The Realization and the Dissemination of Thermodynamic Temperature Scales

Howard W. Yoon
NIST

Outline

1. Brief review of thermodynamic temperature measurements.
2. Motivations for detector-based radiation thermometry.
3. Review of NIST detector-based radiation thermometry.
4. Future improvements in detector-based radiation thermometry.

SI definition of the kelvin

- kelvin
- symbol, K
- **The kelvin, unit of thermodynamic temperature, is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water.**

Thermodynamic temperatures

Ideal gas thermometry

- Constant-volume gas thermometry (< 900 K)

$$PV = nN_A kT$$

- Acoustic gas thermometry (< 900 K)

$$kT = \left(\frac{m}{\gamma}\right)v^2$$

Noise thermometry (< 1300 K)

$$\overline{U^2} = 4kTR\Delta f$$

Detector-based radiometry

- Total radiation thermometry (60 K to 400 K)

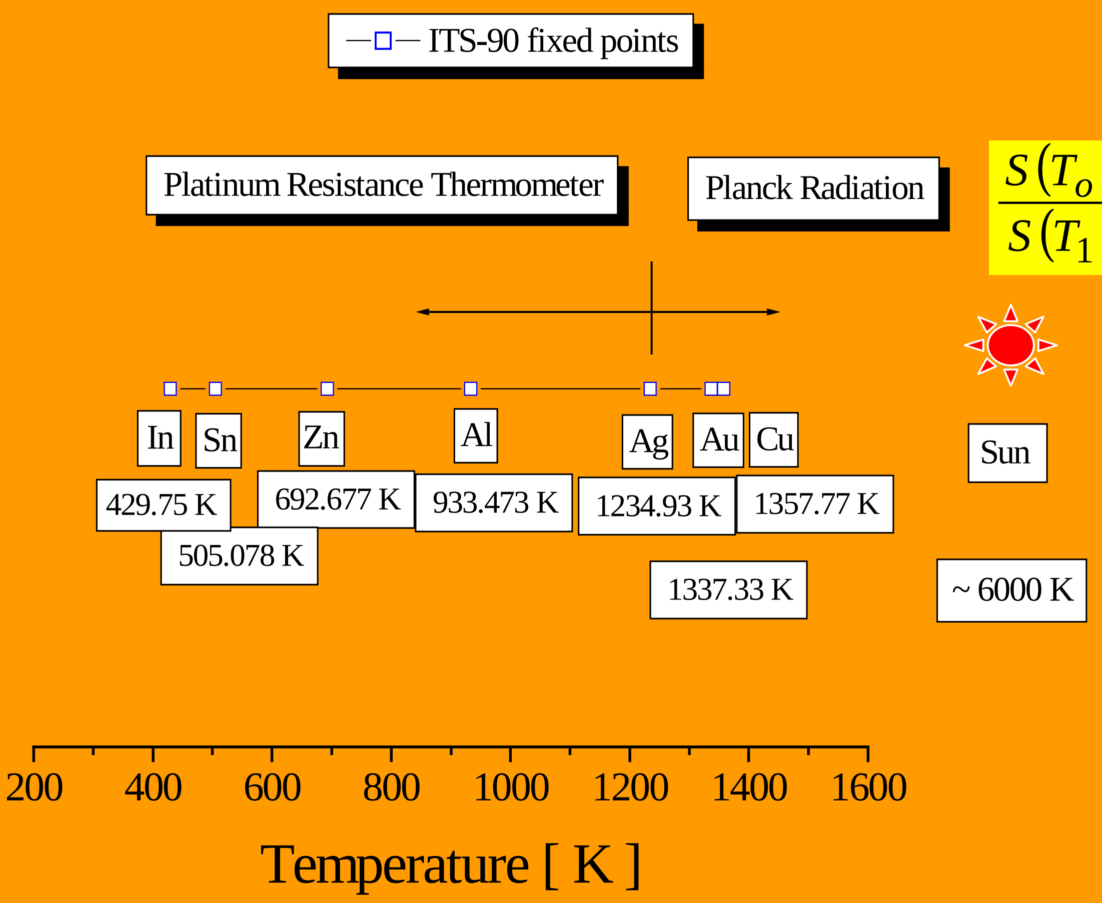
$$M(T) = n^2\sigma T^4, \sigma = \frac{2}{12}\frac{\pi^5 k^4}{h^3 c^2}$$

- Spectral radiation thermometry (900 K to > 3000 K)

$$L(\lambda,T) = \frac{c_{1L}}{n^2\lambda^5\left(\exp\left(\frac{h}{n\lambda c kT}\right)-1\right)}$$

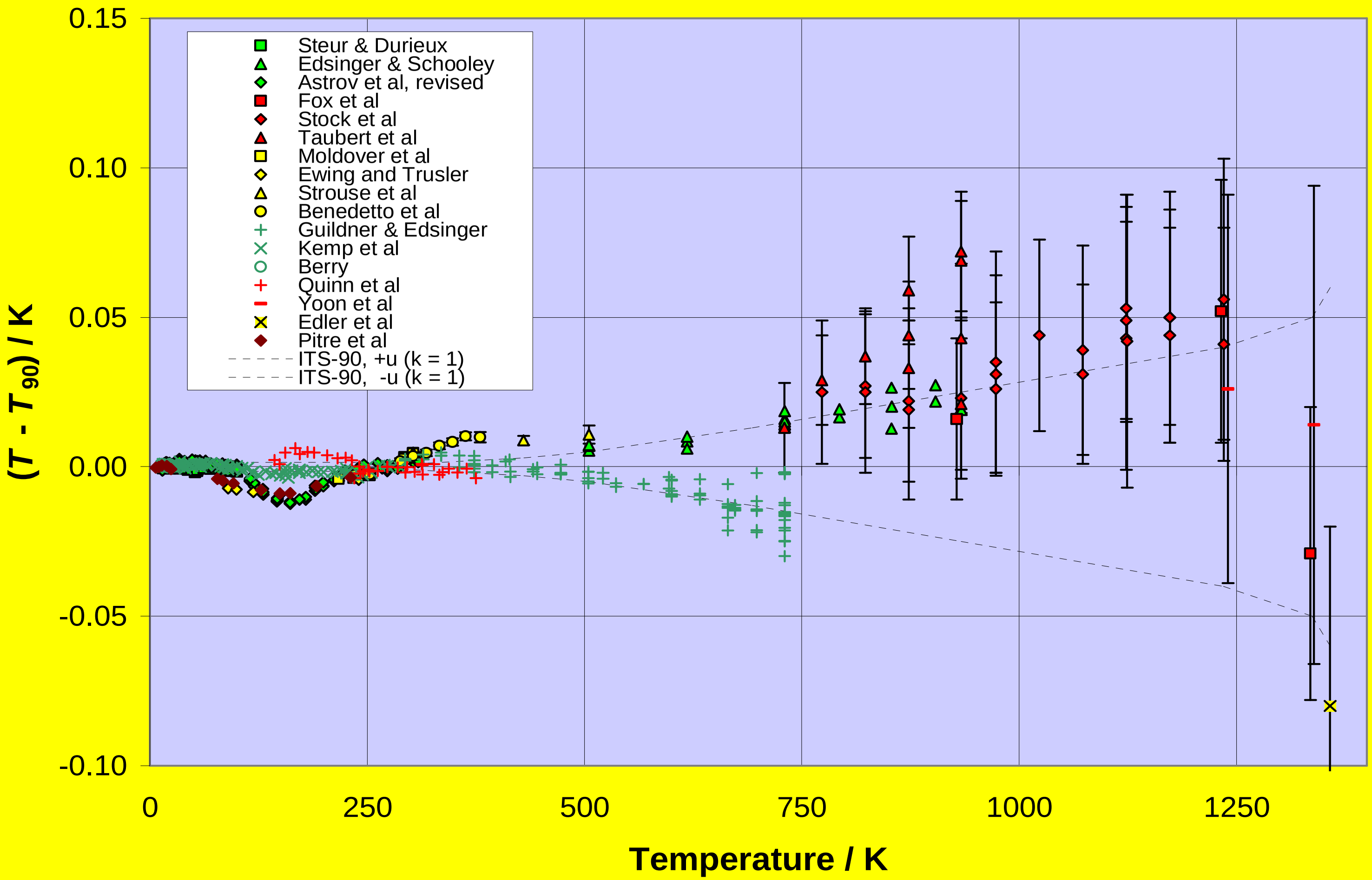
The Boltzmann constant, *k*, is determined at the triple point of water.

International Temperature Scale of 1990 (ITS-90)



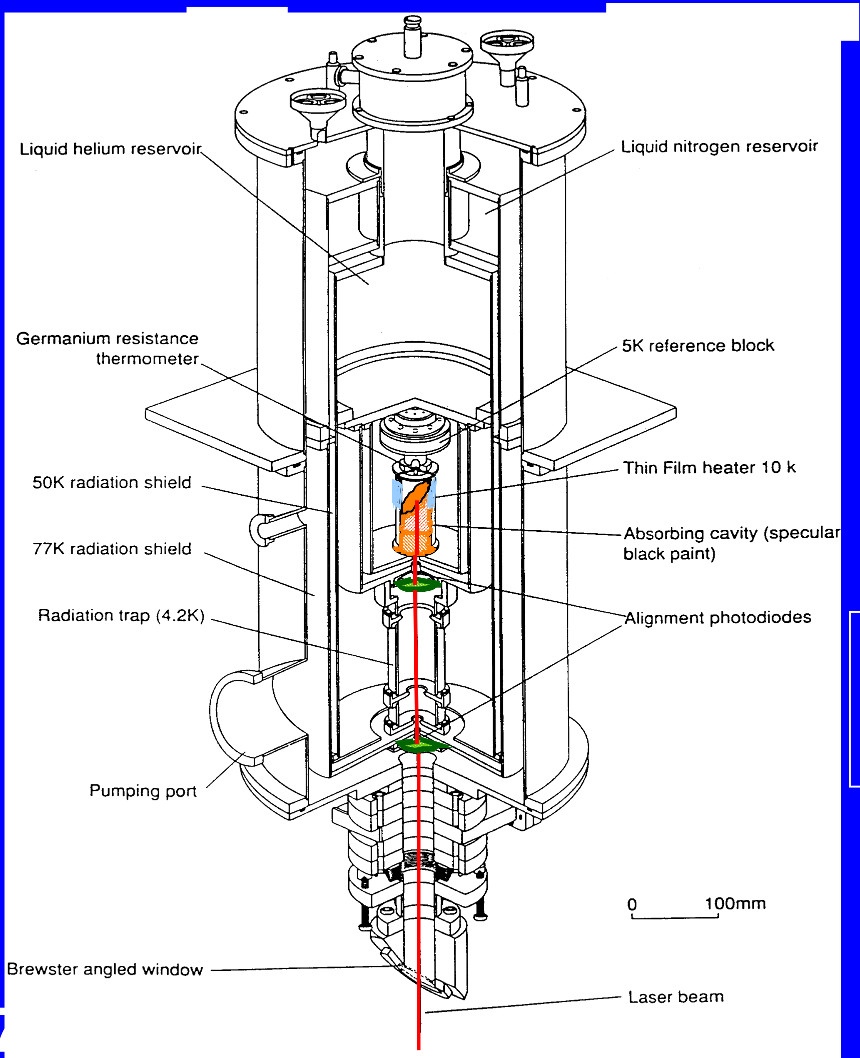
$$\frac{S(T_o)}{S(T_1)} = \frac{\int R(\lambda)\,\varepsilon\, L(\lambda, T_o)\,d\lambda}{\int R(\lambda)\,\varepsilon\, L(\lambda, T_1)\,d\lambda}$$

Primary thermometry results



From M. Moldover, CCT-WG4

Detector-based radiometric scales



Cryogenic electrical substitution radiometer (0.02 %) (k = 2)

↓

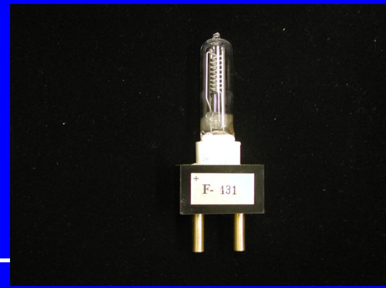
Detector-responsivity scale

↓

Photometric scale (Candela) 1979

Spectroradiometric scales

1990 CCPR Spectral Irradiance intercomparison, labs with scales



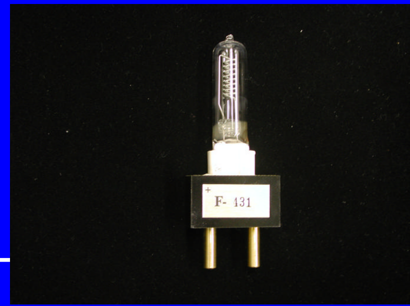
- Source-based

1. NIST
2. PTB
3. NIM
4. ETL (NMIJ)
5. INM
6. VNIIOFI

- Detector-based

1. NRC
2. IOM (IFA-CSIC)
3. CSIR
4. NPL
5. CSIRO (NMIA)

2000 CCPR Spectral Irradiance intercomparison, labs with scales



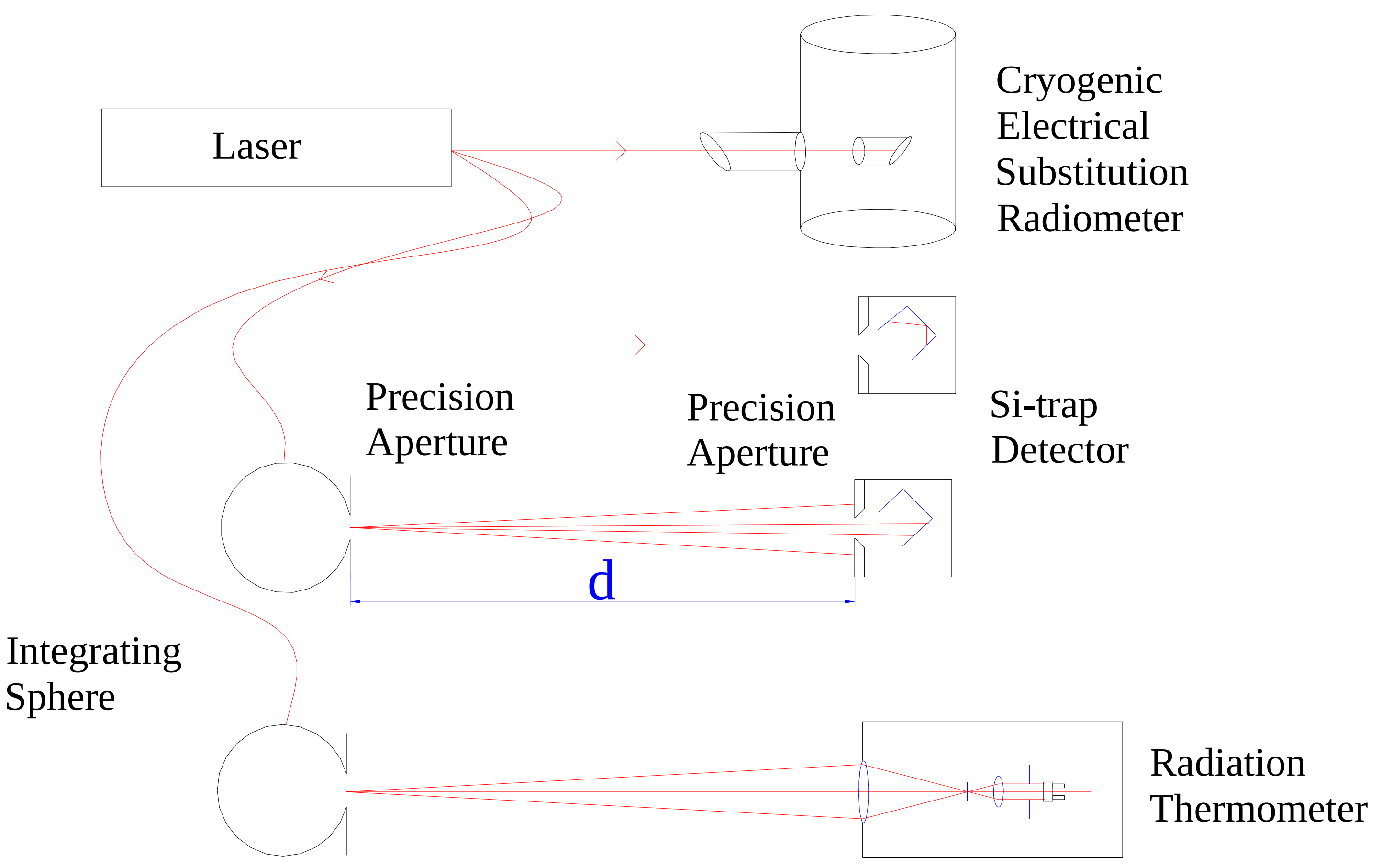
- Source-based

1. NIM
2. ETL (NMIJ)
3. VNIIOFI

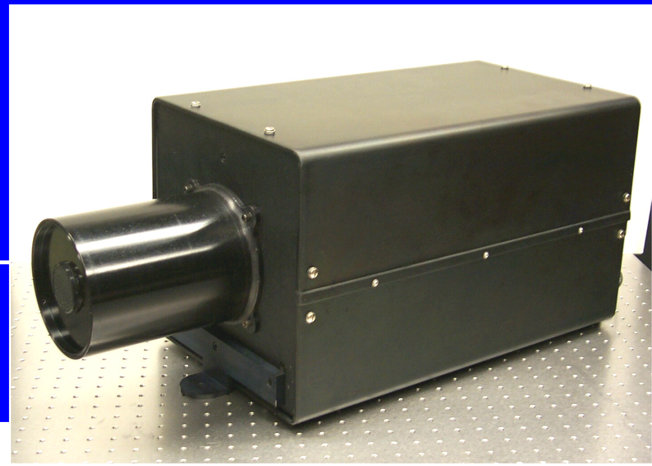
- Detector-based

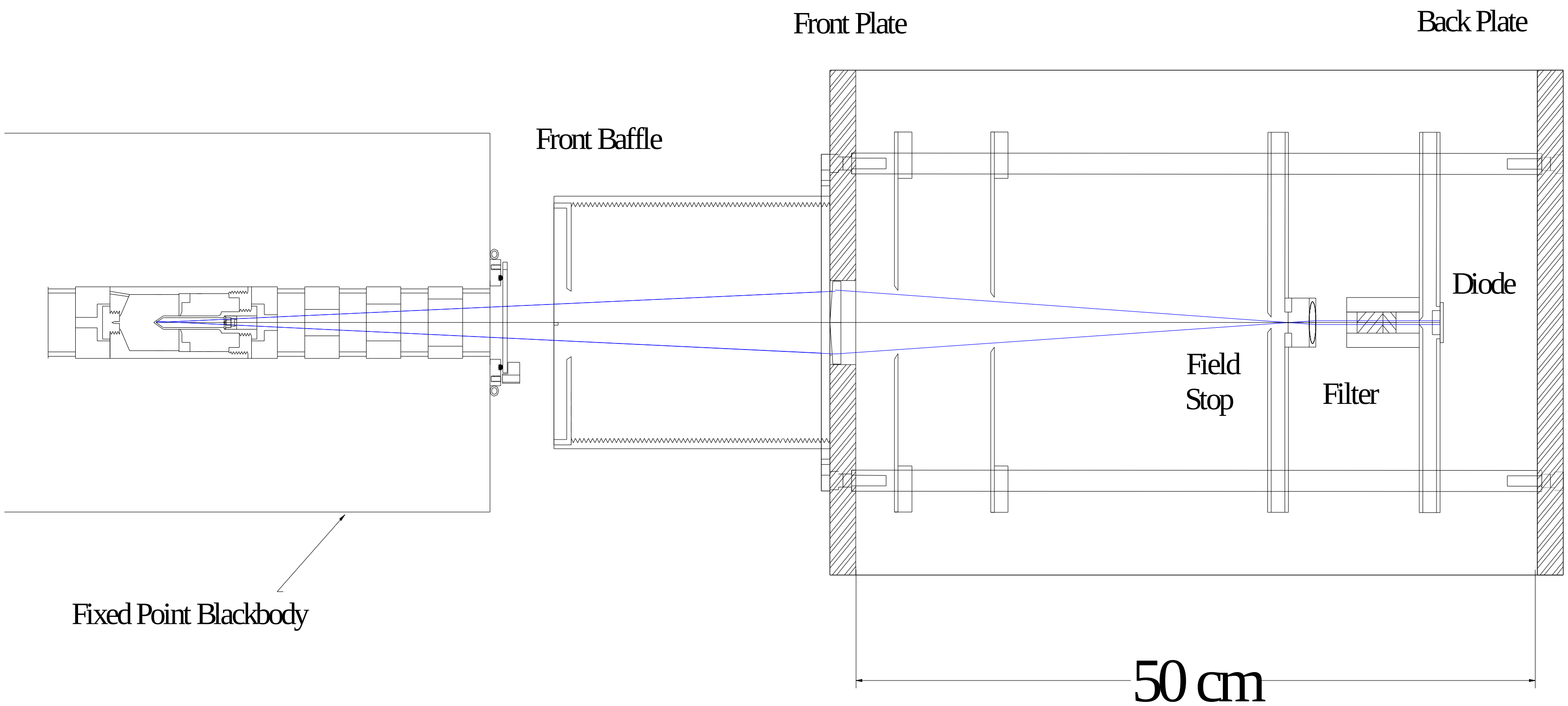
1. NIST
2. PTB
3. HUT (TKK)
4. NRC
5. IFA-CSIC
6. MSL-IRL
7. CENAM
8. NPL
9. NMIA

Detector-based temperature realization

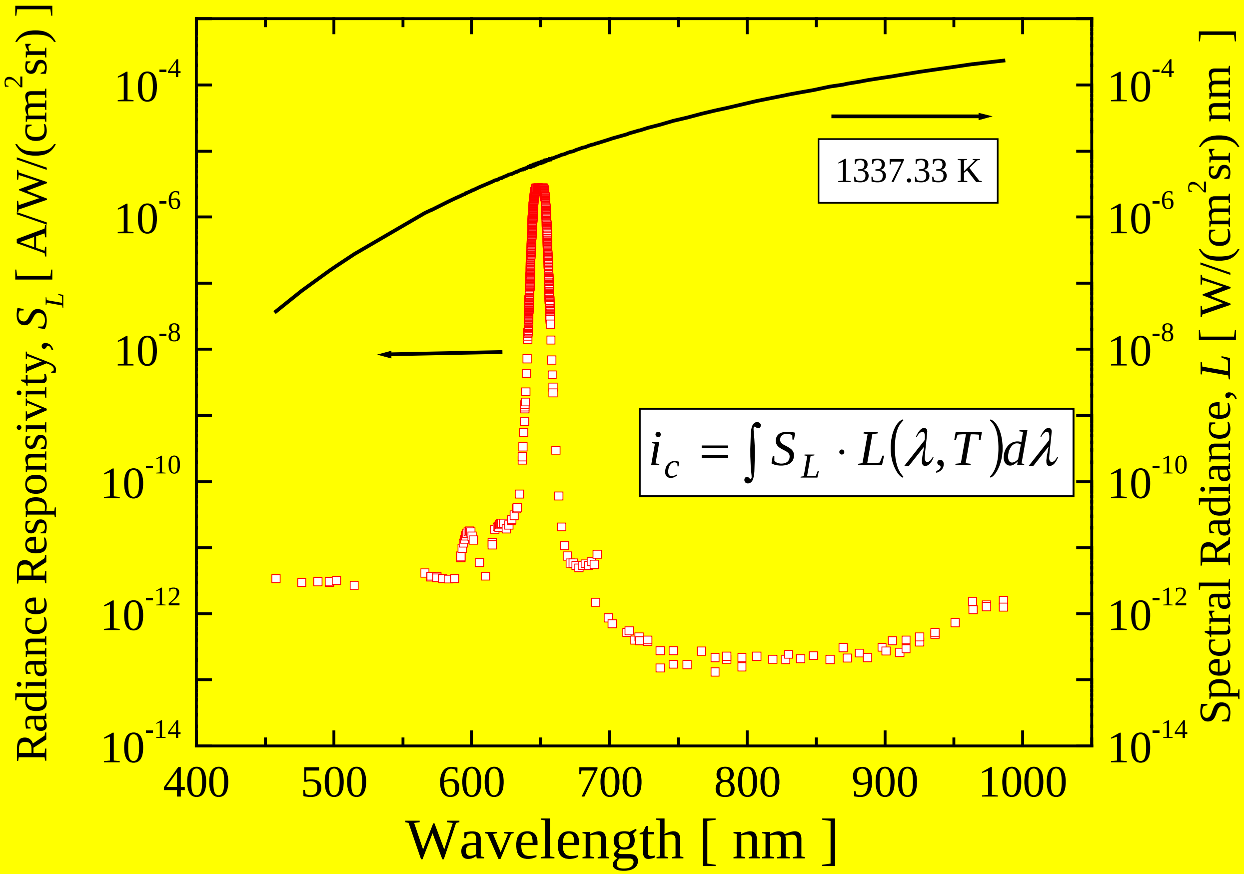


Schematic of the AP1

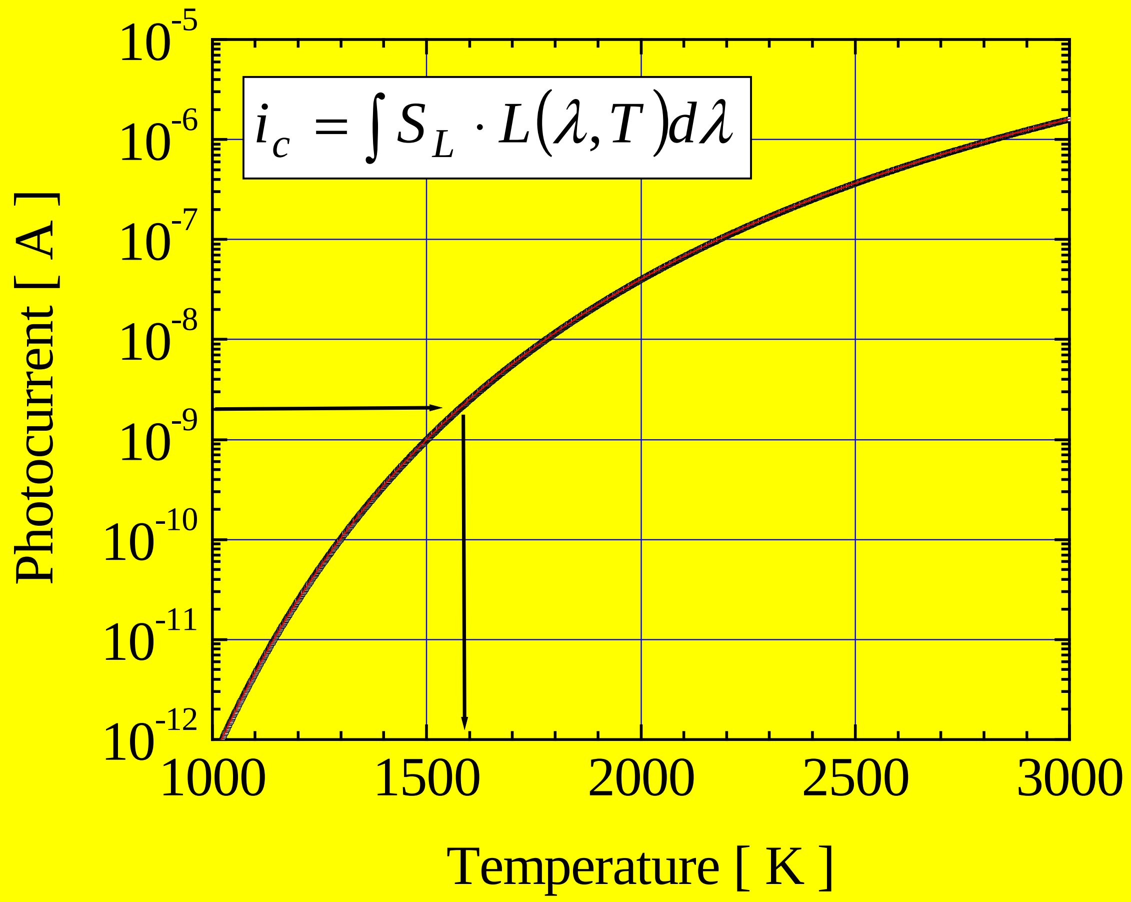




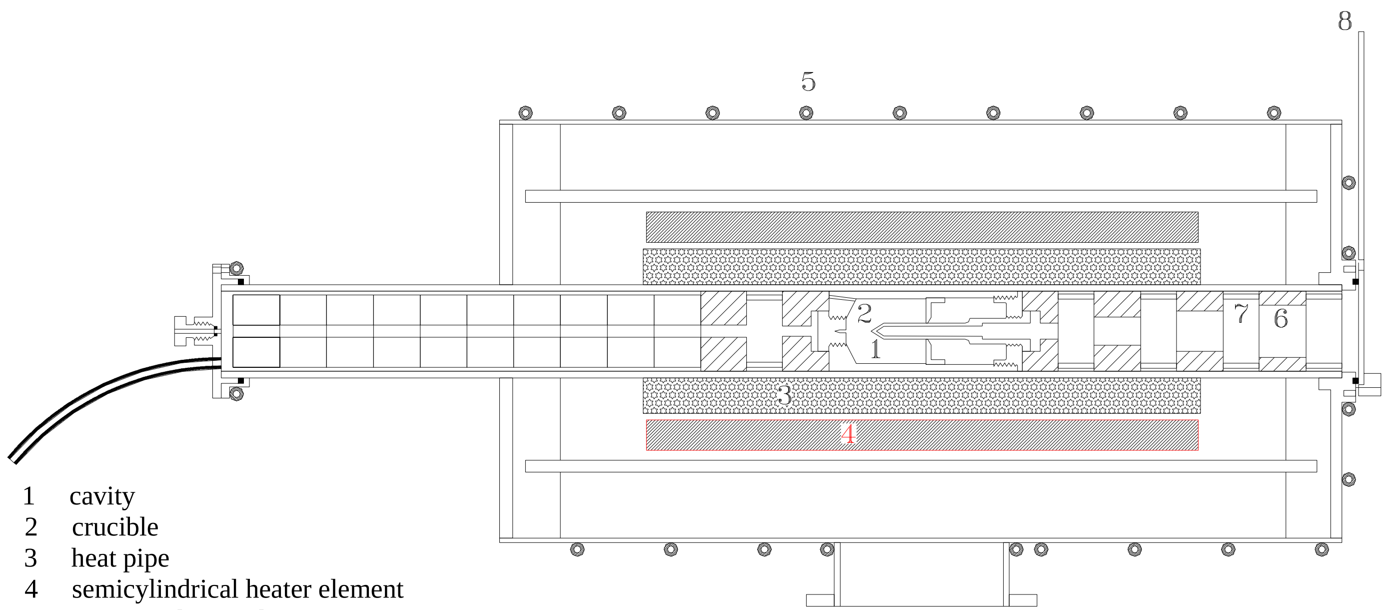
Detector-based radiance responsivity



Calculated photocurrents vs. temperature

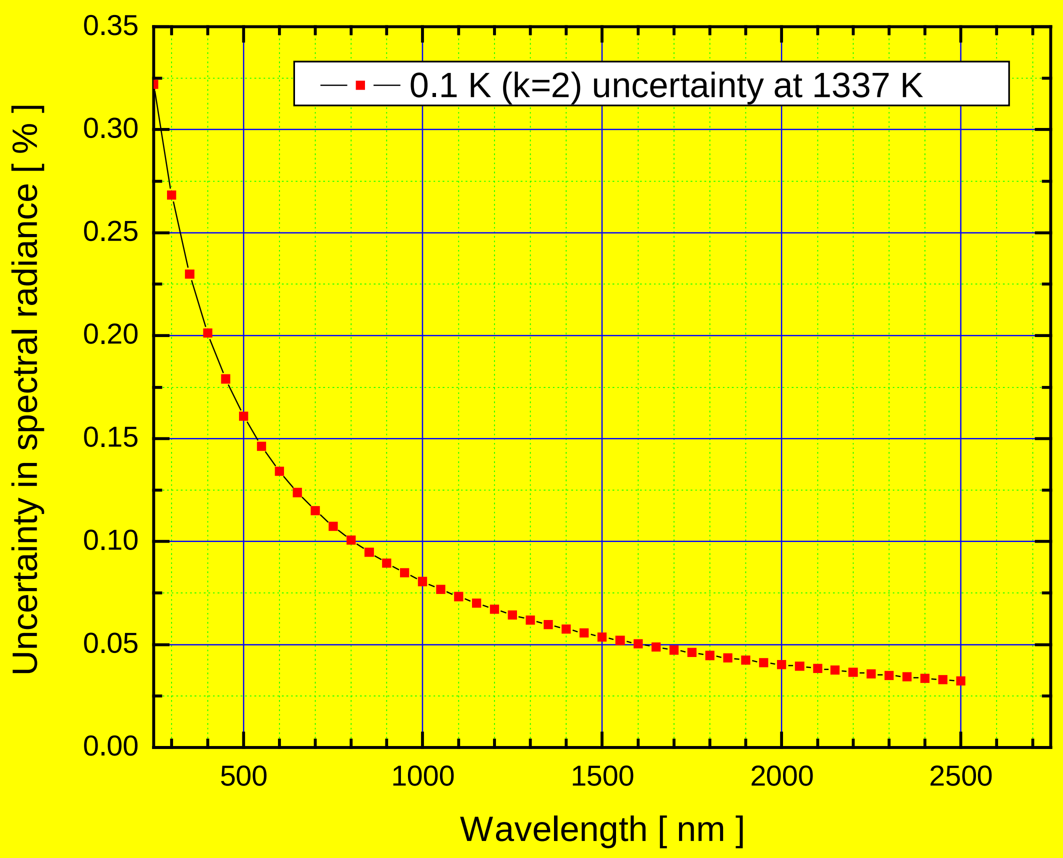


NIST Gold-point blackbody furnace



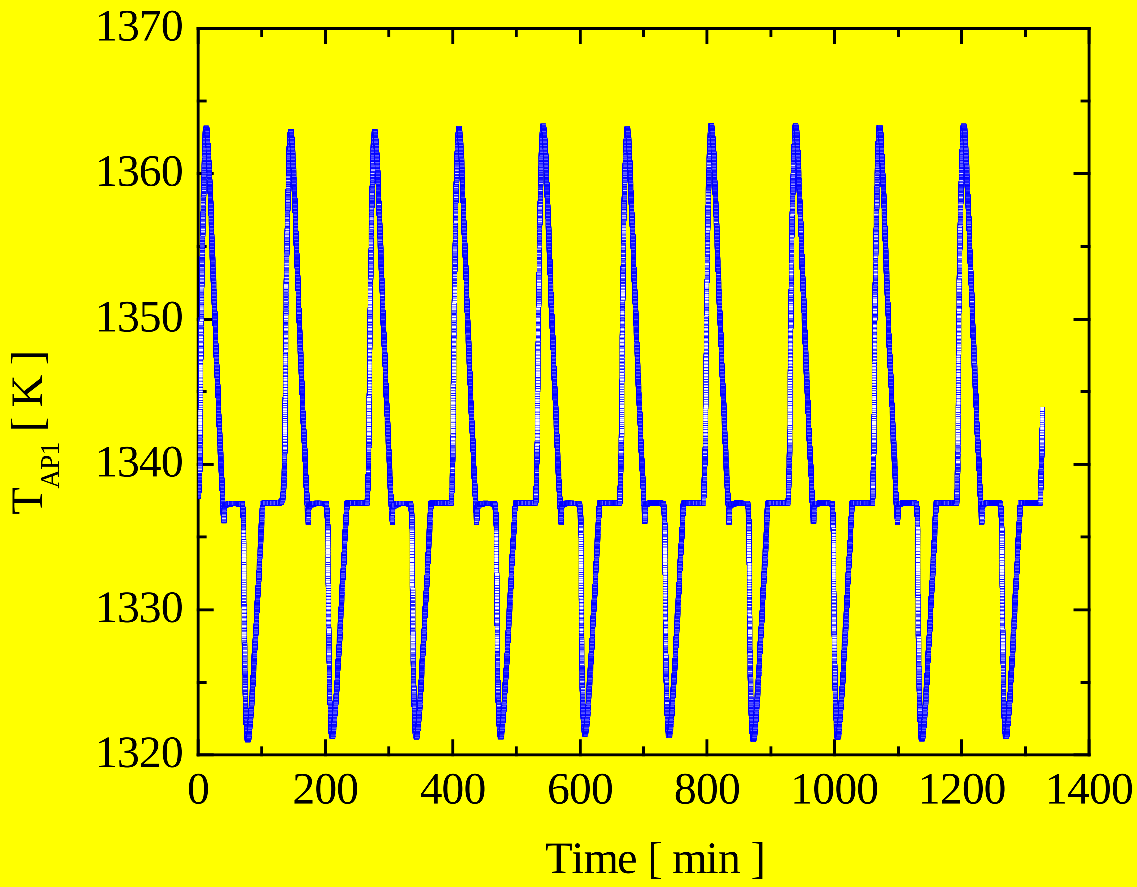
1 cavity
2 crucible
3 heat pipe
4 semicylindrical heater element
5 water cooling coil
6 graphite rings
7 silica glass spacers
8 shutter opening device

100 mK (k=2) uncertainty at the gold-point temperature (1337 K)

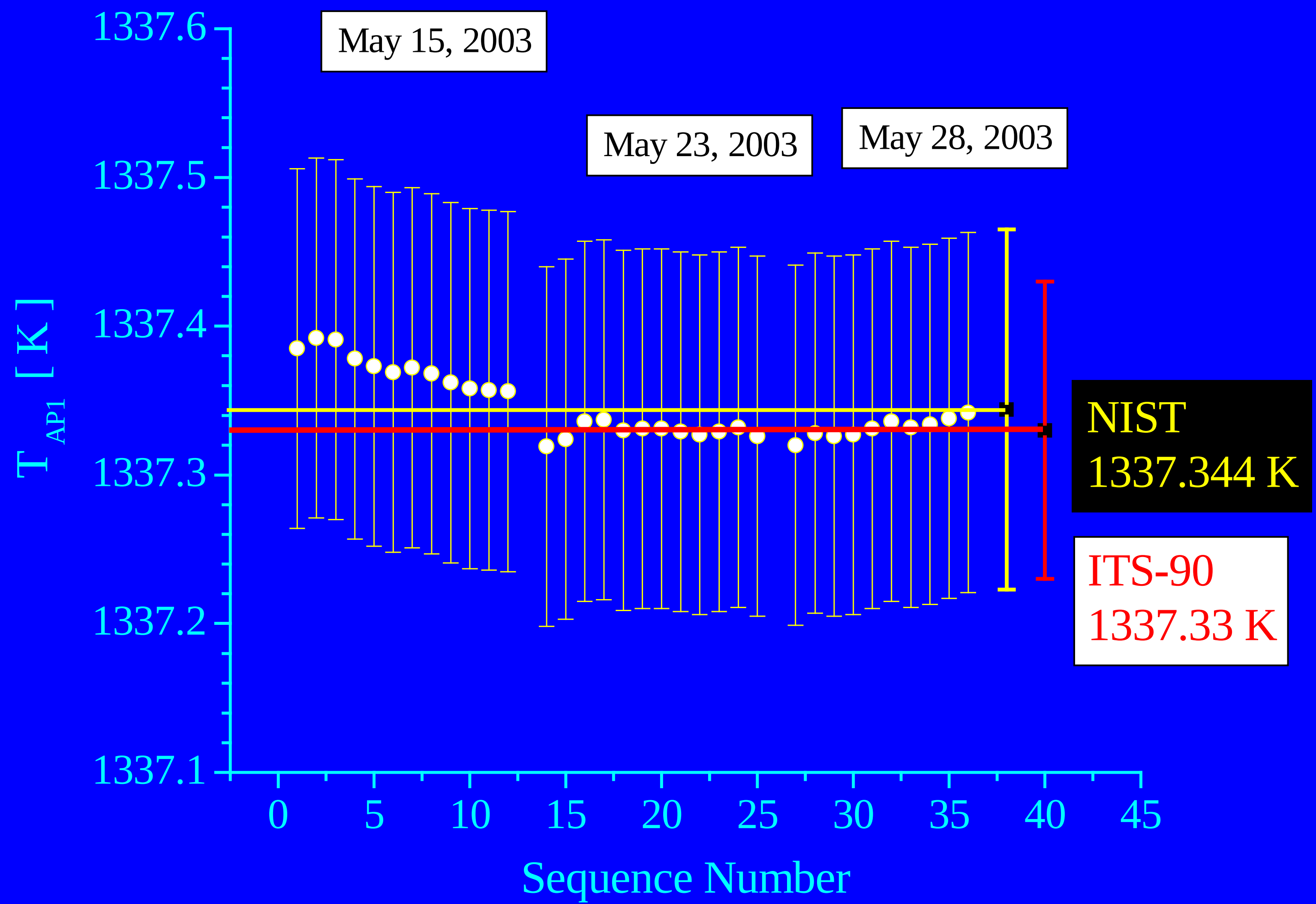


$$\frac{dL}{L} = \frac{c_2}{\lambda}\frac{\Delta T}{T^2}$$

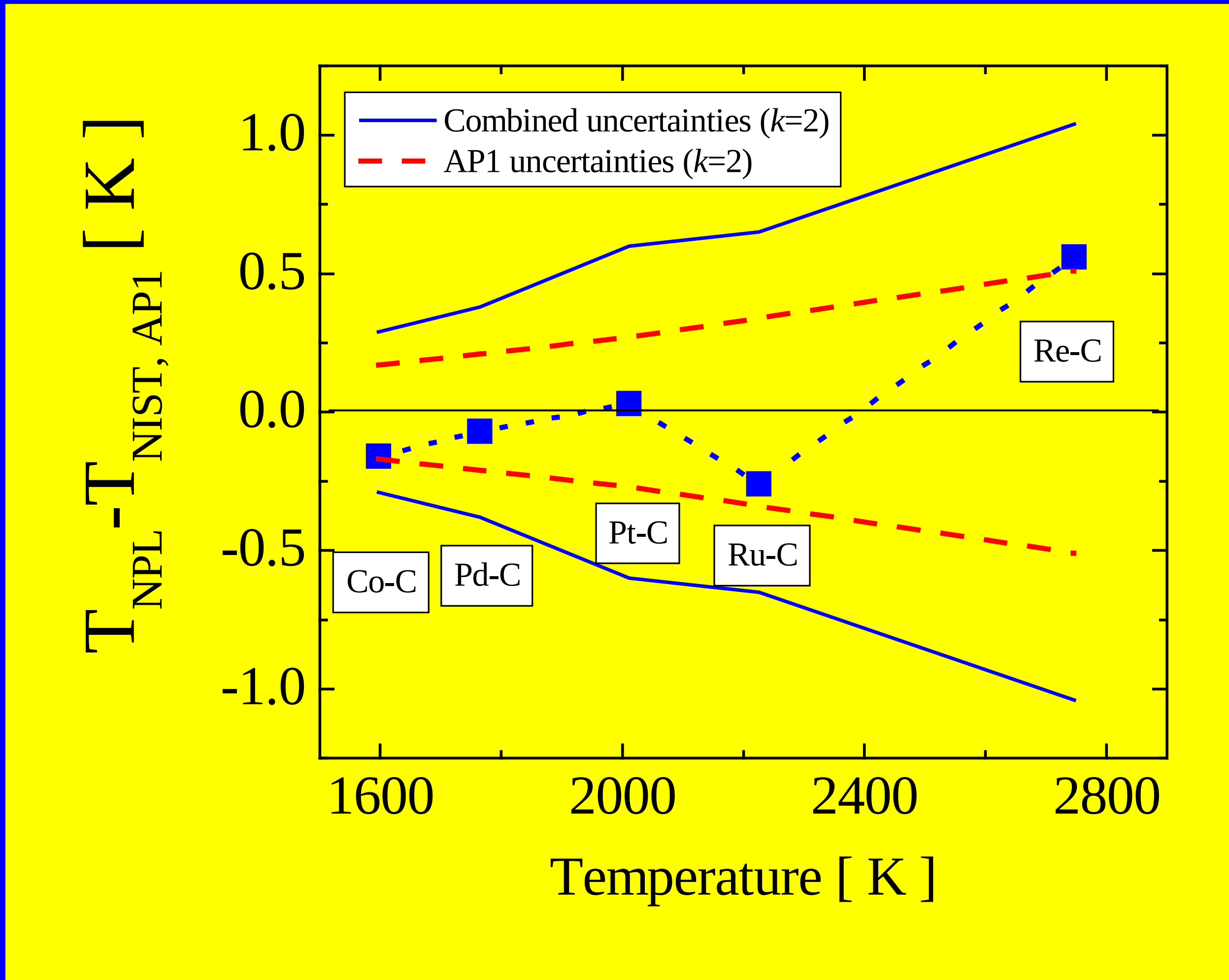
Au melt and freeze cycles



Au-freezing temperature measurements



Bilateral comparison between NPL and NIST using metal-carbon eutectics



Detector-based temperature uncertainties are 1/2 to 1/3 of ITS-90 based temperature uncertainties

CCT-WG5 Metal Carbon Eutectic Research Plan

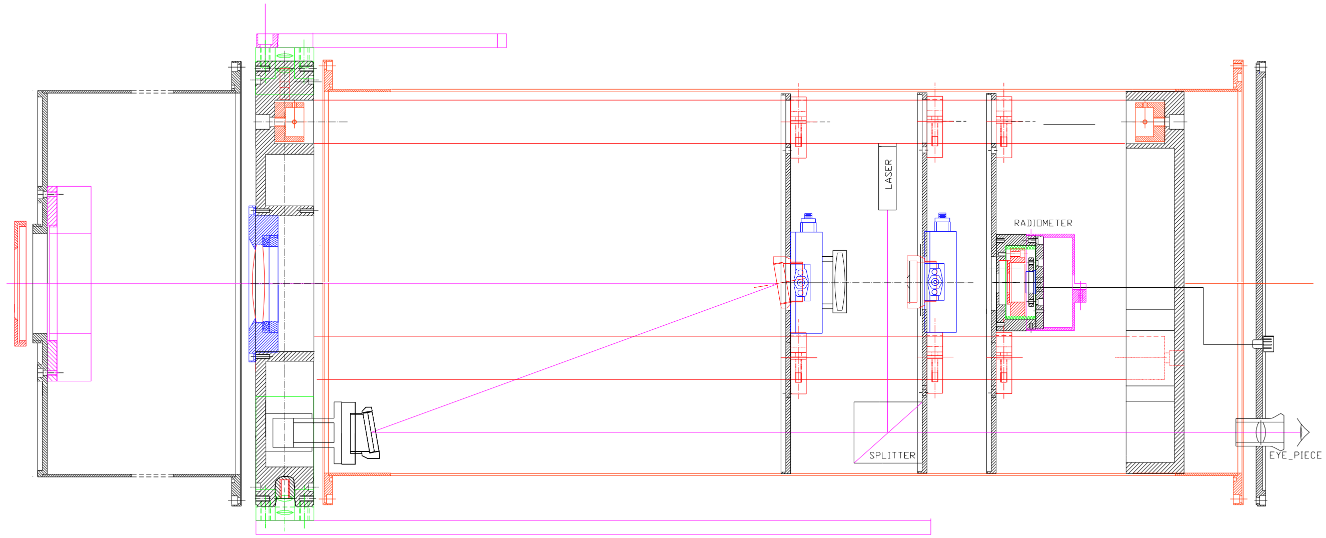
Goal: redefining temperature **above the silver point through absolute radiometry mediated by the use of M(C)-C eutectics**

Phase 1: *Assessing absolute thermometry capability of participating laboratories.*

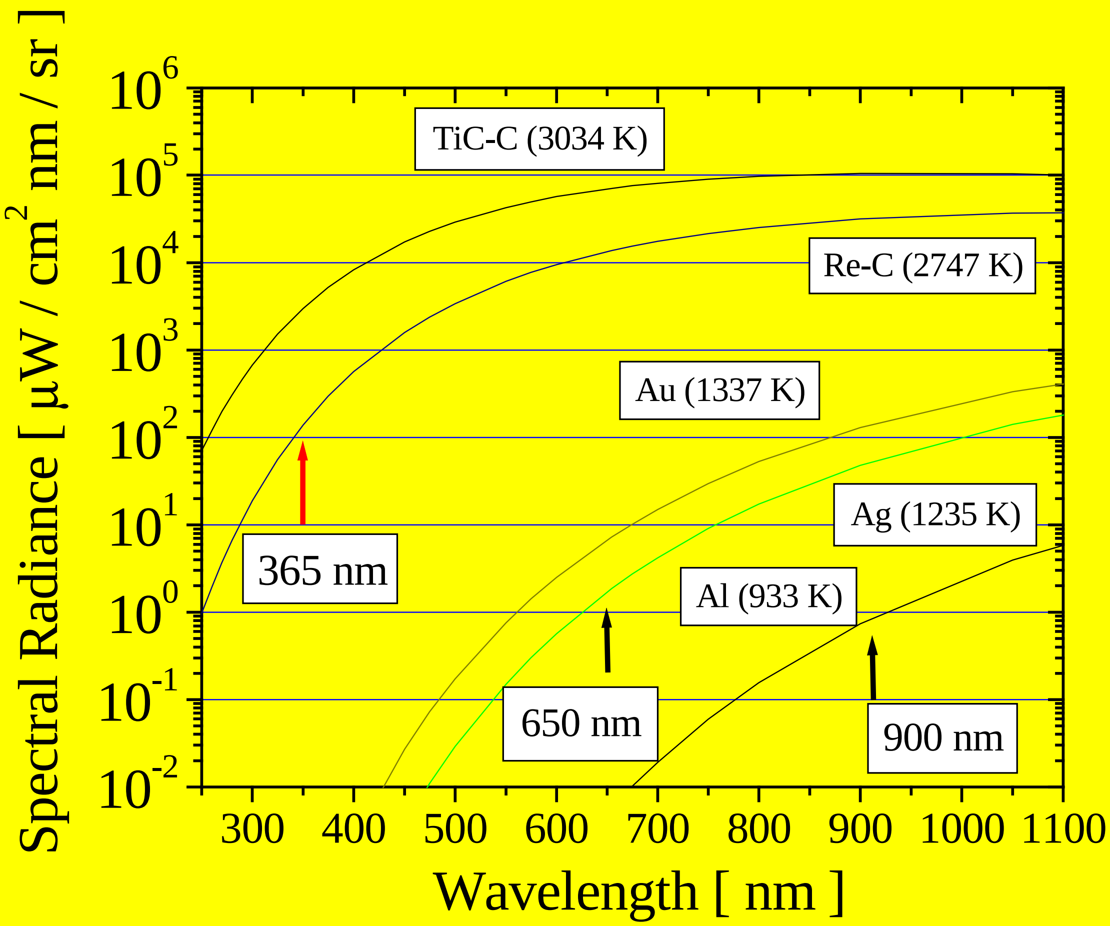
Phase 2: *Assessing the quality of primary cell reproducibility*.

Phase 3: *Assigning thermodynamic temperatures.*

NIST Absolute Pyrometer 2 (AP2) design

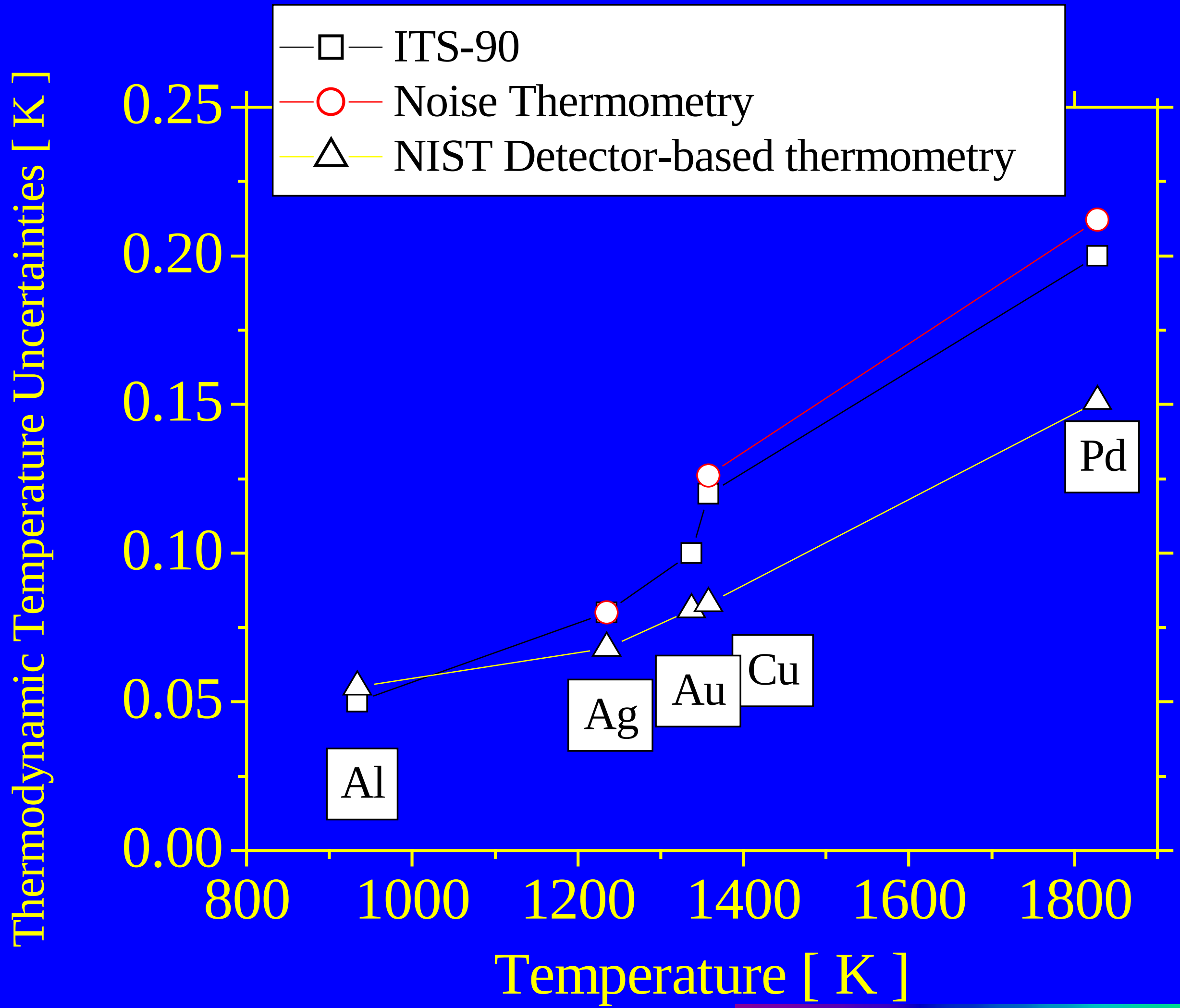


Measurement of metal-carbon eutectics



$$\frac{dL}{L} = \frac{c_2}{\lambda} \frac{\Delta T}{T^2}$$

Comparison of uncertainties



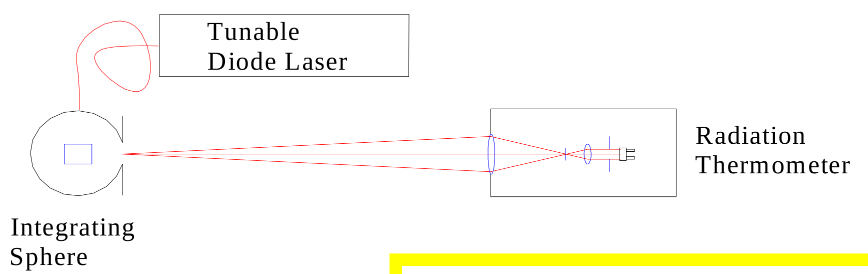
International work in detector-based radiation thermometry

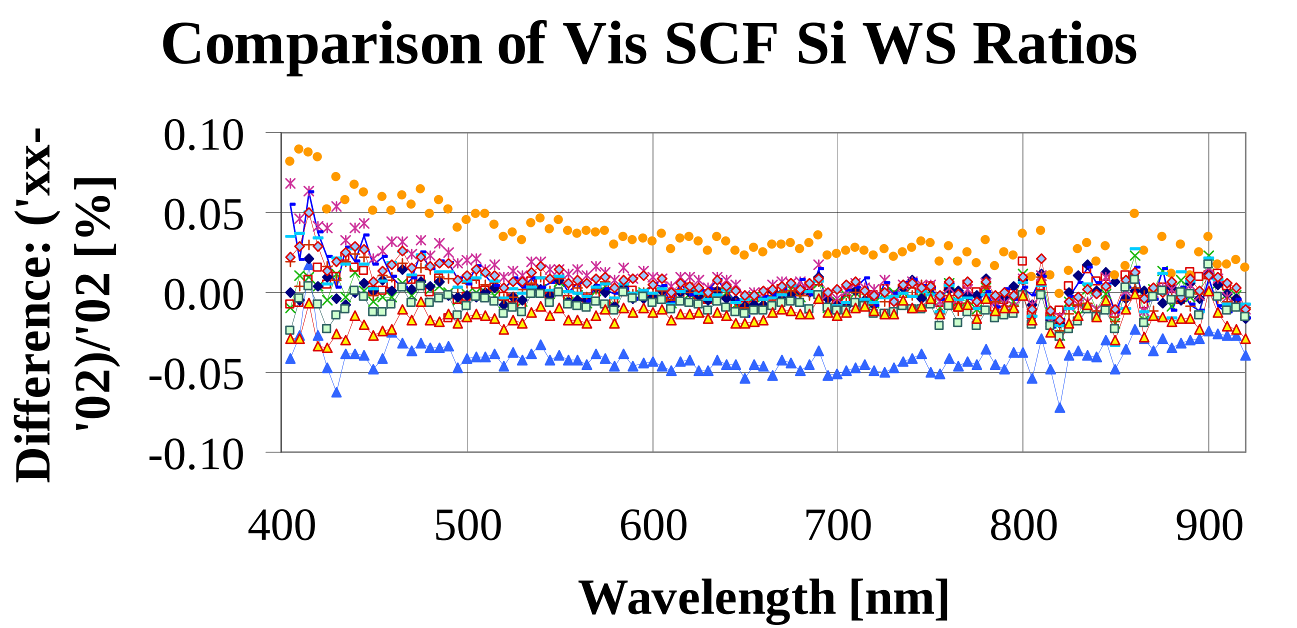
- Current effort at:

1. NIST
2. NPL
3. PTB
4. NMIJ/BIPM
5. HUT
6. BNM/INM
7. NMIA
8. KRISS

- Detector-based radiation thermometry added to the Calibration Measurement Capability (CMC) by CCT-WG8.

Tunable-diode laser based calibrations





CCT-23 recommendation T2 to the CIPM

"national laboratories initiate and continue experiments to determine values of thermodynamic temperature and the Boltzmann constant"

"values of T are needed for the freezing temperatures of zinc, aluminium, silver, gold and copper, **and transition temperatures in eutectic** and other materials at higher temperatures, **to reduce uncertainties in thermometry and radiometry**"

Conclusions

1. Detector-based radiation thermometry is capable of the lowest thermodynamic temperature uncertainties (> 900 K).
2. The next international temperature scale will be revised to reflect these developments.