SIM
SISTEMA INTERAMERICANO DE METROLOGÍA

SIM METROLOGY SCHOOL

Acoustics, Ultrasound and Vibration MWG9 / CCAUV

SPEAKER

TRIANTAFILLOS KOUKOULAS

National Research Council Canada (NRC)

Bogotá, Colombia | August 2024


I'M JUST GOING TO TAKE A SHORT NAP AFTER LUNCH...
...AAAAAND IT'S DARK.
quickmeme.com

Agenda

1. Metrology area domain
2. Historical evolution of measurements
3. Measurands, units and standards
4. Structure of the BIPM consultative committee
5. The SIM metrology working group perspective
6. Uncertainty budgets and traceability
7. Current technical challenges and future trends

Acoustics?...

Acoustics?...

Copyright: Classic FM

Opera?...

Copyright: CNN

Loud concerts?...

Copyright: Harvard Health

Noise and nuisance?...

Ultrasound?...

Ultrasound?...

Copyright: Wall Street Journal

Copyright: Mayo Clinic

Echo-location?...

Scans?...

Copyright: VanCity Physio

Physiotherapy?...

Vibration?...

Vibration?...

Copyright: Capitol Records

Music?...

Copyright: The New York Times

Relaxation?...

(Non-cosmic) strings?...

Copyright: Science Photo Library

Infrasound?...

Infrasound?...

Copyright: NASA JPL

Earthquakes?...

Copyright: National Geographic

Volcanoes?...

Copyright: CBC News

Tsunamis?...

Infrasound?...

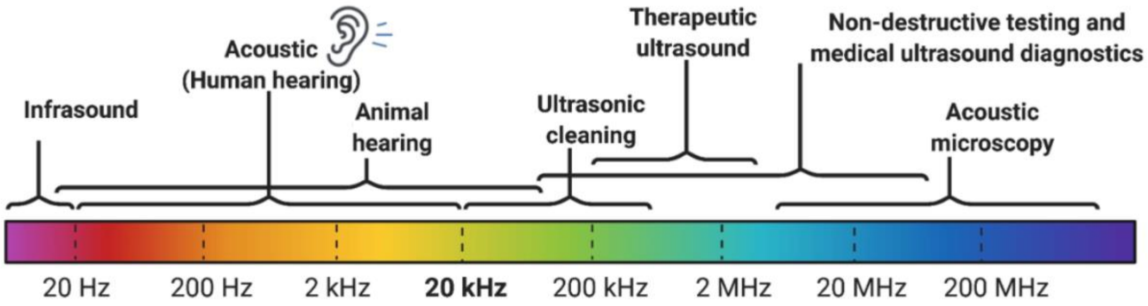
Communication?...

Meteors?...

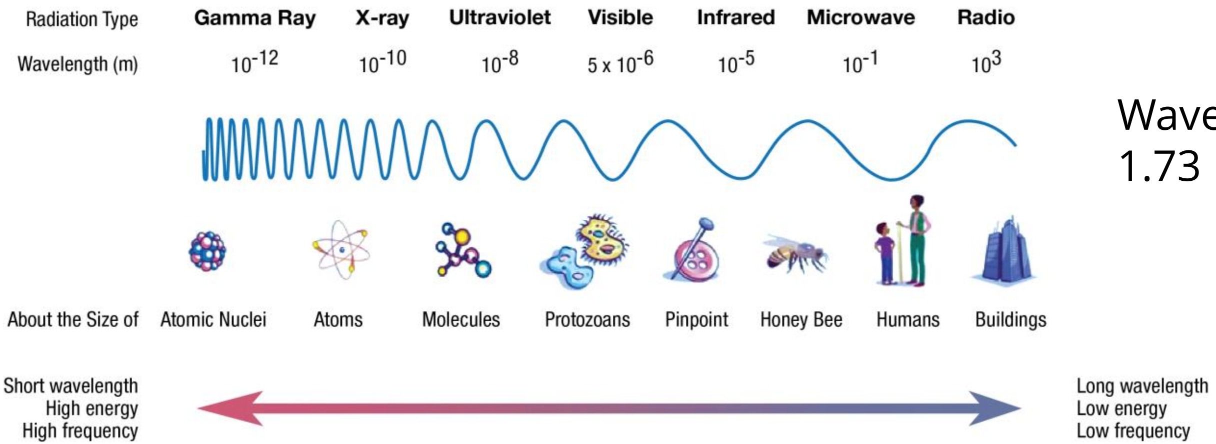
"Listening"?...

Metrology area domain

Sound and the electromagnetic spectrum



Pharmaceutics 2022, 14(10), 2231



Wavelength range:
1.73 µm to 3.5 km

Copyright: NASA

International System of Units – SI

- 7 base units, traceable to 7 defined constants
- In acoustics, ultrasound and vibration, quantities are based on derived units – combination of base units:
  - Pressure → pascal (Pa)
  - Power → watt (W)
  - Acceleration → metre per second squared (m/s^2)
  - dB → log representation of pressure: level
- Device sensitivities are expressed linearly (output divided by quantity) or logarithmically (referenced to a value)
  - V / m/s^2 → accelerometer sensitivity
  - dB reference 20 μPa → microphone sensitivity

International Committee for Weights and Measures – CIPM

Consultative Committees of the CIPM

CCAUV
CONSULTATIVE COMMITTEE FOR ACOUSTICS, ULTRASOUND AND VIBRATION

CCL
CONSULTATIVE COMMITTEE FOR LENGTH

CCPR
CONSULTATIVE COMMITTEE FOR PHOTOMETRY AND RADIOMETRY

CCRI
CONSULTATIVE COMMITTEE FOR IONIZING RADIATION

CCTF
CONSULTATIVE COMMITTEE FOR TIME AND FREQUENCY

CCEM
CONSULTATIVE COMMITTEE FOR ELECTRICITY AND MAGNETISM

CCM
CONSULTATIVE COMMITTEE FOR MASS AND RELATED QUANTITIES

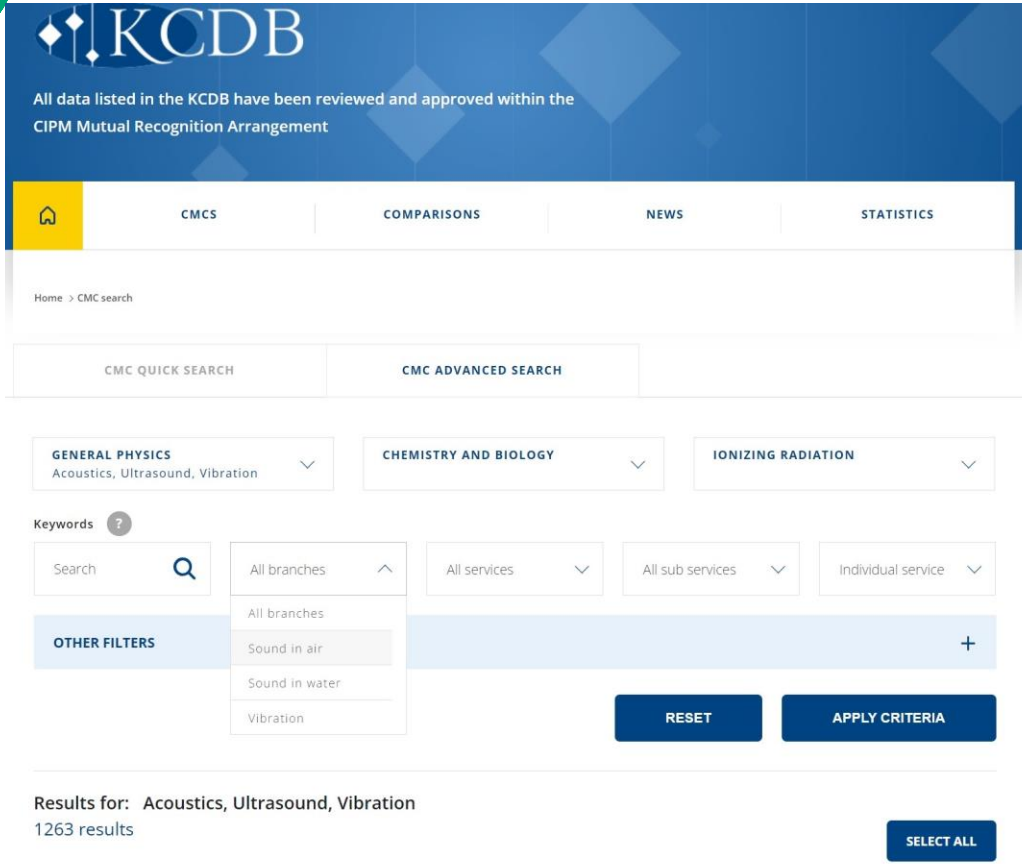
CCQM
CONSULTATIVE COMMITTEE FOR AMOUNT OF SUBSTANCE: METROLOGY IN CHEMISTRY AND BIOLOGY

CCT
CONSULTATIVE COMMITTEE FOR THERMOMETRY

CCU
CONSULTATIVE COMMITTEE FOR UNITS

https://www.bipm.org/en/committees/cc

BIPM key comparison database – KCDB



https://www.bipm.org/kcdb/

- Acoustics, Ultrasound and Vibration:
All 1263, SIM 340
- Electricity and Magnetism:
All 4582, SIM 938
- Length:
All 1680, SIM 331
- Mass and Related Quantities:
All 2965, SIM 864
- Photometry and Radiometry:
All 1558, SIM 331
- Thermometry:
All 2984, SIM 633
- Time and Frequency:
All 828, SIM 188
- Chemistry and Biology:
All 6471, SIM 2380
- Ionizing Radiation:
All 3668, SIM 1127

Historical evolution of measurements

Light and sound

Bronte and Astrape

Copyright: New Scientist

Copyright: Phys.org

- Known even at prehistoric times: light travels faster than sound
- You can see the light source; but where is the sound source?

Ancient Greece and Roman Empire

Epidaurus

Copyright: World History Encyclopedia

Colosseum

Copyright: National Geographic

- Theatre: Place for viewing
- Amphitheatre: Around place for viewing

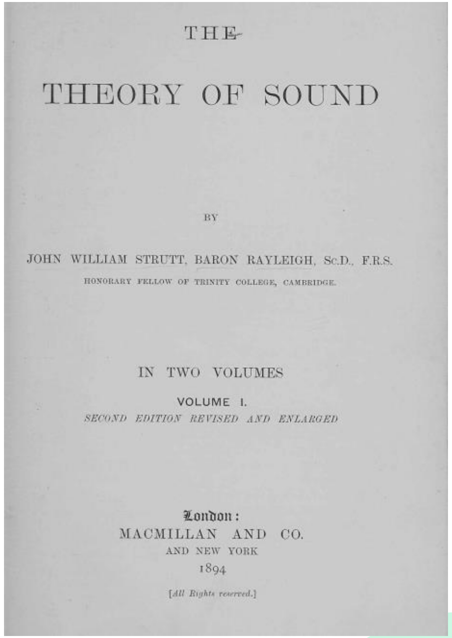
Sound and acoustic(k)s

- Sound has been a puzzle for centuries; even up to the 17th century, natural philosophers struggled devising ways of measuring its properties

- An anonymous author in the Philosophical Transactions of The Royal Society wrote:

"Hearing may be divided into direct, refracted, and reflexted, which are yet nameless unless we call them acousticks, diacousticks, and catacousticks."

- Calculus changed nearly everything: elasticities, densities, strings, propagation...all outlined in The Theory of Sound by Lord Rayleigh.



THE

THEORY OF SOUND

BY

JOHN WILLIAM STRUTT, BARON RAYLEIGH, Sc.D., F.R.S.

HONORARY FELLOW OF TRINITY COLLEGE, CAMBRIDGE.

IN TWO VOLUMES

VOLUME I.

SECOND EDITION REVISED AND ENLARGED

London:

MACMILLAN AND CO.

AND NEW YORK

1894

Speed of sound

- Pierre Gassendi and Marin Mersènne used a pendulum to measure the time between the flash and sound arrival from exploding gunpowder: **448 m/s**
- Gassendi also reached the conclusion that regardless of the source (high-pitched crack from musket or cannon ball), the time difference was the same: different pitches travel at the same speed

- Netwon used calculus to predict the speed of sound: **298 m/s**
- John Flamsteed and Edmond Halley measured the speed of sound and found that their value was 20% higher than Netwon's theoretical value.

- Who was right and who was wrong?
- Netwon's theory was without any flaw; Flamsteed and Halley accounted for everything in their measurements. This could only mean that:
    - Newton won on that occasion. But the challenge was far from over.

A history of speed measurements

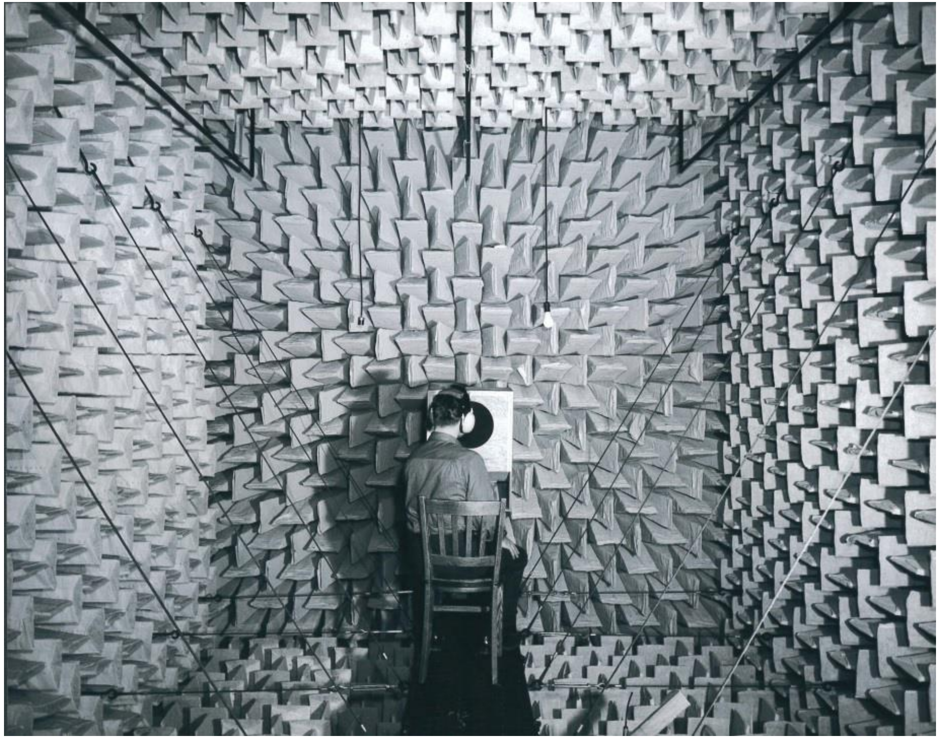
MEASUREMENTS OF THE SPEED OF SOUND PRIOR TO 1800

Publication Date	Experimenter	Speed (English feet per second)	Publication Date	Experimenter	Speed (English feet per second)
1636	Mersenne	1036 [3]	1708	Flamsteed, Halley	1142 [11]
1636	Mersenne	1470 [4]	1708	Derham	1142 [11]
1644	Roberval	600 [5]	1738	Cassini de Thury	1107 [12]
1666	Accademia del Cimento	1148 [6]	1739	Cassini de Thury	1096 [13]
			1744	Blanconi	1043 [14]
1677	Cassini	1152 [7]	1745	La Condamine	1112 [15]
1685	Boyle	1200 [8]	1751	La Condamine	1175 [16]
1687	Newton	920-1085 [9]	1778	Kästner, Mayer	1106 [17]
1698	Walker	1305 [10]	1791	Müller	1109 [18]

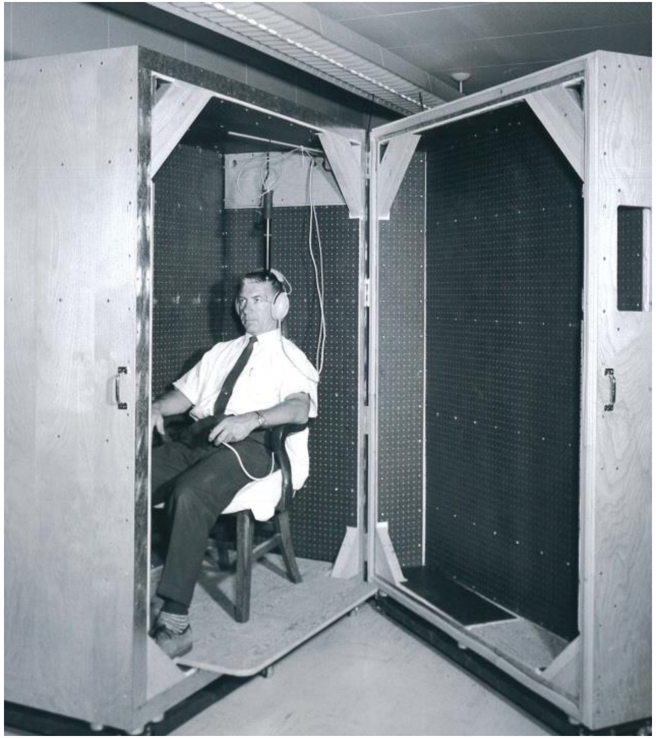
Laplace and The Speed of Sound, Bernard S. Fynn, 1964

- Values in table vary from 182.88 m/s to 448.06 m/s (1 foot = 0.3048 metres)
- Newton's value (280 m/s) assumed isothermal process
- Laplace based on adiabatic process, introduced correction to Newton's formula: 332 m/s (1089 feet/s)
- In 1738 the Academy of Sciences in Paris measured and published the speed of sound within 0.5% of the current accepted value

Acoustics, ultrasound and vibration

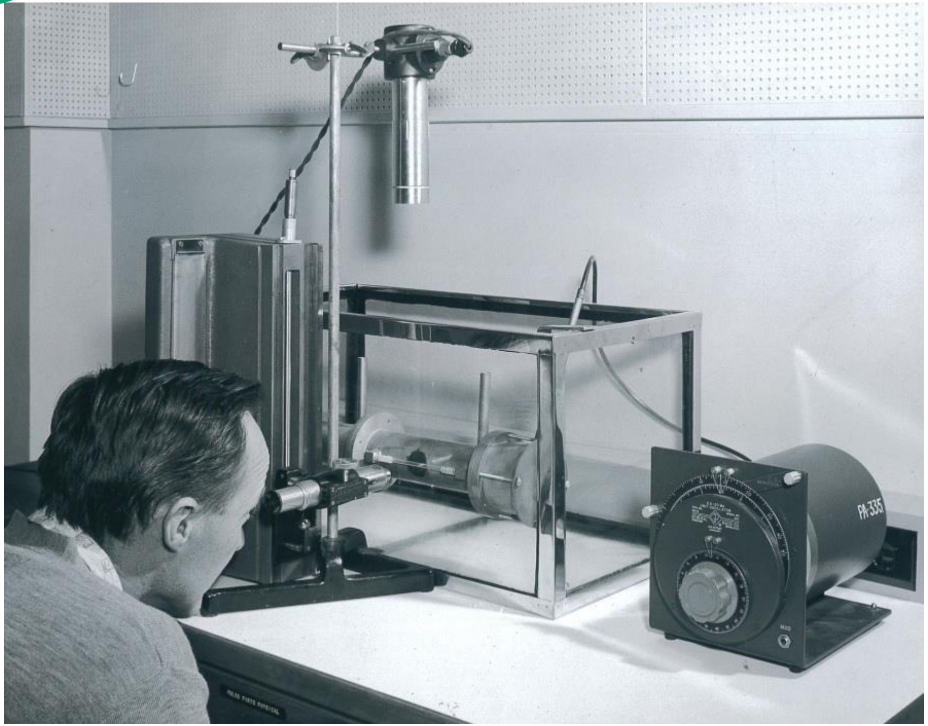


Fully anechoic chamber

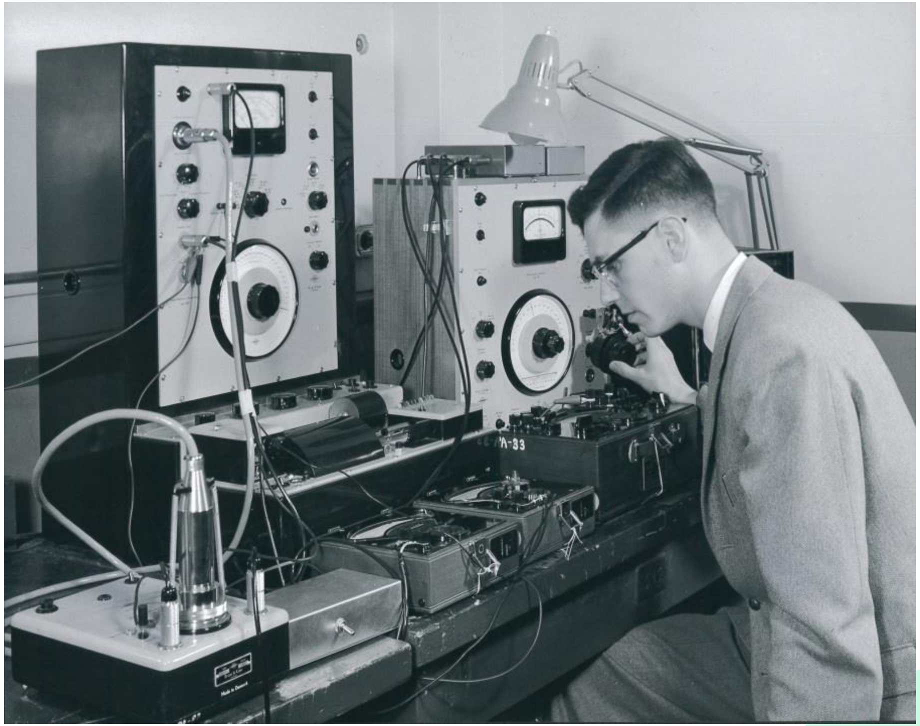


Audiometric testing

Acoustics, ultrasound and vibration



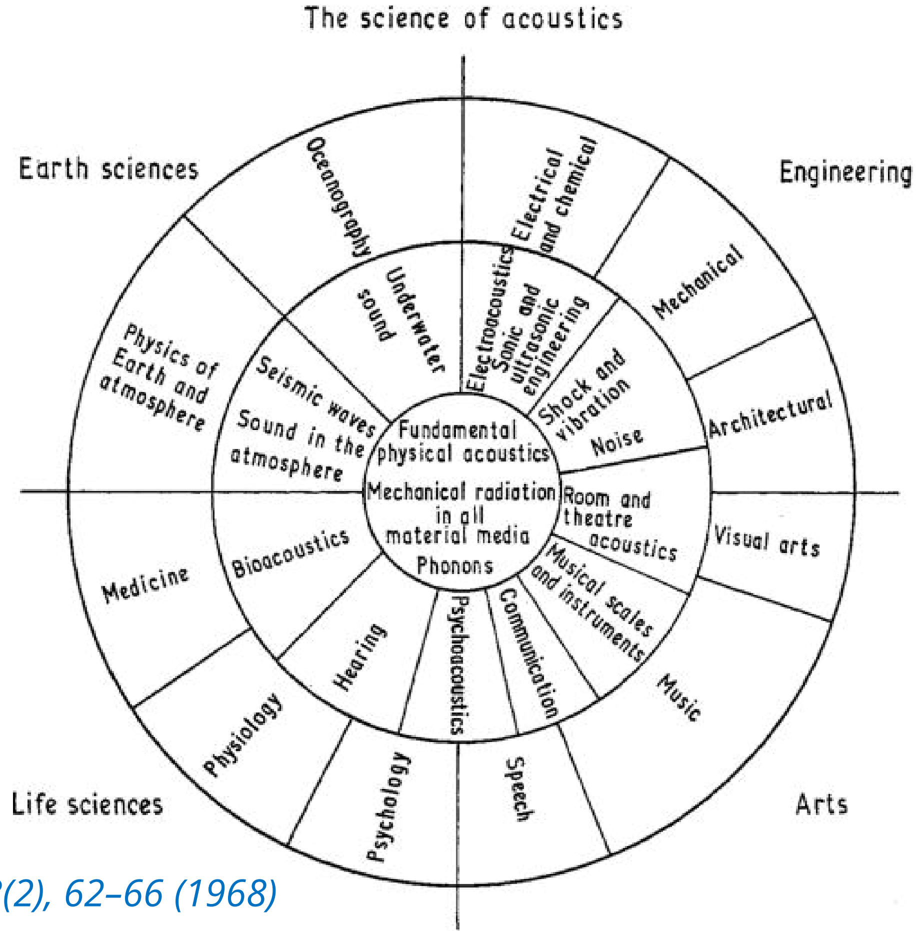
Visualizing and measuring flows



Microphone calibration

Acoustics, ultrasound and vibration

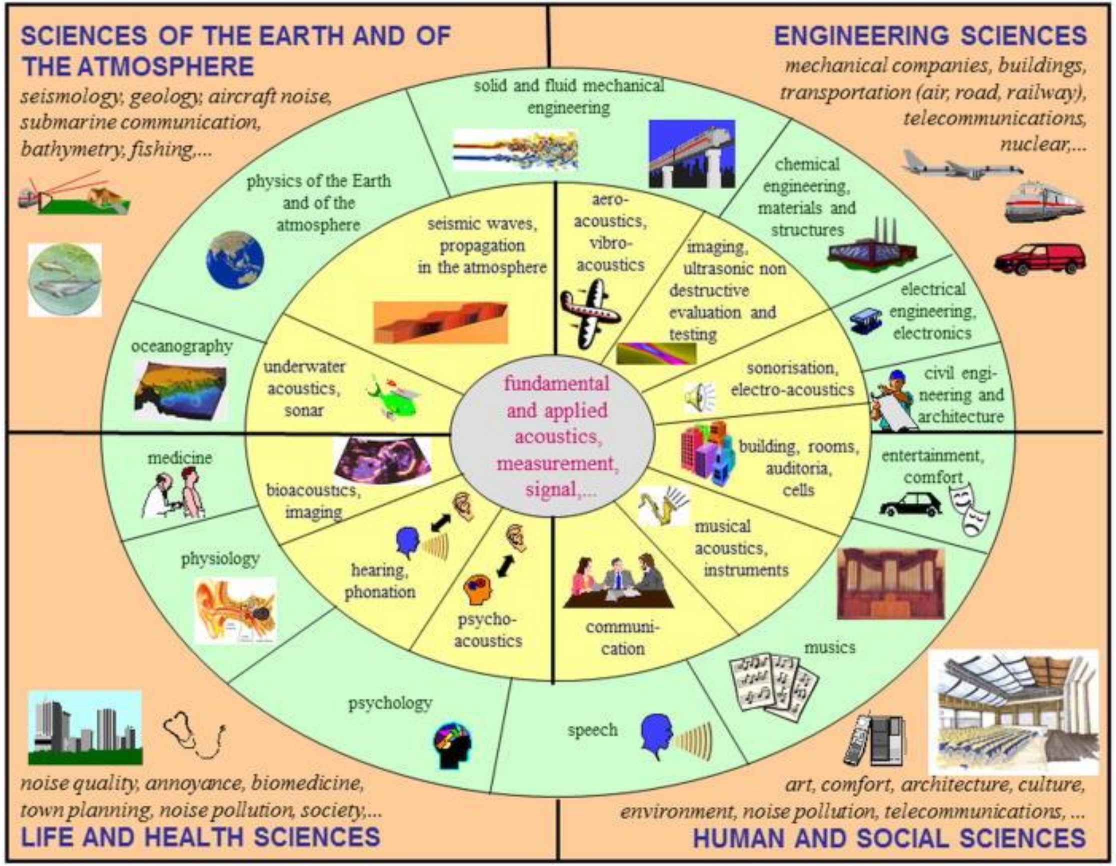
Lindsay's
Wheel of Acoustics



Phys. Educ. 3(2), 62–66 (1968)

Acoustics, ultrasound and vibration

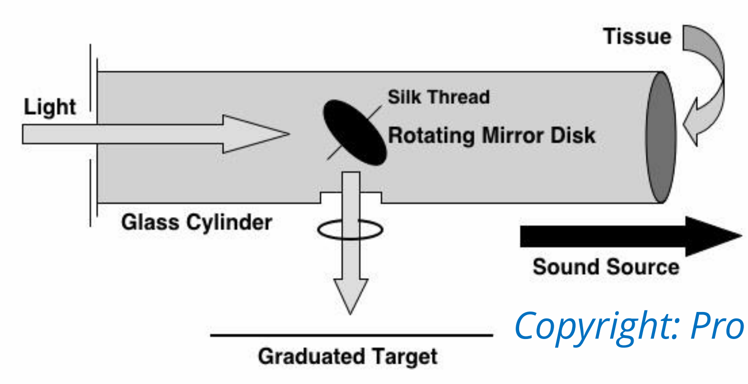
Lindsay's
Wheel of Acoustics
(modernized)



J. Acoust. Soc. Am. 151(2), 1093–1103 (2022)

Evolution of measurement devices

- Rayleigh disk

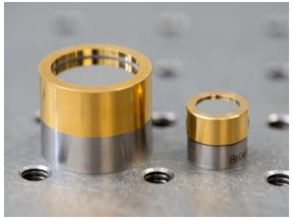


Copyright: Pro Audio Encyclopedia

$$\tau = \frac{4}{3} \cdot \rho \cdot r^3 \cdot u^2$$

- Microphones: convert incident sound pressure to electrical signals
- dynamic (galvanometer), condenser (capacitive) and contact (piezoelectric)

Copyright: Samson



Copyright: National Research Council Canada

Copyright: Phase57

Evolution of measurement devices

- Accelerometers: measure physical acceleration relative to freefall
- Piezoelectric, capacitive or piezoresistive

Copyright: Bruel & Kjaer

Copyright: Honeywell

Copyright: Endevco

- Hydrophones: convert incident pressure to electrical signal
- Piezoelectric type

Copyright: Teledyne

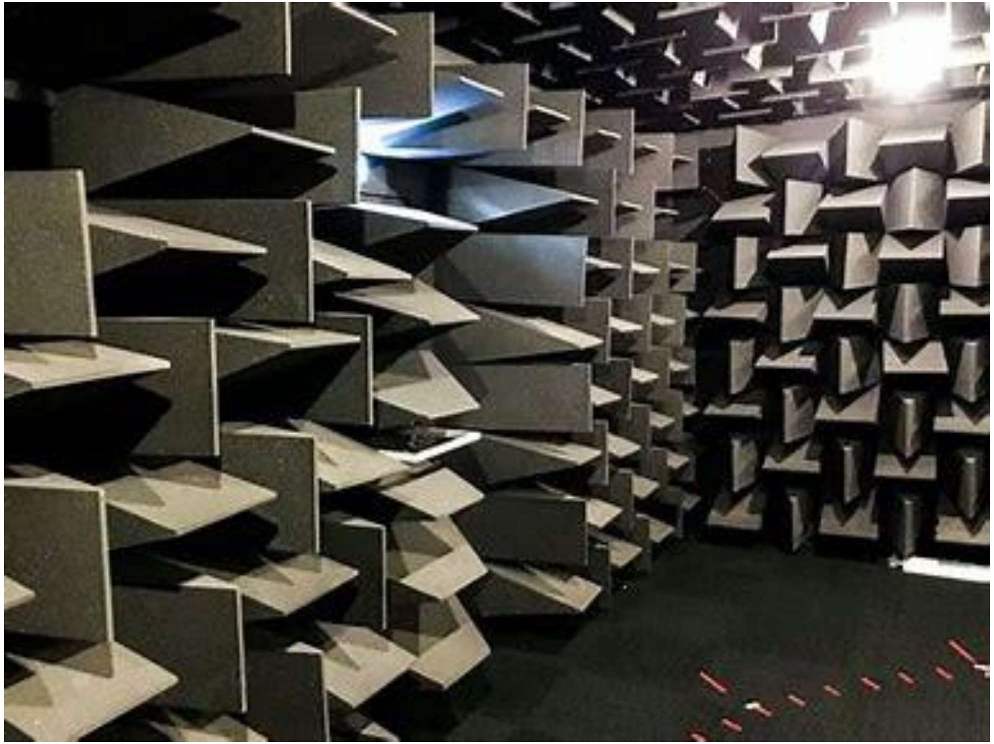
Copyright: S&V Samford Instruments

Copyright: Onda Corporation

Measurands, units and standards

Acoustical chambers

Hemi (left) and fully (right) anechoic chambers



Copyright: University of Derby

Copyright: National Research Council Canada

Acoustical chambers

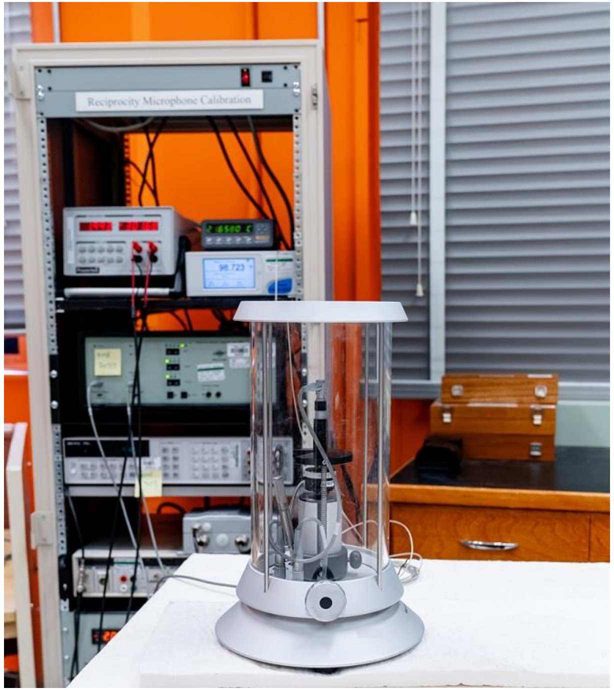
Reverberation chamber (left) and listening room (right)

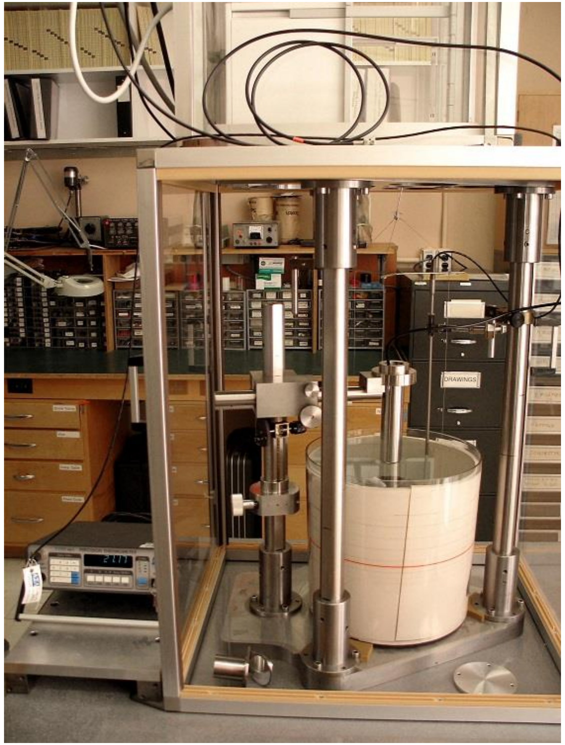
Hak et al., Proceedings of 20th International Congress on Acoustics, ICA 2010

Copyright: Bose

Ultrasound and vibration labs

Acoustics lab (left), ultrasound lab (centre) and vibration lab (right)





Acoustics

Quantity

- Pressure sensitivity
- Free-field sensitivity
- Sound pressure level
- System response level
- Electrostatic actuator response

Units

- dB (reference: 20 μPa)
- dB (reference: 1 V/Pa)
- dB (reference: sensitivity at 250 Hz)
- Degrees °

Copyright: Bruel & Kjaer

Devices under test

- Laboratory standard microphone
- Working standard microphone
- Sound level meter
- Sound calibrator (single or multi frequency)
- Audiometer, artificial ear
- Combined frequency range: 1 Hz – 200 kHz

Methods

- Pressure field reciprocity
- Free field reciprocity
- Comparison

Copyright: National Research Council Canada

Standards - acoustics

- IEC 61094-1:2000 – Measurement microphones – Part 1: Specifications for laboratory standard microphones
- IEC 61094-4:1995 – Measurement microphones – Part 4: Specifications for working standard microphones

- IEC 61094-2:2009+AMD1:2022 CSV – Electroacoustics – Measurement microphones – Part 2: Primary method for pressure calibration of laboratory standard microphones by the reciprocity technique
- IEC 61094-3:2016 – Electroacoustics – Measurement microphones – Part 3: Primary method for free-field calibration of laboratory standard microphones by the reciprocity technique
- IEC 61094-5:2016 – Electroacoustics – Measurement microphones – Part 5: Methods for pressure calibration of working standard microphones by comparison
- IEC 61094-8:2012 – Measurement microphones – Part 8: Methods for determining the free-field sensitivity of working standard microphones by comparison

- IEC TS 61094-7:2006 – Measurement microphones – Part 7: Values for the difference between free-field and pressure sensitivity levels of laboratory standard microphones

Ultrasound and underwater acoustics

Quantity

- Ultrasonic power

Units

- mW
- W

Device under test

- Utrasonic source transducer: 0.5 MHz – 40 MHz

Methods

- Radiation force balance

Copyright: National Research Council Canada

Quantity

- Free-field sensitivity

Units

- μV / Pa
- mV / Pa
- V / Pa

Device under test

- Hydrophone: 1 kHz – 20 MHz

Methods

- Three – transducer spherical wave reciprocity
- Planar scanning technique
- Comparison method
- Laser interferometry

Copyright: National Institute of Metrology China

Standards – ultrasound

- IEC 62127-3:2022 – Ultrasonics – Hydrophones – Part 3: Properties of hydrophones for ultrasonic fields
- IEC TR 61088:1991 – Characteristics and measurements of ultrasonic piezoceramic transducers
- IEC 61828:2020 – Ultrasonics – Transducers – Definitions and measurement methods regarding focusing for the transmitted fields

- IEC 62127-1:2022 – Ultrasonics – Hydrophones - Part 1: Measurement and characterization of medical ultrasonic fields
- IEC 62127-2:2007+AMD1:2013+AMD2:2017 CSV – Ultrasonics – Hydrophones – Part 2: Calibration for ultrasonic fields up to 40 MHz
- IEC 61161:2013 – Ultrasonics – Power measurement – Radiation force balances and performance requirements

Ultrasound and underwater acoustics

Quantity

- Ultrasonic power

Units

- mW
- W

Device under test

- Utrasonic source transducer: 0.5 MHz – 40 MHz

Methods

- Radiation force balance

Copyright: National Research Council Canada

Quantity

- Free-field sensitivity

Units

- µV / Pa
- mV / Pa
- V / Pa

Device under test

- Hydrophone: 1 kHz – 20 MHz

Methods

- Three – transducer spherical wave reciprocity
- Planar scanning technique
- Comparison method
- Laser interferometry

Copyright: National Institute of Metrology China

Standards – underwater

- ISO 18405:2017 – Underwater acoustics – Terminology
- IEC 60500:2017 – Underwater acoustics – Hydrophones – Properties of hydrophones in the frequency range 1 Hz to 500 kHz

- IEC 60565-1:2020 – Underwater acoustics – Hydrophones – Calibration of hydrophones – Part 1: Procedures for free-field calibration of hydrophones
- IEC 60565-2:2019 – Underwater acoustics - Hydrophones - Calibration of hydrophones - Part 2: Procedures for low frequency pressure calibration

Vibration

Quantity

- Charge sensitivity
- Voltage sensitivity
- Acceleration

Units

- pC / m/s^2 and C / m/s^2
- mV / m/s^2 and V / m/s^2
- m/s^2
- Degrees °

Devices under test

- Accelerometer
- Calibrator
- Acceleration measuring chain
- Combined frequency range: 0.5 Hz – 20 kHz

Methods

- Laser interferometry (fringe counting, fringe disappearance and sine approximation)
- Shock excitation
- Comparison

Standards – vibration

- ISO 16063-1:1998 – Methods for the calibration of vibration and shock transducers – Part 1: Basic concepts
- ISO 16063-11:1999 – Methods for the calibration of vibration and shock transducers – Part 11: Primary vibration calibration by laser interferometry
- ISO 16063-13:2001 – Methods for the calibration of vibration and shock transducers – Part 13: Primary shock calibration using laser interferometry
- ISO 16063-21:2003 – Methods for the calibration of vibration and shock transducers – Part 21: Vibration calibration by comparison to a reference transducer
- ISO 16063-22:2005 – Methods for the calibration of vibration and shock transducers – Part 22: Shock calibration by comparison to a reference transducer
- ISO 16063-41:2011 – Methods for the calibration of vibration and shock transducers – Part 41: Calibration of laser vibrometers

Structure of the BIPM consultative committee

Consultative Committee for Acoustics, Ultrasound and Vibration

Board

- President: Dr. Gustavo P. Ripper – INMETRO (Brazil)
- Executive secretary: Dr. Romain Coulon – BIPM
- Ex officio member: Dr Martin .J.T. Milton – BIPM, Director
- Website: https://www.bipm.org/en/committees/cc/ccauv

Liaisons

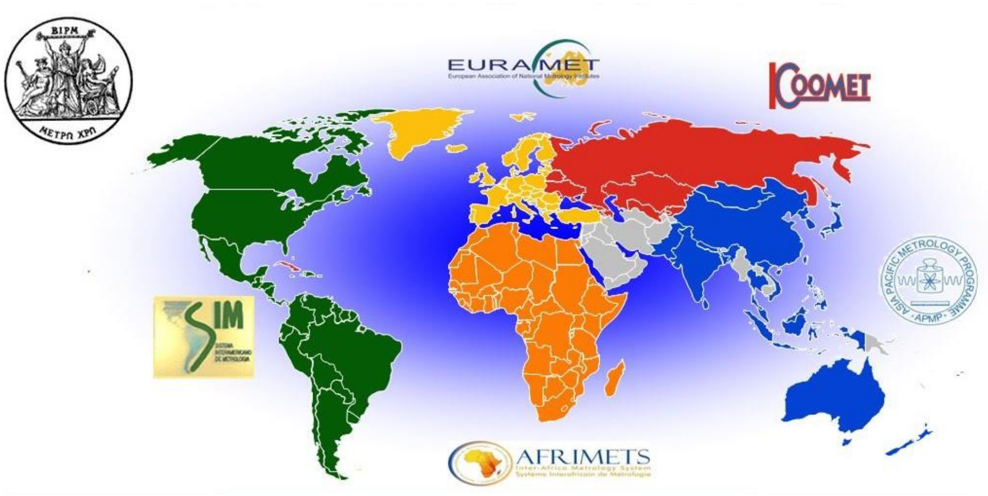
- Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO)
- International Electrotechnical Commission (IEC)
- International Organization for Standardization (ISO)

CCAUV: mission and regional metrology organizations

Mission

- In addition to its formal work in the organization of key comparisons in acoustics, ultrasound and vibration measurements, the CCAUV acts as the focus for this diverse community, seeking to develop common aims and increased collaboration between national metrology institutes and appropriate designated organizations in Member States of the BIPM.

- RMOs:



CCAUV: structure

Members: 18

CENAM (Mexico)
DFM (Denmark)
GUM (Poland)
INMETRO (Brazil)
INRIM (Italy)
KRISS (Republic of Korea)
LNE (France)
METAS (Switzerland)
NIM (China)
NIST (USA)
NMIA (Australia)
NMIJ/AIST (Japan)
NMISA (South Africa)
NPL (UK)
NRC (Canada)
PTB (Germany)
UME (Turkey)
VNIIM (Russia)

Observers: 14

BEV (Austria)
BIM (Bulgaria)
CEM (Spain)
CMI (Czech Republic)
CMS/ITRI (Taiwan)
CSIR/NPLI (India)
INM (Romania)
IPQ (Portugal)
KEBS (Kenya)
NIS (Egypt)
NMC A*STAR (Singapore)
SE "NDI Systema“ (Ukraine)
SMU (Slovakia)
VNIIFTRI (Russia)

CCAUV Working Group for Key Comparisons

CCAUV-KCWG
Members: 11

CENAM (Mexico)
DFM (Denmark)
GUM (Poland)
LNE (France)
NIST (USA)
NIM (China)
NMIA (Australia)
NMIJ/AIST (Japan)
NMISA (South Africa)
NPL (UK)
PTB (Germany)

Terms of reference

- Identify the need and feasibility of CCAUV key and supplementary comparisons
- Review and approve technical protocols for comparisons that are intended to be used for the support of CMC claims
- Give advice on the analysis of KCs, calculation of KCRVs and linking procedures;
- Review and comment Draft B reports prior to their submission to the CCAUV for approval
- Contribute to the SPWG on matters of key comparisons
- Give advice in case of disagreement during a comparison

CCAUV Working Group
for Regional Metrology Organizations Coordination

CCAUV-RMOWG

Members: 6

KRISS (Republic of Korea)
NIST (USA)
NMISA (South Africa)
SASO-NMCC (Saudi Arabia)
UME (Turkey)
VNIIFTRI (Russia)

Terms of reference

- Keep RMO representatives abreast of relevant CCAUV developments
- Strengthen the cooperation between the RMOs
- Resolve inter-RMO CMC review obstacles
- Review the guidelines for CMC table entries
- Provide guidance on the range of CMCs supported by particular KCs and SCs
- Review the list of relevant service categories, in line with the stakeholder requirements
- Harmonize intra-RMO CMC review processes
- Maintain a technical assessor database

CCAUV Working Group on Strategic Planning

CCAUV-SPWG
Members: 10

CENAM (Mexico)
INMETRO (Brazil)
KRISS (Republic of Korea)
LNE (France)
NIM (China)
NIST (USA)
NMIJ/AIST (Japan)
NMISA (South Africa)
NRC (Canada)
PTB (Germany)

Terms of reference

- View on metrological requirements, the way these are driven by needs and the key technologies providing solutions to the challenges;
- Provide input into the CC Strategy Document as the basis for the strategic plan proposed to the CGPM
- Provide expert input and advice to the CC Strategy Document identifying future pilot studies and KCs
- Advise the CCAUV on optimal operational structure
- Share information on national priorities for emerging metrology helping NMIs to formulate improved metrological programmes;
- Identify areas suitable for collaboration
- Respond to developments within other CCs, including the future of the SI

CCAUV Task Group on Digitalization

CCAUV-TG-DIG
Members: 6

CENAM (Mexico)
DFM (Denmark)
INMETRO (Brazil)
NIM (China)
NMISA (South Africa)
NPL (UK)

Terms of reference

- To support the development of the SI Reference Point and BIPM digital services in the field of AUV
- To support the activities of the CIPM Forum on Metrology and Digitalization in AUV

Key and supplementary comparisons

Structure

- Organization: CCAUV or Regional: SIM, APMP, etc.
- Sub-field: acoustics (A), ultrasound (U), vibration (V), underwater (W)
- Type: key or supplementary
- Identifier number: 1, 2, 1.1, etc.

Examples

- SIM.AUV.A-S2: calibration of sound pressure level
- APMP.AUV.U-K3: ultrasonic output power
- CCAUV.V-K2: vibration acceleration
- COOMET.AUV.W-S1: free-field hydrophone calibrations

Consultative Committee for Acoustics, Ultrasound and Vibration

The SIM metrology working group perspective

SIM Metrology Working Group 9 – acoustics, ultrasound and vibration

Board

- Chair: Dr. Akobuije Chijioke – NIST (USA)
- Vice-chair: Dr. Andres Esteban Perez Matzumoto – CENAM (Mexico)
- Website: https://sim-metrologia.org/about-us/structure/technical-committee/acoustics-ultrasound-and-vibration/

SIM MWG 9

Members: 8

CENAM (Mexico)
INACAL (Peru)
INM (Colombia)
INMETRO (Brazil)
INTI (Argentina)
LACOMET (Costa Rica)
NIST (USA)
NRC (Canada)

SIM MWG 9 – mission and objectives

- Supports SIM and its member NMIs/DIs in meeting the obligations under the CIPM MRA in the field of acoustics, ultrasound, and vibration measurements
- Realizes the derived SI units and conducts research in calibration and measurement techniques as a foundation for metrology, which supports a wide range of customer needs
- Organizes regional KCs, SCs and pilot studies links these SIM activities to other RMOs and the CCAUV
- Facilitates cooperation in preparing, publishing, and maintaining calibration and measurement capability claims (CMCs) of member economies and of American laboratories new to international metrology
- Facilitates technical cooperation among its members and guests through meetings, workshops, and training opportunities at various NMIs/DIs
- Seeks harmonization among its members through sustainable networking and cooperation with other communities to promote and share advanced technology

SIM Metrology Working Group 9 – Acoustics, Ultrasound and Vibration

Uncertainty budgets and traceability

Uncertainty budget example: acoustics

Input quantity	Magn.		Source (distribution)
Electrical transfer impedance			
Reference impedance: capacitance at 1 kHz	0.05	pF	Calibrated (*t*, 95 %, *k* = 2)
Reference impedance: leakage resistance	0.1	GΩ	Estimated (Gauss., std uncertainty)
Reference impedance: frequency dependence	23	µF/F	Estimated (Gauss., std uncertainty) [A18, p63]
Voltage ratio: voltmeter	120	µV/V	Calculated (*t*, std uncertainty) [A14, p192-193]
Voltage ratio: phasemeter	0.1	°	Manufacturer (rect., semi-range) [A10, p185]
Voltage ratio: magnitude repeatability	150	µV/V	Measured (Gauss., std dev.) [A5, p167; A11, p156]
Voltage ratio: phase repeatability	0.02	°	Measured (Gauss., std deviation) [A10, p184]
Noise: cross-talk	0.0025	dB	Estimated (Gauss., std uncertainty)
Noise: inherent noise	0.0001	dB	Estimated (Gauss., std uncertainty)
Noise: distortion and harmonics	0.0001	dB	Estimated (Gauss., std uncertainty)
Frequency of signal: tolerance	25	µHz/Hz	Measured (rect., semi-range)
Ground shield: transmitter	0.0015	dB	Estimated (rect., semi-range)
Ground shield: receiver	0.0009	dB	Estimated (rect., semi-range)
Acoustic transfer impedance			
Static pressure: pressure indicator	5	Pa	Calibrated (*t*, 95 %, *k* = 2)
Static pressure: spatial variation	8	Pa	Measured (rect., semi-range) [A9, p13]
Static pressure: temporal variation	10	Pa	Measured (Gauss., 95 %, *k* = 2) [A9, p13]
Temperature: calibration	0.006	°C	Calibrated (*t*, 95 %, *k* = 2)
Temperature: indication error	0.002	°C	Measured (rect., semi-range) [A14, p190]
Temperature: spatial variation	0.9	°C	Estimated (*t*, 95 %, *k* =2) [A9, p109]
Temperature: temporal variation	0.03	°C	Measured (Gauss., 95 %, *k* = 2) [A9, p27]
Relative humidity: calibration	2.0	%	Calibrated (*t*, 95 %, *k* =2) [A18, p39]
Relative humidity: indication error	2	%	Measured (rect., semi-range) [A14, p191]
Relative humidity: spatial variation	0.1	%	Measured (Gauss., std deviation) [A9, p20]
Relative humidity: temporal variation	0.5	%	Measured (rect., semi-range) [A9, p18]
Couplers: length	1.5	µm	Calibrated (*t*, 95 %, *k* =2.1)
Couplers: diameter	1.0	µm	Calibrated (*t*, 95 %, *k* =2.1)
Couplers: leakage	$6.3 \cdot 10^{-4}$	dB	Estimated (Gauss., std uncertainty) [A9, p177]
Pressure radial non-uniformity	0	dB	Estimated (rect., semi-range)
Polarizing voltage: tolerance	0.02	V	NRC tolerance (rect., semi-range)
Polarizing voltage: electrometer	400	µV/V	Calibration (*t*, 95 %, *k* =2)

Reciprocity –
LS1P microphones

Uncertainty budget example: acoustics

Input quantity	Magn.		Source (distribution)
Polarizing voltage: effect at 250 Hz	0.01	dB/V	Manufacturer (rect., semi-range)
Polarizing voltage: frequency dependence of effect	0	dB/V	Manufacturer (rect., semi-range)
Front cavity: depth	10	µm	Calibration (*t*, 95 %, *k* =2)
Front cavity: diameter	30	µm	IEC 61094-1 tolerance limits (rect., semi-range)
Front volume	2.5	mm³	Estimated from results (Gauss., std. uncertainty) [A10, p79]
Diaphragm equivalent volume	15	mm³	Estimated (Gauss., 95 %, *k* = 2)
Diaphragm resonance frequency	0.52	kHz	Rasmussen, 2001 (Gauss., 95 %, *k* = 2)
Loss factor of microphone	0.05	1	Estimated (Gauss., 95 %, *k* = 2)
Diaphragm: effective diameter	0.1	mm	Estimated (Gauss., std uncertainty)
Static pressure coeff.: unc.	0.0005	dB/kPa	Rasmussen, 2001 (Gauss., 95 %, *k* = 2)
Static pressure coeff.: repeat.	5	%	Rasmussen, 2001 (Gauss., rel. std uncertainty)
Temperature coeff.: unc.	0.0016	dB/°C	Rasmussen, 2001 (Gauss., 95 %, *k* = 2)
Temperature coeff.: repeat.	5	%	Rasmussen, 2001 (Gauss., rel. std uncertainty)
Influence of relative humidity	$25 \cdot 10^{-6}$	dB/%	Manufacturer (Gauss., std uncertainty)
Speed of sound: equation	$3 \cdot 10^{-4}$	1	IEC 61094-2 (Gauss., rel. std uncertainty)
Density: equation	$2.2 \cdot 10^{-5}$	1	IEC 61094-2 (Gauss., rel. std uncertainty)
Ratio of specific heats: equation	$3.2 \cdot 10^{-4}$	1	IEC 61094-2 (Gauss., rel. std uncertainty)
Effect of excess volume	0	dB	Estimated (rect., semi-range)
Effect of viscous losses	0	dB	Estimated (Gauss., std uncertainty)
Radial wave motion correction	0	dB	Estimated (Gauss., std uncertainty)
Experiment			
Calculation error	0	dB	Validation (rect., semi-range) [A8, p83]
Repeatability: magnitude	0.004	dB	Measured (Gauss., standard dev.) [A10, p109-110]
Repeatability: phase	0.01	°	Measured (Gauss., standard dev.) [A11, p166]
Rounding of results: magnitude	$5 \cdot 10^{-3}$	dB	Calculated (rect., semi-range)
Rounding of results: phase	$5 \cdot 10^{-3}$	°	Calculated (rect., semi-range)

Reciprocity –
LS1P microphones

Uncertainty budget example: vibration

Component	Source	Estimated relative standard uncertainty (%)	Sensitivity coefficient	Degrees of freedom	Relative uncertainty contribution (%)
$u(\hat{u}_V)$	Voltage measurement, due to calibration	0.0254	1	9	0.0254
	Voltage measurement, drifting after calibration	0.0199	1	∞	0.0199
$u(\hat{u}_D)$	Distortion	0.2887	1	12	0.2887
$u(\hat{u}_T)$	Transverse etc acceleration	0.0007	1	10	0.0007
$u(\hat{s}_Q)$	Displacement quantization	0.0036	-1	∞	-0.0036
$u(\hat{s}_H)$	Trigger hysteresis	0.0005	-1	∞	-0.0005
$u(\hat{s}_\lambda)$	Laser wavelength	0.0002	1	∞	0.0002
$u(\hat{s}_N)$	Refractive index	0.0002	1	∞	0.0002
$u(\hat{s}_F)$	Filtering effect	0.0000	-1	∞	0.0000
$u(\hat{s}_{VD})$	Voltage disturbance	0.0000	-1	∞	0.0000
$u(\hat{s}_{MD})$	Motion disturbance	0.0577	-1	∞	-0.0577
$u(\hat{s}_{PD})$	Phase disturbance	0.0001	-1	∞	-0.0001
$u(\hat{s}_{RE})$	Residual effects	-0.0001	-1	∞	0.0001
$u(f_{FG})$	Vibration frequency	0.0058	-2	∞	-0.0116
$u(S_{RE})$	Repeatability	0.0500	1	4	0.0241
Relative combined uncertainty					0.297
Relative expanded uncertainty (*k*=2)					**0.594**
Effective degrees of freedom					14

Primary
low frequency
sinusoidal calibration
by laser interferometry

Uncertainty budget example: ultrasound

					Estimated contributions (%)		
Source	Description	Type	D. of f.	Distribution	Power 0.5 W	Power 1 W	Power 5 W
Mass	Electronic balance	B	∞	Rectangular	0.28	0.17	0.07
	Temperature	B	∞	Rectangular	0.6	0.3	0.06
	Suspension wires	B	∞	Rectangular	0.0001	0.0001	0.0001
	Residual mass reading	B	∞	Rectangular	0.6	0.3	0.14
Sound speed	Wong & Zhu's formula	B	∞	Rectangular	0.001	0.001	0.001
	Temperature & pressure	B	∞	Normal	0.0095	0.0095	0.0095
	Temperature change	B	∞	Rectangular	0.05	0.05	0.05
	Heating effects	B	∞	Rectangular	0.004	0.004	0.004
	Pressure change	B	∞	Rectangular	0.0001	0.0001	0.0001
	Nonzero salinity	B	∞	Rectangular	0	0	0
Water attenuation	Fisher's formula	B	∞	Rectangular	0.02	0.02	0.02
	Temperature	B	∞	Rectangular	0.018	0.018	0.018
	Distance	B	∞	Rectangular	0.01	0.01	0.01
	Frequency	B	∞	Rectangular	0	0	0
Imperfect target	Reflection coefficient	B	∞	Rectangular	0.4	0.4	0.4
	Misalignment	B	∞	Rectangular	1.6	1.6	1.6
	Cone tip diffraction	B	∞	Rectangular	0.5	0.5	0.5
	Multiple reflection	B	∞	Rectangular	1	1	1
Beam pattern	Practical limitation	B	∞	Rectangular	1	1	1
Gravitation	NRC mass standard	B	∞	Rectangular	0.001	0.001	0.001
Ultrasonic power	Random Effect in Repeats	A	4	Normal	2.2	0.9	0.9
Relative combined uncertainty (%)					2.631	1.602	1.584
Effective degrees of freedom					8	38	36
Expanded uncertainty (%) (k=2.31, 2.02, 2.03)					**6.079**	**3.237**	**3.219**

Calibration of ultrasonic transducers by the radiation force method

Traceability for acoustics

Areas of Metrology

Acoustics
- Measurement microphones

Dimensional
- Plane wave couplers for LS1P and LS2P microphones

Electrical
- Insert-voltage microphone preamplifier
- Phasemeter
- Reciprocity apparatus
- Transmitter unit
- RMS voltmeter

Frequency & Time
- Sine generator

Pressure
- Barometer

Temperature
- Digital Thermometer
- Humidity indicator

Traceability for ultrasound and vibration

Areas of Metrology

Ultrasound
- Reference transducer

Mass
- Electronic balance
- Standard weights

Electrical Standards
- RF RMS voltmeter
- RF power amplifier

Frequency & Time
- Sine generator

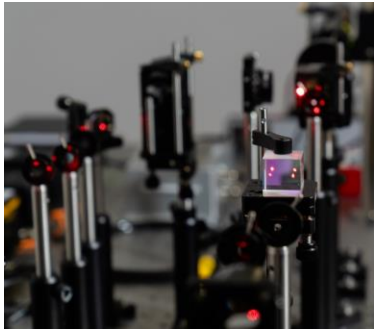
Pressure
- Barometer

Temperature
- Hygrometer

Areas of Metrology

Vibration
- Shaker

Electrical
- Photo Detector
- Amplifier
- Power amplifier
- RMS voltage
- Oscilloscope



Frequency & Time
- Function generator
- He-Ne laser
- Frequency counter

Pressure
- Barometer

Temperature
- Hygrometer

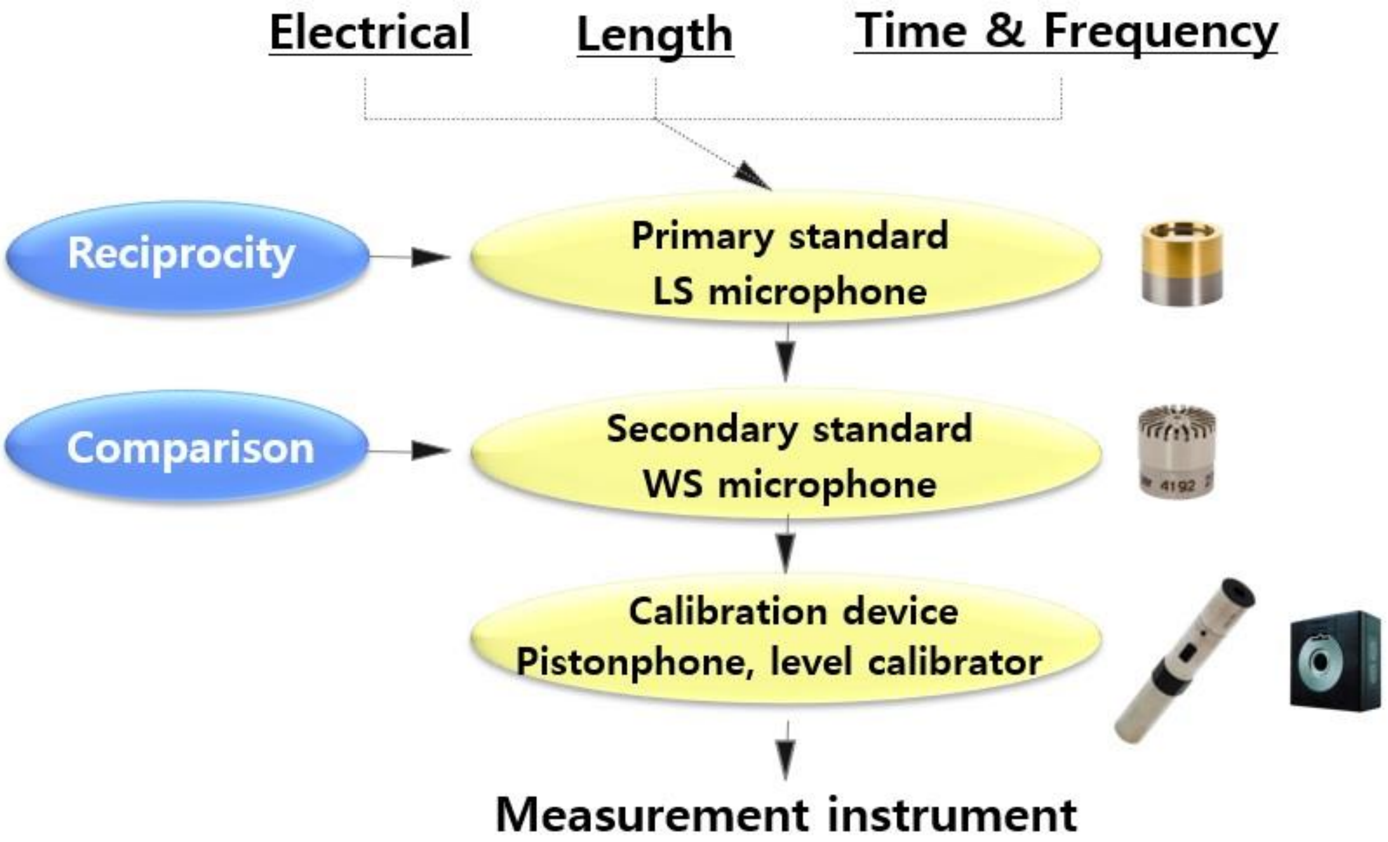
Traceability

- All exclusively defined and traceable to combinations of fundamental constants
- This does not imply that derived units are also defined likewise
- Acoustics: artefact (microphones and couplers) and method (reciprocity) dB

Copyright: BIPM

Copyright: Bruel & Kjaer

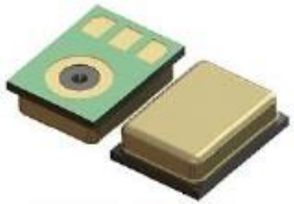
Traceability



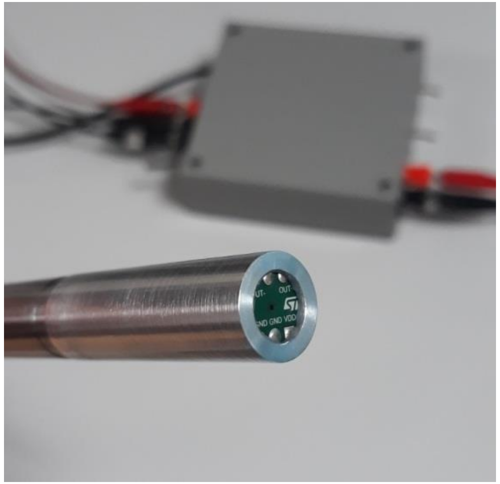
Traceability

Copyright: Bruel & Kjaer

Copyright: Ono Sokki



Copyright: STMicroelectronics



Copyright: National Institute of Metrological Research Italy

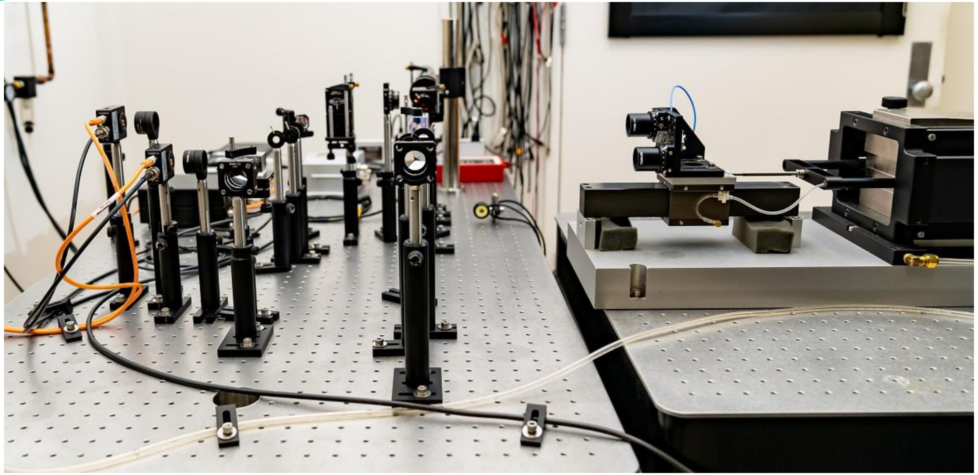
Reciprocity: past, current and future but very limited microphones coverage

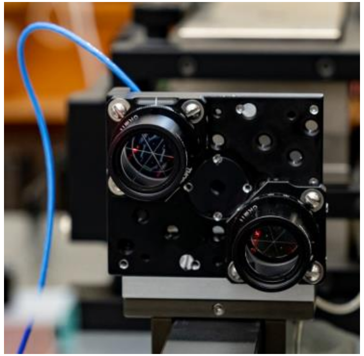
Free-field: pressure comparison and optical including laboratory standard microphones and MEMS

Current technical challenges and future trends

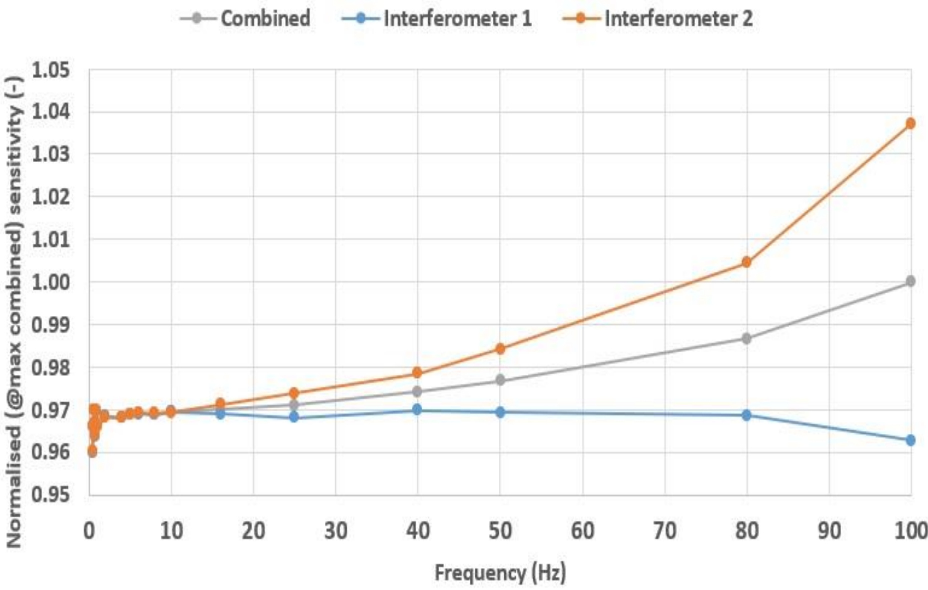
Vibration

Homodyne Michelson interferometers and acceleration profiles



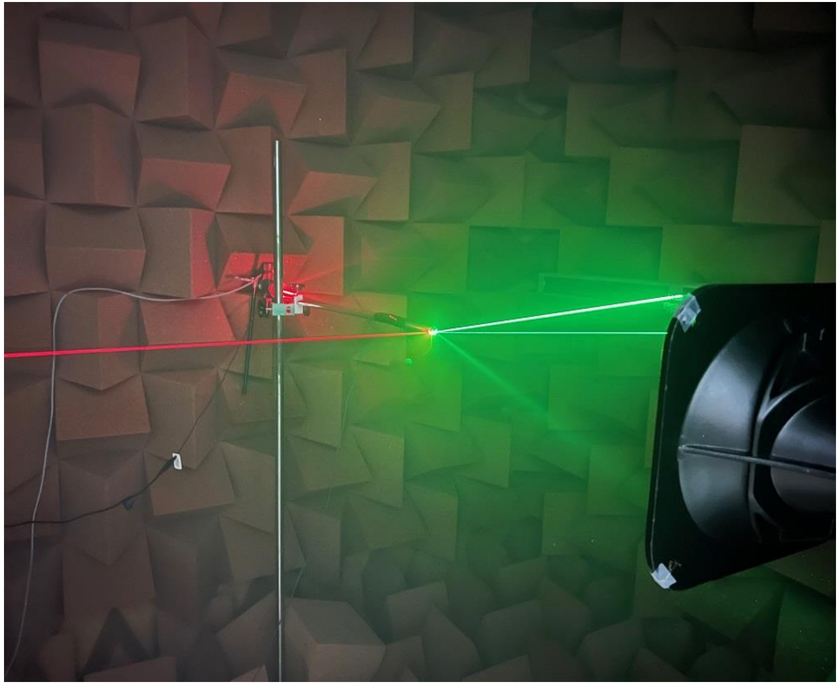


Copyright: National Research Council Canada

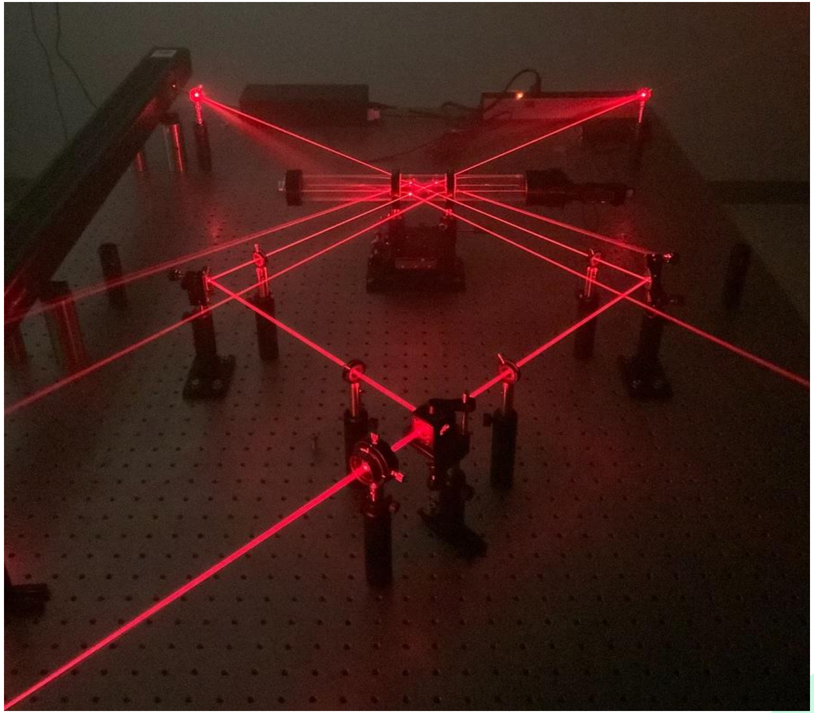


Acoustics

Optical realizations of the acoustic Pa and MEMS calibrations



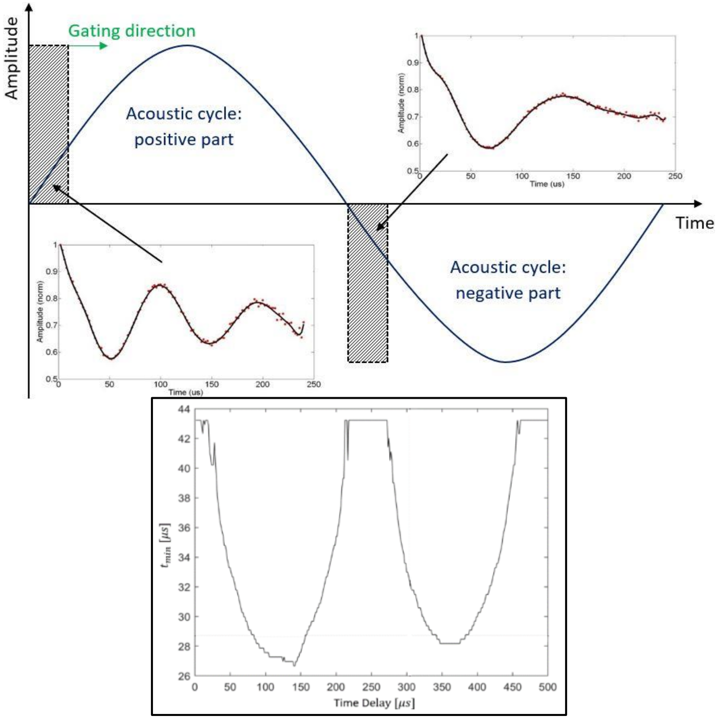
Copyright: Korea Research Institute of Standards and Science



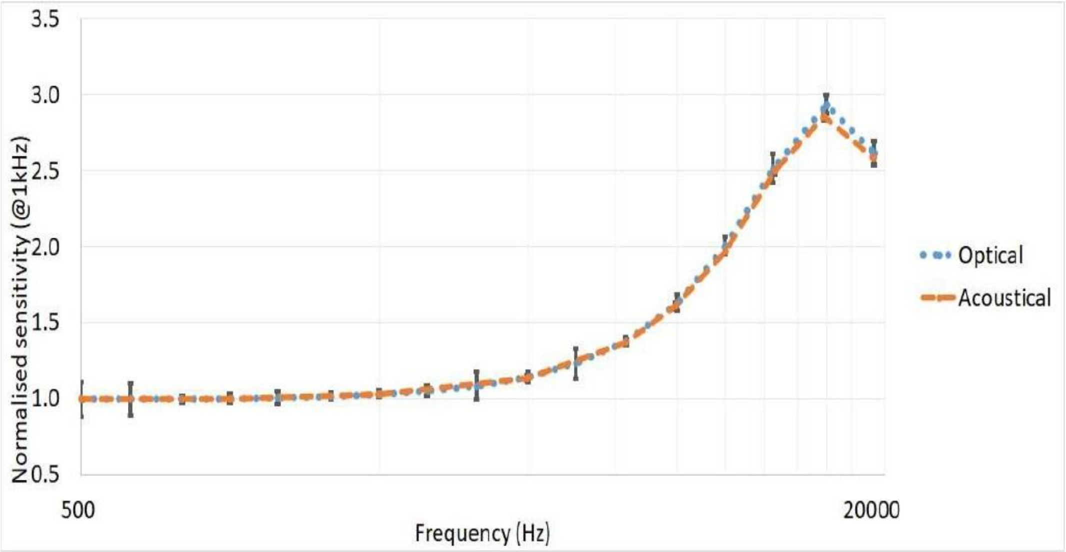
Copyright: National Research Council Canada

Acoustics

Optical realizations of the acoustic Pa and MEMS calibrations



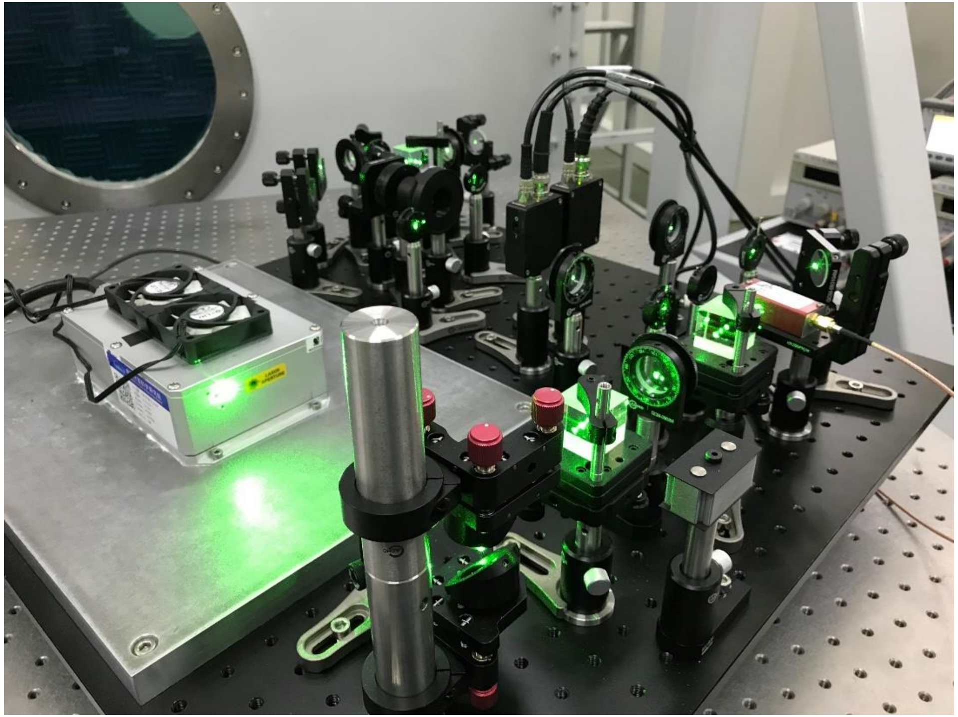
Bouchard et al., Proceedings 28th International Congress on Sound and Vibration 2022

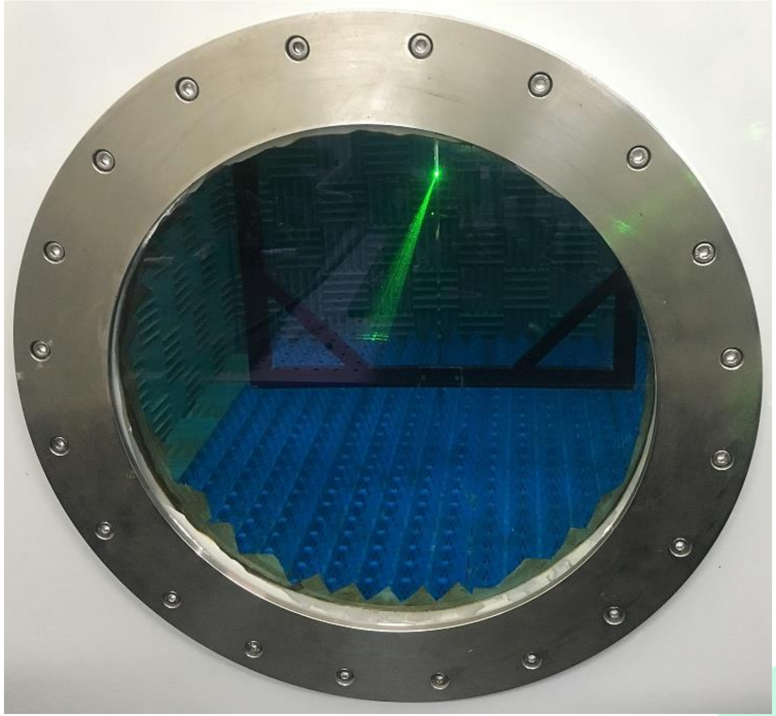


Copyright: National Research Council Canada, Korea Research Institute for Standards and Science, National Institute of Metrological Research Italy

Underwater acoustics / ultrasound

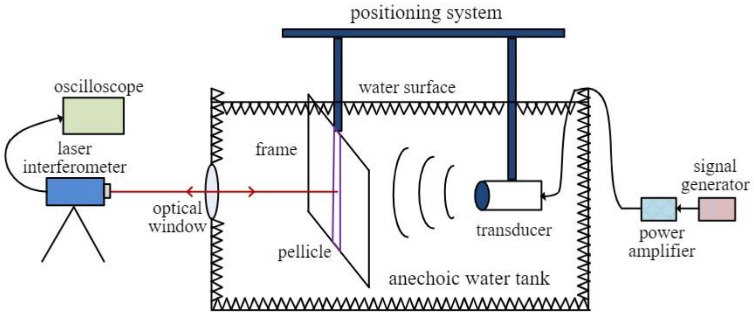
Heterodyne interferometry for hydrophone calibrations

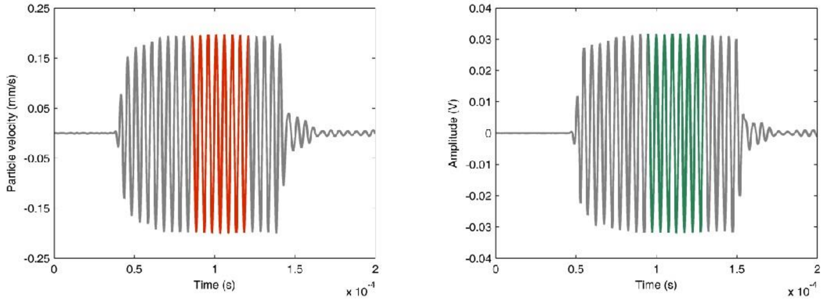


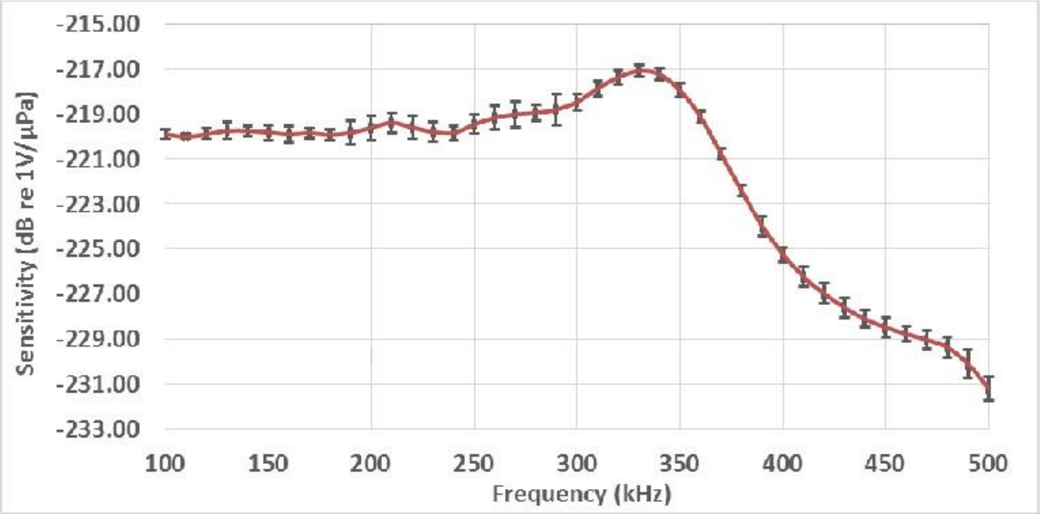


Underwater acoustics / ultrasound

Heterodyne interferometry for hydrophone calibrations



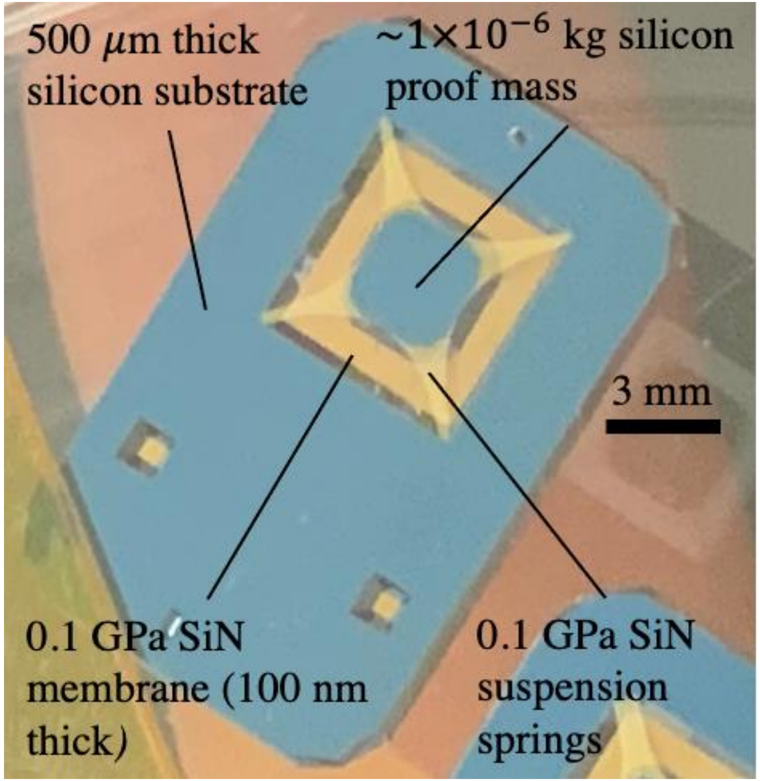


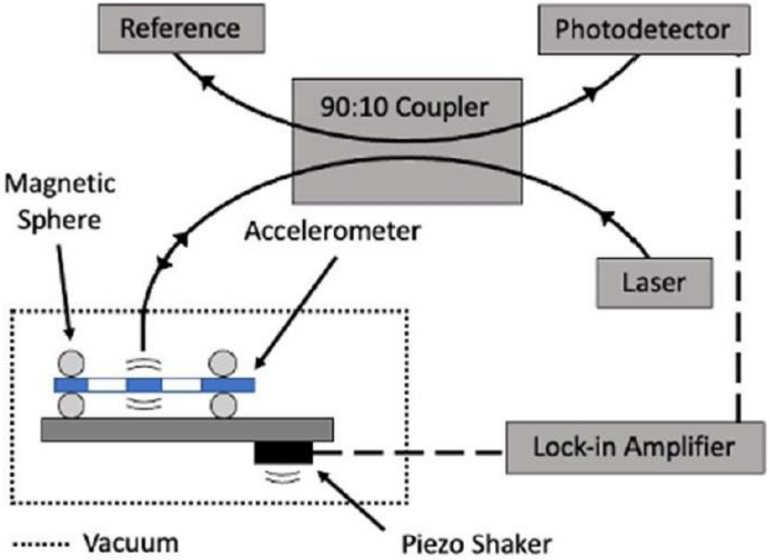


Wang et al., Proceedings 25th International Congress on Sound and Vibration, 2018

Vibration

Silicon Nitride mass-loaded MEMS accelerometers



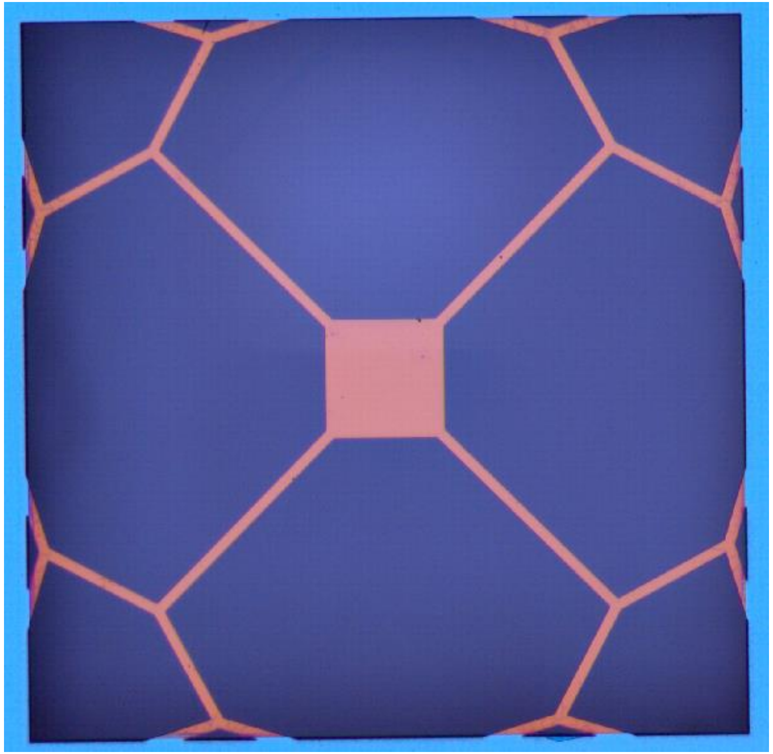


$$S_{a,tmech} = \left(\frac{4k_B T\omega_0}{mQ}\right)^{\frac{1}{2}}$$

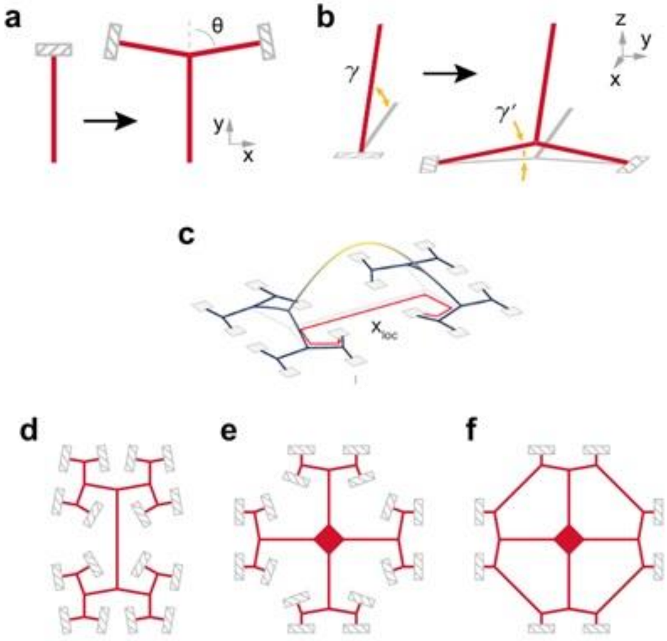
Hodges et al., Proceedings of 2022 IEEE International Symposium on Inertial Sensors and Systems, France

Vibration

Silicon Nitride non-mass-loaded MEMS accelerometers

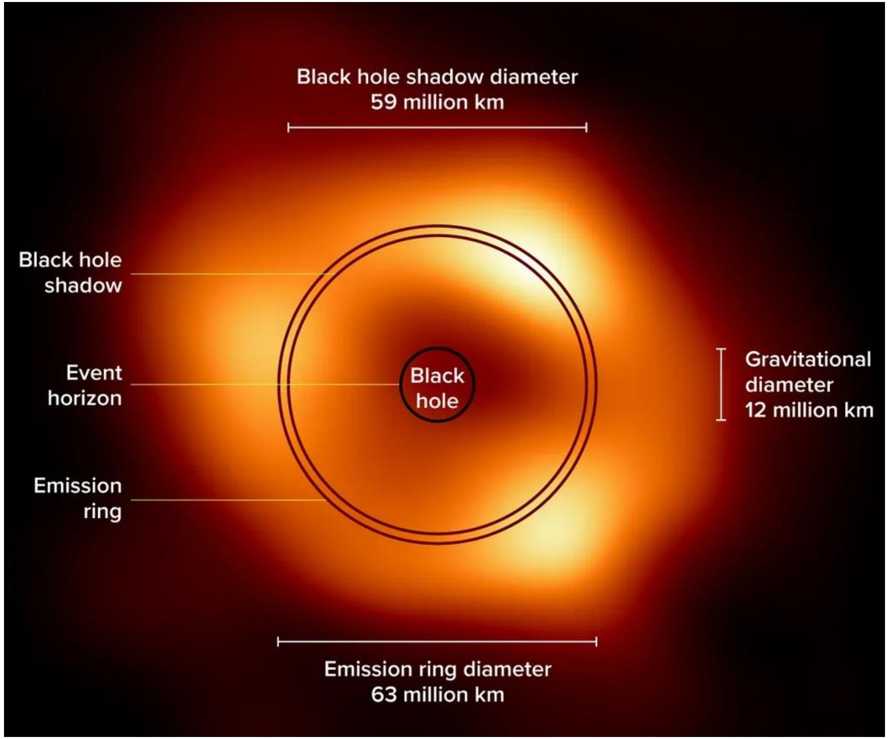


Copyright: UOMEMS Lab, University Of Ottawa

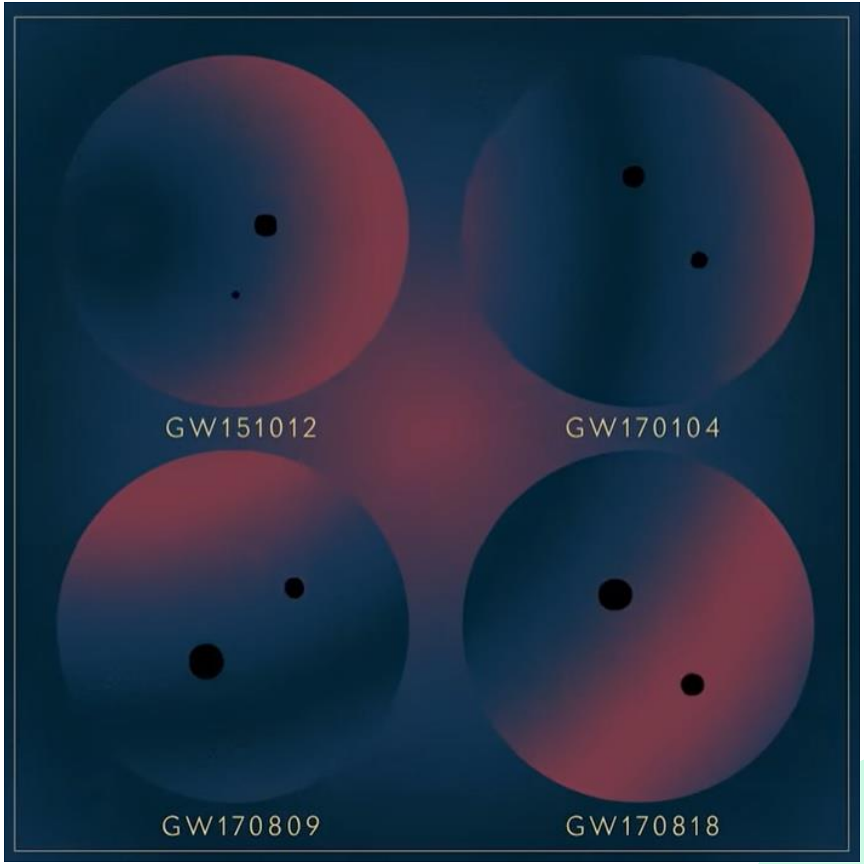


$$S_{a,tmech} = \left(\frac{4k_B T\omega_0}{mQ}\right)^{\frac{1}{2}}$$

Black holes and mergers

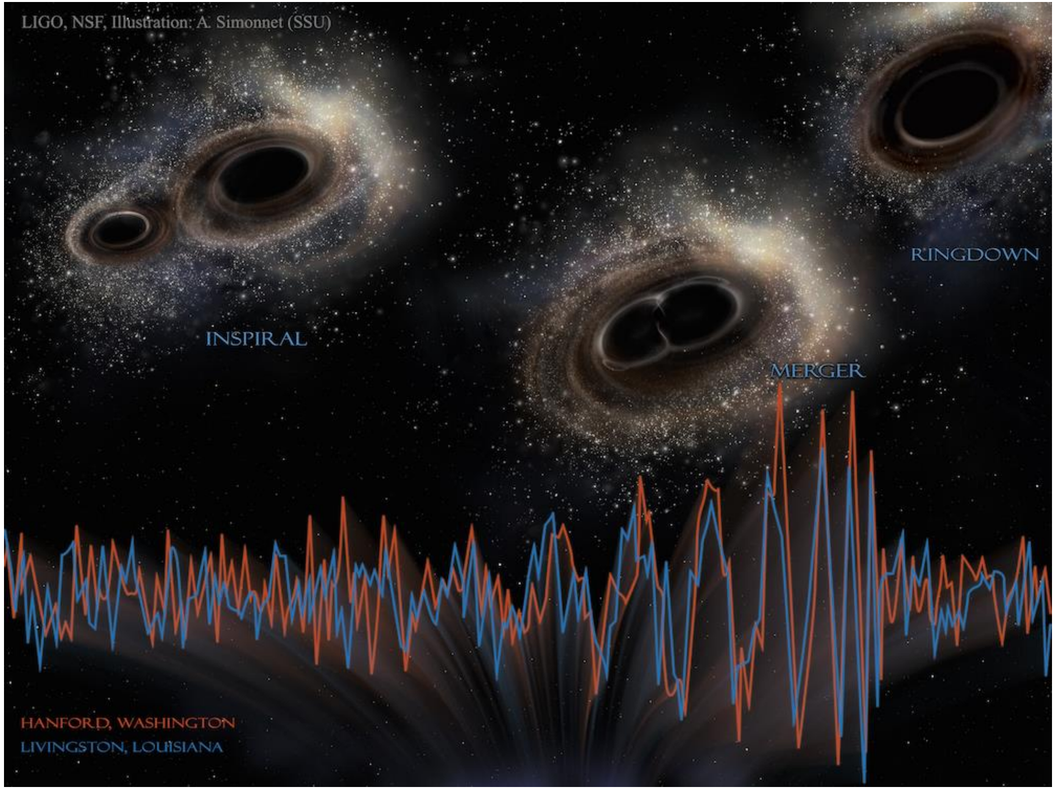


Copyright: Smithosian Magazine



Copyright: Scientific American

Black holes and mergers

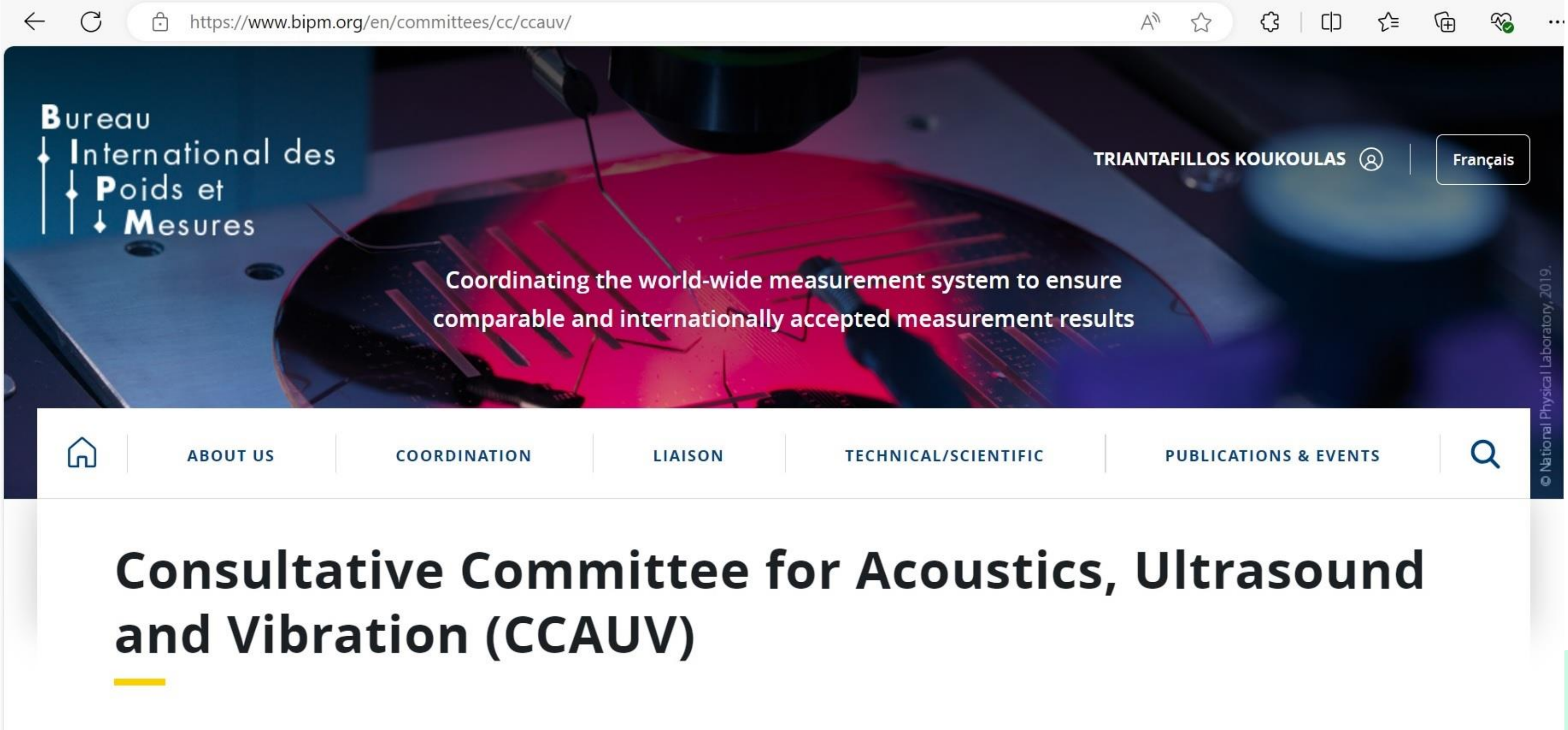


Copyright: LIGO

- The oscillations in the light signals received at the LIGO were within the human hearing range: light frequencies converted into sound frequencies
- The result (chirp) is the sound of the black holes colliding

Resources

CCAUV BIPM resources



CCAUV BIPM resources

https://www.bipm.org/en/committees/cc/ccauv/meetings

BIPM | ABOUT US | COORDINATION | LIAISON | TECHNICAL/SCIENTIFIC | PUBLICATIONS & EVENTS

WORKSHOP

CCAUV Workshop on "The contribution of CCAUV to the "Evolving needs in Metrology""

24 OCTOBER 2023

ROMAIN COULON CCAUV-WS

PAST MEETING

CCAUV-SPWG

24 OCTOBER 2023

ROMAIN COULON CCAUV-SPWG

PAST MEETING

CCAUV-KCWG

23 OCTOBER 2023

ROMAIN COULON CCAUV-KCWG

PAST MEETING

CCAUV-RMOWG

23 OCTOBER 2023

ROMAIN COULON CCAUV-RMOWG

PAST MEETING

13th meeting of the CCAUV (online)

FROM 16 TO 18 NOVEMBER 2021

PAST MEETING

CCAUV-SPWG

16 SEPTEMBER 2021

CCAUV BIPM resources

https://www.bipm.org/en/committees/cc/ccauv/meetings

BIPM | ABOUT US | COORDINATION | LIAISON | TECHNICAL/SCIENTIFIC | PUBLICATIONS & EVENTS

5th meeting of the CCAUV
FROM 25 TO 26 SEPTEMBER 2006
ROMAIN COULON · CCAUV

CCAUV-RMOWG
29 SEPTEMBER 2004
ROMAIN COULON · CCAUV-RMOWG

PAST MEETING
4th meeting of the CCAUV
FROM 27 TO 28 SEPTEMBER 2004
ROMAIN COULON · CCAUV

PAST MEETING
3rd meeting of the CCAUV
FROM 01 TO 02 OCTOBER 2002
ROMAIN COULON · CCAUV

PAST MEETING
2nd meeting of the CCAUV
FROM 04 TO 05 OCTOBER 2001
ROMAIN COULON · CCAUV

PAST MEETING
1st meeting of the CCAUV
FROM 20 TO 21 JULY 1999
ROMAIN COULON · CCAUV

SIM METROLOGY SCHOOL

Thanks!

Triantafillos Koukoulas
National Research Council Canada (NRC)

Triantafillos.Koukoulas@nrc-cnrc.gc.ca

Follow us on:

facebook.com/metrosim
youtube.com/simmetrology7958
www.sim-metrología.org