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The Status and Future of Johnson Noise Thermometry

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2016.6.28, Tempmeko@Zakopane

Outline

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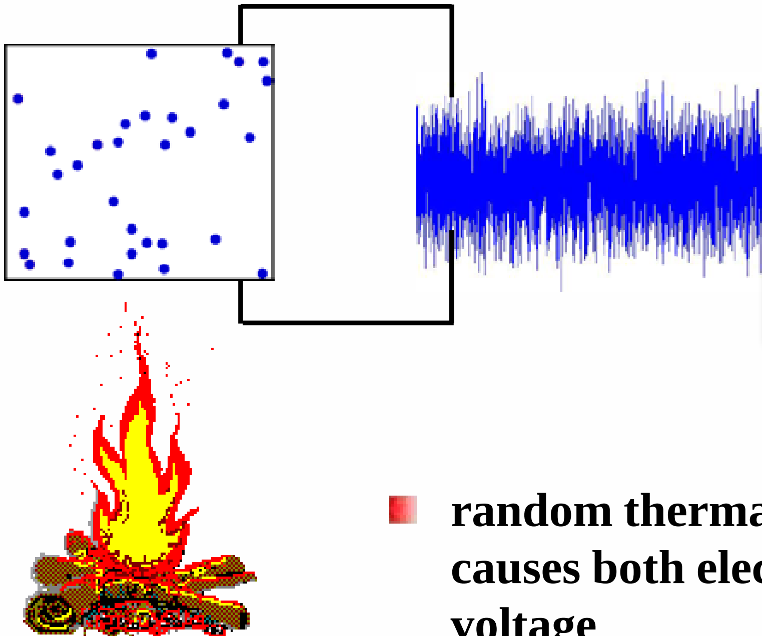
1 **Johnson noise thermometry**

2 Absolute measurement

3 Different implementations and applications

4 Conclusion

Johnson noise

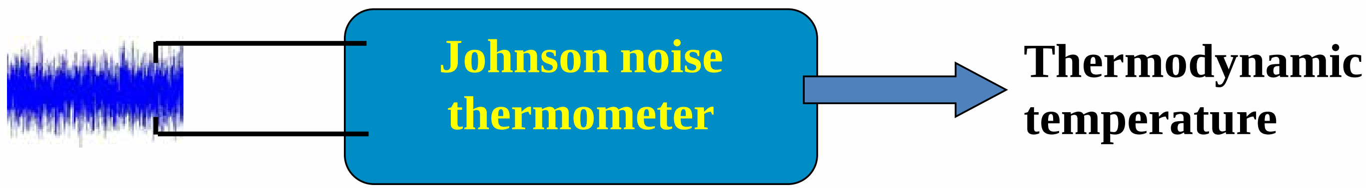


$$S_R = 4hfR\left[\frac{1}{2} + \frac{1}{\exp(hf/kT) - 1}\right] \quad (1)$$

$$\langle V^2 \rangle = 4\,kT\,R\,\Delta f \quad (2)$$

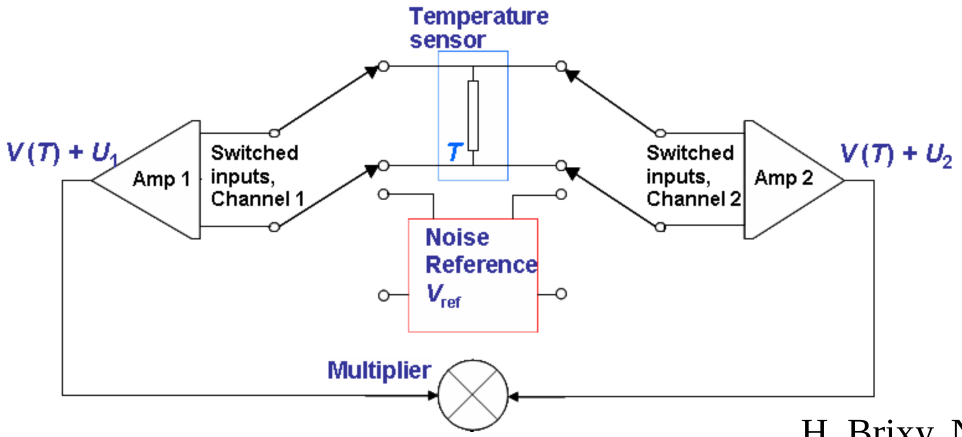
- **random thermal motion of electrons in a conductor causes both electrical resistance and a fluctuating voltage**
- **predicted by Einstein in 1906, measured by Johnson in 1927, and theoretically described by Nyquist in 1928**
- **fluctuation-dissipation theorem**

Johnson noise thermometry



- **Pros:**
  - pure electronic measurement of thermodynamic temperature
  - immune from chemical and mechanical changes in the material properties
  - periodic calibration is not necessary
- **Cons:**
  - extremely small voltage, 100 ohm, 273K, ~1.2nV/√Hz (amplify by 10^5)
  - random, very long time integration ($\sigma \sim 1/\sqrt{t}$) (weeks or months)
  - distributed over wide bandwidths ($\sigma \sim 1/\sqrt{\Delta f}$) (a few hundred kHz)

Switching correlator



$$\frac{T}{T_{ref}} = \frac{\langle V^2(T) \rangle / R}{\langle V_{ref}^2 \rangle / R_{ref}}$$

H. Brixy, Nucl. Instrum. Methods, 97, 75-80 (1971)

- **four wire connection defines the source impedance**
- **eliminates uncorrelated noise by cross-correlation**
- **eliminates the effect of amplifier gain drift by switching**
- **impossible to match both the noise power and frequency response**
- **affected by electronic nonlinearity or narrow bandwidth**
- **relative measurement, uncertainty limited to 10^{-5}**

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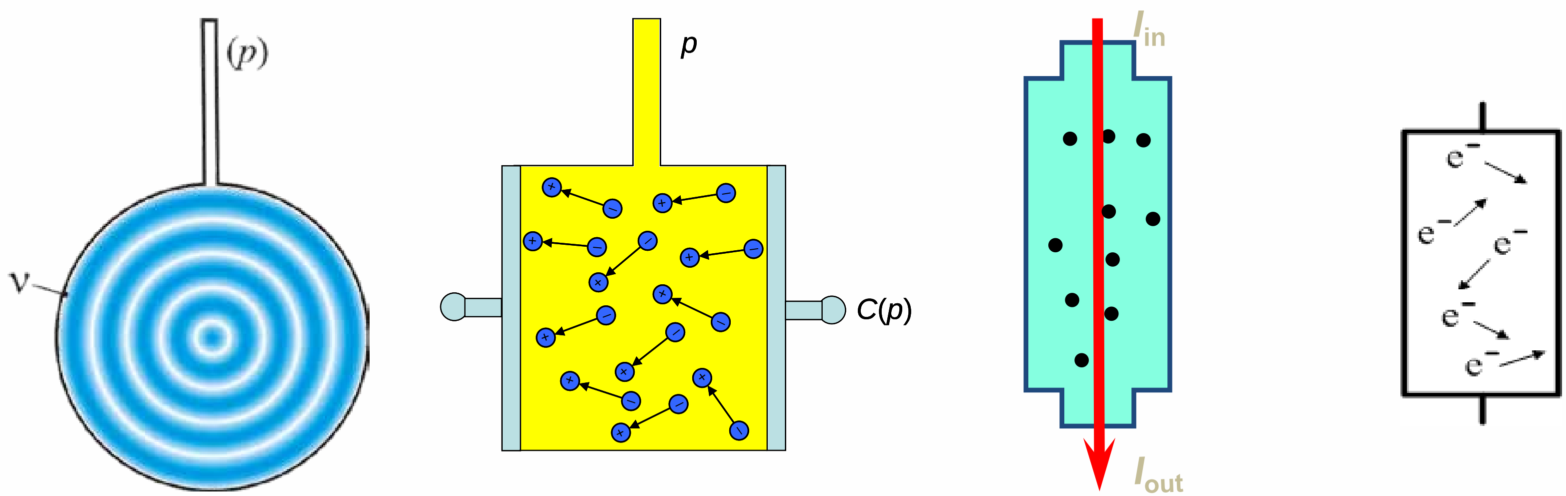
Primary thermometry

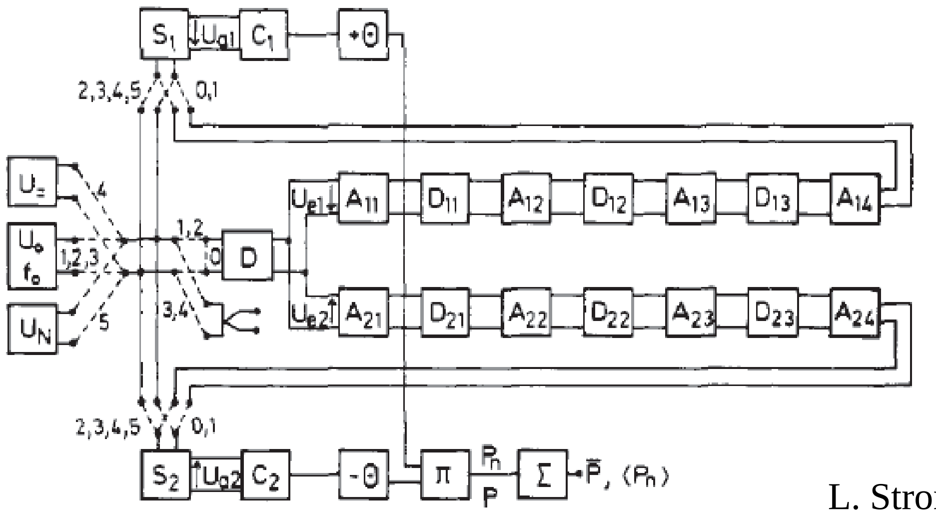


AGT | DCGT | DBT | JNT

- primary gas thermometry limited by non-ideal properties of real gas
- JNT uses electron gas
- pure electronic approach, attracting increasing interest

Joachim Fischer, Metrologia 52 S364, 2015

Early attempt to measure k_B

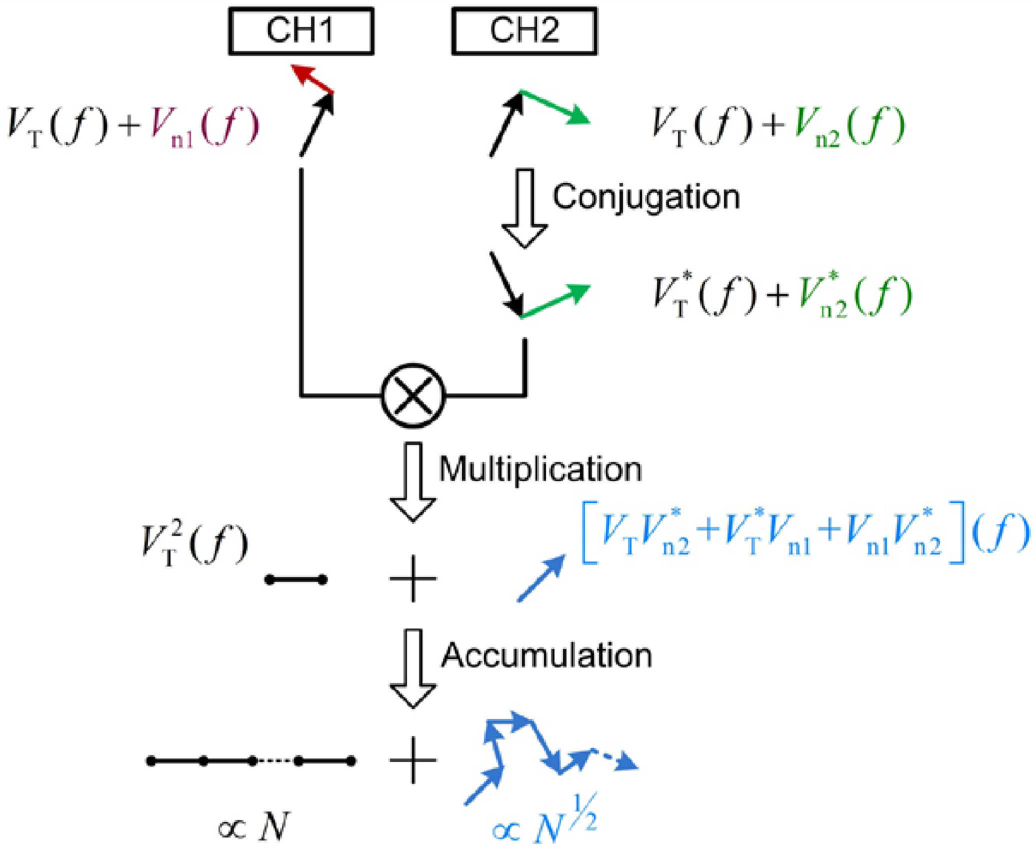


L. Strom, Metrologia 22, 229 (1986)

To achieve 10 ppm in k_B determination:

- **5 additional connections for calibration**
- **keep the temperature of all electronics constant within 0.02 K**
- **measure the divider factors with uncertainty less than 0.5 ppm**
- **accumulate data for more than 1 year!**

Digital signal processing in frequency domain

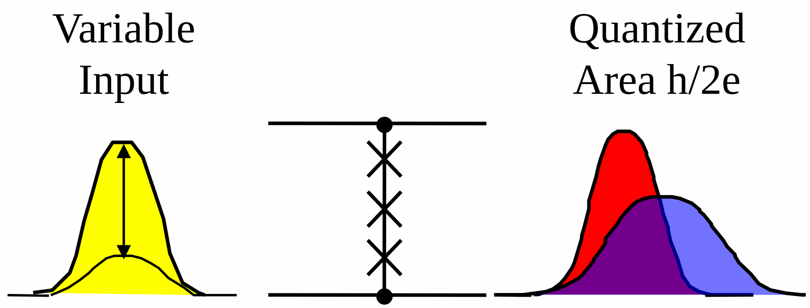


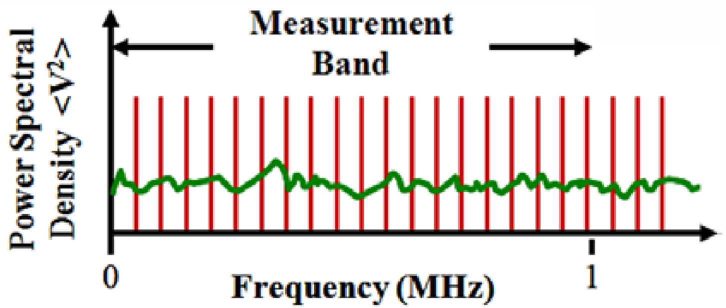
- **Brixy introduced fast and accurate ADC to JNT**
- **Digital signal processing in frequency domain**
- **Bandwidth can be defined accurately**

H. Brixy et. al., Temperature: It's measurement and control in science and industry, vol 6, 993 (1992)

Quantum voltage noise source

Josephson Pulse Quantizer



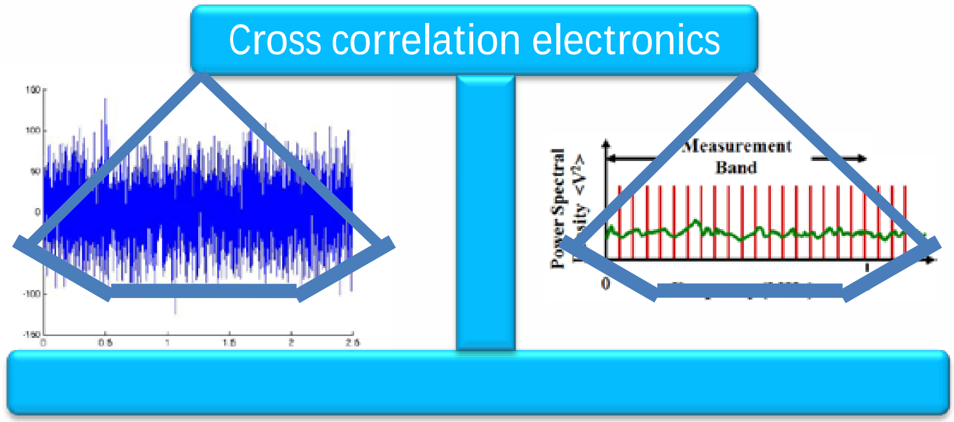


$$\int V(t)\,dt = \frac{h}{2e}$$

- **Samuel Benz, Clark Hamilton (NIST)**
- **quantum accurate (<<1 ppm up to 4 MHz)**
- **calculable PSD**
- **arbitrary distribution**

S.P. Benz, and C. A. Hamilton Appl. Phys. Lett. 68, 3173 (1996)

Quantum voltage calibrated noise thermometer



Johnson noise

$S_V \rightarrow K_J^2 = \dfrac{4e^2}{h^2}$

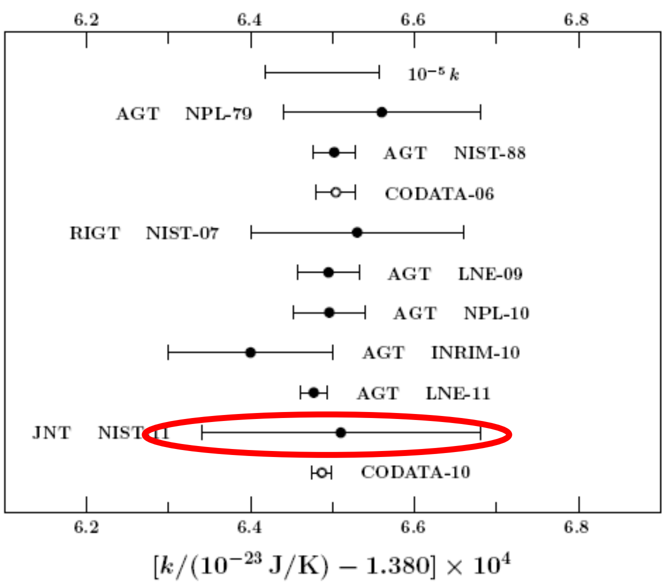
Quantum voltage noise

$S_T \rightarrow R_K = \dfrac{h}{e^2}$

$$k = \left.\frac{\langle V_R^2 \rangle}{\langle V_Q^2 \rangle}\right|_{f=0} \frac{\langle V_Q^2 \rangle_{cal}}{4TR}$$

- **John, Martinis (NIST)**

Electronic measurement of k_B



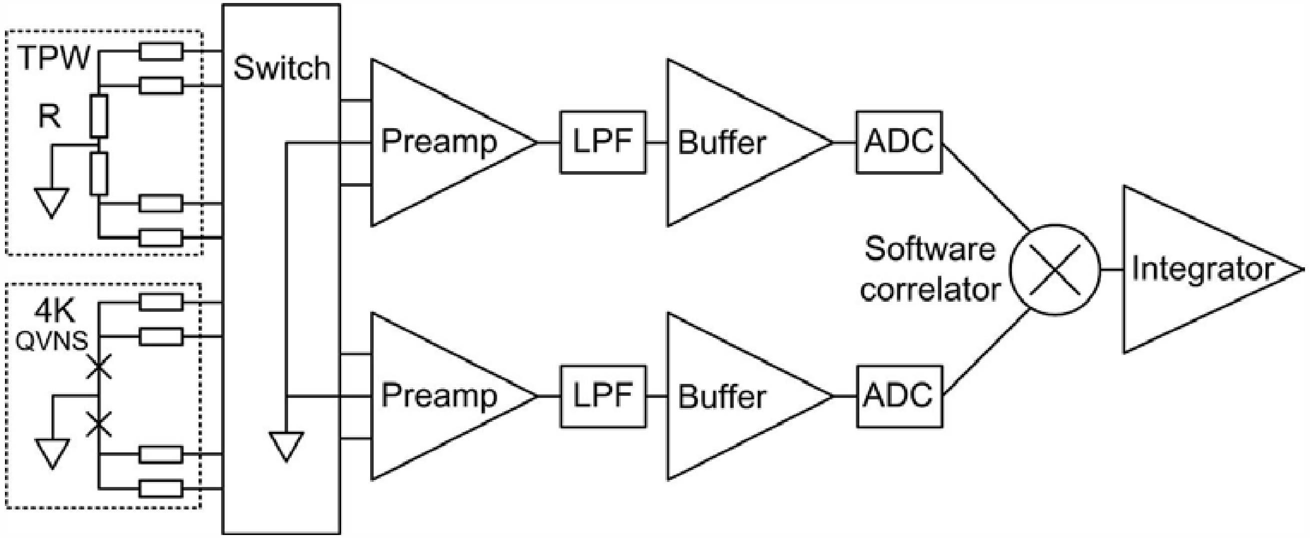
CODATA 2010 k_B input data

- **NIST reported first electronic measurement of k_B with $u_r = 12.1 \times 10^{-6}$**
- **NIM/NIST collaboration, $u_r = 3.9 \times 10^{-6}$**
- **CCT required at least two methods with $u_r < 3 \times 10^{-6}$ to redefine the kelvin**
- **NIST, NIM, NMIJ, pursuing even lower uncertainty**

Mohr et al., *Rev. Mod. Phys.* 84 1527 (2012)

Benz et al., *Metrologia* 48 142 (2011)

QVNS-JNT system



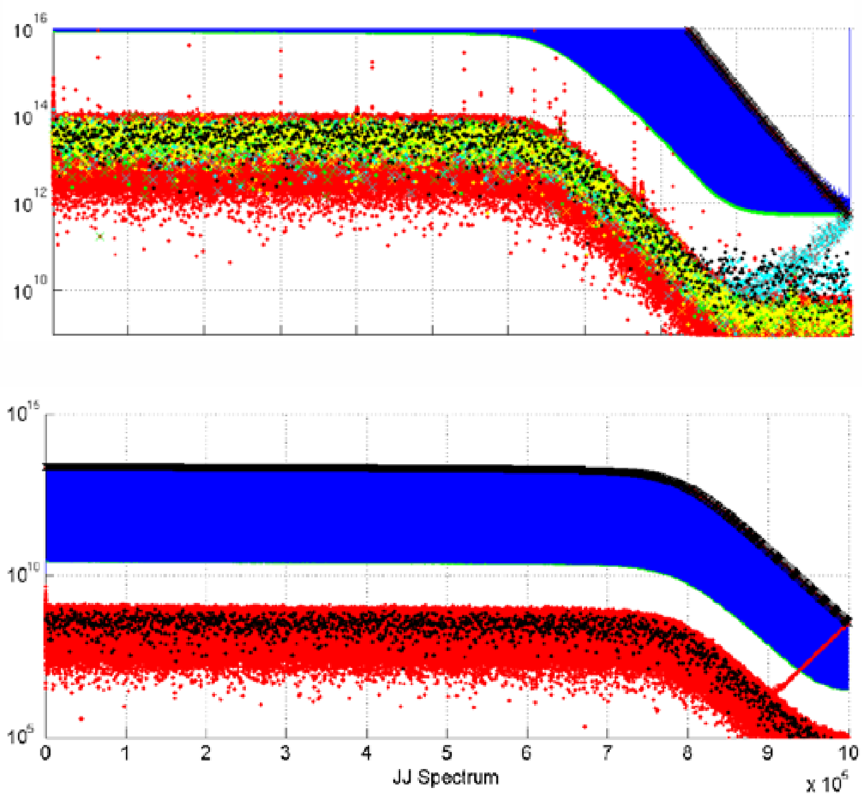
$$S_R = 4kT_\mathrm{W} X_R R_\mathrm{K}$$

$$S_\mathrm{Q\text{-}calc} = D^2 N_\mathrm{J}^2 f_\mathrm{s} M / K_\mathrm{J}^2$$

$$k = \frac{D^2 N_\mathrm{J}^2 f_\mathrm{s} M}{4T_\mathrm{W} X_R R_\mathrm{K} K_\mathrm{J}^2} \frac{\langle S_R \rangle}{\langle S_\mathrm{Q} \rangle}$$

Qu et al., *Metrologia* 52 S242 (2015)

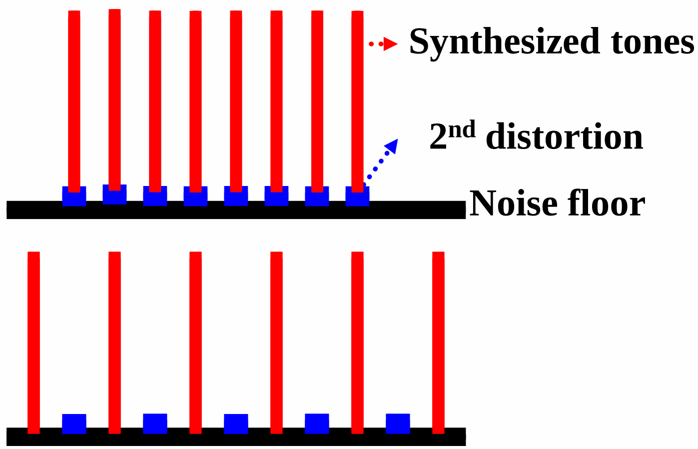
Shielding and grounding

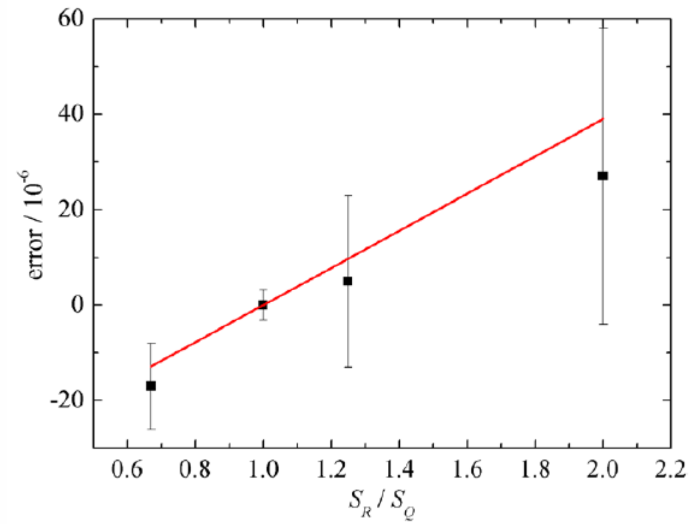


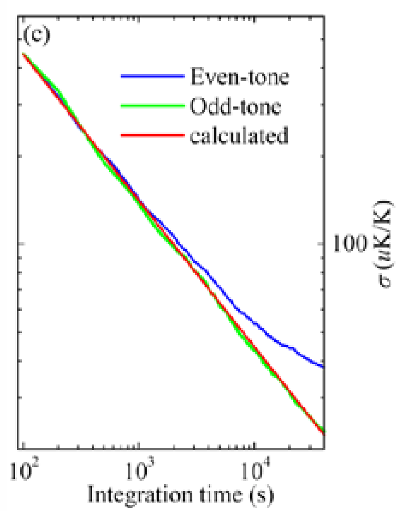
Measured spectra of the synthesized quantum noise waveform with (upper) and without (lower) observable EMI, blue green, and red are auto-correlation in each channel, and correlation spectra, respectively, and black ´ is the synthesized tones.

- **underground screened room**
- **shielding with aluminum and high-permeability nickle-alloy boxes**
- **powered by batteries**
- **eliminate ground loop**

Effect of nonlinearity

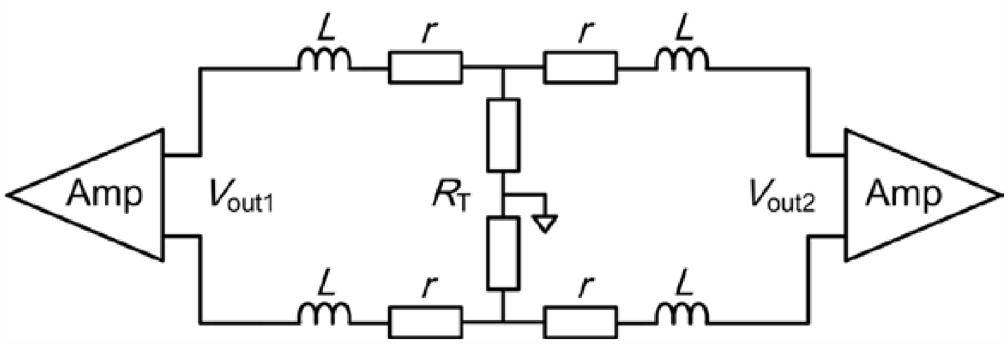


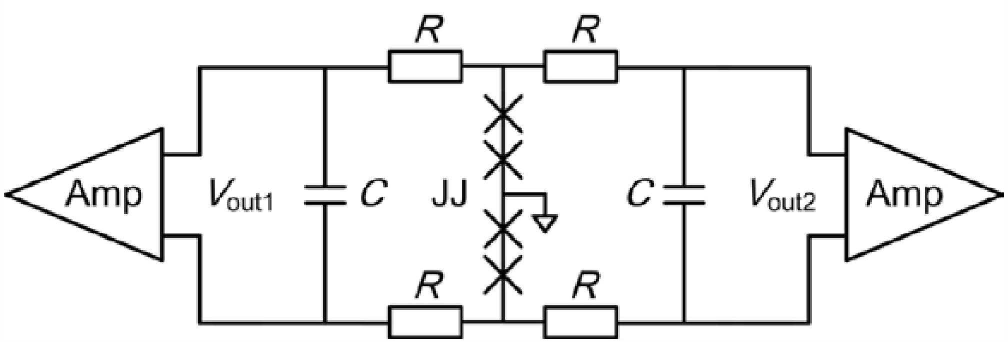




- **nonlinearity introduces significant errors**
- **PSDs are the same, Gaussian distribution, uncorrelated noise power are the same**
- **change the voltage of QVNS without changing any other parameters to measure the nonlinearity effect**
- **~0. 4´ 10^{-6} error for 1% mismatch**

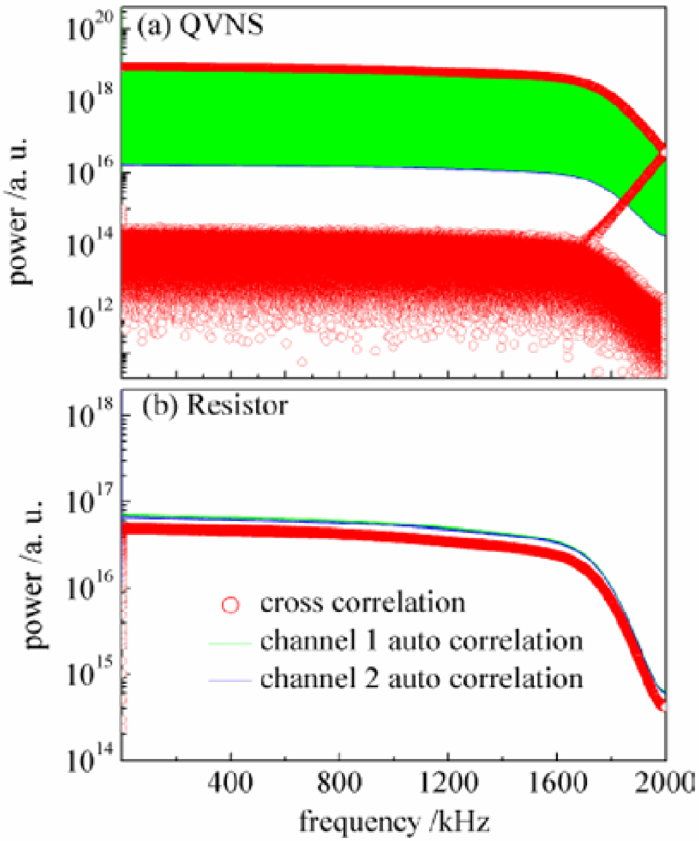
Match the noise sources and transmission lines

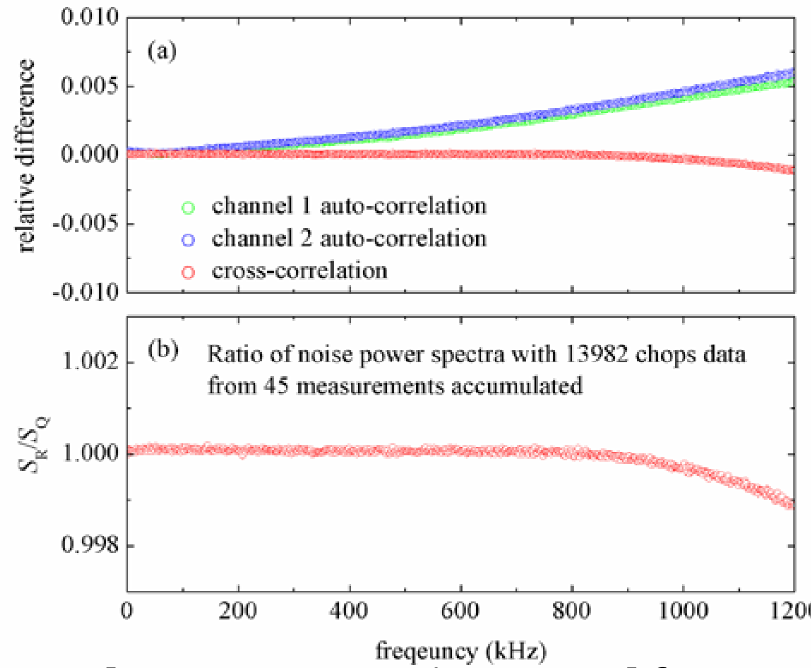




- insert uncorrelated resistor to match both the noise powers and impedances
- insert trimming inductance and capacitance to match the transmission lines

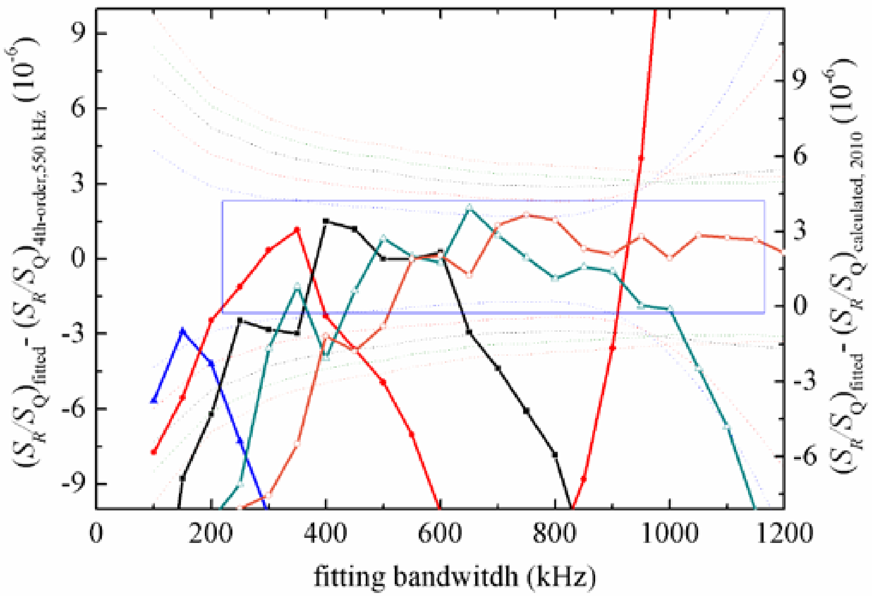
Measurement result





- **Each measurement integrated for about 15-20 hours**
- **45 measurements accumulated**

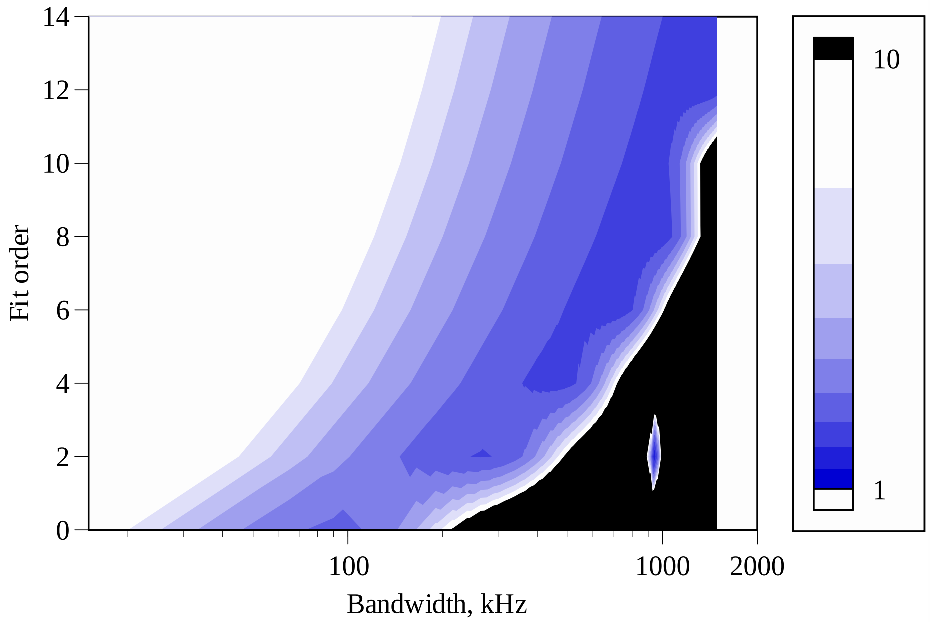
Polynomial fit



- short connections-lumped components
- even-order polynomial fit
- increase bandwidth
- uncertainty increase with the number of fitting parameters
- ambiguity–which model to use?

$$R(f)=\frac{S_{\mathrm{R}}}{S_{\mathrm{Q}}}\left(1+a_2 f^2+a_4 f^4+a_6 f^6+\ldots\right)$$

Model selection method



- **contour plot of total uncertainty versus model complexity and bandwidth**
- **cross-validation method** (Kevin, Coakley et. al., arXiv:1606.05907)
- **select the optimal polynomial model and bandwidth by minimizing the uncertainty that accounts for both random and systematic effects**

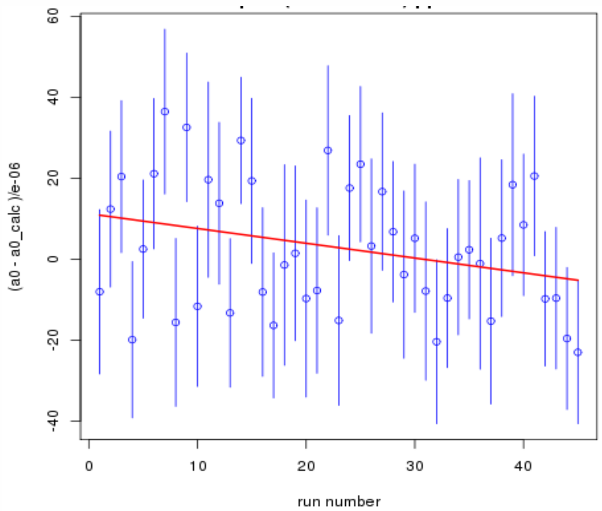
Uncertainty Budget

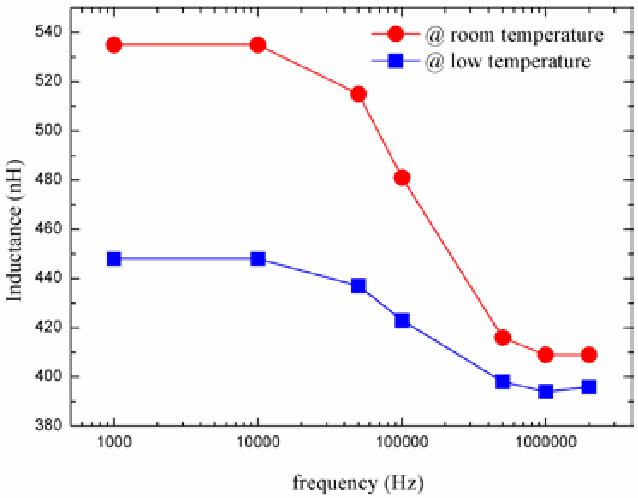
- $(k_B - k_B^{2010}) / k_B^{2010} = +1.8 \times 10^{-6}$

Component	$u_r/10^{-6}$
Statistical	3.2
Correction Model ambiguity	1.8
Dielectric losses	1.0
EMI	0.4
Nonlinearity	0.1
R measurement	0.53
TPW	0.35
QVNS waveform	0.1
$u_r(k_B)$	3.9

Qu et al., *Metrologia* 52 S242 (2015)

What's next?





Problems to solve:

- **drifting trend, probably caused by instability of the stray impedance**
- **the stray inductance dependent on both frequency and temperature**
- **thin, low TCR, coax cable**

What's next?

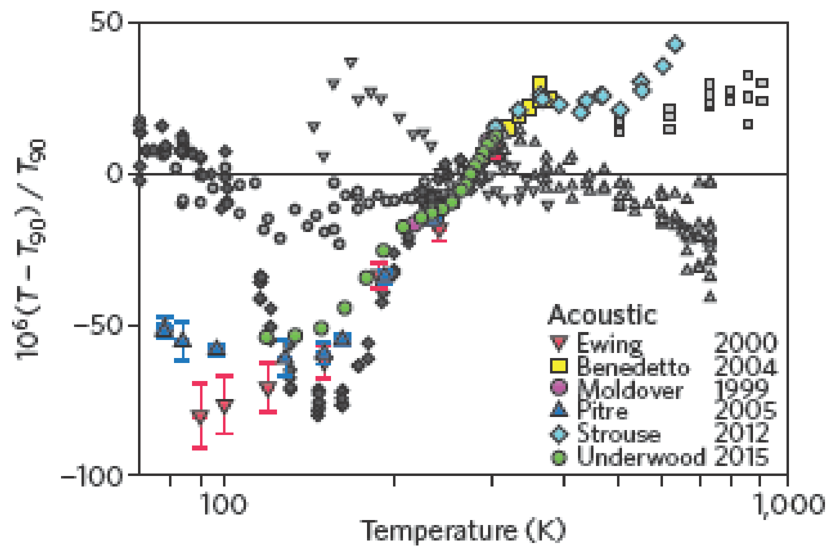
Problems to solve:

- match source impedance to the transmission line characteristic impedance
- four channel system to halve the measurement time (NIST)

Uncertainty limitation?

- fundamental limitation?
- practical limitation
  - bandwidth
  - time (1000 h for 3 ppm, 1 year for 1 ppm!)

What's next?



M. R. Moldover et. al., Nature Physics, 12 (2016) pp 7-11.

High temperatures

- **different fixed-point temperatures of Zn, Ag, Cu and Pd (PTB)**
- **uncertainty < 0.004% has been demonstrated up to 800 K (NIST)**
- **T-T_{90}, by NIST, NIM, NMIJ, PTB**
- **could be competitive in 600-1000 K with AGT and radiation thermometry**

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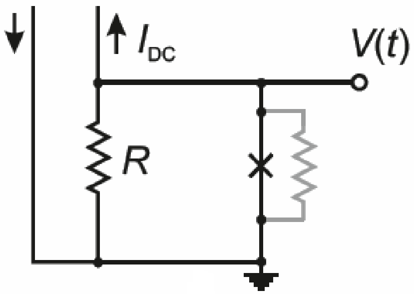
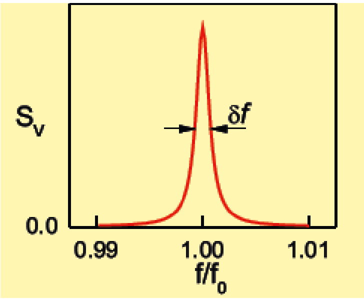
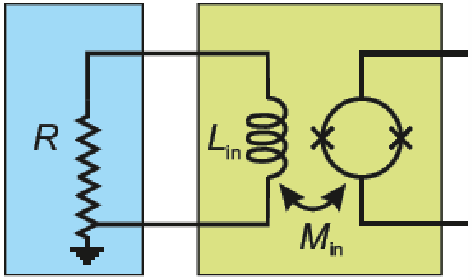
SQUID-based noise thermometer





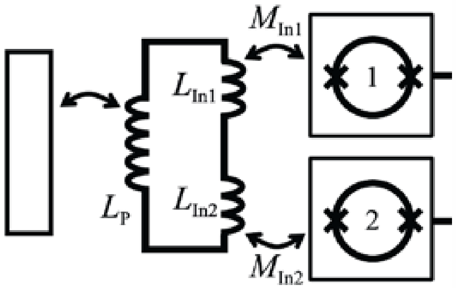
Kamper, Zimmermann, JAP 42 (1971), 132

- **R-SQUID noise thermometer**



Shibahara *et al*, Phil. Trans. R. Soc. A 374 (2016) 20150054.

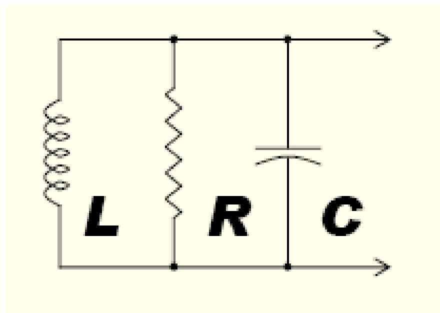
- **Current Sensor Noise Thermometer**



Kirste *et al*, Phil. Trans. R. Soc. A 374 (2016) 20150050.

- **Magnetic Field Fluctuation Thermometer**
- **1 mK – 5 K, thermodynamic temperature**

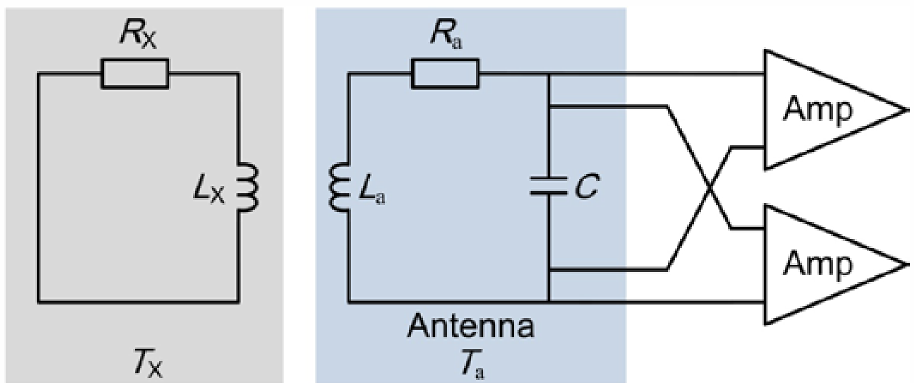
Tuned-RLC noise thermometer



ENBW = 1/(4*RC*)

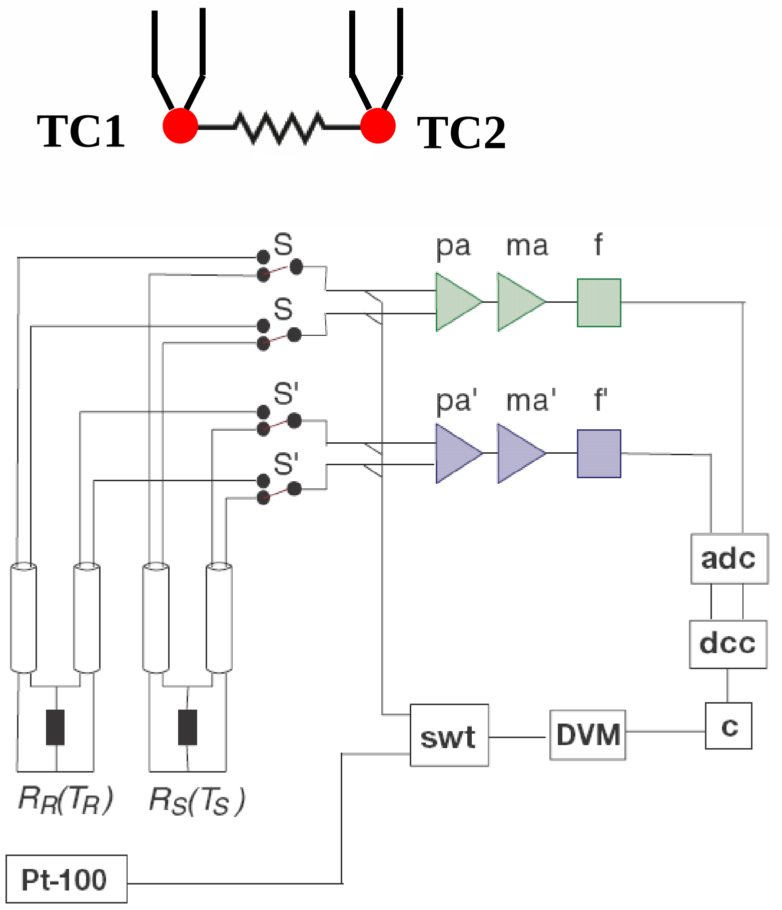
$\langle V^2 \rangle = kT / C$

Pepper, Brown, J Phys. E, 42 (1979), 31



- the noise amplitude is determined by a capacitor
- resistance measurement is not necessary
- inductively coupling allows non-contact measurement
- steel industry

Dual noise-thermocouple thermometer

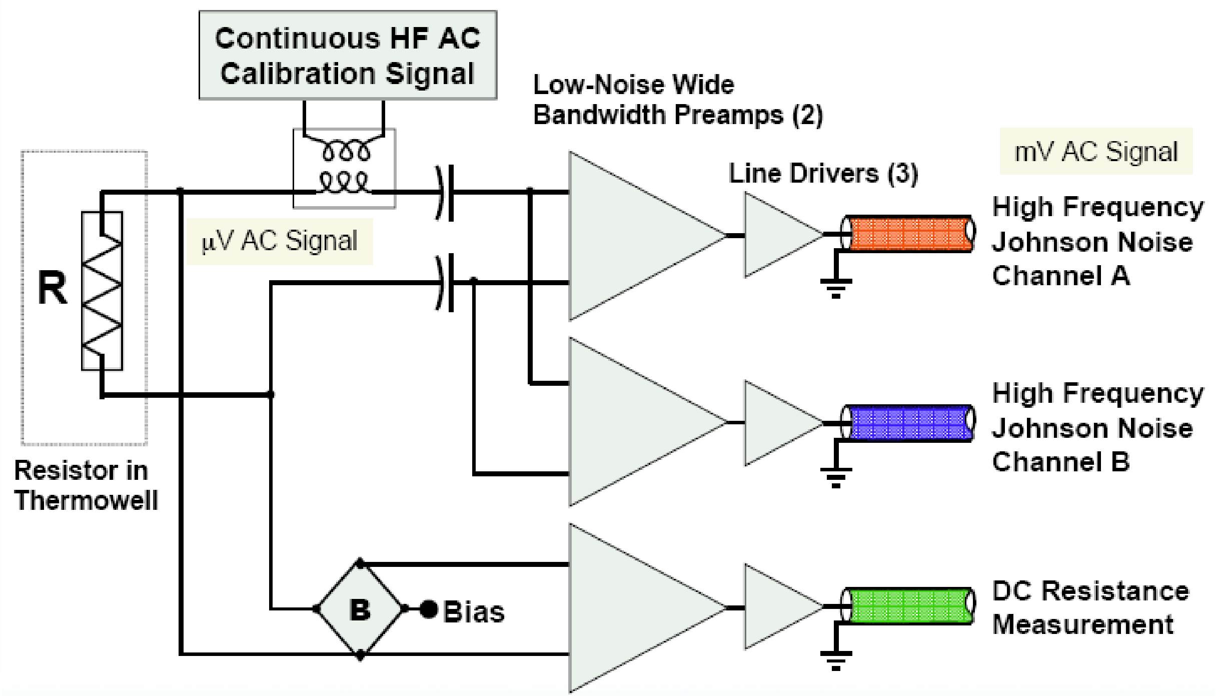


F Edler *et al*, Meas. Sci. Technol.26 (2015) 015102.

- combine noise and thermocouple thermometry
- proposed by Brixy for use in nuclear plant or space satellite power system
- calibration in situ

- recently demonstrated up to 1450 °C at PTB
- uncertainty of 0.1% under lab conditions, and double under industrial conditions

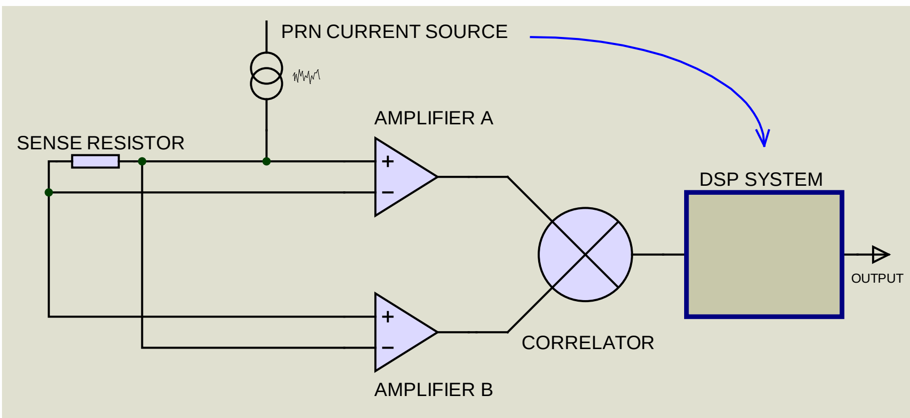
Dual noise-resistance thermometer



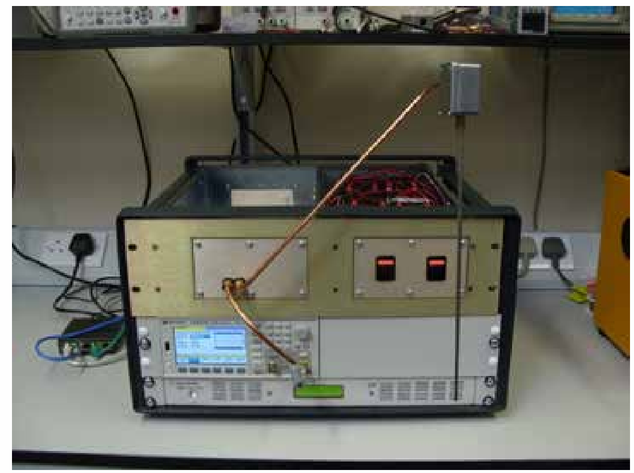
from David Holcomb, ORNL

- single sensor, fast resistance mode or slow noise thermometry mode
- continuous AC signal is used to calibrate

Practical noise thermometer



(from Paul Bramley of Metrosol)



- **inject precision current as calibration signal**
- **5 kWsensor, 1MHz bandwidth**
- **standard deviation 0.14°C at 20 °C**

Possible new applications

- **remaining challenges: strong EMI, harsh environments**
- **rapid progress of electronics made it viable for industry**

- **suited for high-temperature, high accuracy applications:**

- next generation of nuclear power plant (~850 °C)

- emission controls (0.1 °C @ ~850 °C)

- aerospace (satellite with significant solar exposure, ionizing radiation)

- high value manufacture (turbine, technical ceramics)

Outline

Summary

- purely electronic approach, appealing alternative to other primary thermometry
- technology breakthroughs (switch correlator, ADC, QVNS) made it possible to contribute to the redefinition of kelvin
- could be competitive with AGT and radiation thermometry in range of 600 K - 1000 K
- different implementations have been demonstrated under lab conditions, cover temperature from millikelvin to over 1500 °C
- high temperature, high accuracy applications in industry becoming more practical

Acknowledgement

- NIST: Samuel Benz, Kevin Coakley, Alessio Pollarolo, Horst Rogalla, Weston Tew
- MSL: Rod White
- PTB: Frank Edler, Alexander Kirste,
- NPL: Jonathan Pearce
- Metrosol Limited: Paul Bramley

National Institute of Metrology

Thanks for your attention!