CCT/17-29

Bureau International des Poids et Mesures

1st June 2017

BIPM

28th Meeting of the Consultative Committee for Thermometry (CCT)

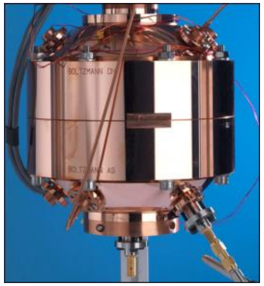
Acoustic Gas Thermometry

INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

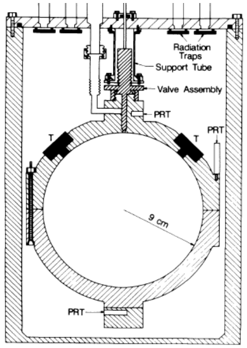
Roberto M. Gavioso

outline   Acoustic Gas Thermometry

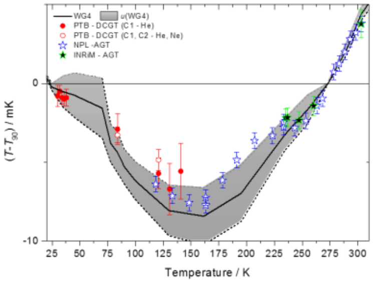
hystorical development
- development of theory: Laplace was finally right
- wide ranging applications of acoustic gas thermometry ...
- ... including primary temperature standards



milestones along a successful road
- theory and practice of a sphere
- son et lumiere: advantages of the new SI



results
- determinations of the molar gas constant *R* and the Boltzmann constant *k*
- determinations of T-T_{90}



ongoing work and future perspectives
- extending the temperature range of primary acoustic thermometers
- alternatives for dissemination: simplification of primary methods
- practical acoustic thermometers

1627 - Francis Bacon
gedanken experiment

To try exactly the time wherein sound is propagated

[..] let a man stand in a steeple, with a candle, veiled; and let another man stand a mile off: then let the person in the steeple strike a bell and at the same instant withdraw the veil; the other, at a distance, may measure the time between the light seen and the sound heard, for light is propagated instantaneously*

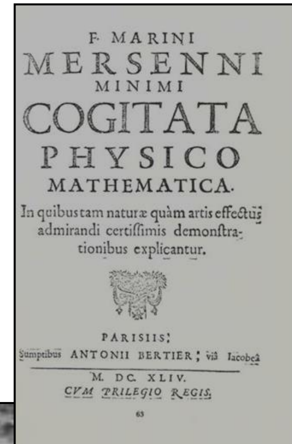
*Or what comes very near thereto, for in the space of seven or eight minutes it is thought by some to travel from the sun to the earth.

Sylva Sylvarum **1627**

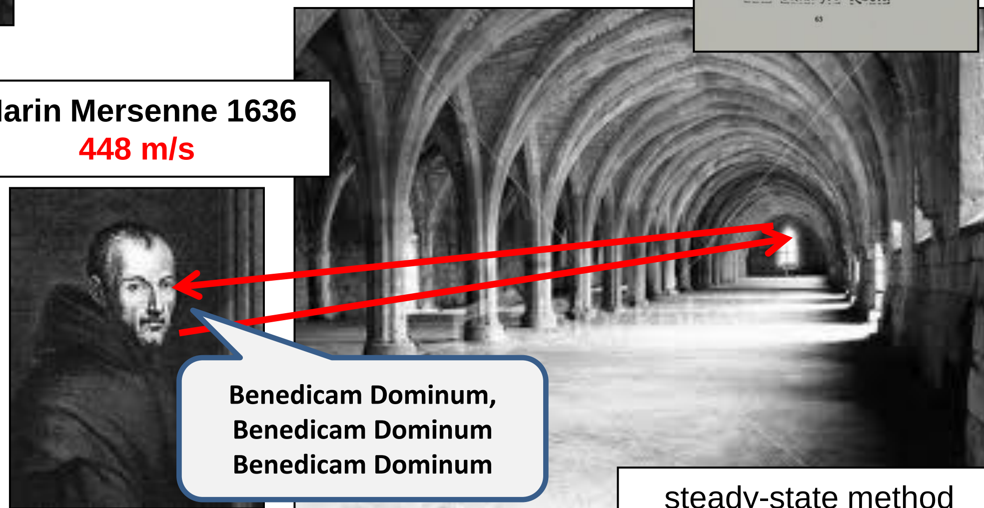
transient method

1635 - Pierre Gassendi
478 m/s

Cogitata Physico Mathematica



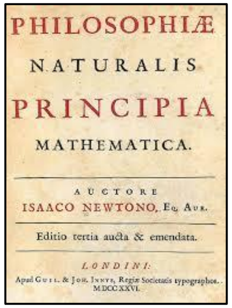
Marin Mersenne 1636
448 m/s



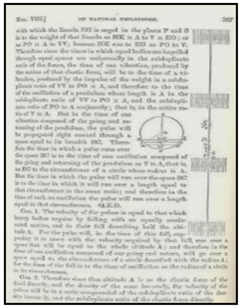
steady-state method

1656 - Viviani, Borelli
360 m/s
1708 - Derham, Flansted, Halley
348 m/s

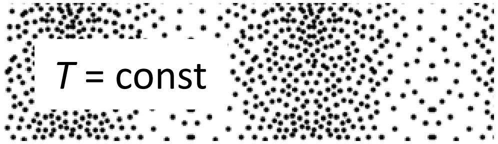
at 20 °C, 1 atm, 50% relative humidity
speed of sound in air
344 m/s



PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.
AUCTORE
ISAACO NEWTONO, Eq. Aur.
Editio tertia aucta & emendata.
LONDINI:
Apud Guil. & Joh. Innys, Regiæ Societatis typographos.
MDCCXXVI.



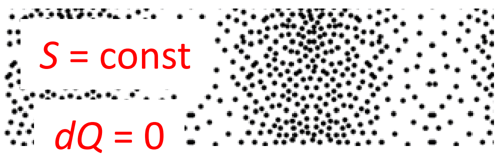
Newton (isothermal)



$$\kappa_T = 1/p$$

$$\kappa_S = 1/\gamma p$$

Laplace (adiabatic)



wavelength $\equiv \lambda \gg l \equiv$ mean free path

Theory

1687 Newton

1[st] ed. *Philosophiae Naturalis Principia Mathematica*

pendulum analogy (elasticity/density)

$$c^2 = \frac{p}{\rho} = \frac{1}{\kappa_T \rho}$$ (air) 295 m·s^{-1}

Q. F. F. Q. S.
DISSERTATIO PHYSICA
DE SONO,
QUAM
ANNUENTE NUMINE DIVINO
JUSSU MAGNIFICI ET SAPIENTISSIMI PHI
LOSOPHORUM ORDINIS
PRO
VACANTE PROFESSIONE PHYSICA
Ad d. 18. Febr. A. MDCCXXVII.
In Auditorio Juridico hora 9.
Publico Eruditorum Examini subjicit
LEONHARDUS EULERUS
A. L. M.
Respondente
Praestantissimo Adolescente
ERNESTO LUDOVICO BURCARDO
Phil. Cand.
BASILEÆ,
Typis E. & J. R. THURNISIORUM, Fratrum.

1727 Euler

$$c^2 = \frac{4}{\pi}\frac{p}{\rho}$$ (air) 375 m·s^{-1}

1759 – Lagrange

generic acoustic perturbation

$$u^2 = \left(\frac{p}{\rho}\right)$$

1816 Laplace

$$c^2 = \gamma \frac{p}{\rho} = \frac{1}{\kappa_S \rho} \qquad \gamma = \frac{c_p}{c_V}$$

Experiment

1627 – Francis Bacon

proposal of virtual experiment

1636 – Mersenne

sources -> guns, musical instruments
time meas -> pulse beat

448 m·s^{-1}

1656 – Viviani, Borrelli (Galilei's disciples)

guns, pendulum

361 m·s^{-1}

1708 – Derham, Flanstead, Halley

account for wind influence

348 m·s^{-1}

1738 – Cassini de Thury

exchange source-receiver
measure of temperature

337 m·s^{-1}

1868 – Regnault

Paris underground, in pipelines of different diameter, extrapolating results to free field, dry air at 0 °C

330.7 m·s^{-1}

1953 – Hardy, Smith

dry air, 0 °C, 100 kPa

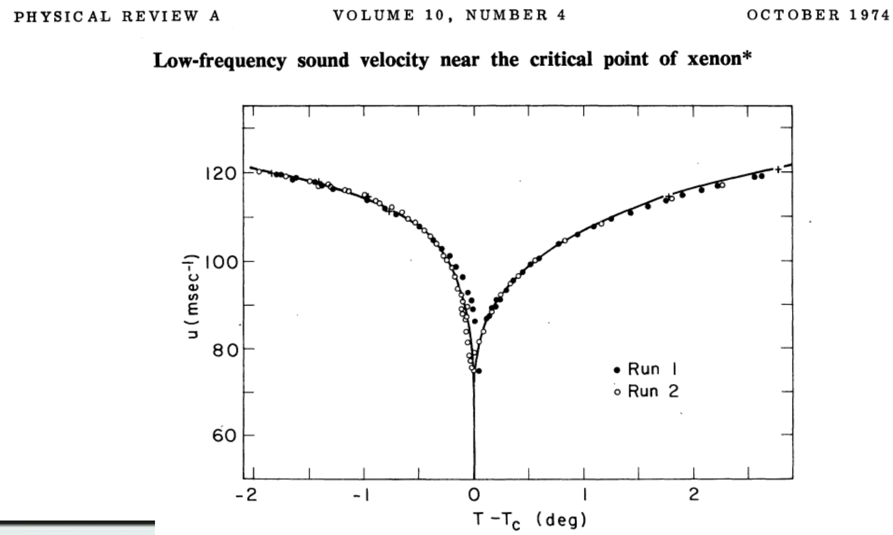
331.45 m·s^{-1}

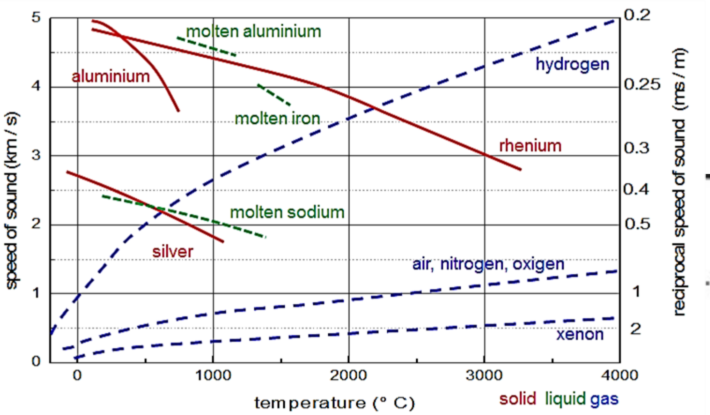
versatility of Laplace equation

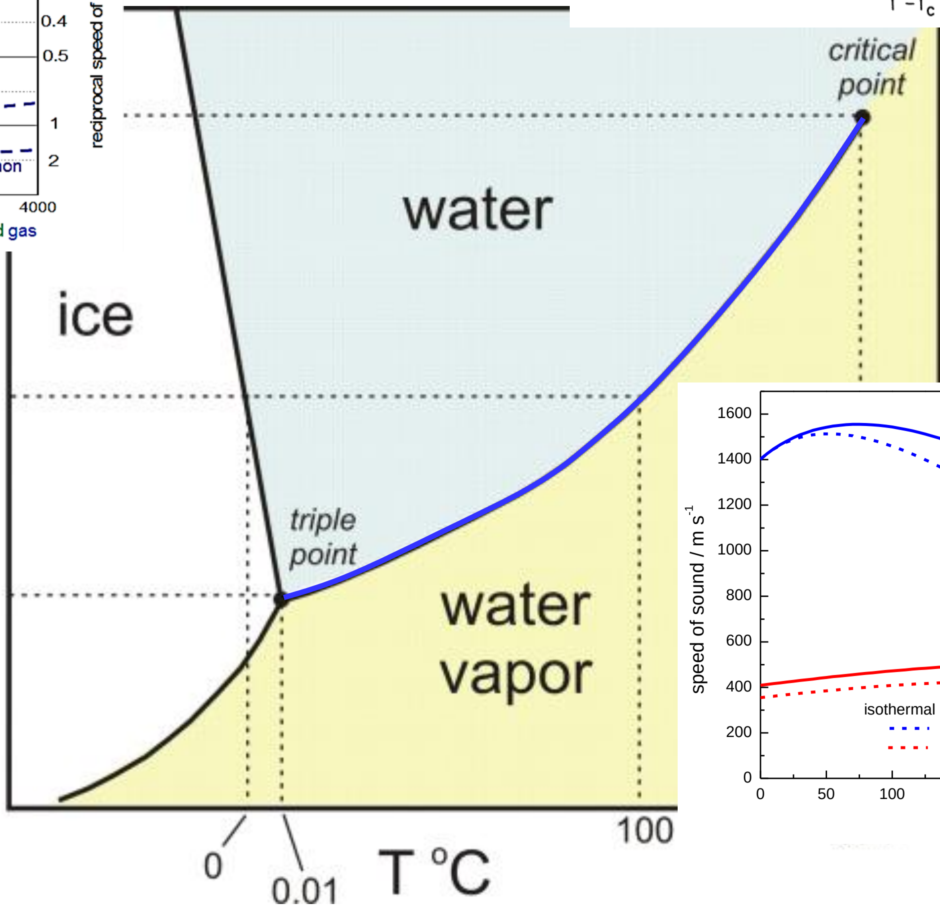
$$c^2 = \left(\frac{\partial p}{\partial \rho}\right)_S = 1/\kappa_S \rho$$

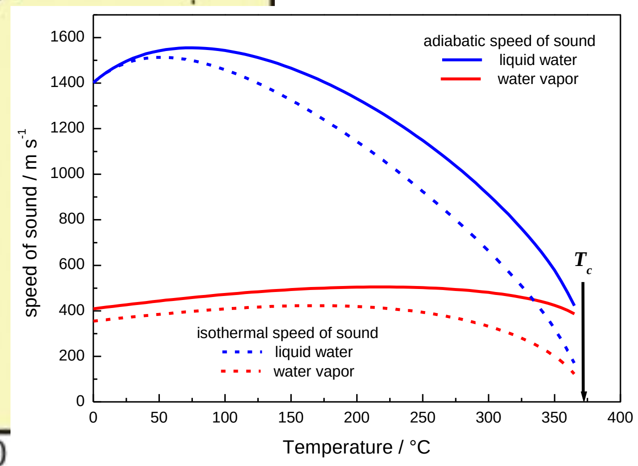
$$\kappa_S = -\frac{1}{V}\left(\frac{\partial V}{\partial p}\right)_S$$

$$\kappa_s = 1/\gamma p$$









longitudinal waves

bulk modulus

$$c_L^2 = \left(\frac{\partial p}{\partial \rho}\right)_S = 1/\kappa_s \rho = \frac{K}{\rho}$$

shear modulus

$$c_T^2 = \left(\frac{\partial p}{\partial \rho}\right)_S = \frac{G}{\rho}$$

shear waves

1962

He: 300 K - 2000 K, 2 MPa

1965 - 1975

up to 20000 K

THE REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 33, NUMBER 4 APRIL, 1962

Acoustic Thermometry

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(Received July 3, 1961; and in final form, January 8, 1962)

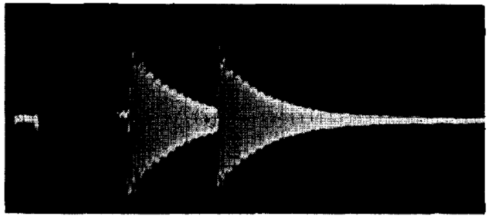


Fig. 2. Oscilloscope trace of voltage across transceiver. The transmitted burst occurs during the blank space and is followed by the reflected and "ringing" signals. From the decay of the ringing signal the cavity Q can be determined.

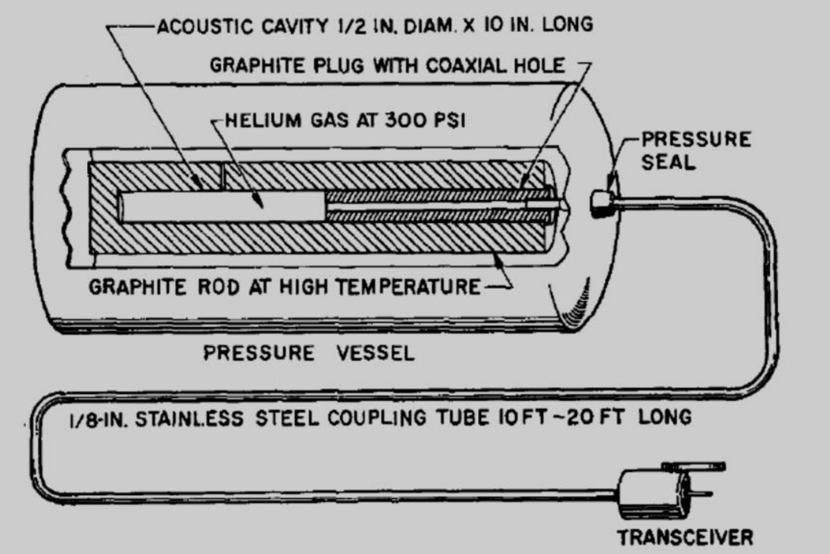


Fig. 5. Pictorial representation of experiment.

THE PHYSICS OF FLUIDS VOLUME 10, NUMBER 7 JULY 1967

;imultaneous Ultrasonic and Line Reversal Temperature Determination in a Shock Tube

E. H. Carnevale, S. Wolnik, G. Larson,* C. Carey
Parametrics, Inc., Waltham, Massachusetts
and
G. W. Wares
Air Force Cambridge Research Laboratories, Bedford, Massachusetts

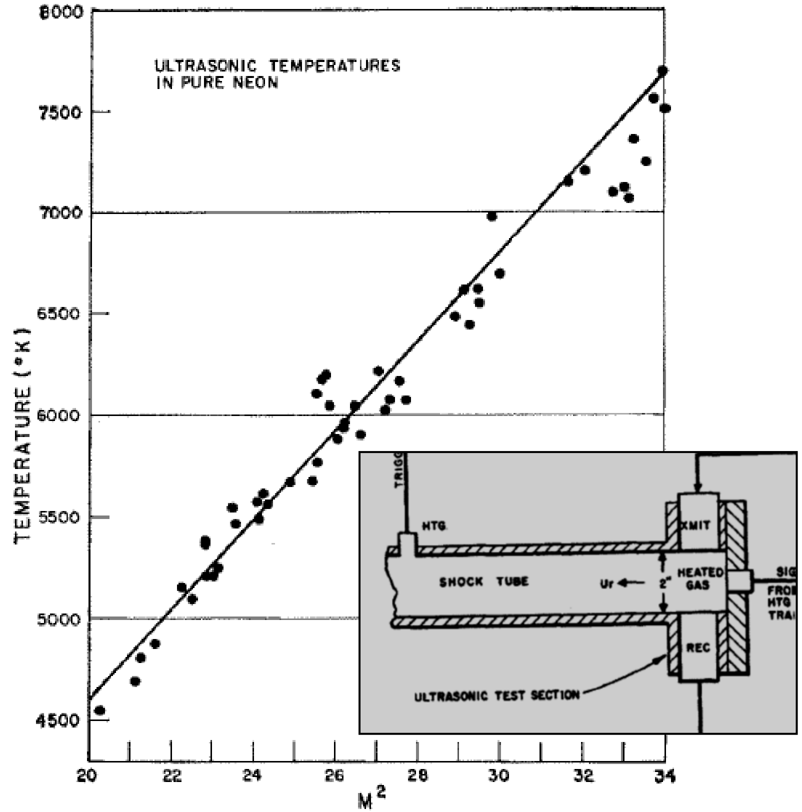
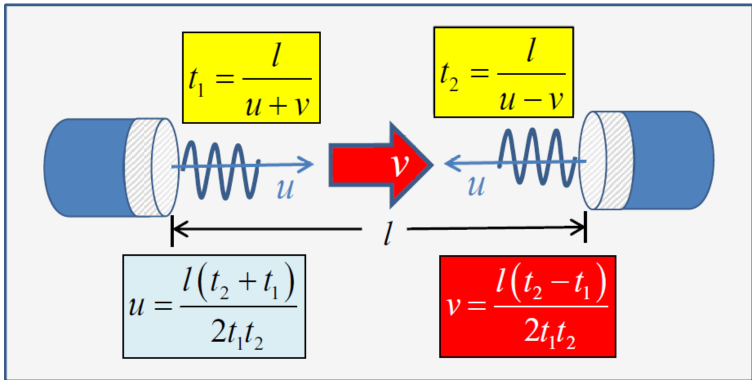
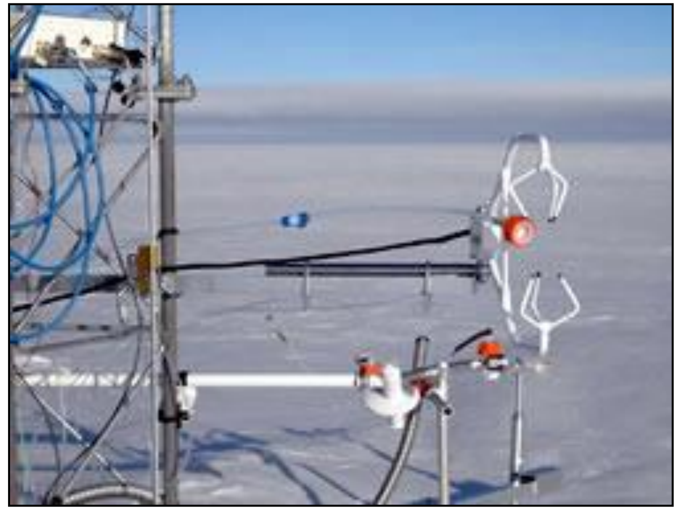


Fig. 7. Temperatures in reflected shock region in pure neo obtained by ultrasonics.

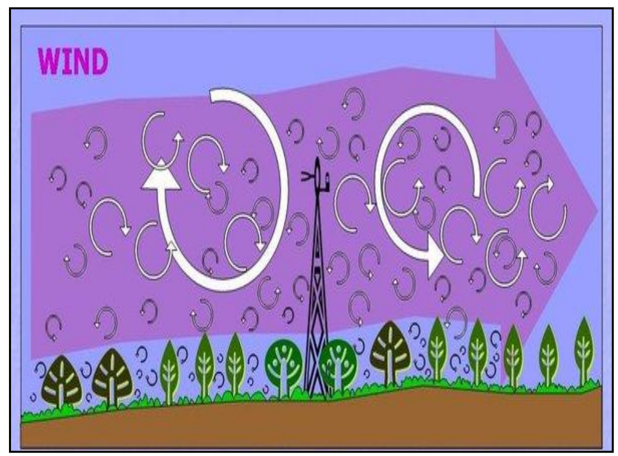
sonic anemometry (& thermometry)





sonic anemometers are sensors that are able to estimate wind speed vector by measuring the influence of local wind speed on the transmission of ultrasound signals between pairs of emitters and receivers that configure acoustic paths. This estimation is normally assigned to the geometric center of acoustic path midpoints

sonic anemometers are used to evaluate the turbulent heat flux from the sonic kinematic heat flux (or “temperature flux”), i.e. the covariance of the vertical wind velocity w and the sonic temperature T the vertical wind velocity w and the speed of sound c being simultaneously measured by the anemometer, and the speed of sound being then corrected for the effect of the crosswind



sonic kinematic heat flux

$$T = u^2 \frac{M}{\gamma R} \quad \Rightarrow \quad \boxed{\overline{w'T'}} \quad \Rightarrow \quad \text{turbulent heat flux}$$

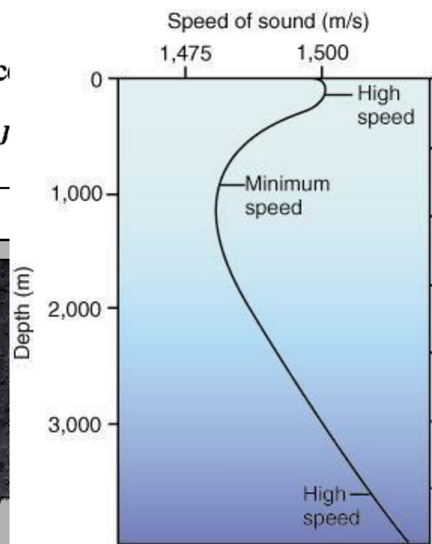
sonic temperature

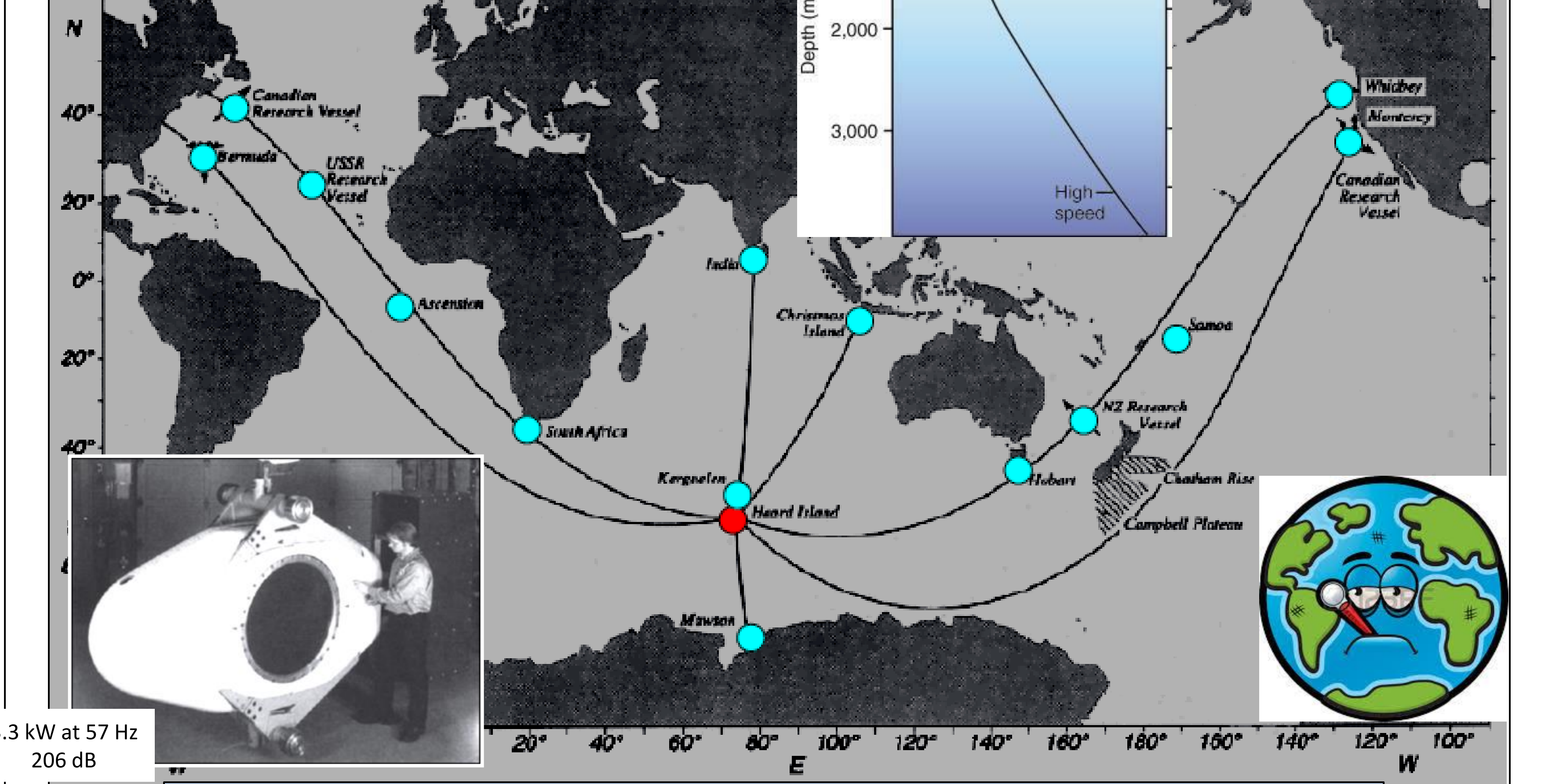
The Heard Island Feasibility Test

Walter H. Munk
Scripps Institution of Oceanography, University of California, San Diego, La J

(Rec... May 1994; accepted 7 June 1994)

1994





3.3 kW at 57 Hz
206 dB

Acoustic Thermometry of Ocean Climate (ATOC) precision 50 ms – accuracy 0.1 s ≈ 0.05 K

FIG. 1. Ray paths from source to receiver sites are refracted geodesics, i.e., great circles corrected for Earth flattening and horizontal sound speed gradients. The source array was suspended from R/V Cory Chouest 50 km southeast of Heard Island. Single dots indicate sites with single receivers. Dots connected by horizontal lines designate horizontal bottom-mounted arrays, vertical lines designate vertical arrays, and slanted lines designate arrays towed in the direction of the arrow. Signals were received at all sites except for the vertical array at Bermuda (which sank) and the Japanese station off Samoa.

Geophysical Research Letters

RESEARCH LETTER
10.1002/2015GL063438

Monitoring deep-ocean temperatures using acoustic ambient noise

2015

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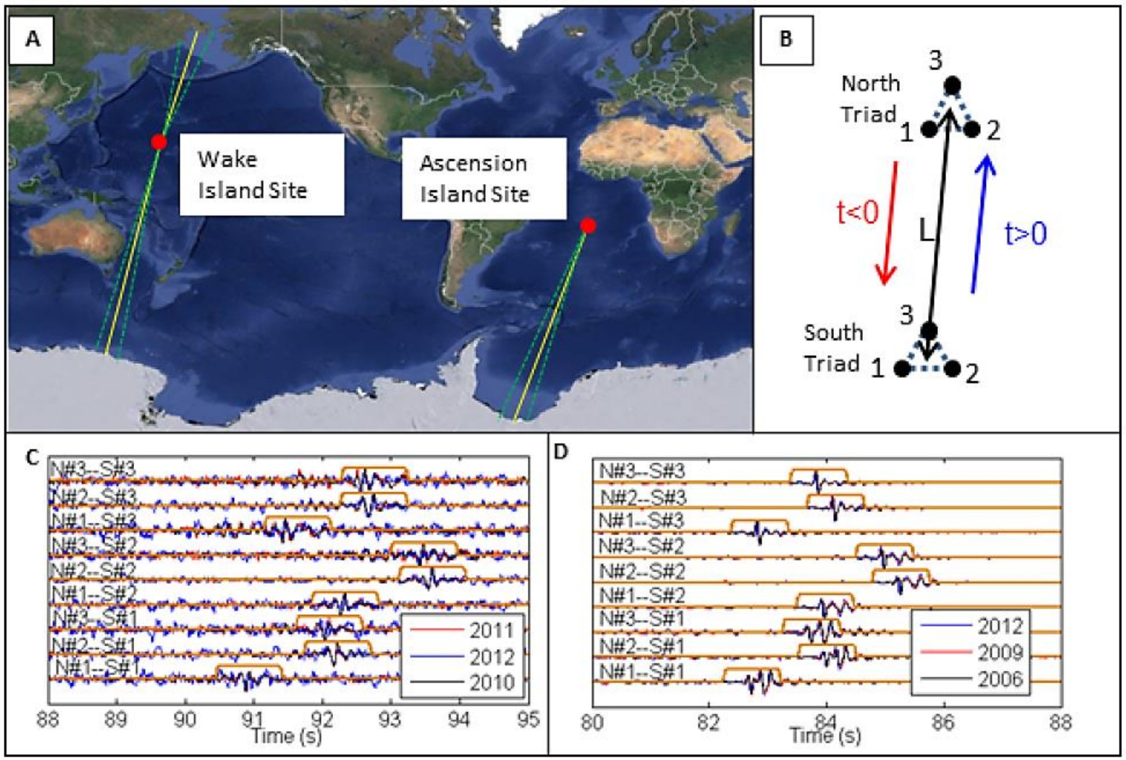
Key Points:
- Deep-ocean temperature variations can be measured using only ambient noise
- This method can be more precise than direct temperature measurements

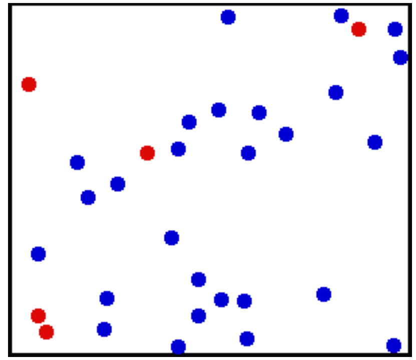
abstract: measuring temperature changes of the deep oceans, important for determining the oceanic heat content and its impact on the Earth's climate evolution, is typically done using free-drifting profiling oceanographic floats with limited global coverage. Acoustic thermometry provides an alternative and complementary remote sensing methodology for monitoring fine temperature variations of the deep ocean over long distances between a few underwater sources and receivers. We demonstrate a simpler, totally passive (i.e., without deploying any active sources) modality for acoustic thermometry of the deep oceans (for depths of ~ 500–1500 m), using only ambient noise recorded by two existing hydroacoustic stations of the International Monitoring System. We suggest that passive acoustic thermometry could improve global monitoring of deep-ocean temperature variations through implementation using a global network of hydrophone arrays



(A) Locations of the two hydroacoustic stations (red dots) near Ascension and Wake Islands.. (B) Zoomed-in schematic of the hydrophone array configurations for the Ascension and Wake Island sites, which both have a similar layout. Each hydroacoustic station consists of a northern and southern triangle array of three hydrophones (or triad), with each triangle side equal to approximately 2 km. The distance L between triad centers is equal to 126 km and 132 km for the Ascension and Wake Island stations, respectively.
(C) Noise cross-correlation waveforms, averaged over three different years, obtained between all 9 pairwise combinations of the elements of the north and south triads for the Wake Island. (D) Same as C, but for Ascension Island. The beams shown by dashed lines in A are centered on the lines joining the centers of the south and north triads of each hydroacoustic station (yellow line) and which intersect the Polar regions where potential ice noise sources contributing to the coherent arrivals shown in C-D are located (18b).

ideal gas assumptions:

- the molecules of the gas are indistinguishable, small, hard spheres
- collisions are elastic and motion is frictionless (no energy loss)
- Newton's laws apply
- average distance between molecules is much larger than molecular size
- the molecules constantly move in random directions with a distribution of speeds
- there are no attractive or repulsive forces between the molecules



ideal gas equation of state $p = \rho RT/M$

mean kinetic energy $\frac{1}{2} m v_{rms}^2 = \frac{3}{2} kT$

$$u_0^2(T) = \left(\frac{\partial p}{\partial \rho}\right)_S = \gamma_0 \frac{kT}{m} = \gamma_0 \frac{RT}{M} = \frac{1}{3}\gamma_0 \; v_{rms}^2$$

molecular mass; molar mass; squared mean molecular speed

$\gamma_0 = 5/3$

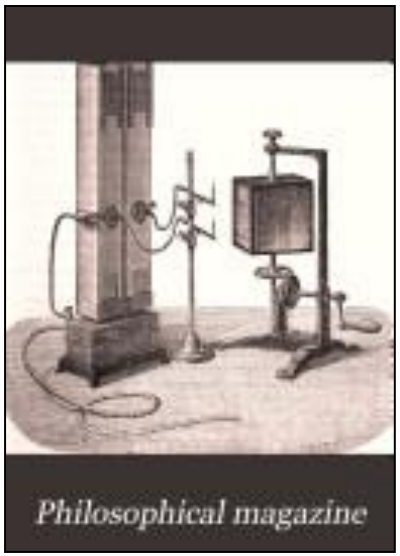
monoatomic gas

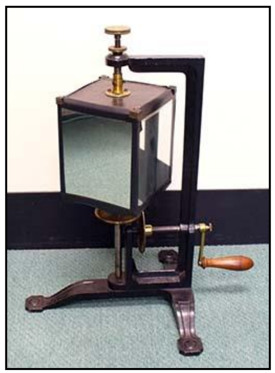
$$u_0^2 \approx \frac{v_{rms}^2}{2}$$

1873

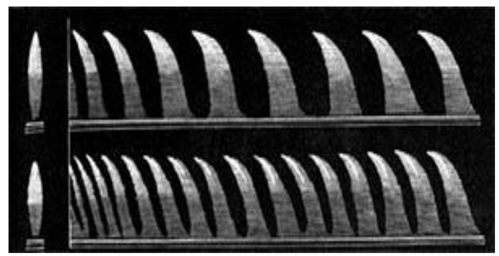
ambient to 1000 °C

Alfred Marshall Mayer





Wheatstone revolving mirror (1834)



Koenig flame manometer (1862)

Acoustical Thermometer

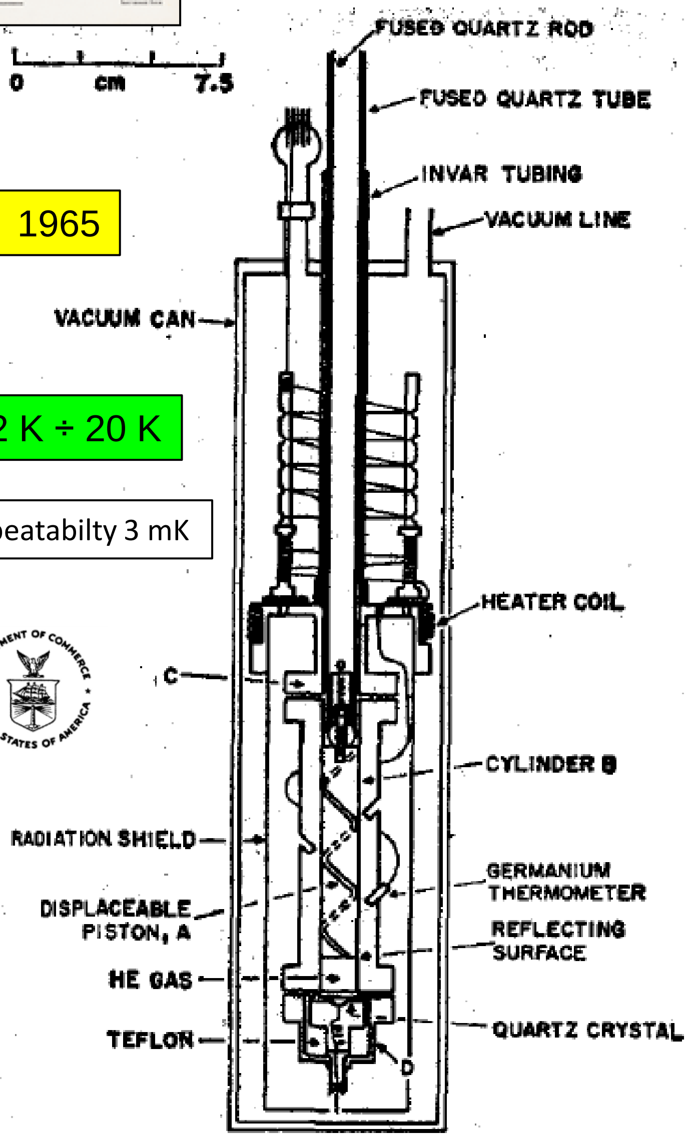
ultrasonic interferometer provides a new method for the precise measurement of low temperature.

Harmon H. Plumb and George Cataland

1965

2 K ÷ 20 K

repeatabilty 3 mK



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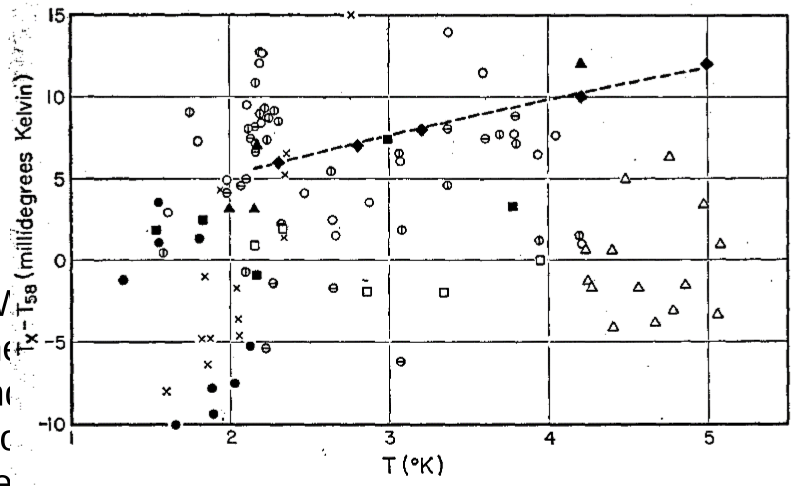

Fig. 4. A comparison, with values of the T_{58} scale, of temperatures derived from (i) pressure-volume isotherm measurements, (ii) gas thermometry measurements, and (iii) acoustical-thermometer measurements (*19*). (Open circles, plain or bisected) Gas-thermometer values [Schmidt and Keesom (*20*)]; (solid circles) gas-thermometer values [Kistemaker (*21*)]; (crosses) isotherm values [Kistemaker (*21*)]; (open triangles) gas-thermometer values [Berman and Swenson (*22*)]; (open squares) He[4] isotherm values [Keller (*23*)]; (solid squares) He[3] isotherm values [Keller (*23*)]; (solid triangles) preliminary acoustical-thermometer values [Cataland et al. (*24*)]; (solid diamonds) acoustical-thermometer values obtained in the work described. T_x represents actual values of temperature as determined by the experimenters.

ppm

[..]
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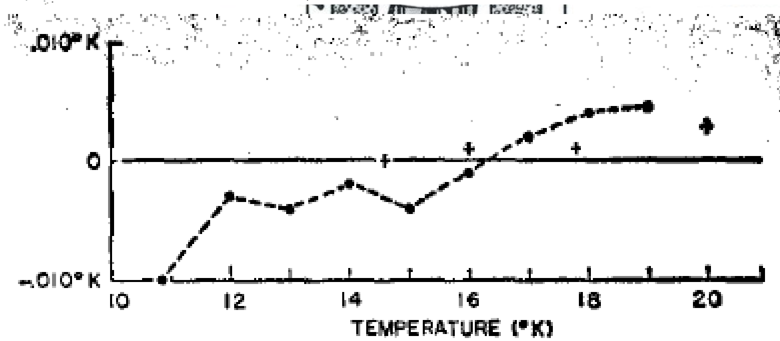

Fig. 5. A comparison between the acoustically derived temperature scale [NBS Provisional Scale 2-20 (1965)] and the NBS (1955) temperature scale (*25*). The difference in the values of the two scales, as indicated by two germanium resistors, is plotted as a function of the Kelvin temperature.

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Gas-filled spherical resonators: Theory and experiment

Michael R. Moldover
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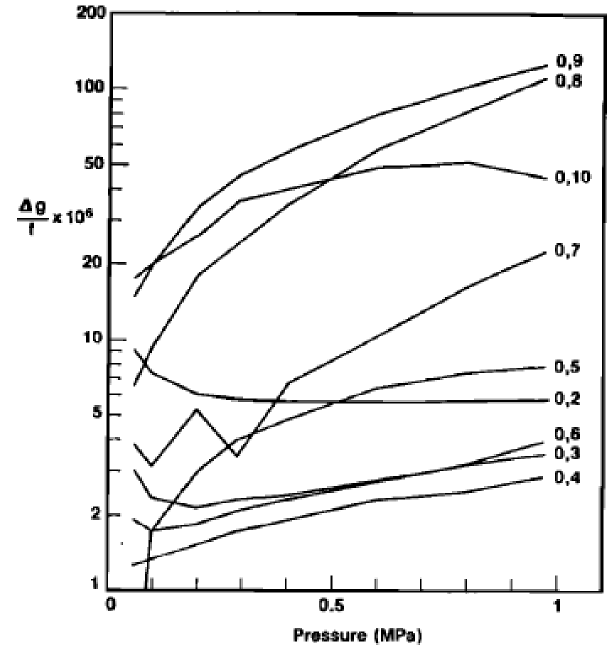
12 Granville Drive, Silver Spring, Maryland 20901

(Received 9 August 1985; accepted for publication 20 October 1985)

1979 - 1988

$$u = \frac{2\pi a}{z_N}\left(f_N - \Delta f_{\text{thermal}} - \Delta f_{\text{viscous}} - \Delta f_{\text{shell}} - \Delta f_{\text{ducts}} \right)$$

$$g_N = g_{\text{bulk}} + g_{\text{thermal}} + g_{\text{viscous}} + g_{\text{ducts}}$$



VOLUME 60, NUMBER 4 PHYSICAL REVIEW LETTERS 25 JANUARY 1988

Measurement of the Universal Gas Constant *R* Using a Spherical Acoustic Resonator

1988

M. R. Moldover, J. P. M. Trusler,[a] and T. J. Edwards[b]
Thermophysics Division, National Bureau of Standards, Gaithersburg, Maryland 20899

J. B. Mehl
Physics Department, University of Delaware, Newark, Delaware 19716

and

R. S. Davis
Length and Mass Division, National Bureau of Standards, Gaithersburg, Maryland 20899

(Received 6 November 1987)

$$k = R/N_A = (1.380\,651\,3 \pm 0.000\,002\,5)\times 10^{-23}\ \text{J mol}^{-1}\ \text{K}^{-1} \quad (1.8\ \text{ppm})$$

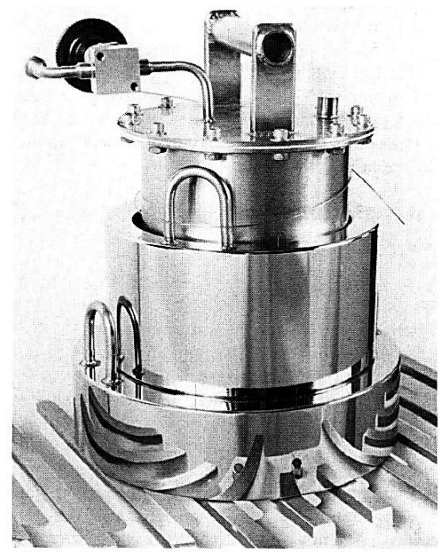


Figure 10. Photograph of weights and weighing bottle ready to be loaded into the balance.

National Institute of Standards and Technology
U.S. Department of Commerce

PHYSICAL REVIEW A VOLUME 34, NUMBER 4 OCTOBER 1986

1986

Measurement of the ratio of the speed of sound to the speed of light

James B. Mehl
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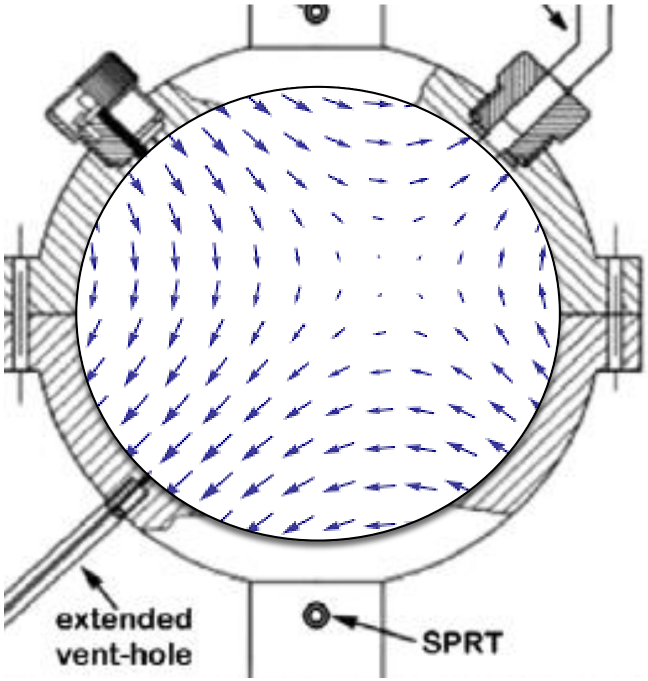
Michael R. Moldover
Thermophysics Division, National Bureau of Standards, Gaithersburg, Maryland 20899

(Received 2 June 1986)

$$u(p,T) = f_{\mathrm{ac}}(p,T)\frac{2\pi a(p,T)}{z_{\mathrm{ac}}}$$

$$c(p,T) = \langle f_{\mathrm{mw}}(p,T)\rangle \frac{2\pi a(p,T)}{z_{\mathrm{mw}}}$$

$$\frac{u(p,T)}{c(p,T)} = \frac{f_{\mathrm{ac}}(p,T)}{\langle f_{\mathrm{mw}}(p,T)\rangle}\frac{z_{\mathrm{mw}}}{z_{\mathrm{ac}}}$$



$$[\text{temperature}] = \frac{[\text{energy}]}{[k_{\mathrm{B}}]} = \frac{[\text{mass}][\text{velocity}]^2}{[k_{\mathrm{B}}]} = \frac{[\text{mass}]}{[k_{\mathrm{B}}]} c_0^{\,2} \lim_{p\to 0} \frac{[\text{frequency}]^2_{\text{sound}}}{[\text{frequency}]^2_{\text{light}}}$$

1999

217 K to 303 K

Thermodynamic Temperatures of the Triple Points of Mercury and Gallium and in the Interval 217 K to 303 K

NIST

M. R. Moldover, S. J. Boyes[1], C. W. Meyer, and A. R. H. Goodwin[2]

$$\frac{T}{T_{\mathrm{TPW}}}=\lim_{p\to 0}\left(\frac{u^2(p,T)}{u^2(p,T_{\mathrm{TPW}})}\right)$$

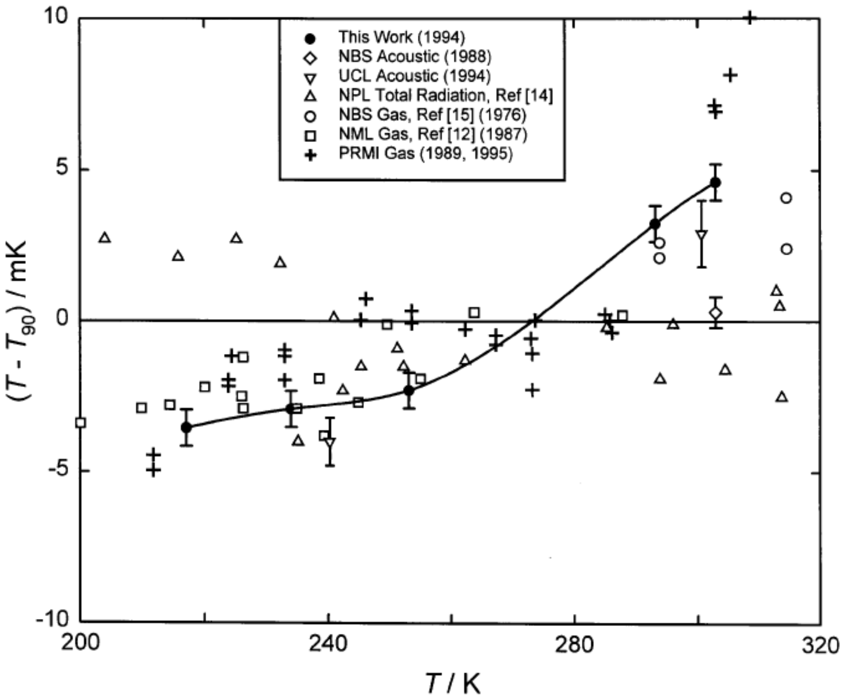


Table 2. Standard uncertainties $u_s\times10^6$ from various sources in the re-determination of $(T-T_{90})/T$ is calculated twice: first, including Rows 4 and 5, but not Rows 6 and 7; and second, including

Source	217 K	234 K
	Microwave values for $[a(T)/a(T_w)]^2$	
1. Discrepancies among triplets	0.32	0.27
2. $\delta_m(T)$ calc. from resistivity ($0.04\times\rho$)	0.39	0.25
3. $\delta_m(T)$ calc. $-\delta_m(T)$ meas.	0.24	0.24
	Acoustic (isotherm fits)	
4. Uncertainty of $A_0(T_w)/a^2$	1.67	1.67
5. Uncertainty of $A_0(T)/a^2$	2.31	1.85
	Acoustic (surface fit)	
6. Uncertainty of $A_0(T_w)/a^2$	0.25	0.25
7. Uncertainty of $A_0(T)/a^2$	0.52	0.38
	Thermometry	
8. SPRT & bridge repeat. @ T_w (10 μΩ)	0.46	0.43
9. Difference between calibrations	0.22	0.15
10. Temperature gradient	0.46	0.43
11. Non-uniqueness of ITS-90	0.9	0.0
	Additional sources	
12. Thermal conductivity (0.3 %)	0.20	0.20
13. Uncertainty of pressure zero	0.21	0.12
14. Isotherm fits: RSS	3.13	2.62
15. Surface fit: RSS	1.42	0.92
16. Isotherm fits: RSS×(T/mK)	0.68	0.61
17. Surface fit: RSS×(T/mK)	0.31	0.22

Primary acoustic thermometry between $T = 90$ K and $T = 300$ K

J. Chem. Thermodynamics 2000, 32, 1229–1255

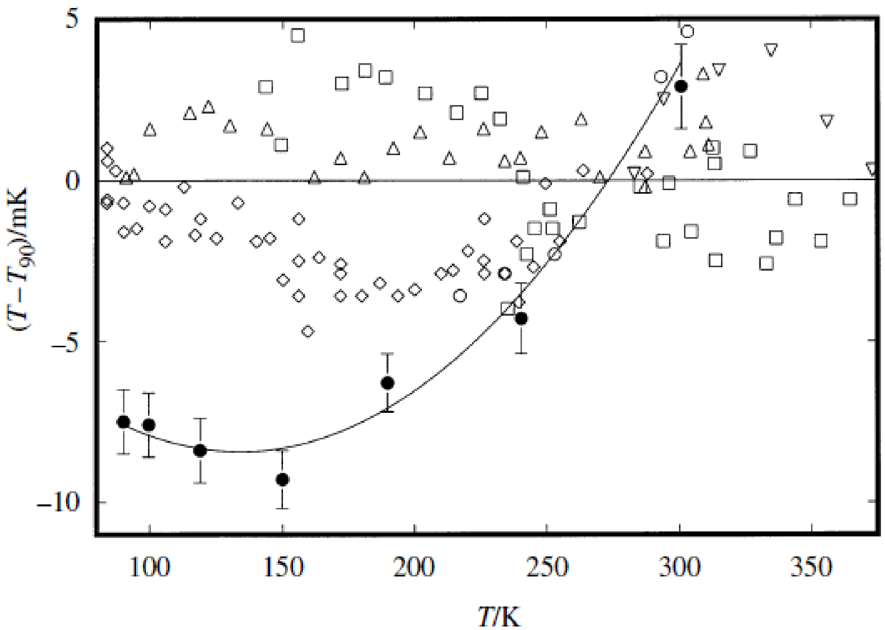
M. B. Ewing and J. P. M. Trusler

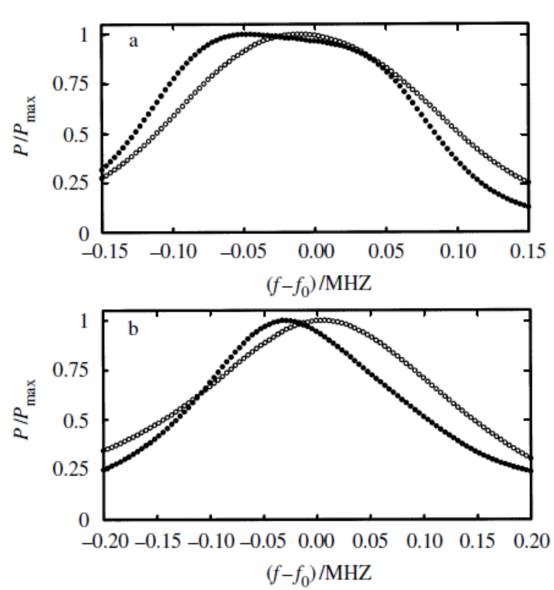
University College London

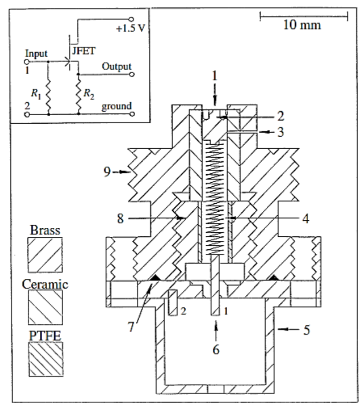
Imperial College London

2000

90 K to 300 K







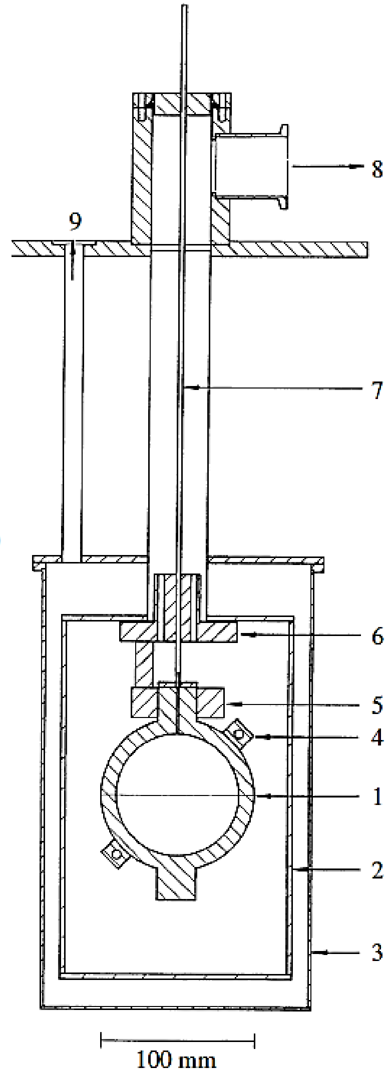


FIGURE 1. The spherical resonator and its thermal environment: 1, spherical resonator; 2, isothermal shield; 3, vacuum jacket; 4, thermometer mount; 5, copper block; 6, copper block; 7, inlet tube; 8, to vacuum; 9, to vacuum guage.

2003

303 K, 430 K, 505 K

Progress in Primary Acoustic Thermometry at NIST: 273 K to 505 K

G. F. Strouse, D. R. Defibaugh, M. R. Moldover, and D. C. Ripple

NIST

TABLE 3. NIST Acoustic Thermometer uncertainty budget in millikelvins for the determination of $T - T_{90}$.

	Ga MP 303 K	In FP 430 K	Sn FP 505 K
u (k=1)	0.6	1.5	3.0
$(T - T_{90})$ / mK	4.7	8.8	10.7

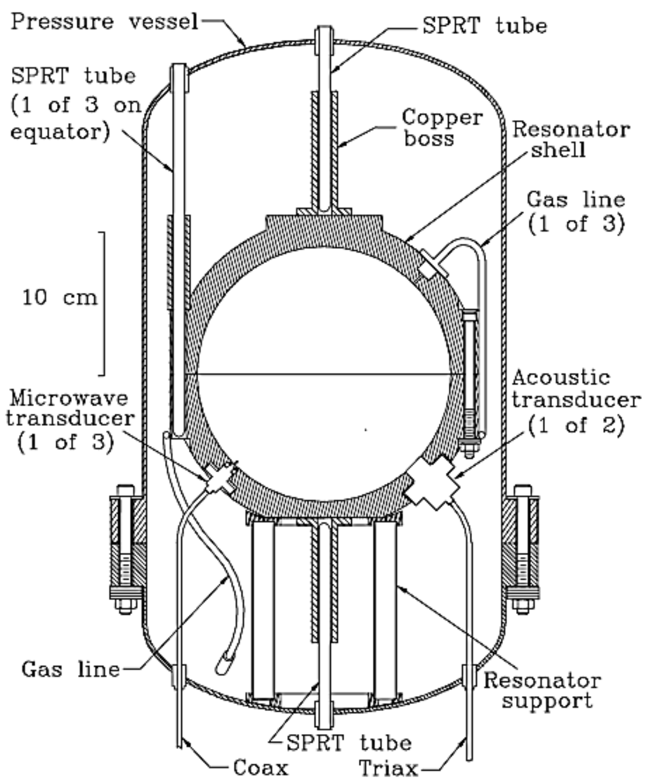


FIGURE 1. Schematic of the NIST acoustic thermometer inside the pressure vessel.

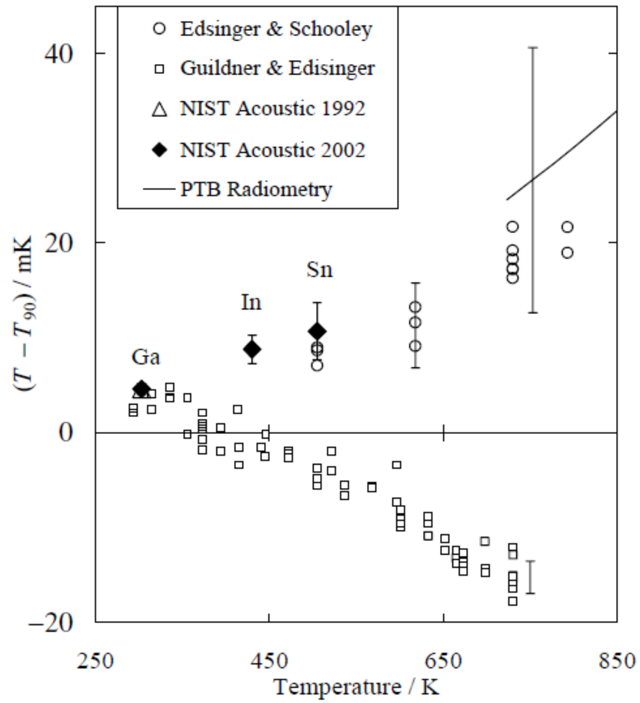


FIGURE 3. $T - T_{90}$ and corresponding uncertainty ($k = 1$) values for the NIST Acoustic Thermometer and results from the literature.

INSTITUTE OF PHYSICS PUBLISHING METROLOGIA
Metrologia **41** (2004) 74–98 PII: S0026-1394(04)72948-5

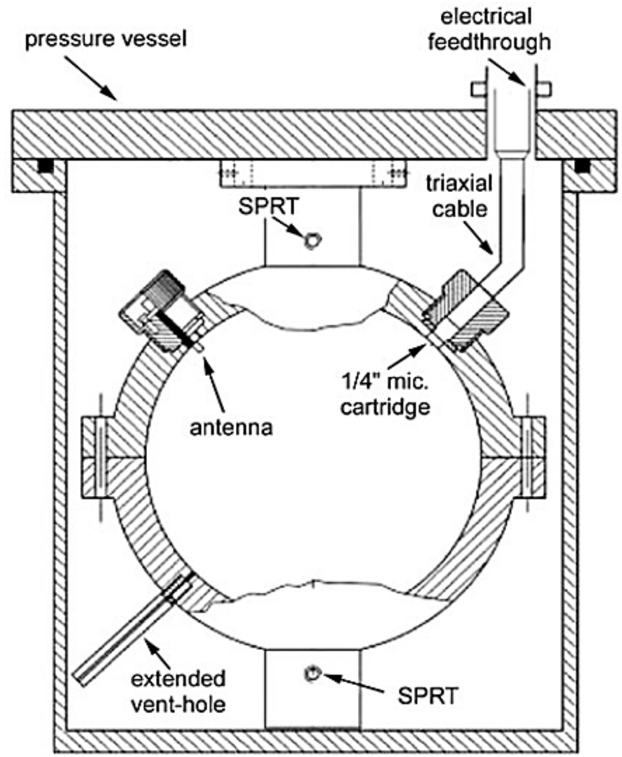
2004

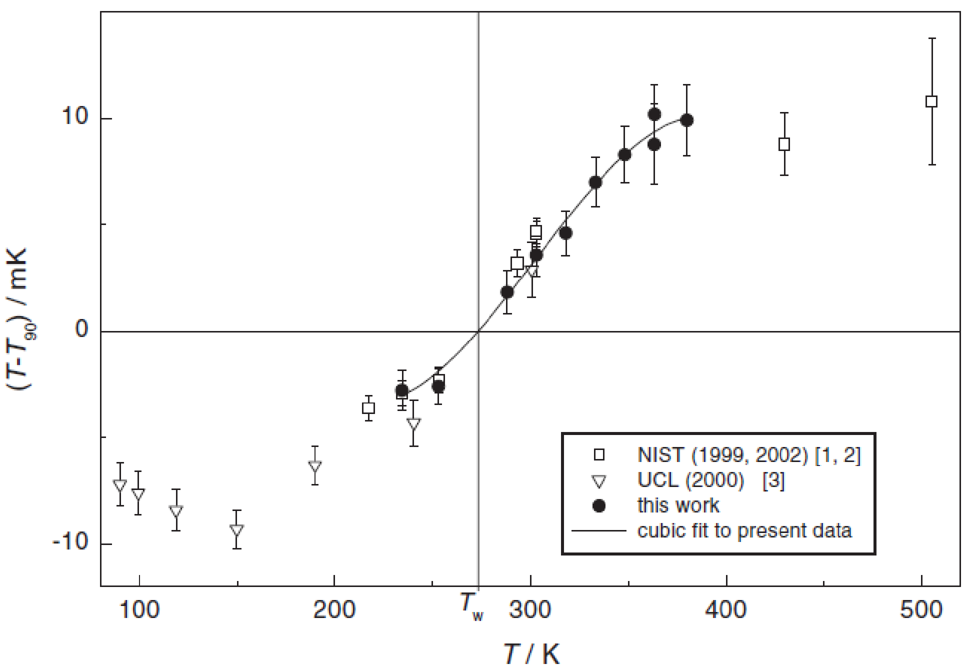
234 K to 380 K

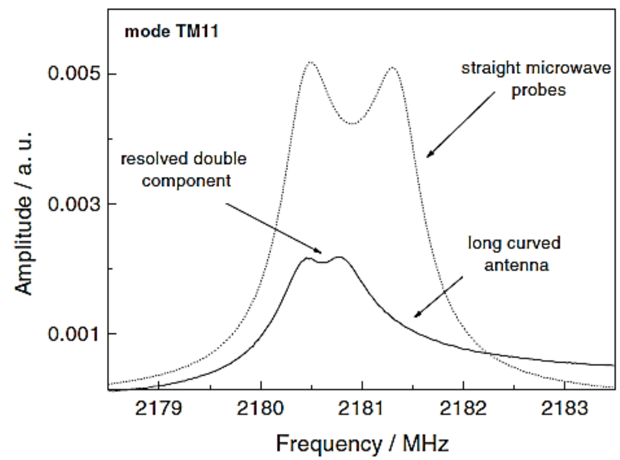
Acoustic measurements of the thermodynamic temperature between the triple point of mercury and 380 K

G Benedetto[1], R M Gavioso[1], R Spagnolo[1], P Marcarino[2] and A Merlone[2]

[1] Acoustics Department, IEN, Istituto Elettrotecnico Nazionale Galileo Ferraris, Torino, Italy
[2] Thermometric Division, IMGC-CNR, Istituto di Metrologia G Colonnetti, Torino, Italy







REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 75, NUMBER 10 OCTOBER 2004

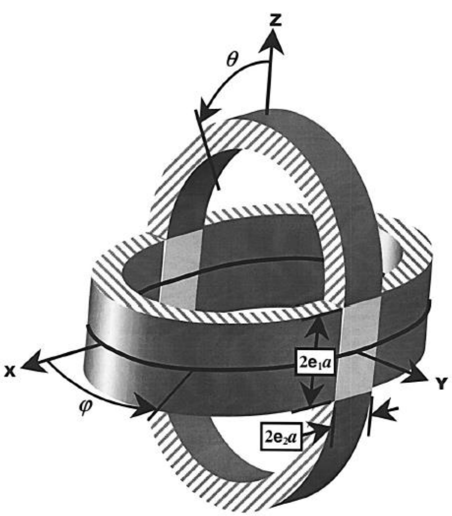
2004

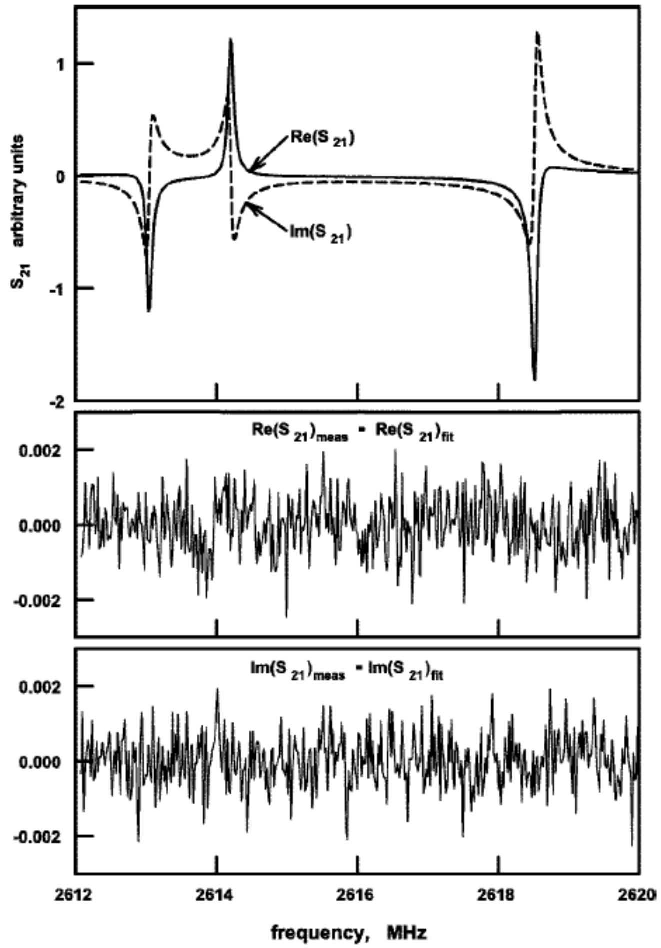
Quasi-spherical cavity resonators for metrology based on the relative dielectric permittivity of gases

Eric F. May,[a] Laurent Pitre,[b] James B. Mehl,[c] Michael R. Moldover,[d] and James W. Schmidt
Process Measurement Division, National Institute of Standards and Technology, Gaithersburg, Maryland 20899-8360

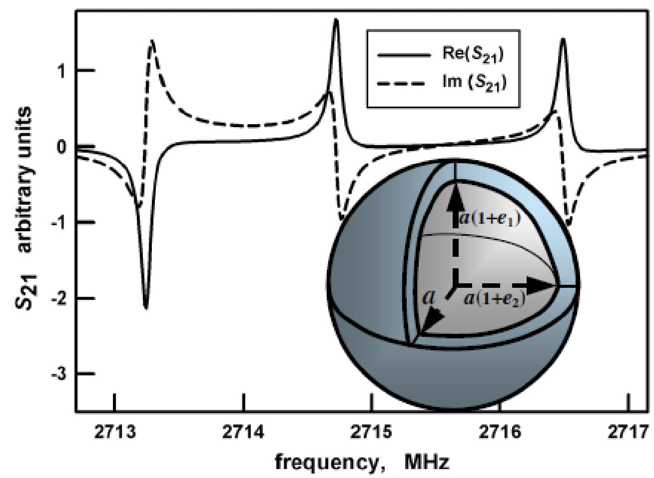
NIST National Institute of Standards and Technology U.S. Department of Commerce

(Received 20 April 2004; accepted 23 June 2004; published 22 September 2004)





improved frequency measurement



$$\frac{\sigma f}{f} \approx 1 \cdot 10^{-8}$$

precision

$$\frac{\sigma f}{f} < 1 \cdot 10^{-6}$$

accuracy

INSTITUTE OF PHYSICS PUBLISHING METROLOGIA
Metrologia 43 (2006) 142–162 doi:10.1088/0026-1394/43/1/020

2006

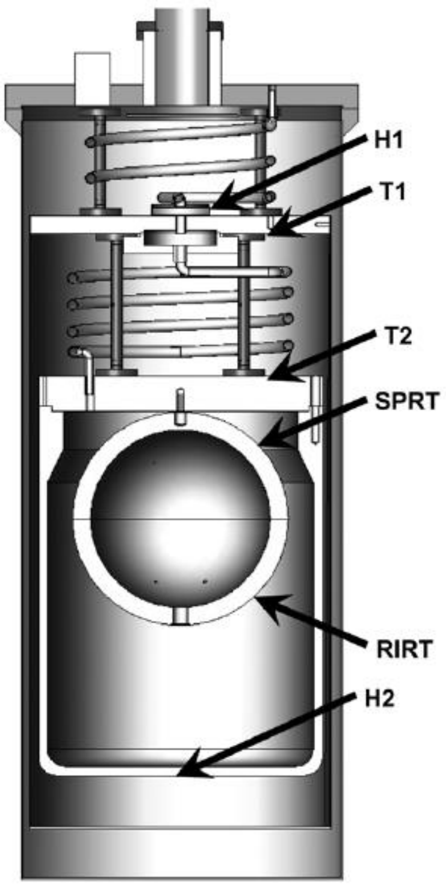
77 K to 273 K

Acoustic thermometry: new results from 273 K to 77 K and progress towards 4 K

Laurent Pitre[1,2], Michael R Moldover[1] and Weston L Tew[1]

NIST

LNE
Le progrès, une passion à partager



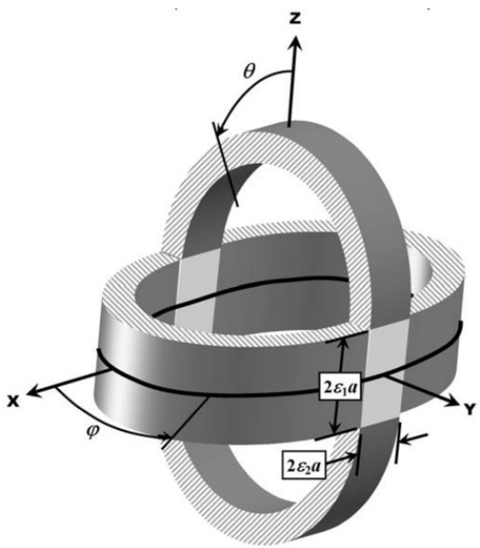
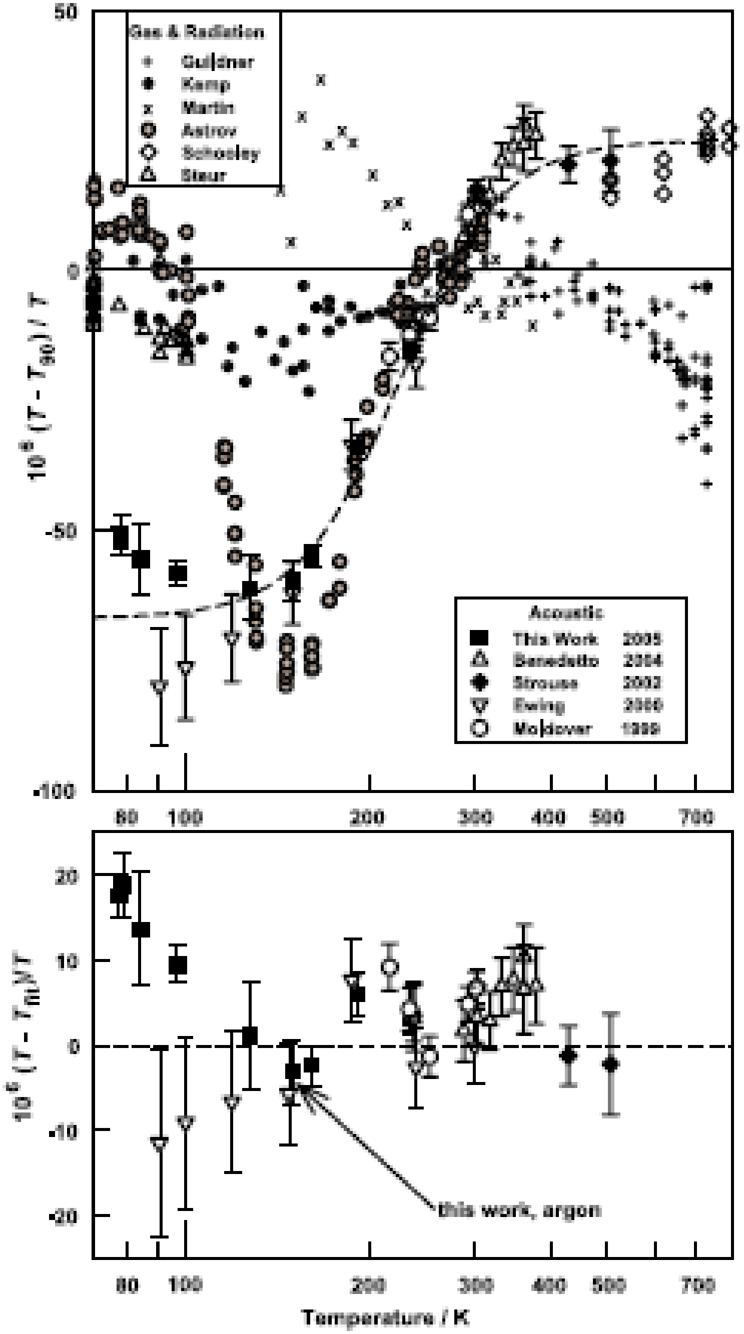


Figure 1. Cylindrical and planar portions of a quasi-sphere.

Metrologia, **41** (2004) 295–304



2007

271 K to 552 K

Int J Thermophys (2007) 28:1789–1799
DOI 10.1007/s10765-007-0255-2

NIST

Acoustic Thermometry Results from 271 to 552 K

D. C. Ripple · G. F. Strouse · M. R. Moldover

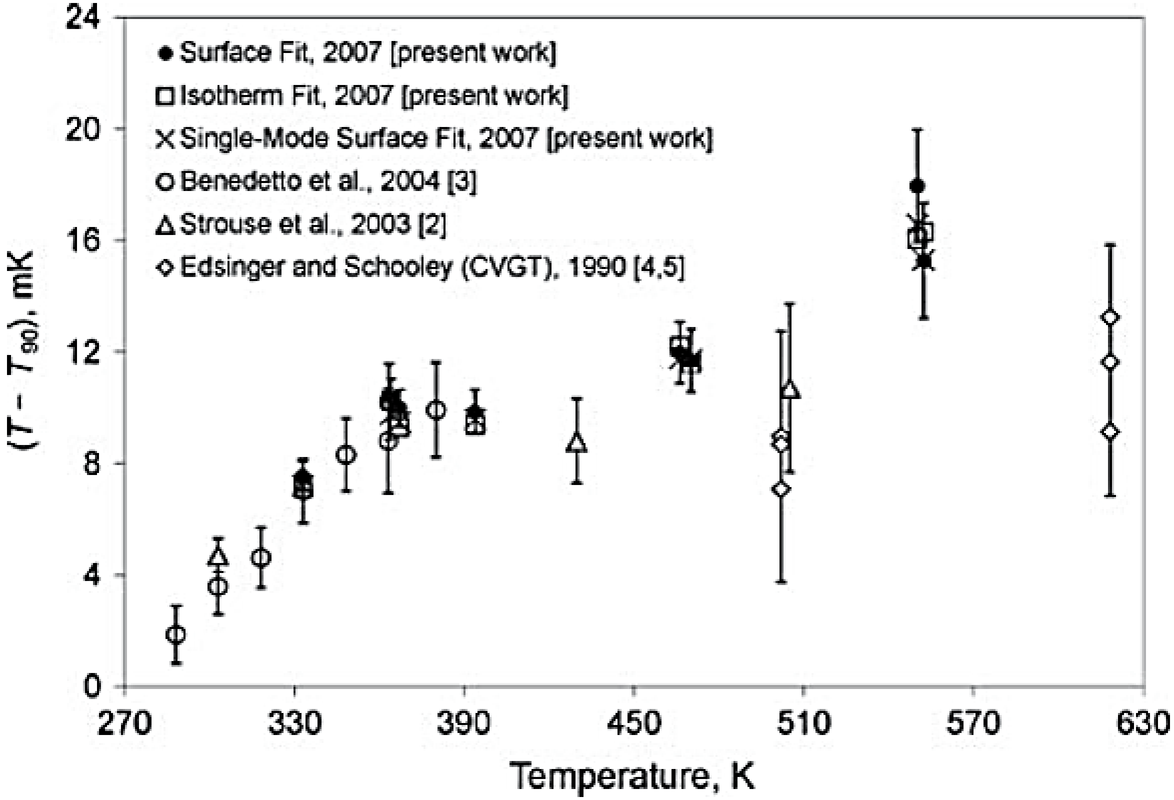


Fig. 1 Deviation of measured thermodynamic temperature T from T_{90} for recent acoustic determinations and the constant-volume gas thermometry (CVGT) of Edsinger and Schooley [4] and Schooley [5]. For the present work, standard uncertainties are only shown for the recommended Surface Fit

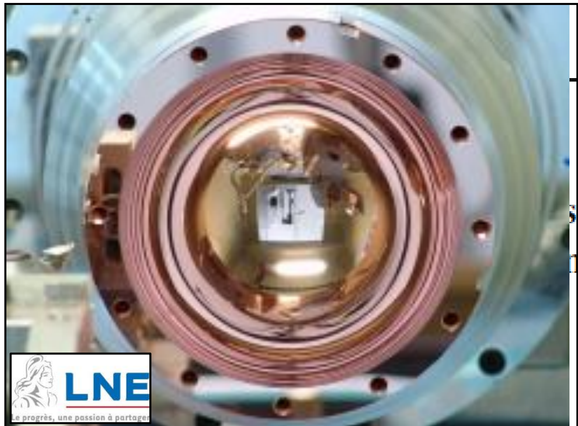
coordinator J. Fischer

2008 -2011 iMERA- Plus Research Project

Determination of the Boltzmann constant for the redefinition of the kelvin

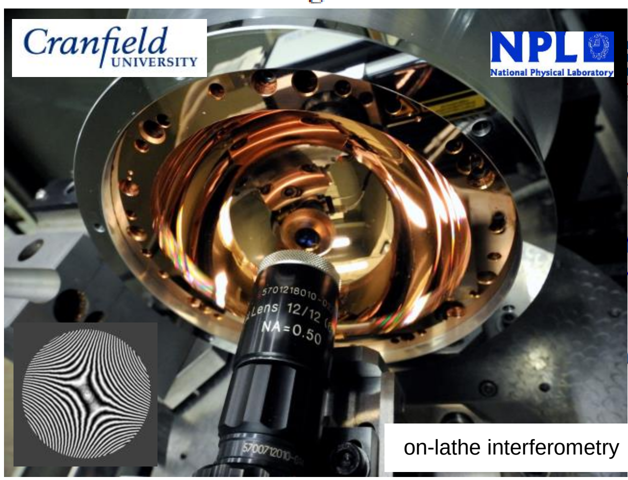
National Institute of Standards and Technology
U.S. Department of Commerce

PTB · INRiM Istituto Nazionale di Ricerca Metrologica · Universidad de Valladolid · CEM Centro Español de Metrología · LNE · IRMM Institute for Reference Materials and Measurements · NPL National Physical Laboratory



P. A. Giuliano Albo · R. Cuccaro ·
L. Pitre · D. Truong

14 15 16 17 18 19 20 21
Frequency, kHz

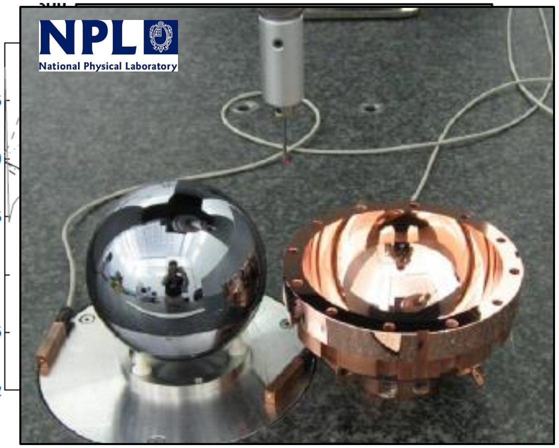


on-lathe interferometry

IOP Publishing Metrologia
Metrologia 47 (2010) 588–604 doi:10.1088/0026-1394/47/5/010

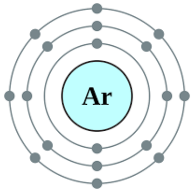
Characterization of the volume and shape of quasi-spherical resonators using coordinate measurement machines

M de Podesta[1], E F May[2], J B Mehl[3], L Pitre[4], R M Gavioso[5], G Benedetto[5], P A Giuliano Albo[5], D Truong[4] and D Flack[1]

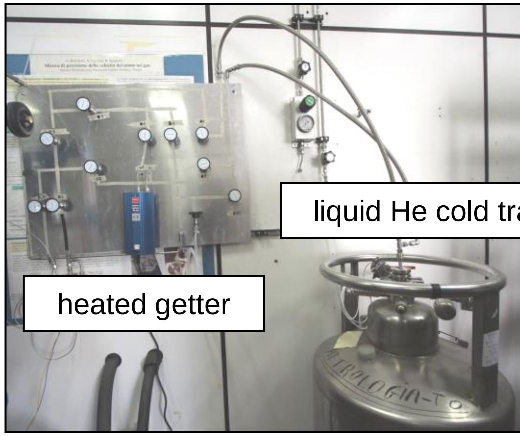


composition (including isotopes) of test gases

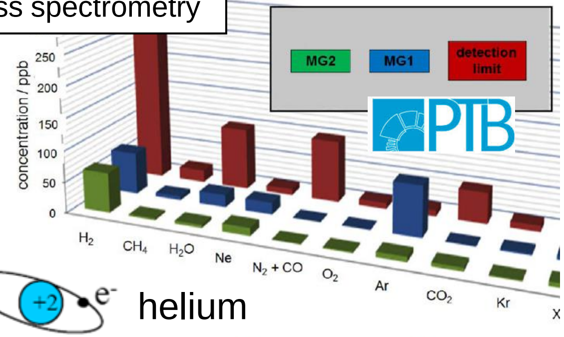
$$\frac{3}{2}kT = \frac{1}{2}mv_{rms}^2$$

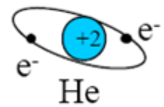


argon



mass spectrometry





helium

ss spectrometric analysis of gas impurities in two helium samples

$$0.03\times10^{-6} < {}^3\mathrm{He}/{}^4\mathrm{He} < 1\times10^{-6}$$

$$\Delta M/M < 0.25\times10^{-6}$$

2010

Contents lists available at ScienceDirect

International Journal of Mass Spectrometry

journal homepage: www.elsevier.com/locate/ijms

Preparation of argon Primary Measurement Standards for the calibration of ion current ratios measured in argon

S. Valkiers[a,*], D. Vendelbo[a], M. Berglund[a], M. de Podesta[b]

[a] Institute for Reference Materials and Measurements, EC-JRC, B-2440 Geel, Belgium
[b] National Physical Laboratory, Hampton Road, Teddington TW11 0LW, UK

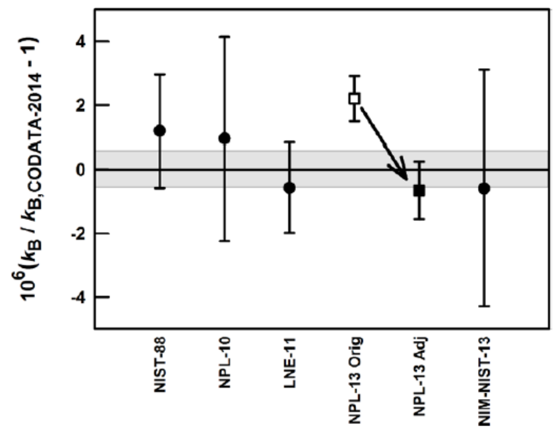
$$u_r\left(M_{\mathrm{Ar}}\right) \le 0.1\ \mathrm{ppm}$$

IOP Publishing | Bureau International des Poids et Mesures — Metrologia

Metrologia 52 (2015) S394–S409 — doi:10.1088/0026-1394/52/5/S394

Improving acoustic determinations of the Boltzmann constant with mass spectrometer measurements of the molar mass of argon

Inseok Yang[1], Laurent Pitre[2], Michael R Moldover[3], Jintao Zhang[4], Xiaojuan Feng[4] and Jin Seog Kim[1]



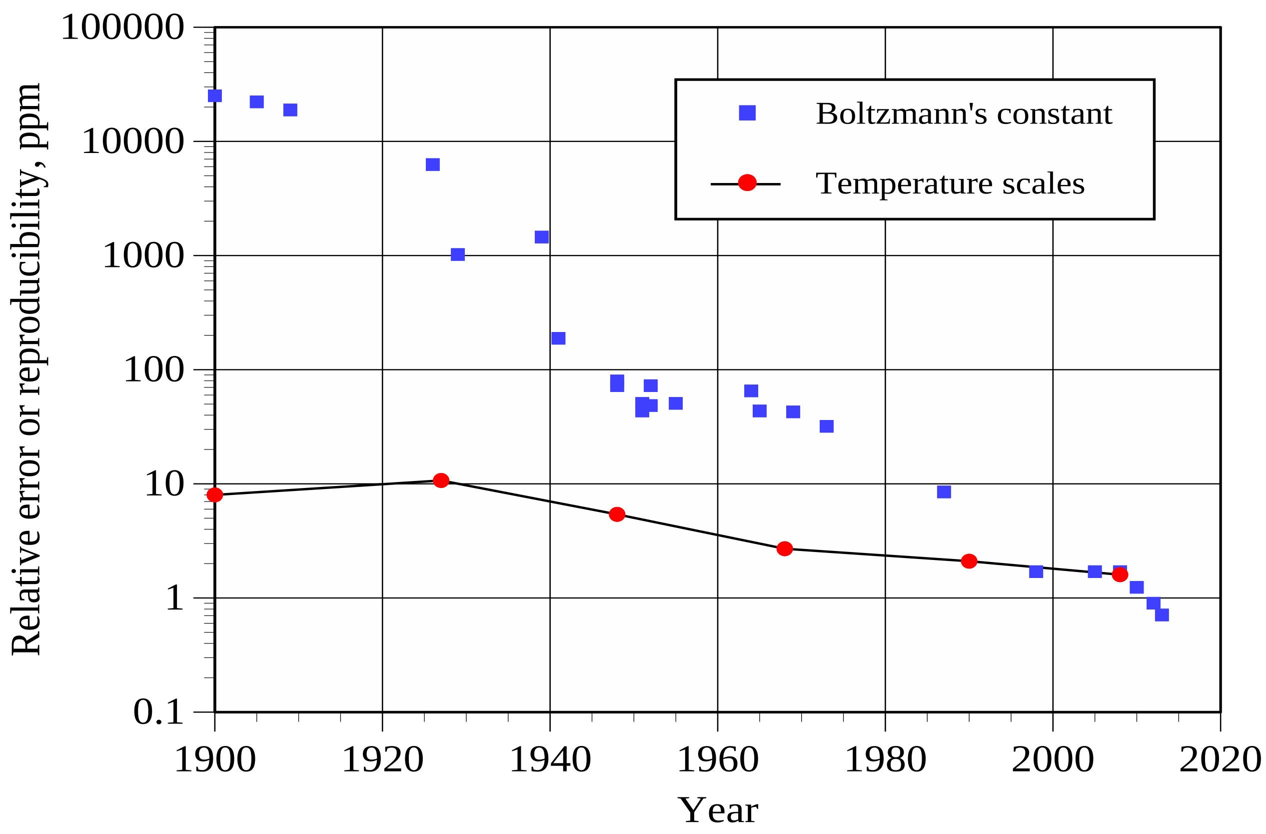
2015

$$u_r\left(M_{\mathrm{Ar}}\right) \cong 0.6\ \mathrm{ppm}$$

june 2017

$$u_r\left(M_{\mathrm{Ar}}\right) \cong 0.4\ \mathrm{ppm}$$

Thermodynamics vs. ITS

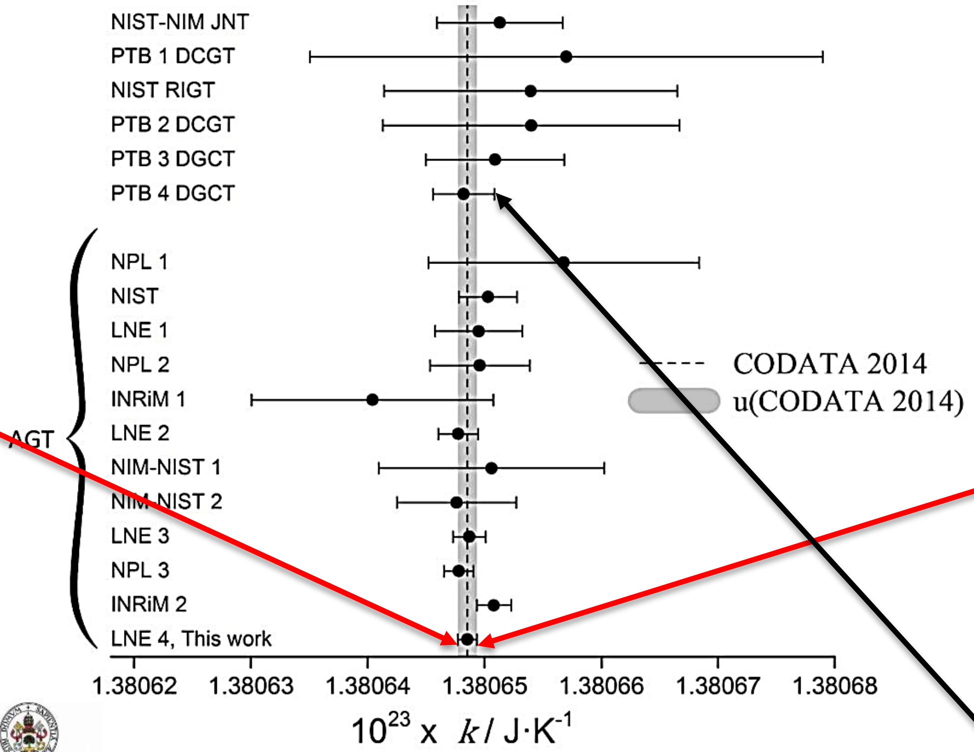


Metrologia Boltzmann Special Issue 2015, R. White and J. Fischer

Figure 1: Relative uncertainty in the value of **Boltzmann's constant**. Also shown is the relative reproducibility of the **practical temperature scales, in the vicinity of 100 °C**.

determinations of *k* with AGT and other methods 2017 (yesterday)

$u_r(k) = 0.59 \times 10^{-6}$



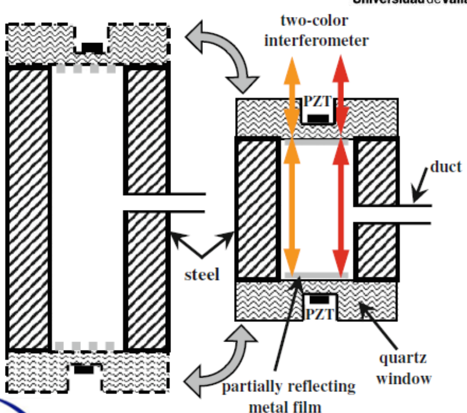
$u_r(k) = 0.70 \times 10^{-6}$

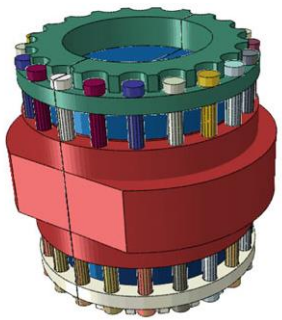
NPL National Physical Laboratory

$u_r(k) \cong 7.5 \times 10^{-6}$

CEM Centro Español de Metrología

Universidad de Valladolid





NIM

NIST National Institute of Standards and Technology U.S. Department of Commerce

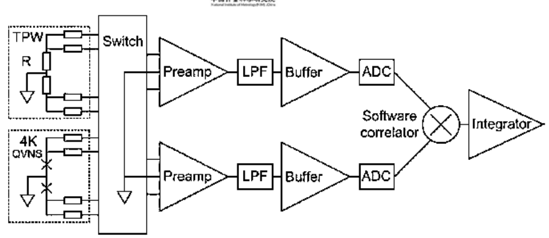
AGT with cylindrical cavities

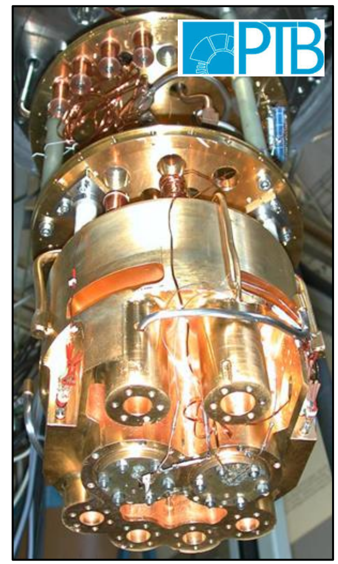
$u_r(k) \cong 2 \times 10^{-6}$

Johnson noise thermometry (JNT)

NIM

NIST National Institute of Standards and Technology U.S. Department of Commerce



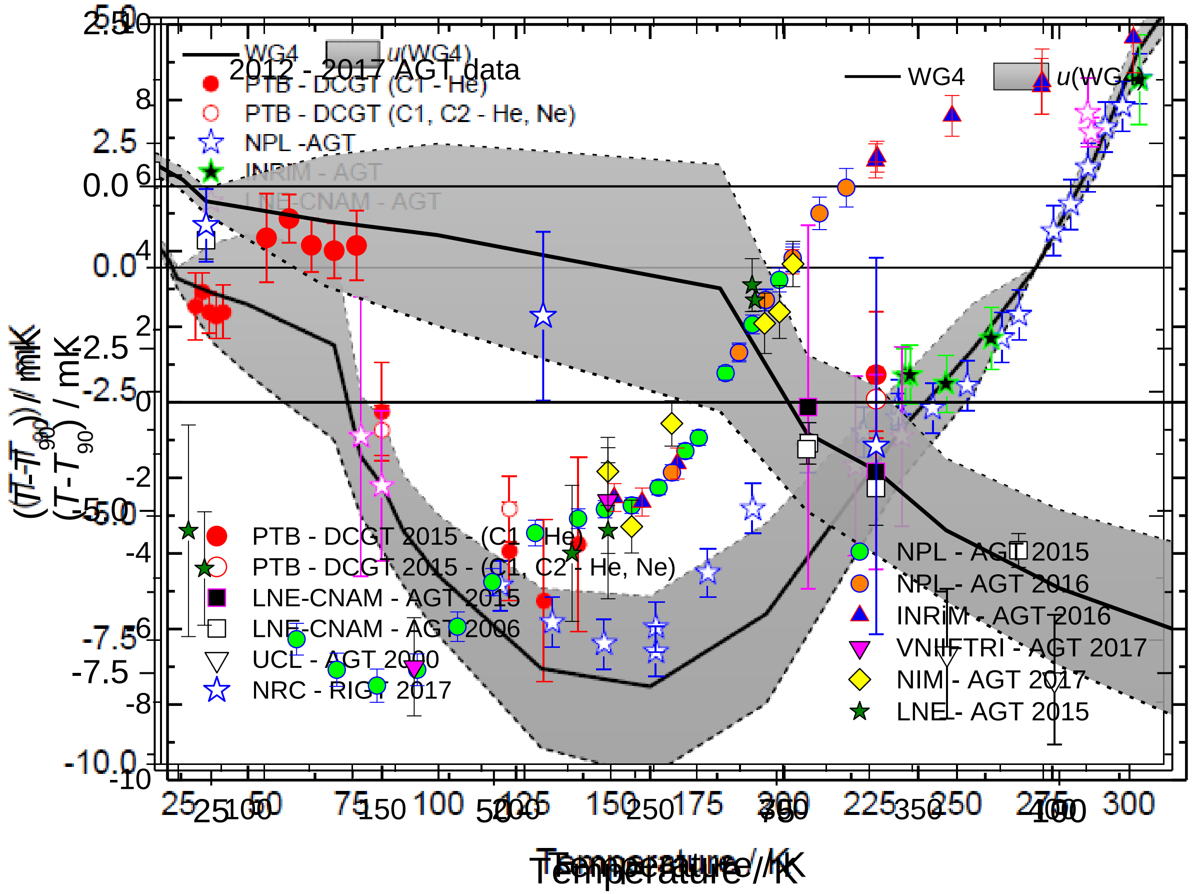


$u_r(k) = 1.95 \times 10^{-6}$

coordinator G. Machin

2012 - 2015 EMRP Research Project

Implementing the new kelvin - InK



2016 -2019 EMRP Research Project

Implementing the new kelvin 2 - InK2

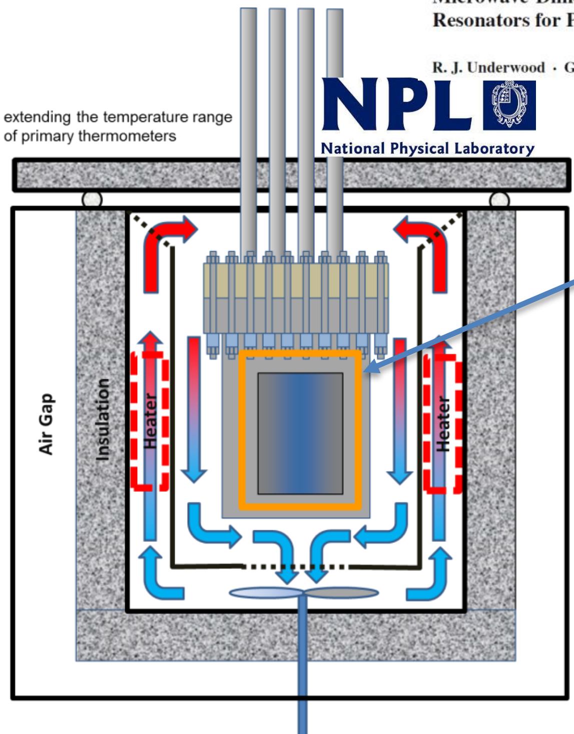
coordinator G. Machin

T-T_{90} by Acoustic Gas Thermometry (AGT) between 430 K and 933 K

Int J Thermophys (2014) 35:971–984
DOI 10.1007/s10765-014-1726-x

Microwave-Dimensional Measurements of Cylindrical Resonators for Primary Acoustic Thermometry

R. J. Underwood · G. J. Edwards

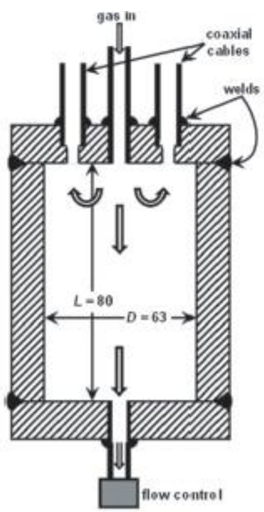


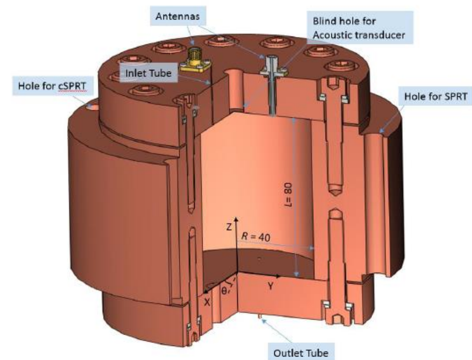
Inconel pressure vessel 1 MPa @ 1000 K

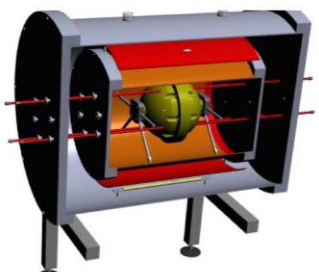
IOP Publishing — Metrologia
Metrologia 50 (2013) 219–226 doi:10.1088/0026-1394/50/3/219

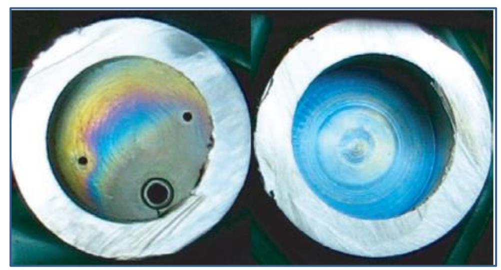
Microwave-cavity measurements for gas thermometry up to the copper point

XiaoJuan Feng[1], Keith A Gillis[2], Michael R Moldover[2] and James B Mehl[2,3]









EMRP
European Metrology Research Programme
Programme of EURAMET
The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union

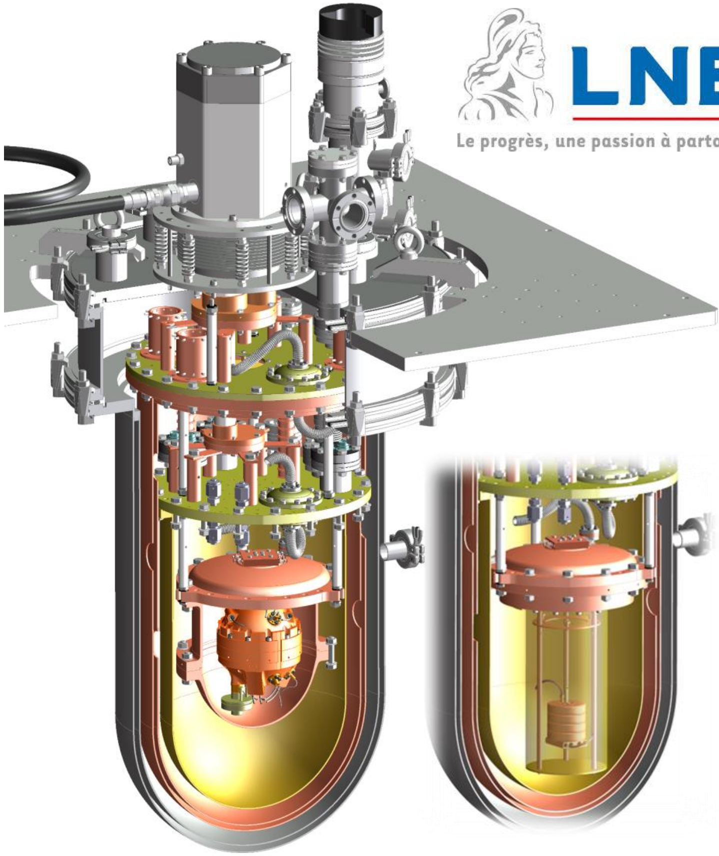
NPL National Physical Laboratory

EURAMET

coordinator G. Machin

2016 -2019 EMRP Research Project
Implementing the new kelvin 2 - InK2

T-T_{90} by Acoustic Gas Thermometry between 5 K and 200 K



LNE
Le progrès, une passion à partager

Benefits

- 2-stage pulse-tube cryostat ➔ no LHe
- 2 thermal shields and 2 vacuum chambers
- minimum temperature < 4 K
- same calorimeter for T and T_{90} realization
- houses a larger number of CSPRTs
- provides good stability especially in ranges 30 K – 77 K and 150 K – 234 K

Risks and drawbacks

- vibrations could affect measurements
- complex design, needed long realization time

AGT at *T* < 4 K

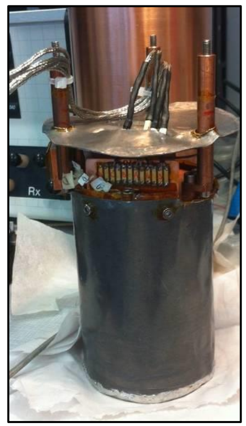
The cold valve

The prototype sphere

LNE

Le progrès, une passion à partager

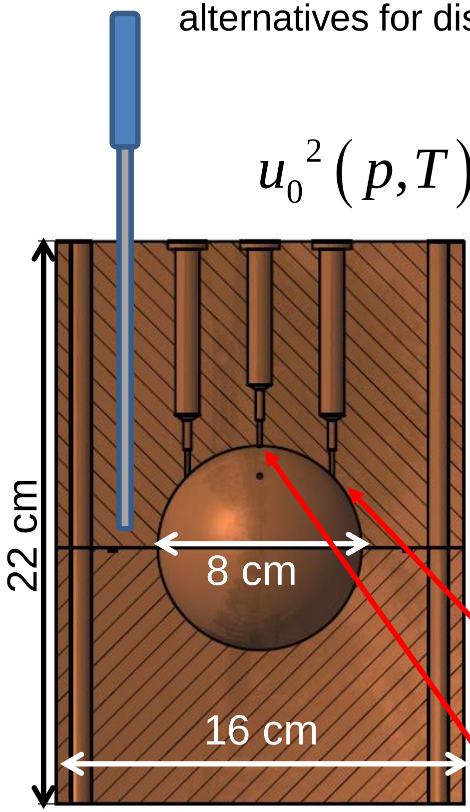
The Cryogenic Current Comparator Amplification and its shield

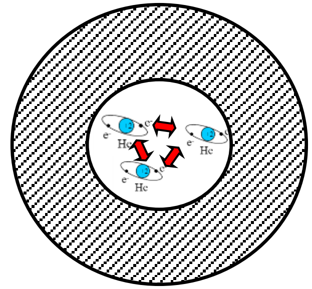


alternatives for dissemination: simplification of primary methods

$$u_0^2(p,T) = \boxed{u^2(p,T)} - \left[A_1(T)\,p + A_2(T)\,p^2 + \ldots \right]$$

measured — calculable for He

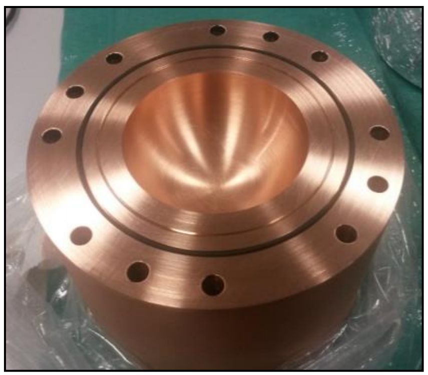


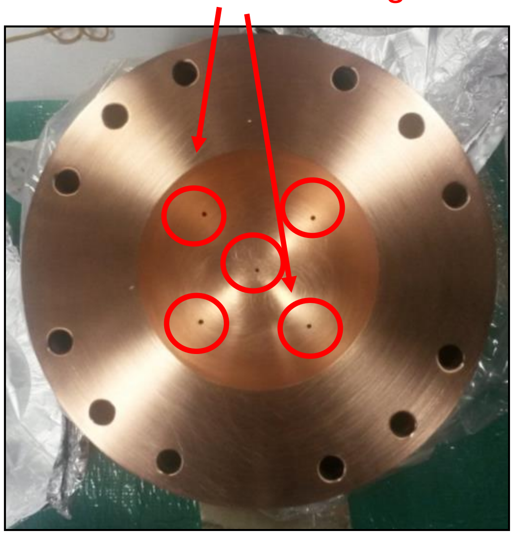


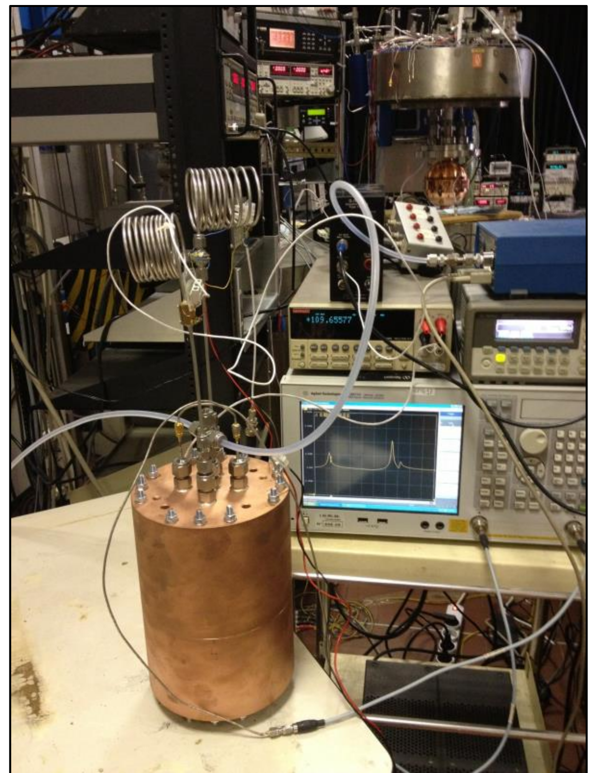
- material: **copper**; shape: **triaxial ellipsoid**; interrnal **radius**: **4 cm**; interrnal **volume**: **260 cm³**; **thick wall to minimize shell coupling**; the cavity is designed to be **vacuum- and pressure tight**
- excitation of **acoustic** and **microwave** resonances by **waveguides**
- embedded thermometer **wells** for **cSPRTs** and **long-stem SPRTs**
- working gas: **helium** (calculable properties) purity maintained by a getter
- temperature range of initial tests: **230 K to 430 K**;
- aimed accuracy: ± 5 ppm

INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

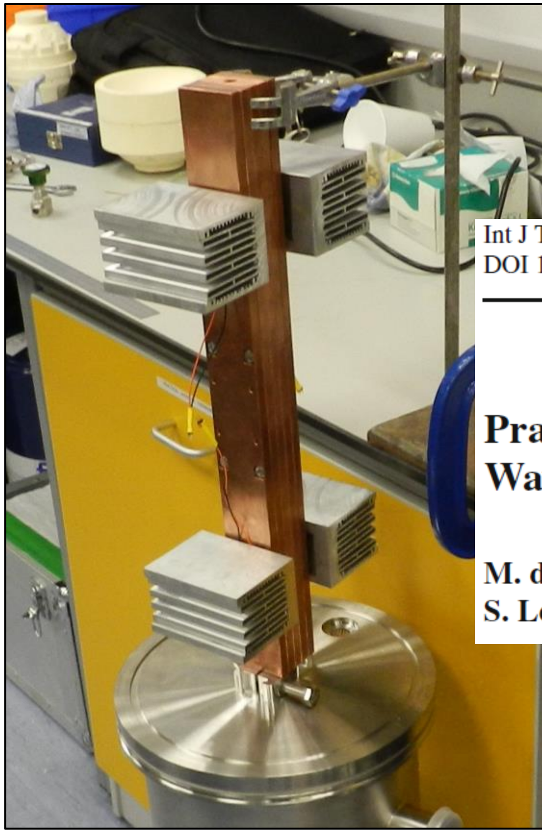
termination of acoustic and microwave waveguides







assembled



calibration zone with Peltiers

Int J Thermophys
DOI 10.1007/s10765-010-0793-x

Practical Acoustic Thermometry with Acoustic Waveguides

M. de Podesta · G. Sutton · R. Underwood ·
S. Legg · A. Steinitz

National Physical Laboratory

Microphone and Loudspeaker in stabilised zone