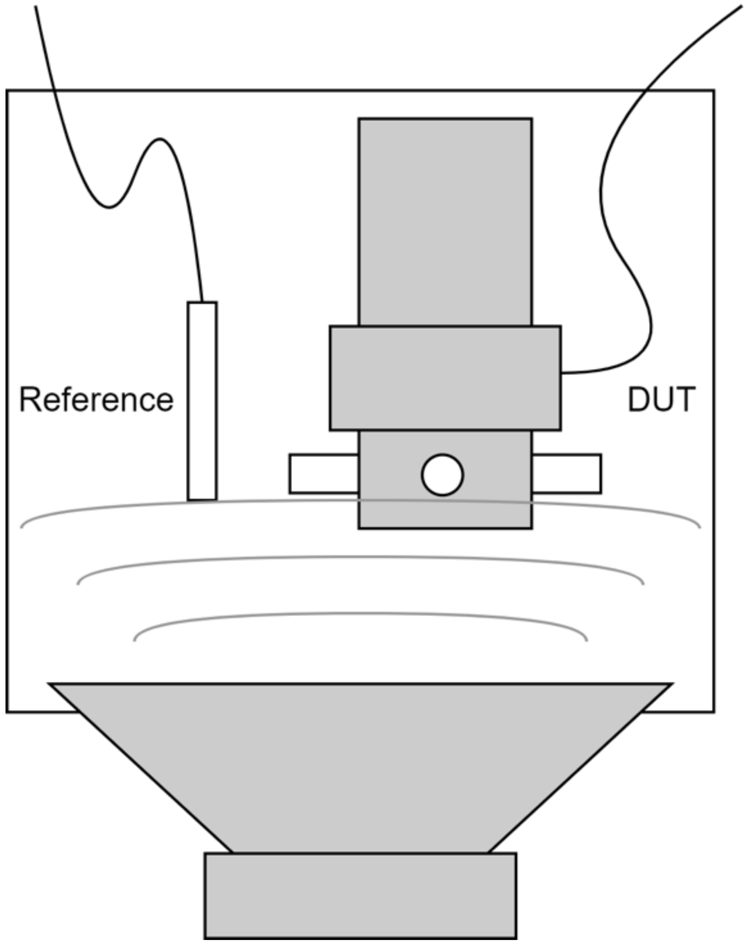


Secondary Calibration: Simultaneous excitation

- Reference and DUT placed directly next to each other

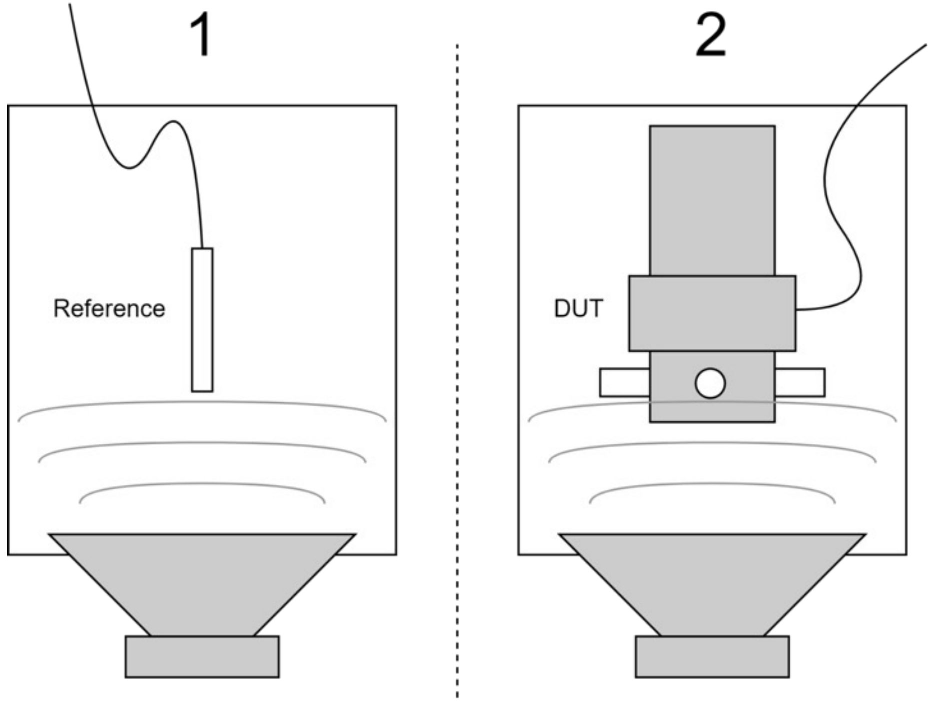
- Subjected to the stimulus **at the same time**
  - Excitation source: Loudspeaker, piston
  - Closed chamber for high signal level

- Sound field must be homogeneous
  - Given when the chamber is small compared to the acoustical wavelength
  - ➢ Suitable for infrasound calibration



Secondary Calibration: Sequential excitation

- Reference and DUT placed at the same location one after the other
- Subject reference and DUT to the stimulus **one after the other**
- Excitation source (sound source) must not change in level over time
  - Can be confirmed using a monitor microphone
- Mainly used for airborne sound with shorter wavelengths



Laser pistonphone (secondary calibration, LNE)

- Closed and sealed cavity, piston as sound generator
- Frequency range: **10 mHz to 20 Hz**
- Working amplitude: Up to 50 Pa, typically 10 Pa
- Reference sensors: Brüel & Kjær type 4193 (microphone), SETRA 278 (static pressure sensor)
- DUT: microphones, microbarometers, manometers, barometers
- Uncertainty (typical):
  - 0.08 dB / 0.5° @ 1 Hz to 20 Hz
  - Up to 0.3 dB / 1.5° @ 10 mHz

Dominique Rodriges, LNE

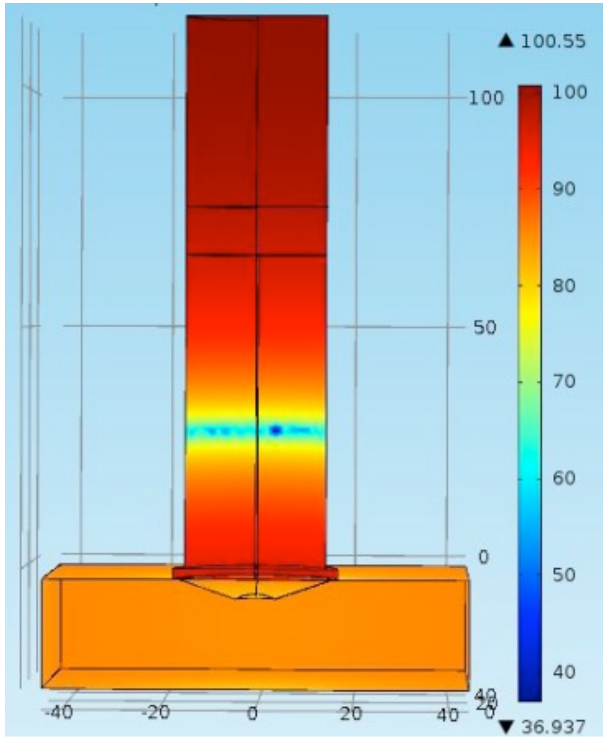
Saturn calibration bench (CEA)

- Closed and sealed cavity, pistonphone-like infrasound generator
- Frequency range: **1 mHz to 100 Hz** (10 mHz to 20 Hz connected to SI)
- Working amplitude: 1 Pa to 30 Pa
- Reference sensors: Brüel & Kjær type 4193 (microphone), Keller PAA33X (barometer), interferometer
- DUT: 1 to 8 microbarometers
- Variable equivalent altitude (static pressure): from 4000m to -500m (600-1100hPa)

Paul Vincent, CEA

Sound tube (PTB)

- Acrylic tube, closed volume, Ø 30 cm, height 110 cm
- Loudspeaker as sound source at the bottom
- Frequency range: **0.5 Hz to 100 Hz**
- Working amplitude: typically 2 Pa
- Reference sensors: Brüel & Kjær type 4160, Brüel & Kjær type 4193 (microphones)
- DUT: Microphones, microbarometers, sound level meters
- Uncertainty (typically): 0.2 dB (microphones), 0.3 dB (sound level meters)



Sound field in the tube at 100 Hz (simulation)

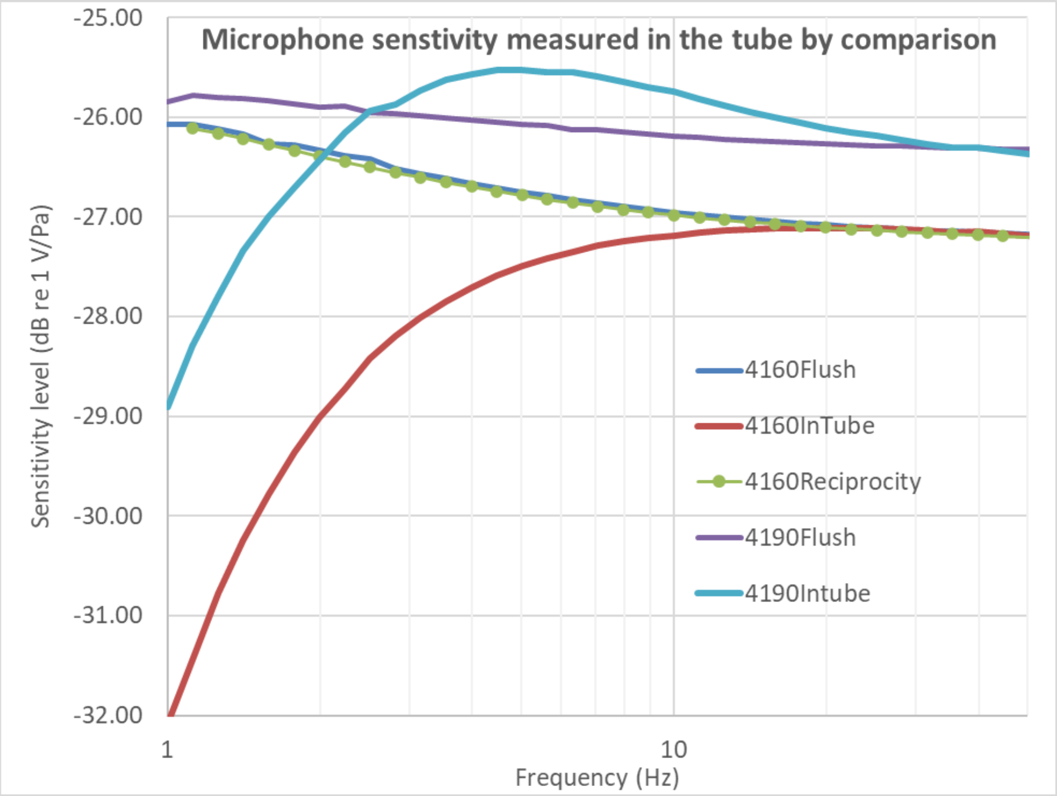
Sound tube (DFM)

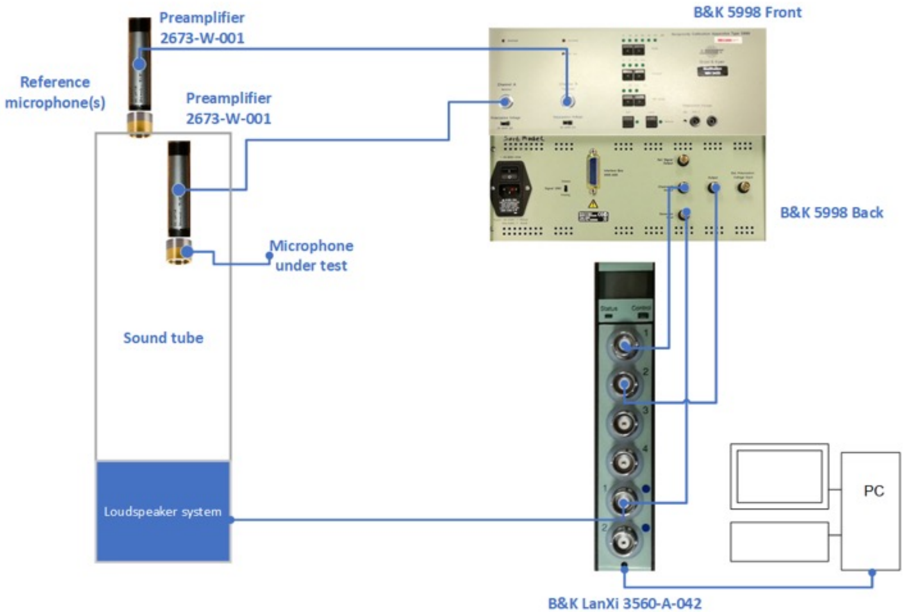
Made of PMMA (Plexiglass)
- Internal diameter 250 mm
- Length (1250 mm)

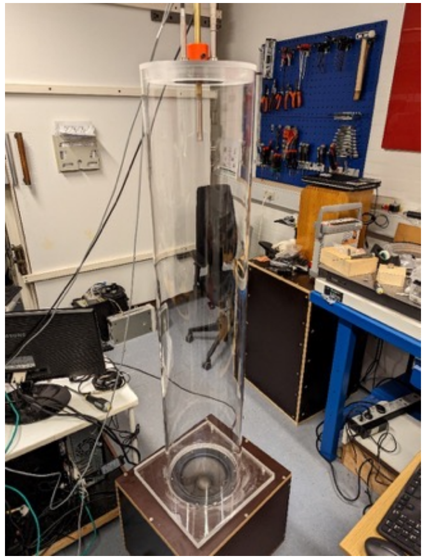
Loudspeaker
- 250 mm subwoofer in a 0.08 m^3 closed cabinet

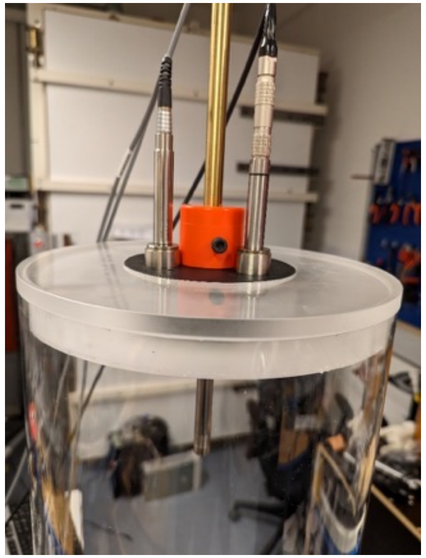
Frequency range
- 200 mHz to 80 Hz

Repeatability
- < 0.05 dB





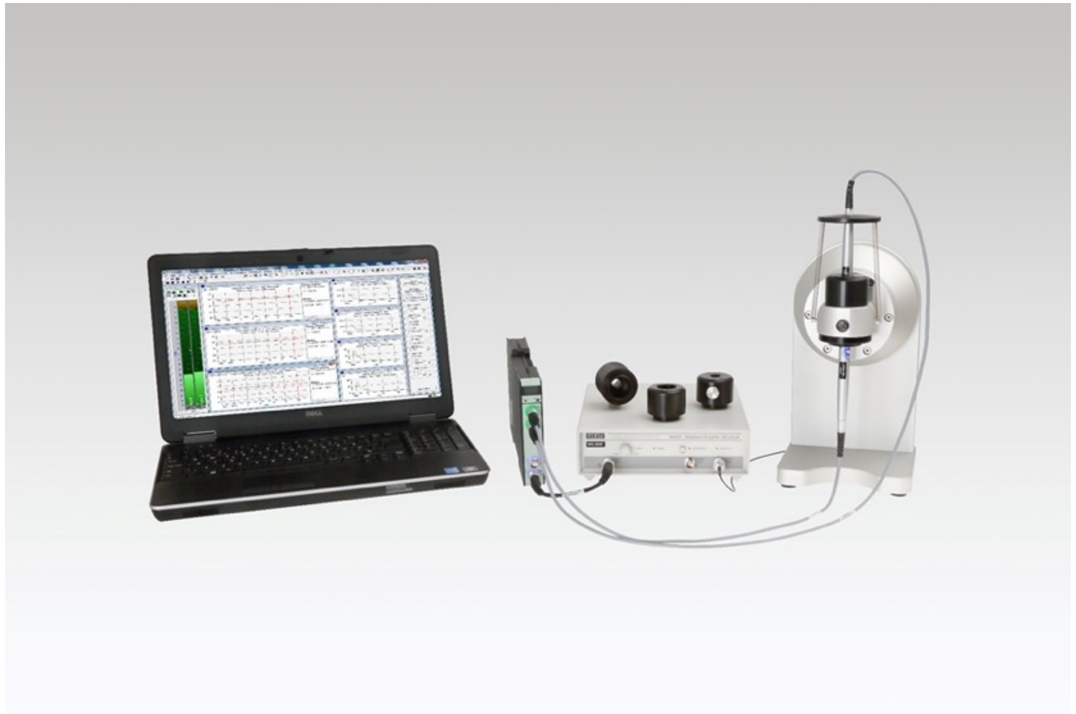




Salvador B. Figueroa, DFM

Brüel & Kjær 9757 (HBK)

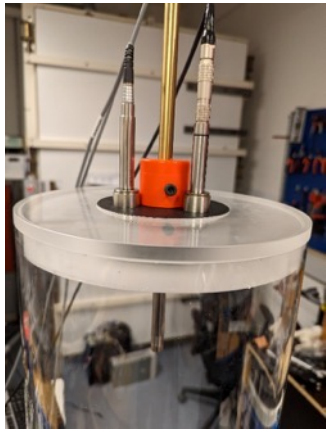
- Low frequency comparison coupler WB 3570
- Reproducibility down to 25 mHz
- Reference sensors: 1” microphones (e.g. B&K 4160), ½” microphones (e.g. B&K 4193)
- DUTs: ½” microphones
- Vent inside or outside the sound field

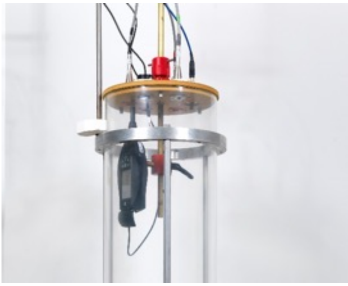


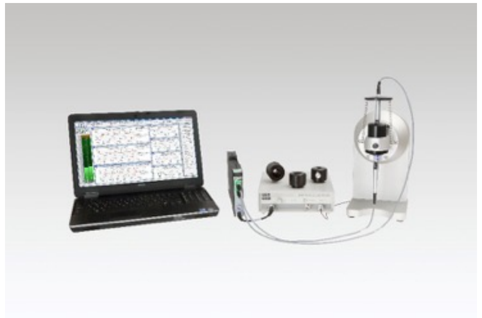
Erling Sandermann Olsen, HBK

Conclusion

- Primary calibration methods are limited in sensor selection
- Laboratory standards are generally not suited for field use
- Secondary calibration: Comparison to a reference
- Objective: Transfer calibration from laboratory standards to field equipment
- Two major principles: Simultaneous and sequential excitation
  - For infrasound: Mainly simultaneous excitation in a closed cavity
- Multiple calibration setups with sealed cavities







Outlook: on-site calibration (tomorrow)

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Workshop on Metrology for the IMS

Hydrophone calibration in the laboratory and at simulated ocean conditions

Stephen Robinson[1], Ben Ford[1], Freya Malcher[1], Peter Harris[1], Sei-Him Cheong[1], Justin Ablitt[1], Lian Wang[1], Richard Barham[2]

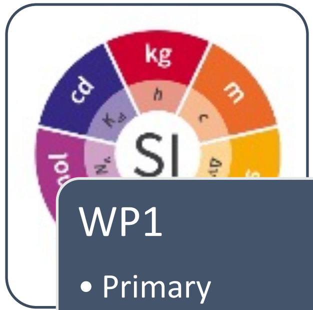
[1]NPL, UK; [2]ASN, UK;

InfraAUV

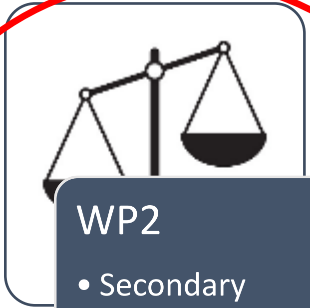
INFRA-AUV STRUCTURE & OBJECTIVES

- Establish the necessary calibration procedures and methods, to provide traceability to the SI for AUV measurements at very low frequencies.
- Demonstrate the implementation and the resulting benefits of improved data quality.

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



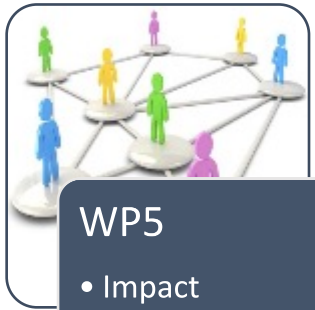
WP1
- Primary calibration



WP2
- Secondary calibration

WP3
- On-Site calibration

WP4
- Consequences & improve data quality



WP5
- Impact

Task 2.3: Development of secondary methods for underwater calibration of hydrophones in a frequency range from 0.5 Hz to 100 Hz

GENERAL OVERVIEW

Established using a
primary method of measurement

The **Primary method** of measurement provides the essential first link in the chain of traceability from the definition of a unit of the International System of Units (SI)

SI

National Metrology Institutes
Primary reference standard

Accredited / Expert Laboratories
Working standard

One site calibration laboratories
Travelling standard

Final user
Measuring equipment

Metrological traceability

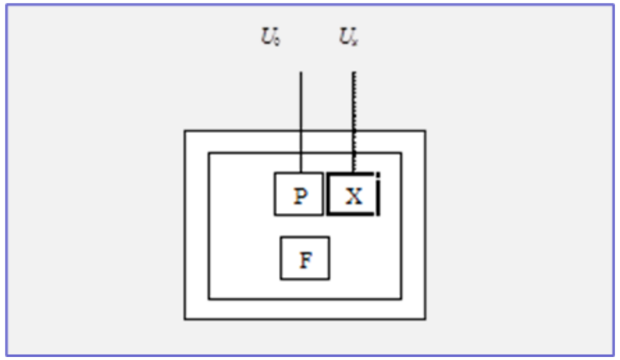
Property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty.

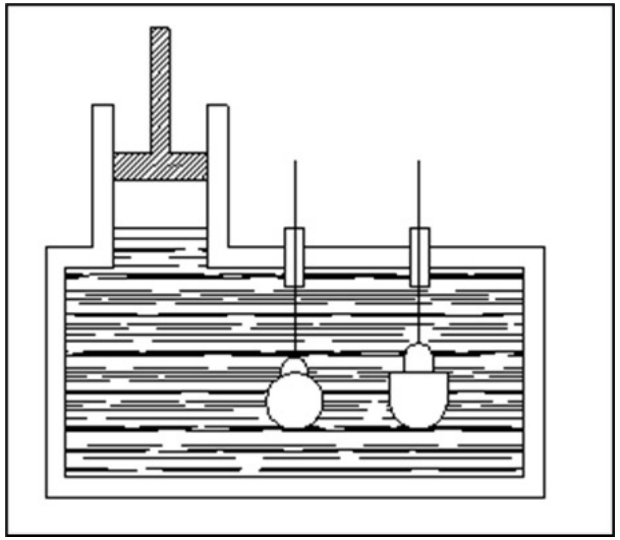
Pressure versus free-field calibration

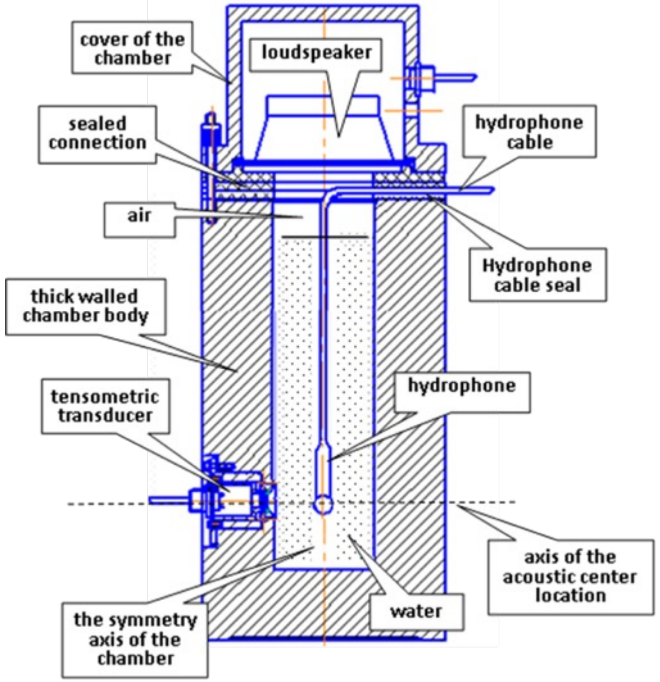
- A hydrophone responds to the pressure averaged across the active element - average of the magnitude *and* phase of the pressure
- **Pressure calibration of a hydrophone**
  - Calibration method where the hydrophone element is exposed to an oscillating pressure, often in an enclosed chamber
- **Free-field calibration**
  - Calibration method where the response of the hydrophone is determined to a plane sound wave incident in a given direction
- A difference between pressure and free-field sensitivity is the hydrophone directional response
- At low frequencies, pressure and free-field sensitivity are identical when:
  - a) the diffraction factor of the hydrophone is unity (omnidirectional)
  - b) the hydrophone has negligible response to particle velocity and pressure gradient,
  - c) the frequency of calibration is sufficiently below the lowest resonance frequency of the hydrophone so that the sensitivity of the hydrophone is independent of acoustic impedance

Comparison methods in small chamber

- Hydrophone under test and reference are exposed to same pressure field in small chamber
    - Described in IEC 60565-2
- Ideally, pressure is the same in all parts of the chamber (if not, corrections needed for wave modes)
- Comparison calibration undertaken
- Sound generation can be by pistonphone, loudspeaker (in air) or by auxiliary transducer
- Hybrid air/water configurations may be applied





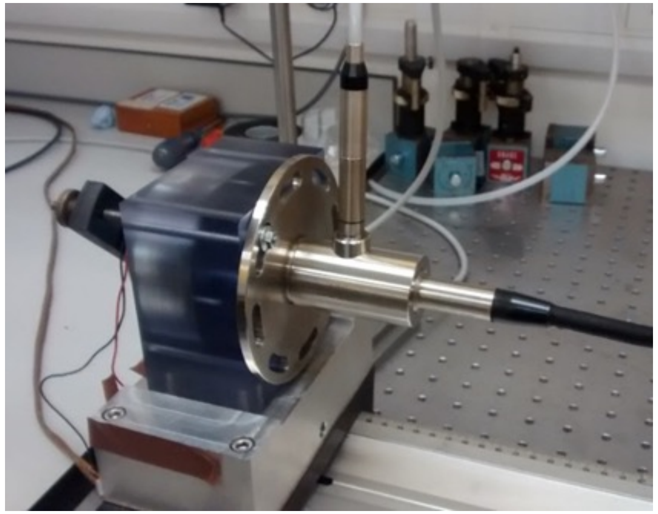


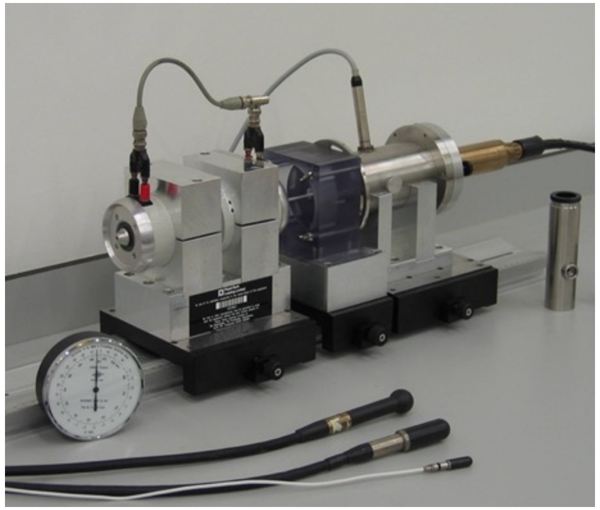
$$M_x = \frac{U_x}{U_0} M_0$$

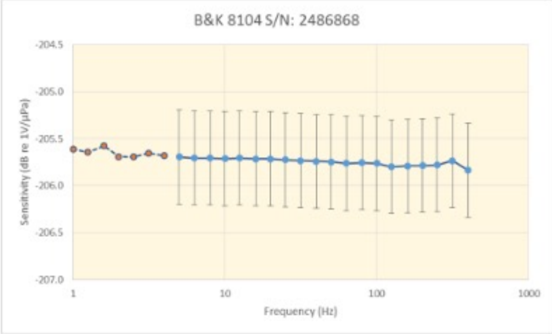
NPL comparison methods in small chamber

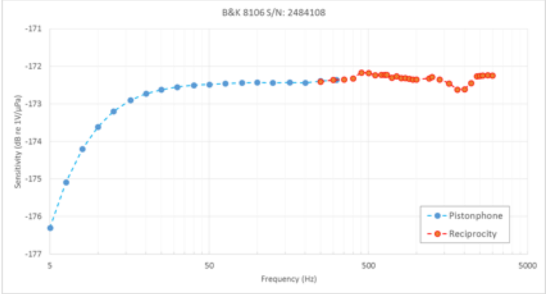
- frequency range from 0.5 Hz to 315 Hz
- Low distortion piston source
- loudspeaker source or piston
- Flexible drive levels to suit different sensitivity hydrophones
- Flexible couplers to suit different hydrophone models and sizes
- Uncertainty: 0.5 dB

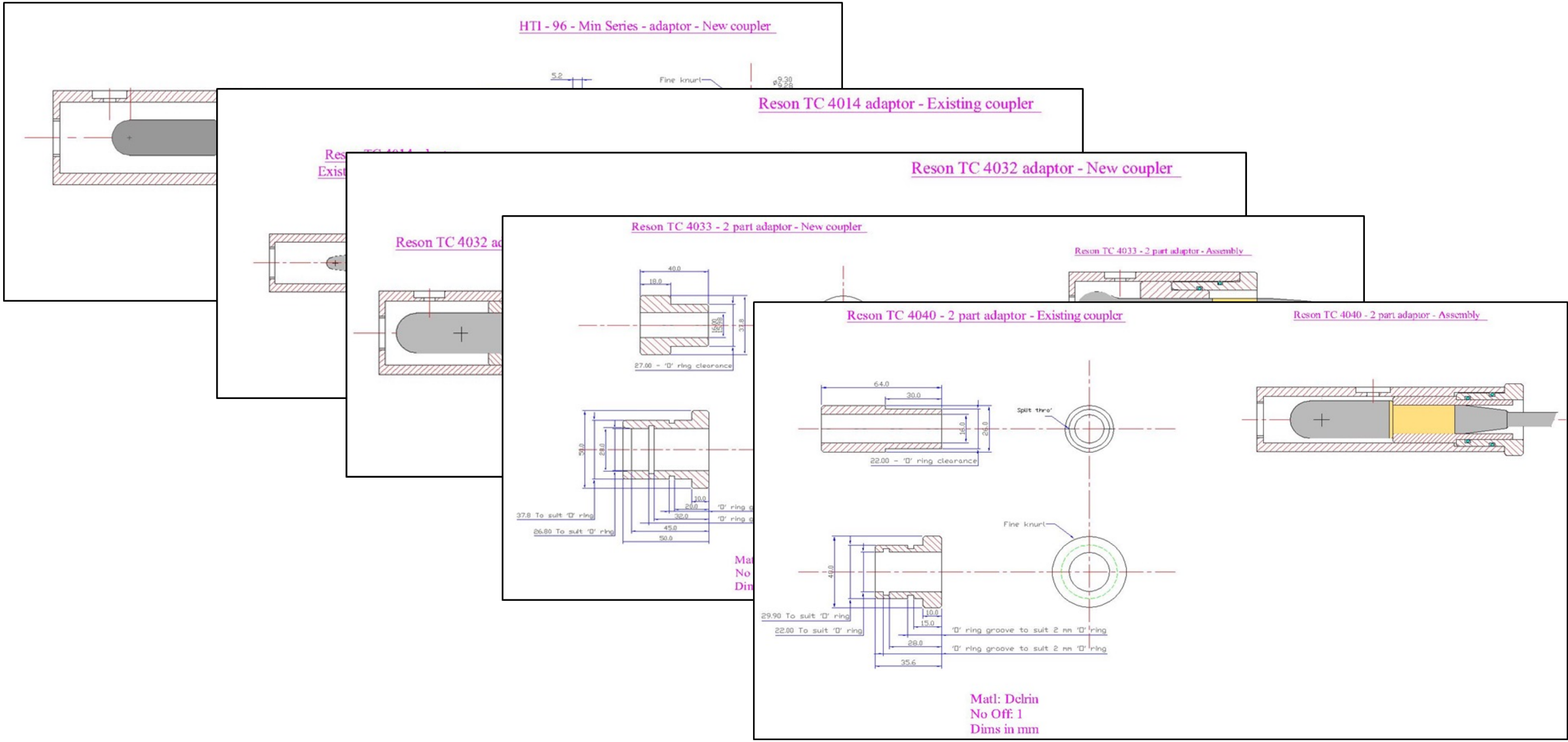
$$M_x = \frac{U_x}{U_0} M_0$$









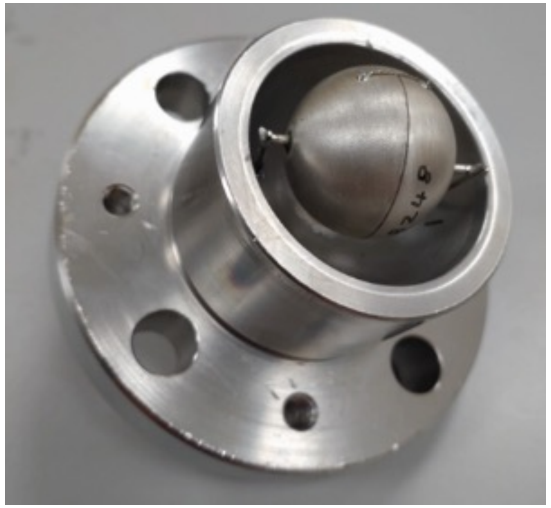

HTI - 96 - Min Series - adaptor - New coupler
Reson TC 4014 adaptor - Existing coupler
Reson TC 4032 adaptor - New coupler
Reson TC 4033 - 2 part adaptor - New coupler
Reson TC 4033 - 2 part adaptor - Assembly
27.00 - 'O' ring clearance
37.8 To suit 'O' ring
26.80 To suit 'O' ring
Reson TC 4040 - 2 part adaptor - Existing coupler
Reson TC 4040 - 2 part adaptor - Assembly
Split thro'
22.00 - 'O' ring clearance
Fine knurl
29.90 To suit 'O' ring
22.00 To suit 'O' ring
'O' ring groove to suit 2 mm 'O' ring
'O' ring groove to suit 2 mm 'O' ring
Matl: Delrin
No Off: 1
Dims in mm

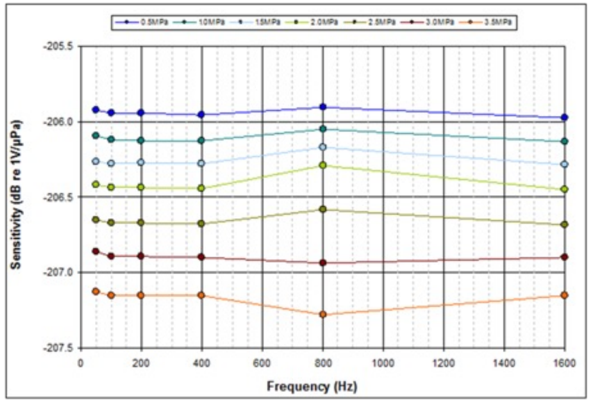
Calibrations at simulated ocean conditions

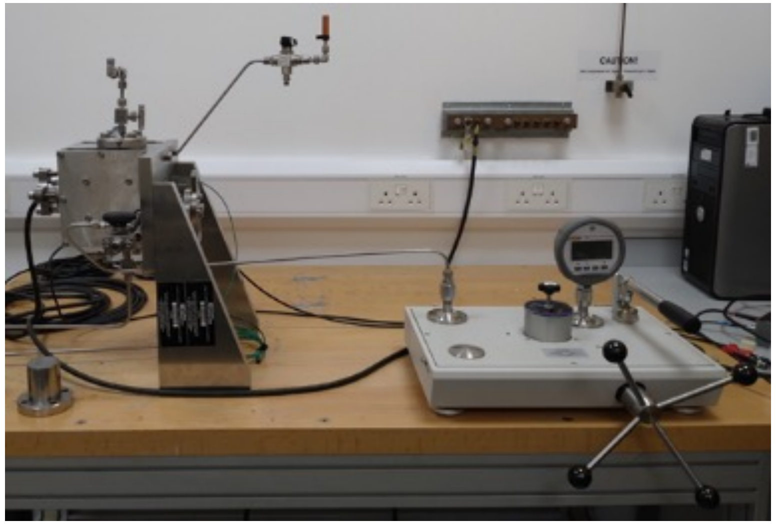
- Hydrophone performance can vary with immersion **depth and temperature**
- Need reference hydrophones and transducers to use for comparisons
- Need to be calibrated by absolute method under simulated ocean conditions
  - Couper reciprocity
  - Free field reciprocity
- calibrate reference devices using reciprocity over the complete range of temperature and pressure
- reference devices then used to calibrate device under test by relative calibration method
- Best to choose reference devices that are quite stable with temperature and depth
- Same methods used as for laboratory open tanks and open-water facility

Primary Method: Coupler reciprocity (NPL)

- Reference – Transfer method established by NPL
  - fluid filled with deionised degassed water
- Reference transducers are spherical transducers
  - no compliant material
  - compliance of reference chamber only required
- Lock-in amplifiers used for signal detection
- Problems with lowest frequencies
  - repeatability must be improved
  - very high electrical impedance of transducers
  - must prevent any electrical conductance through water
- Hydrostatic pressure: up to 7 MPa (~700 m depth)
  - difficult to operate at ambient pressure(trapped air)
- Temperature control (water jacket):



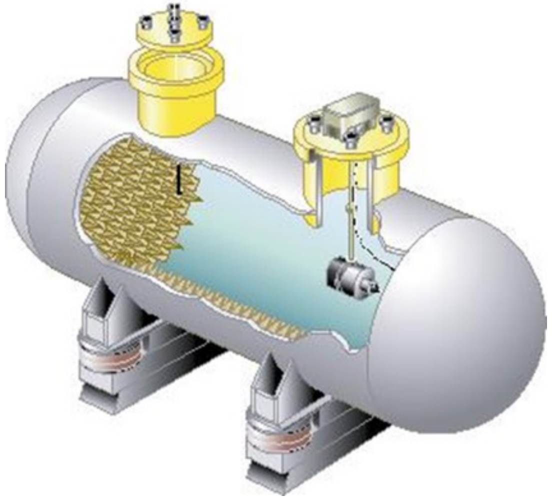




NPL Acoustic Pressure Vessel

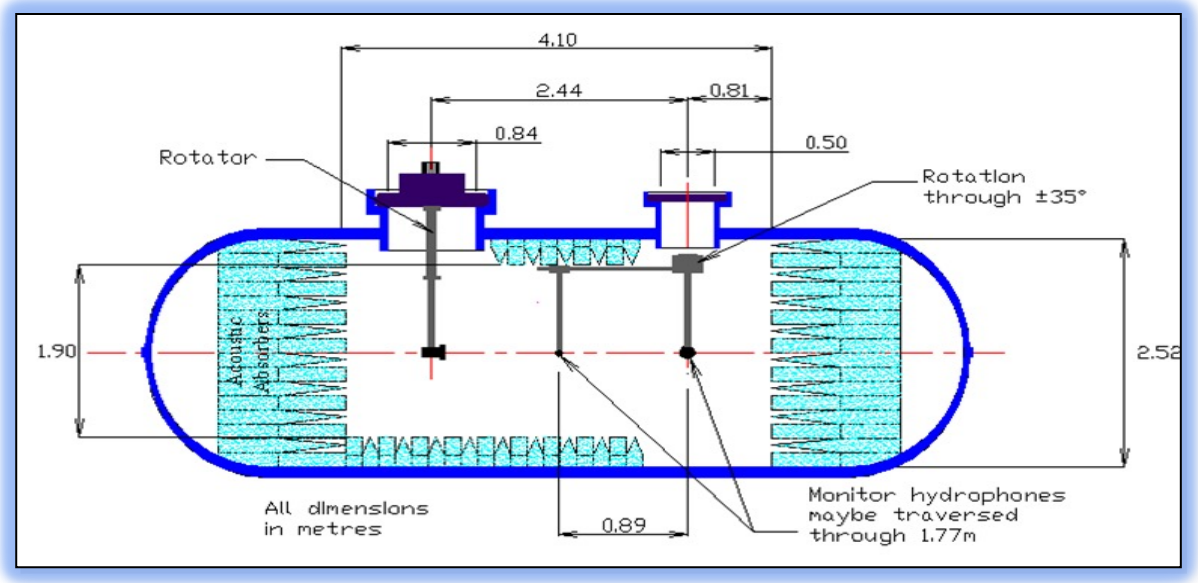
- NPL Acoustic Pressure Vessel enables free-field acoustic measurements to be made at **simulated** ocean conditions

- The steel test chamber is 7.5 m long by 2.5 m diameter
- It weighs 69,000 kg excluding water (99,000 kg full)
- Access port diameters of 0.84 m and 0.50 m (rotator on large lid allows 360°rotation of test objects)



- Hydrostatic pressure up to 7 MPa
- Water temperature 2 °C to 35 °C
- Pressure cycling at defined rates
- Air mounts for both vibration and acoustic isolation

- Low frequency comparisons possible
- Generate VLF signals and undertake comparison
- 0.5 Hz to 100 Hz



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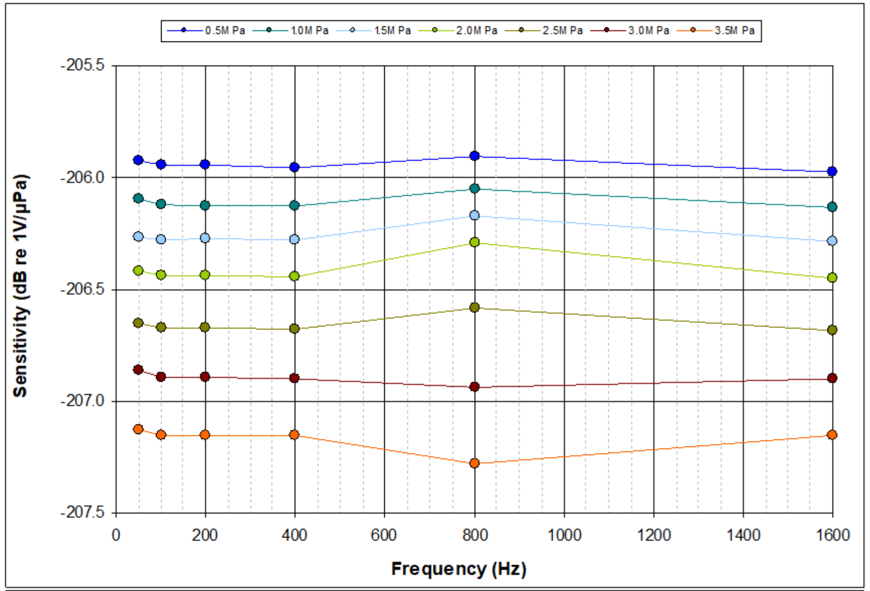
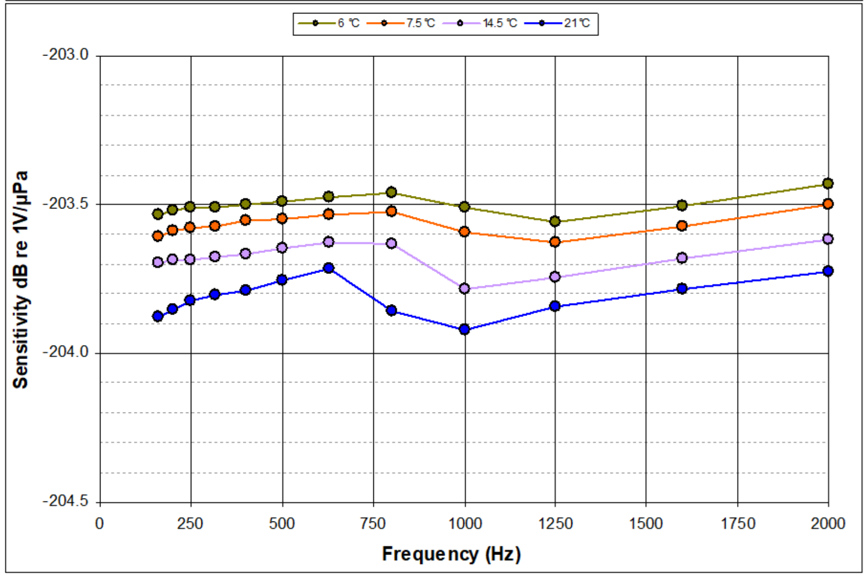
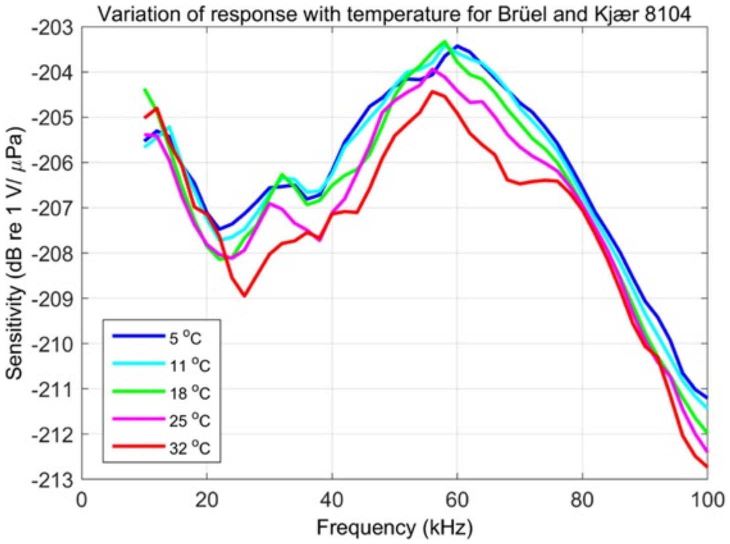
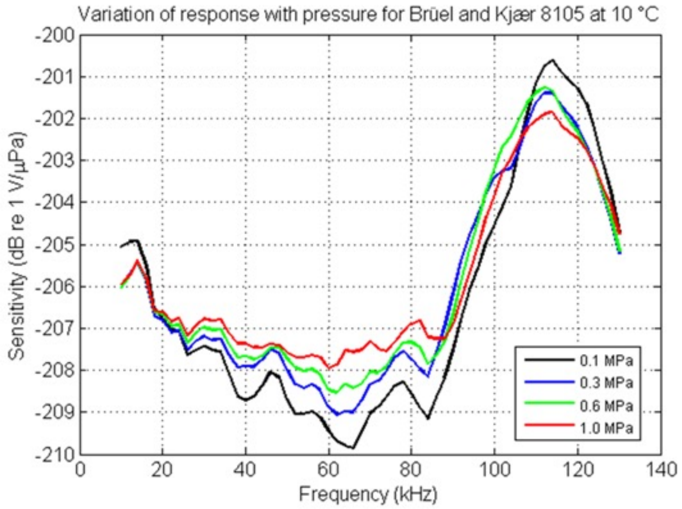
Workshop on Metrology for the IMS

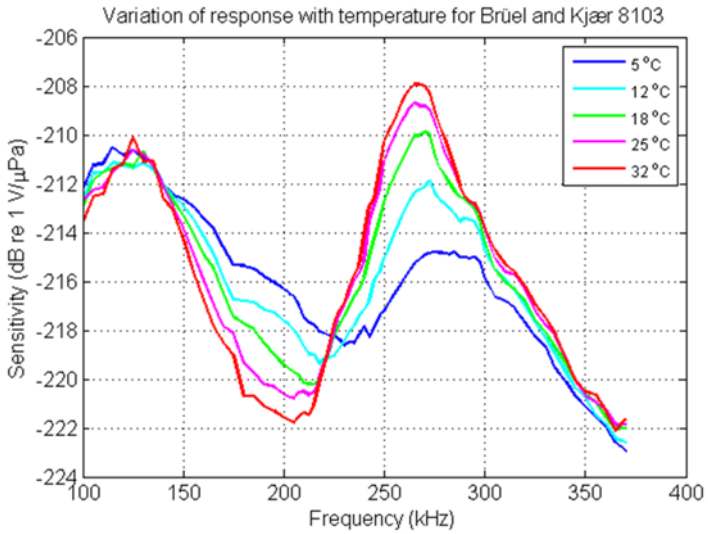
Hydrophone calibration in the laboratory and at simulated ocean conditions

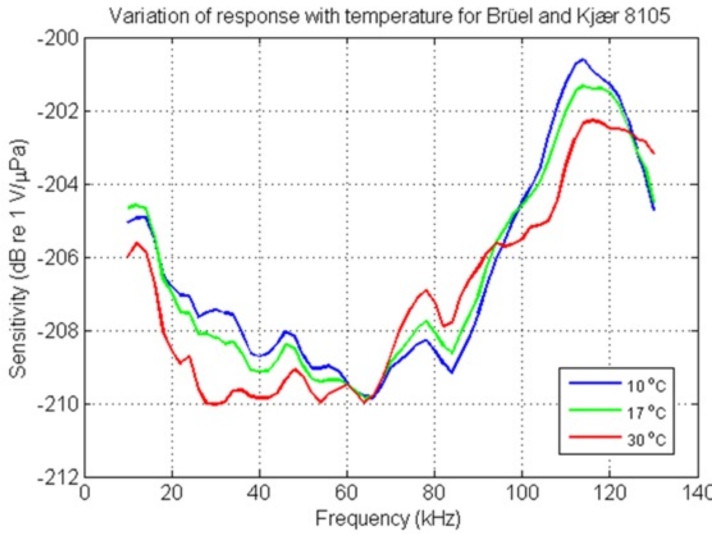






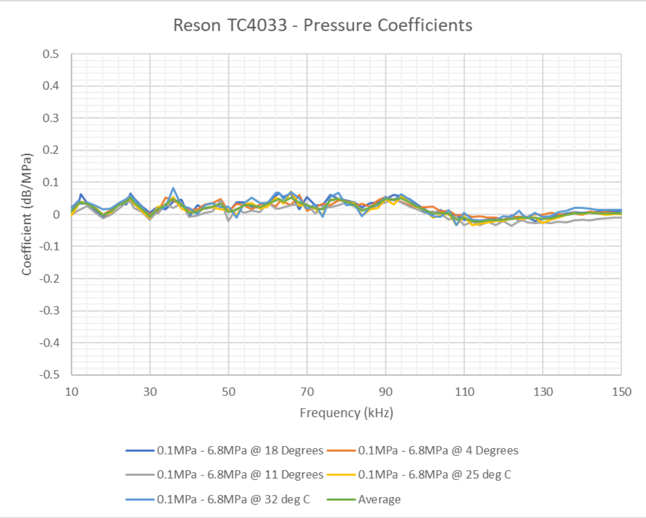


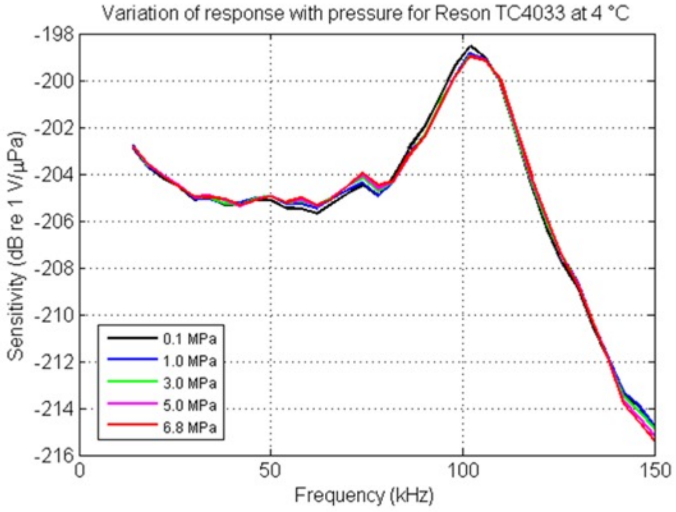


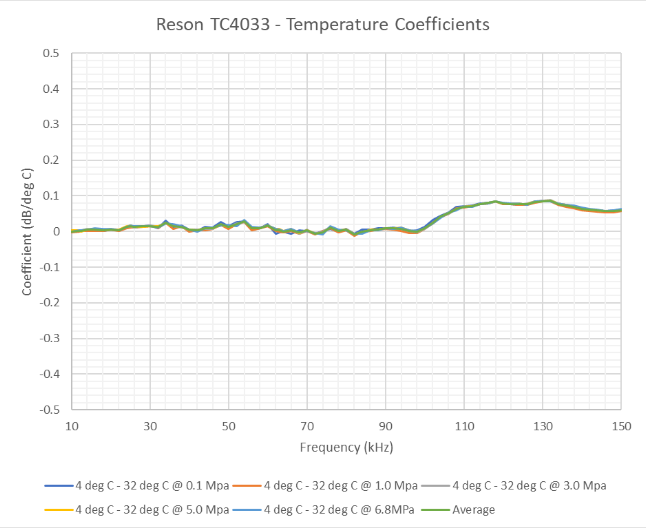


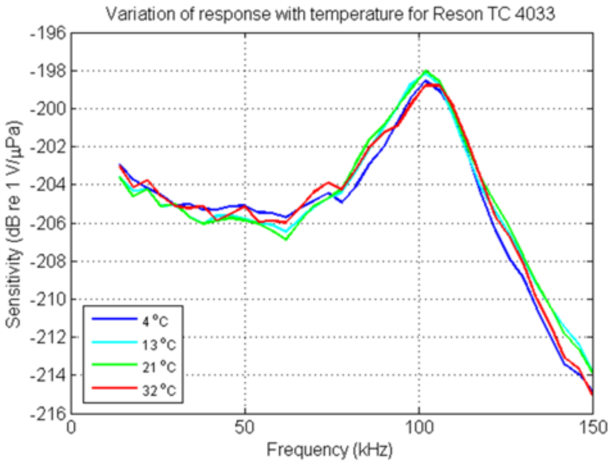
Hydrophone calibration in the laboratory and at simulated ocean conditions

- NPL report on the stability of current hydrophones at varying temperatures and hydrostatic pressures
- Simple hydrophones have stable responses (eg spherical hydrophone elements)
- Example hydrophone:
  - Reson TC4033
- Good stability for depth and temperature

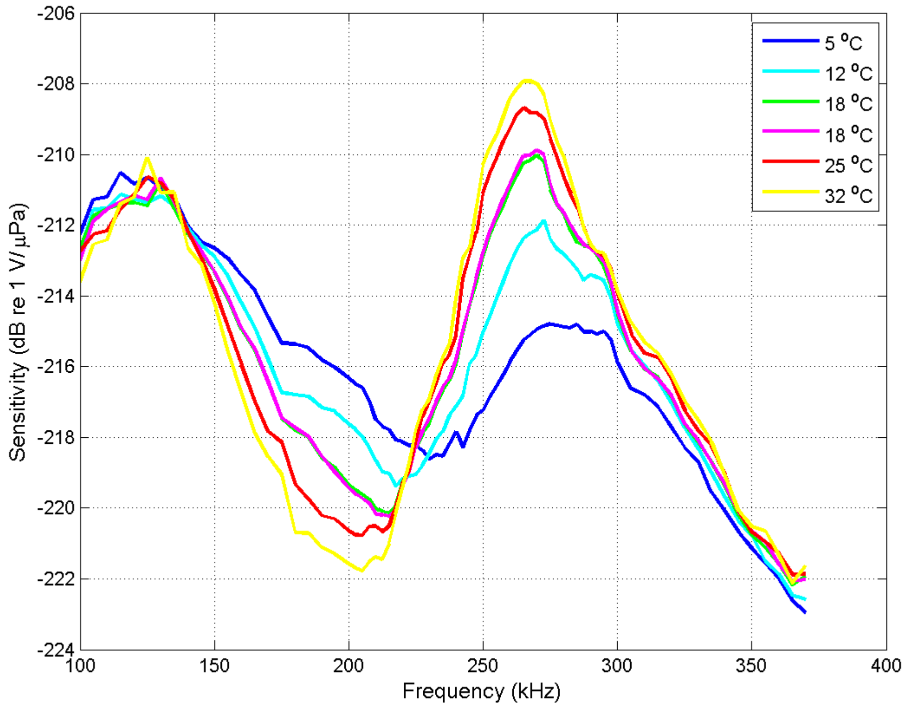








Sensitivity and electrical impedance

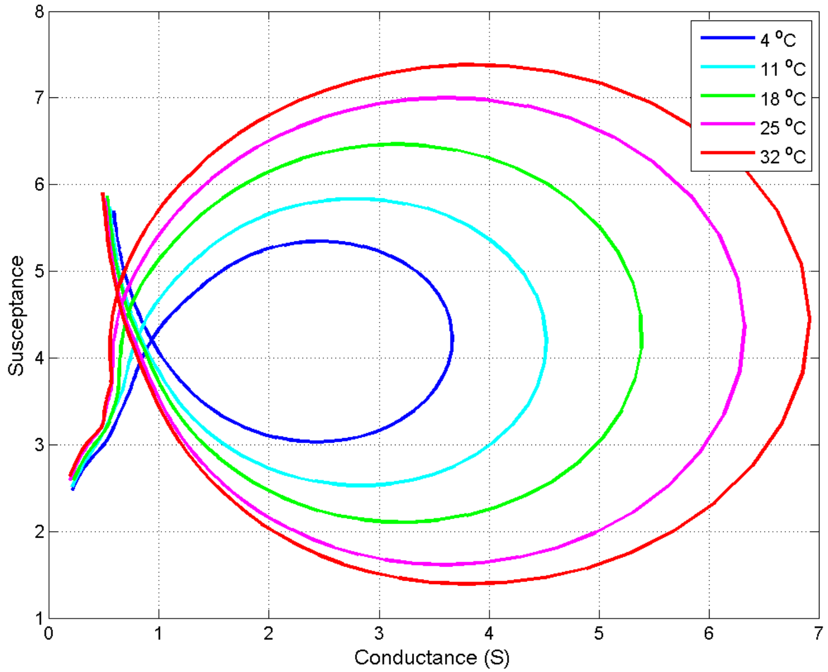


Small 8mm dia 8mm long cylindrical hydrophone

Performance with temperature

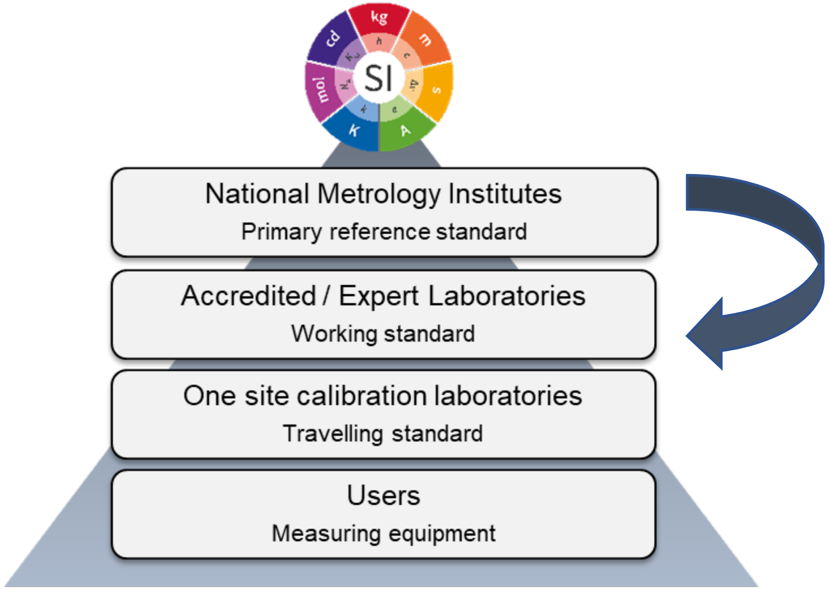
(B&K8103 or Reson TC4013)

Sensitivity variation evident from electrical impedance data



CONCLUSION AND NEXT STEPS

- Comparison methods available for secondary dissemination of standards
- Hydrophones can experience changes in sensitivity when exposed to variations in temperature and hydrostatic pressure
- Review of hydrophone stability undertaken for Infra-AUV project
- Less complex transducer element designs tend to be more stable with temperature and pressure variations



- <u>Next steps</u>
- Experimental trials in NPL APV using coupler reciprocity as primary standard
- Trials of Gabrielson’s method with real experimental data acquired in NPL facilities

SnT 2023

CTBT: SCIENCE AND TECHNOLOGY CONFERENCE

HOFBURG PALACE - Vienna and Online

19 TO 23 JUNE

Workshop on Metrology for the IMS

Laboratory calibration of seismometers at low frequencies by comparison

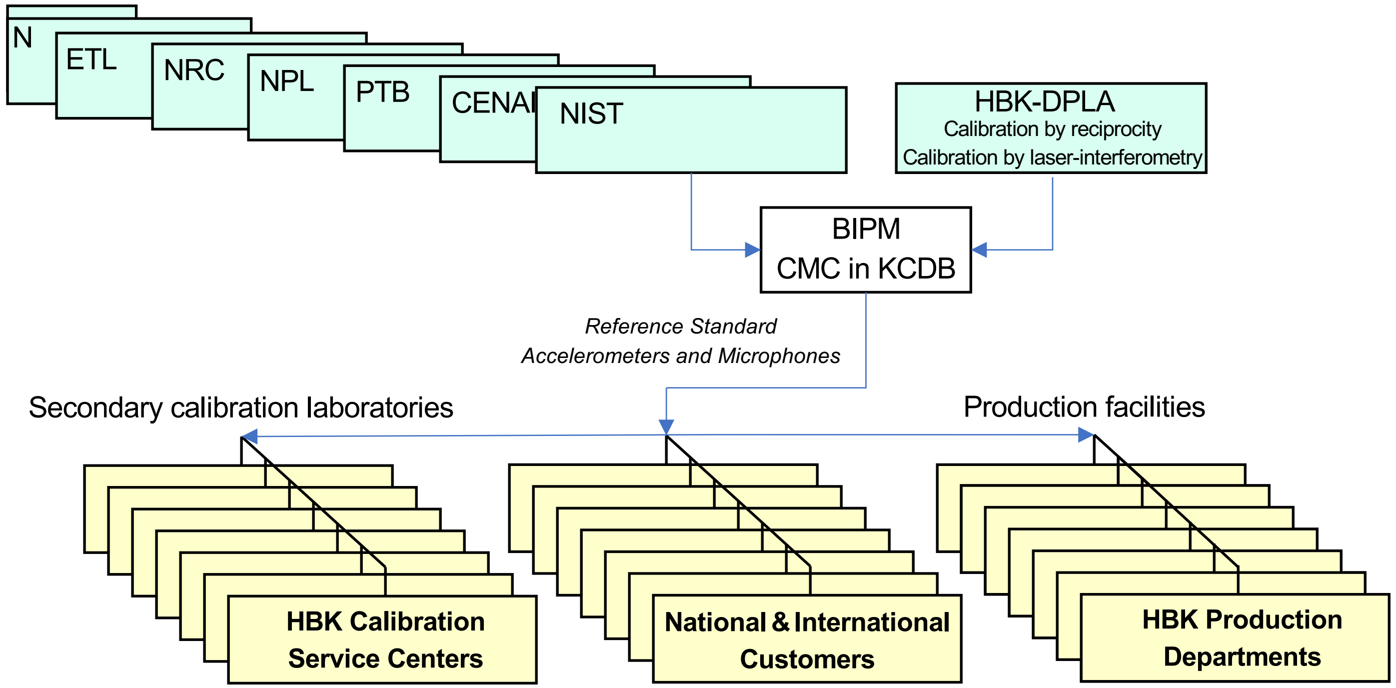
Jacob Holm Winther

Department Manager / Danish Primary Laboratory of Acoustics / HBK-DPLA / Hottinger Bruel & Kjaer, Copenhagen, Denmark

InfraAUV

Formal traceability chain & hierarchy

Infra-AUV project: Linking IMS measurements to the International System of Units (SI)



Formal link to SI provided by: National Metrology Institutes (NMIs) & Designated Institutes (DIs)

Calibration Measurement Capability (CMC) listed in the Key Comparison Database (KCDB) under BIPM

- fundamental relevant quantity e.g. ***[V/ms]*** *or* ***[V/(m/s^{-2})]***

Motivation - Vibration in high mass environment

Examples of IRL applications – large structure vibration modes at e.g., 0,2 Hz to 2 Hz

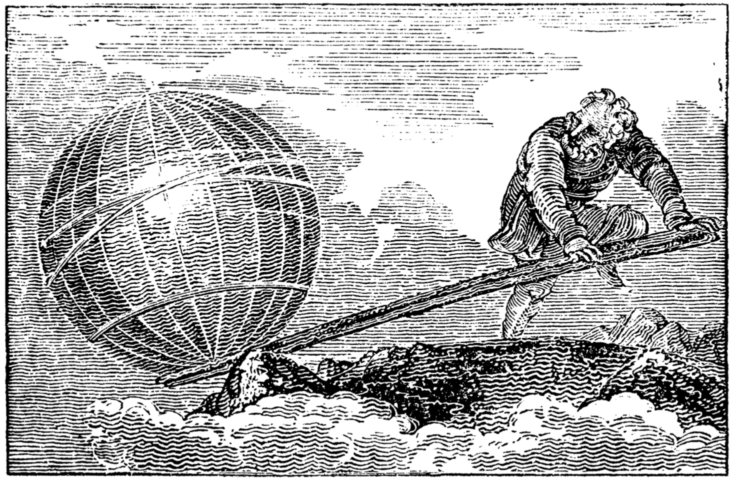
Wind turbine

- *Total mass: > 1000 t*
- *Moving mass: 10 t to 50 t (x3)*
- *Height: 50 m to 100 m*
- *Blades length: 50 m to 90 m*
- *Max Velocity: > 80 km/h*

Commercial aircraft

- *Weight: 150 t to 250 t*
- *Wingspan 40 m to 50 m*
- *Length: 40 m to 80 m*
- *Max Velocity: > 1000 km/h*

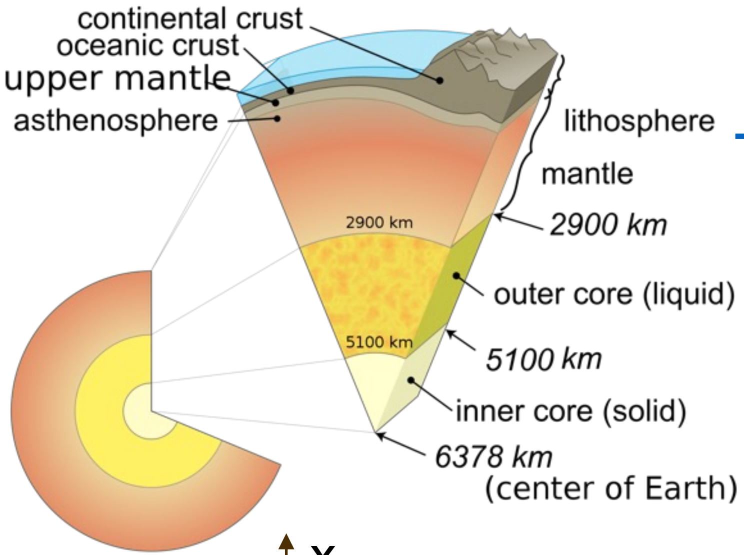
Planet Earth



- *SI base unit:* **M⊕**
- *Weight:* 5.9722×10^{24} *kg*
- *Diameter: >12700 km*

"give me a lever long enough and a fulcrum on which to place it, and I will move the earth" (Archimedes)

Large structure high mass vibration modes and resonance frequency



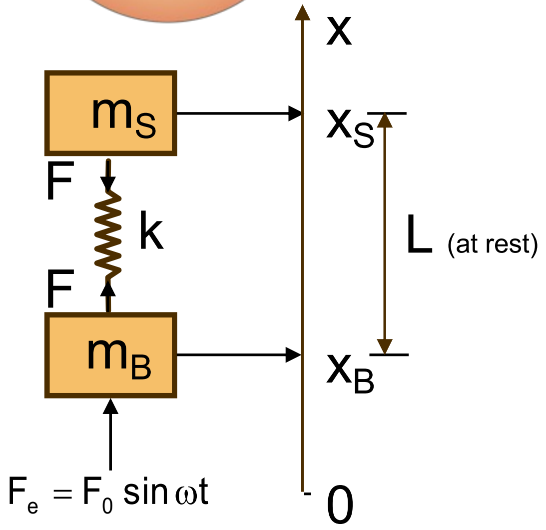
Free hanging resonance frequency

$$f_n = \frac{1}{2\pi}\sqrt{k \cdot \left(\frac{1}{m_S} + \frac{1}{m_B}\right)}$$

Mounted resonance frequency

$$f_m = \frac{1}{2\pi}\sqrt{\frac{k}{m_S}} \left(m_B \to \infty\right)$$

f_m is the resonance frequency of spring-mass system (LF transducer) mounted on a heavy structure



Spring Force: $F = k\left(x_S - x_B - L\right)$

Force on Base: $m_B \ddot{x}_B = F + F_e$

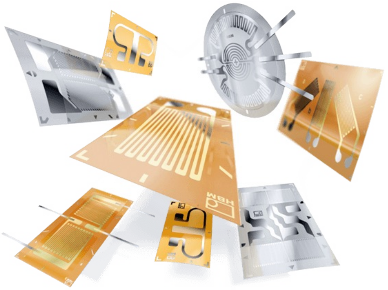
Force on Seismic Mass: $m_S \ddot{x}_S = -F$

Equation of motion:

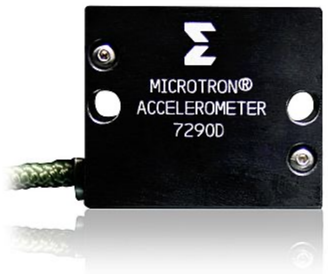
$$\ddot{x}_S - \ddot{x}_B = -\frac{F}{m_S} - \frac{F + F_e}{m_B}$$

Examples of traditional transducer technologies relevant for LF area measurements and calibration – DC & AC systems

Strain Gauges



Variable Capacitance accelerometer



Frequency range: DC to – 1000 Hz
10mV – 200mV/(m/s²)

Electromagnetic Geophone

Frequency range: 0.5 Hz – 500 Hz
20 V – 100 V/(m/s)

Servo Accelerometers

Frequency range: DC to – 200 Hz
20mV – 1000mV/(m/s²)

Piezoelectric Force transducer

Frequency range: 0.08 Hz – 3000 Hz
1 mV – 500mV/N

Piezo-Resistive accelerometer

Frequency range: DC to – 1000 Hz
10mV – 200mV/(m/s²)

Low frequency accelerometers

Frequency range: 0.008 Hz – 3000 Hz
100mV – 500mV/(m/s²)

Mid frequency triaxial accelerometer

Frequency range: 0.3 Hz – 10000 Hz,
1mV – 100mV/(m/s²)

Examples of seismometers relevant for LF area measurements and calibration (Infra-AUV transfer standard candidates)

Geotech Instruments GS-13


Nanometrics Trillium 360GSN


Streckeisen STS-2.5

Initial considerations on primary calibration ISO16063-11 method 3

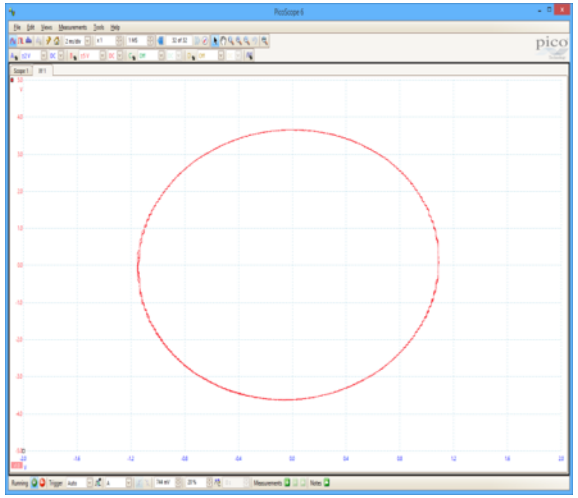
- *Higher mass introduced to laboratory setup; >15 kg*
- *Higher sensitivity introduced to electrical laboratory equipment; >2 kV/(m/s)*
- *Different mechanical setup needed*
- *Extended frequency range, 100mHz -> 10mHz*
- *Different influence on equipment used for calibration; bending, modes..*
- *Different influence from setup during calibration; curvature, modes…*
- *Several unknown parameters for uncertainty estimation*
- *Investigation needed on conditioning and output*
- *Great care taken in system performance to avoid damaging devices*
- *Great care taken to avoid damaging laboratory equipment*
- *Transport of devices*
- *Comparable measurements and setups*
- *Not much help from current primary standard, major amendment needed*
- ..
- ..

Current CMC based on Primary calibration according to ISO16063–11:1999 method 3 - magnitude and phase

- Frequency range (current CMC) 0,1Hz to 10kHz
- Based on the *extremely* stable and well-known wavelength of the HeNe laser light
- Uses the quadrature outputs of a laser interferometer to make a simple primary calibration system according to known standard
- Only one unit mounted on exciter
- Reflecting surface selected a known and correct position related mechanical transfer to seismic element
- Relative displacement between HeNe laser and transducer is measured.
- The two quadrature outputs from the interferometer and the DUT output are measured simultaneously

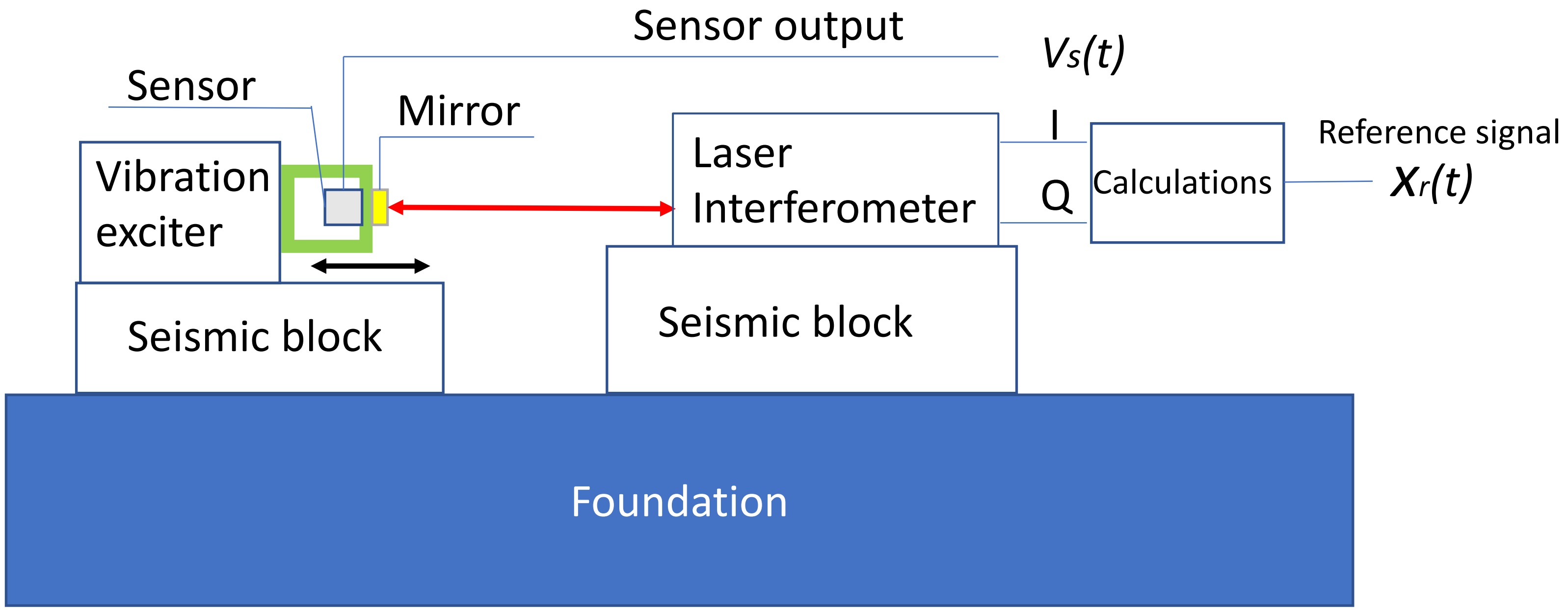
$$x(t) = \frac{\lambda}{4\pi} arctg\left(\frac{SignalB(t)}{SignalA(t)}\right)$$

Reduced formula:



SignalA and SignalB represent the two quadrature outputs (circle on X/Y plot) often named I and Q

Set-up for LF primary calibration



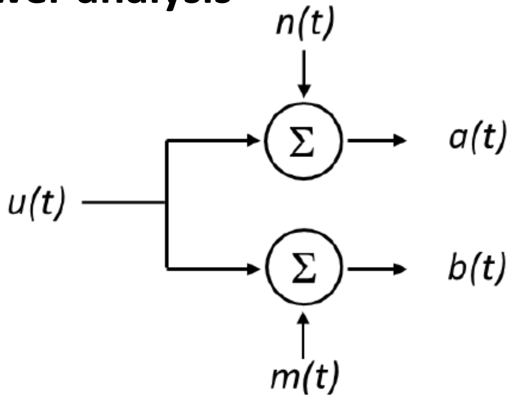
Alternative solution (or in addition to ISO16063-11/-21), dual signal analysis, Coherent Power/Coherent Argument - COPA

- Coherent power analysis already used in the field (T. B. Gabrielson's method) and within GPS, interferometers, free field calibration, underwater acoustics..
- Interesting possibilities if implemented for ULF calibration using multiple conventional transducers – laboratory and in field…?

Coherent power analysis

$$a_j(t_i) = u_j(t_i) + n_j(t_i)$$

$$b_j(t_i) = u_j(t_i) + m_j(t_i)$$



$$S_{AB}(f_k) = \frac{1}{N}\sum_{j=0}^{N-1} A_j(f_k)B_j^*(f_k)$$

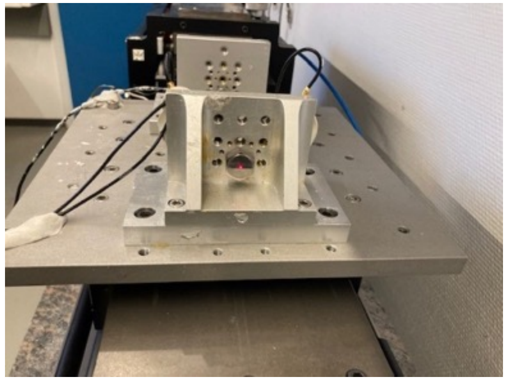
$$S_{AB}(f_k) = \frac{1}{N}\sum_{j=0}^{N-1} U_j(f_k)U_j^*(f_k) \overset{\text{def}}{=} S_{UU}(f_k)$$

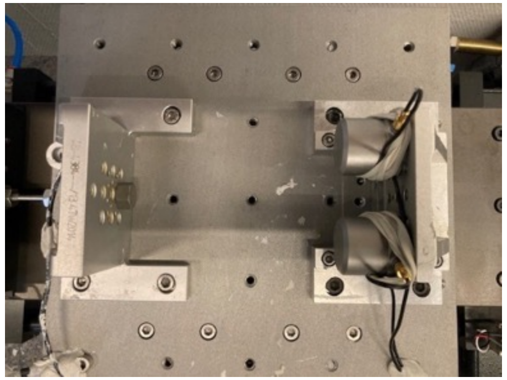
$$COP(f_k) = S_{AB}(f_k)$$

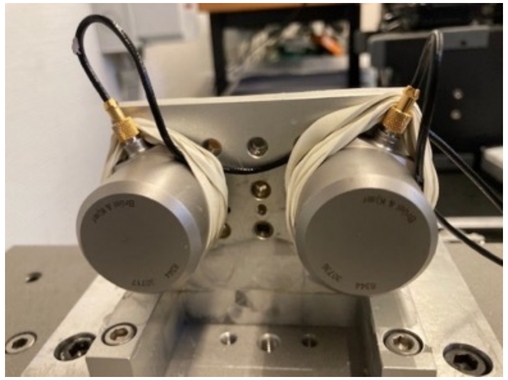
Primary & Secondary calibration according to ISO16063-11/-21 & COPA

Initial measurement setup of two (or more) units:

- Vibration level measured according to ISO16063-11 method 3 or ISO 16063-21
- Two signals exposed to same stimuli (rigid coupling) measured simultaneously
- Result of coherent power (COP) - magnitude
- Result of coherent argument (COA) – phase

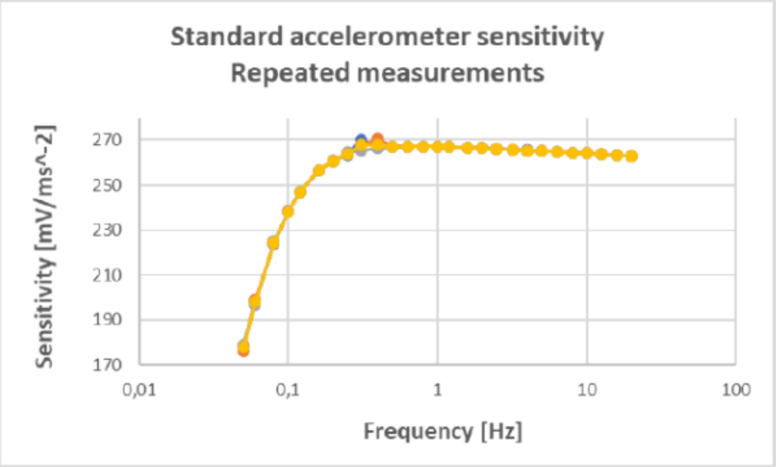


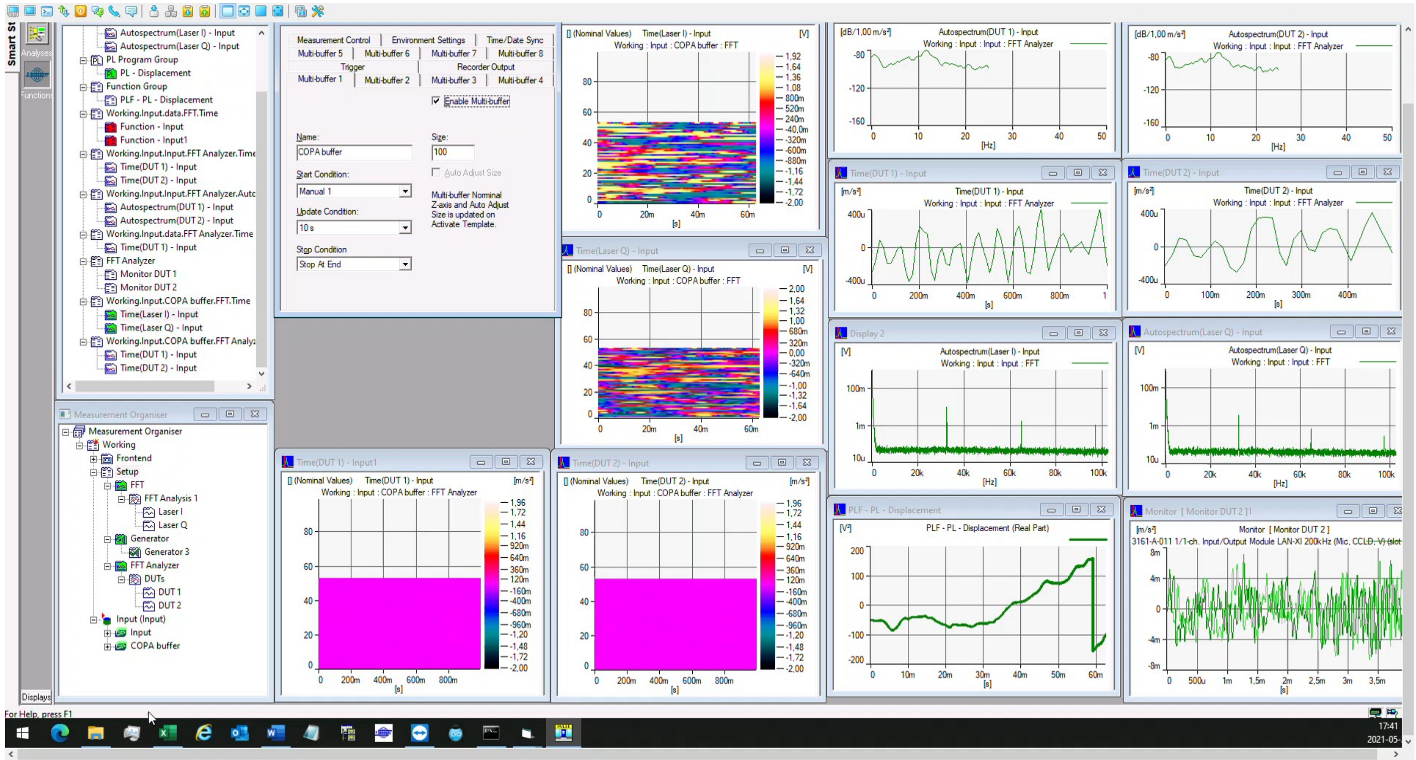




Initial measurement result and COPA method proof of concept

- Measurements of one unit according to 16063-11 Method 3 @ relatively high level
- COPA measurements @ relatively high level
- COPA measurements @ relatively low level





Comparison calibration of vibration transducers according to ISO16063–21 - magnitude and phase

Methods:

- **Direct comparison**

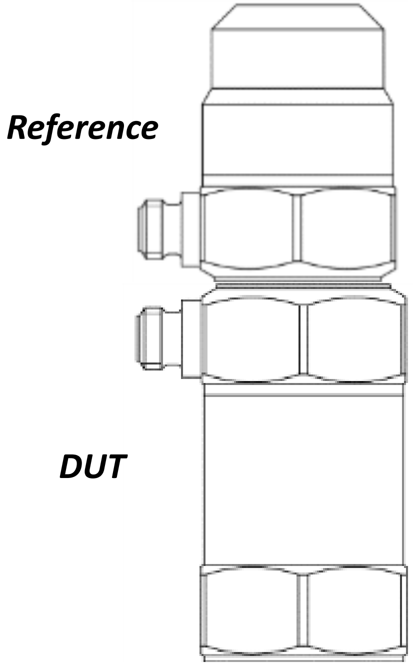
The sensitivities of two transducers are compared by using the ratio of their outputs to a known reference

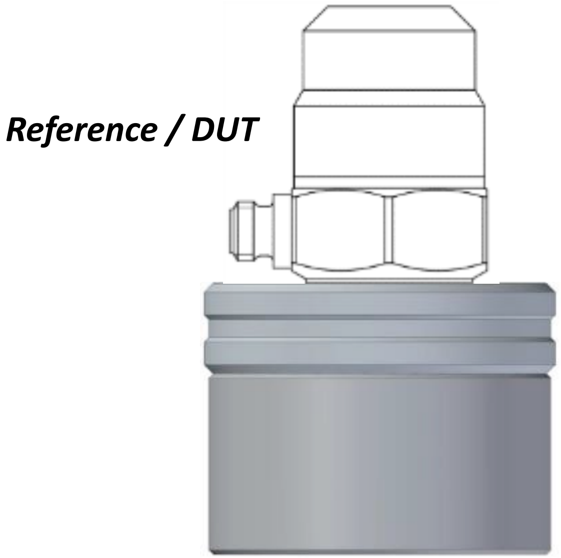
- **Back-to-back by substitution**

The transfer function between a *working standard* transducer and a *reference standard* transducer is measured and stored; this is often referred to as a reference spectrum.

When performing a calibration, the transfer function between the DUT and the working standard is measured, and the resulting frequency response is calculated using the reference spectrum and reference standard calibration data.

All things considered, how could one calibrate high mass seismometers in similar way?

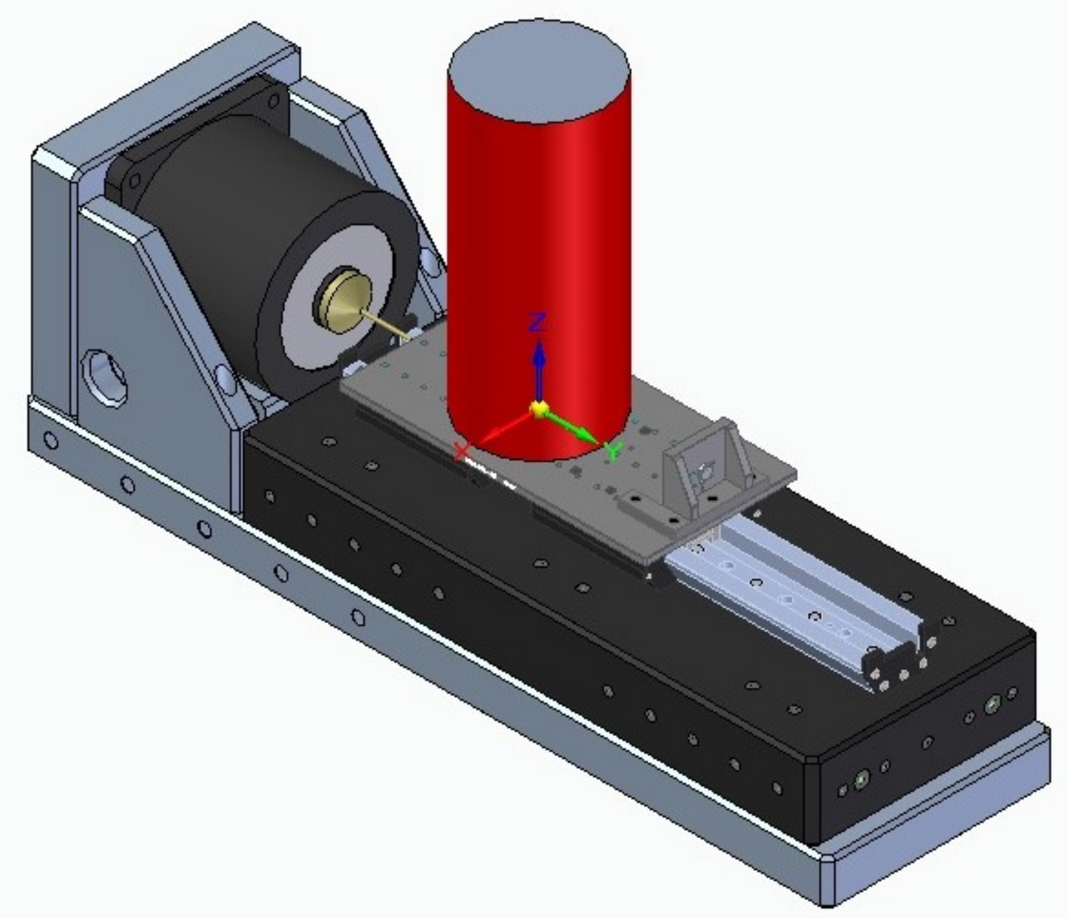




$$S_u(f) = S_r(f) * \frac{H_u(f)}{H_r(f)}$$

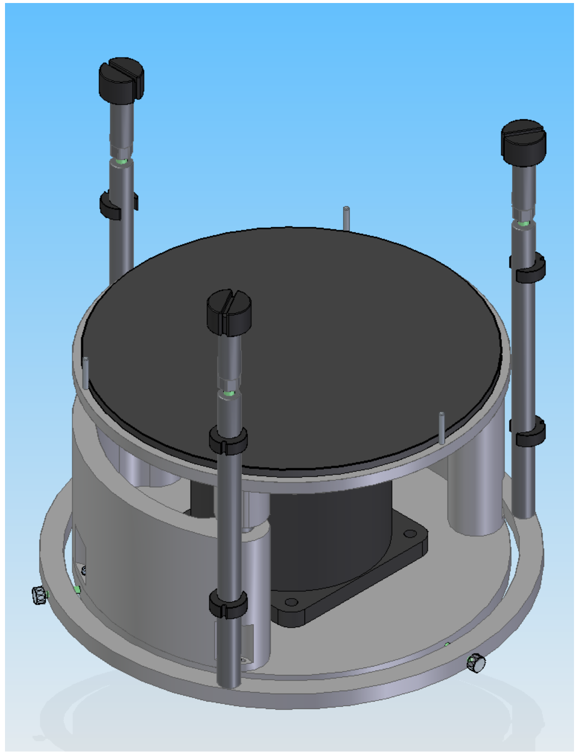
Initial considerations on secondary calibration according to ISO16063-21 - horizontal

- *Higher mass introduced to laboratory setup – **improved bearing needed***
- *Higher sensitivity introduced to electrical laboratory equipment **- conditioning***
- *Different mechanical setup needed – **one*** **bare table/slide per unit needed**
- *Extended frequency range, 100mHz -> 10mHz – **primary reference needed***
- *Influence on equipment used for calibration – **curvature..***
- *Influence from setup during calibration – **mechanical transmission to ref***
- *Some unknown parameters still for uncertainty estimation – **curvature, setup.***
- *Comparable measurements probably significantly easier – **known method***
- *Current secondary standard covers methodology –* **amendment needed**
- Limitation on highest frequency – ***higher mass = higher force***



Initial considerations on secondary calibration according to ISO16063-21 - vertical

- *Higher mass introduced to laboratory setup – **improved and stiff bearing needed to avoid different longitudinal modes***
- *Different mechanical setup needed – **counterweight measures to normalize static mass loaded exciter***
- *Extended frequency range, 100mHz -> 10mHz – **primary reference and working standard needed***
- *Influence on equipment used for calibration – **curvature, base bending, longitudinal modes minimized***
- *Influence from setup during calibration – **mechanical transmission to ref seems good***
- *Some unknown parameters still for uncertainty estimation – **curvature, exciter modes reduced..***
- *Comparable measurements probably significantly easier – **known method***
- *Current secondary standard covers methodology –* **minor or no amendment needed**
- Limitation on highest frequency – ***higher mass = higher force***



Conclusion

- The higher mass, sensitivity and properties of seismometers needs further attention to implement secondary calibration laboratories
- Different laboratory setup and equipment is needed to fully facilitate secondary calibration of seismometers
- The lower frequency limit for secondary calibration is currently based on the primary reference standard and associated uncertainty
- With counterweight measures to normalize static mass load of a vertical exciter it seems feasible to calibrate according to ISO16063-21
- The Influence from equipment used for secondary calibration related e.g., curvature, base bending, longitudinal modes.. needs further investigation
- Some unknown parameters related e.g., curvature and different exciter modes still needs clarification for uncertainty estimation

NMIs needed to provide reference standard measurements, if secondary laboratories could e.g. provide a reference per each station (calibration potentially be done remotely..?)…….

Thank you!

https://www.ptb.de/empir2020/infra-auv

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