Novel Flux Calibration Source

CORM 2007
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OSRAM

OSRAM SYLVANIA

LED Calorimetry

- Absolute Radiometry
- Design Goals
- Proof of Concept - Design and Results
- Total Spectral Flux Calibration

Absolute Radiometry

- Optical energy quantified by measurement of generated heat.

- Electrical Substitution Detector Issues (corrections)
  - Reflectance losses (absorption < 100 %)
  - Electrical leads remove heat through conduction and add heat from ohmic heating
  - Temperature distribution differs between radiation and electrical heating
  - Stray radiation heating of thermal reservoir
  - Broad spectral response
  - Diffraction and aperture size errors

Absolute Radiometry

- Electrical Substitution LED Source
  - Optical output equals electrical input minus heat lost

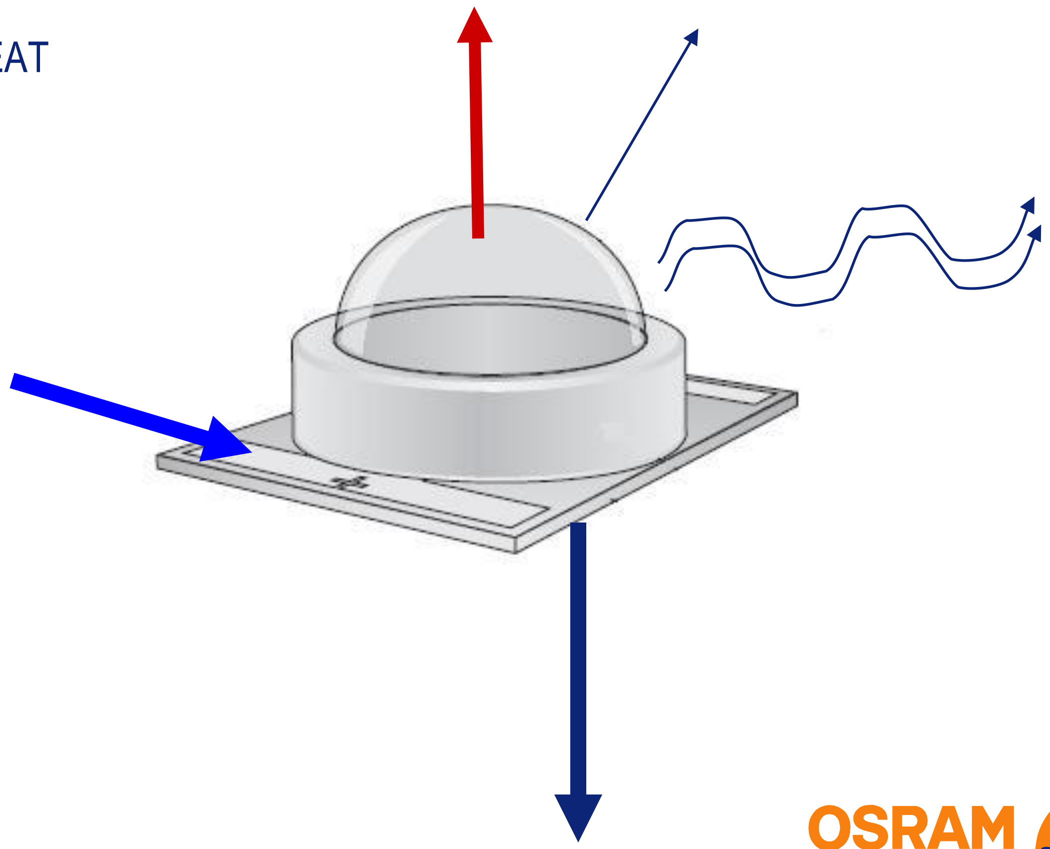
    $W_{OPT} = W_{ELE} - W_{HEAT}$

Optical output

Electrical input

Heat losses

- Radiation
- Convection
- Conduction

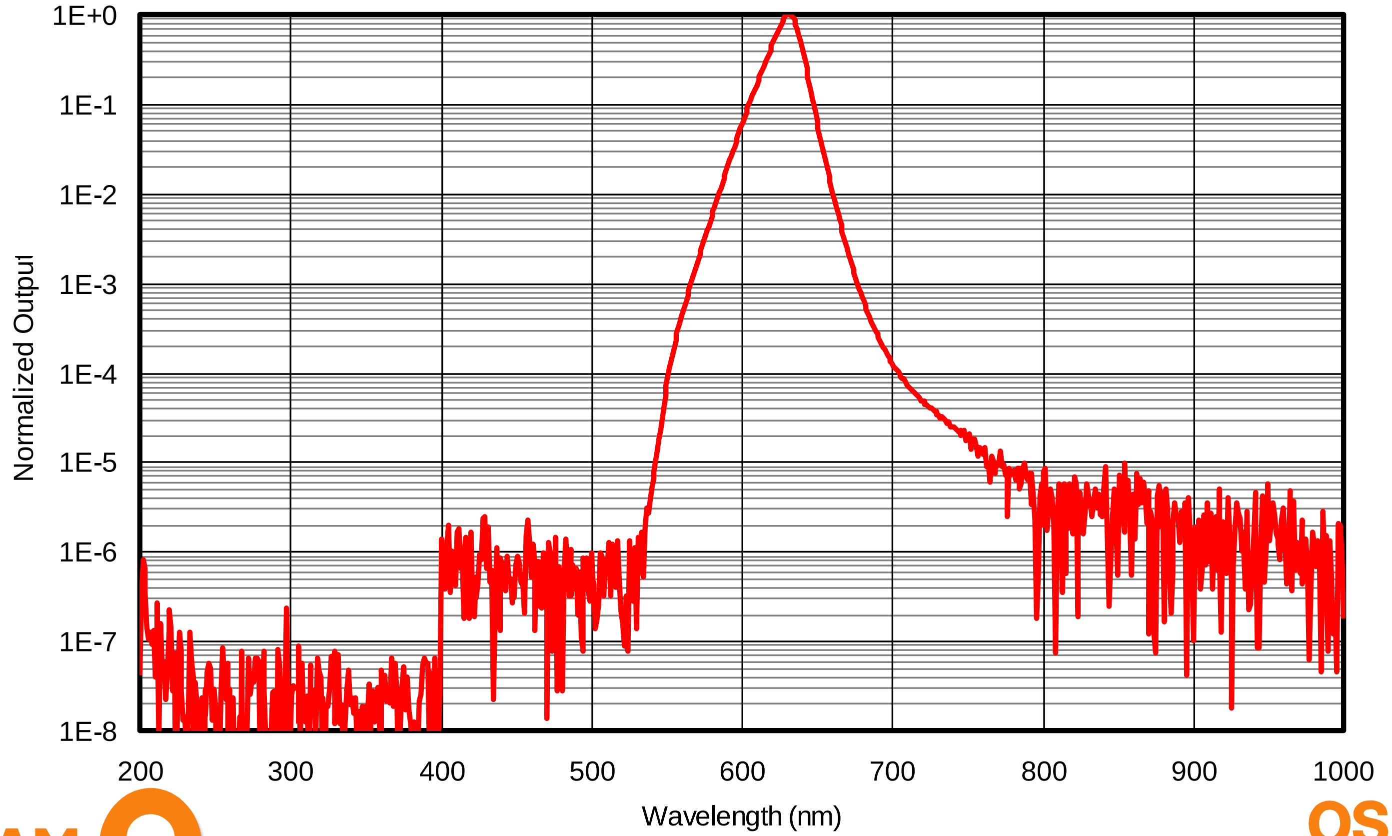


Absolute Radiometry

- Electrical Substitution LED Source
  - High efficiency LEDs
    - > 20 % efficiency ($W_{Optical}$ / $W_{Electrical}$)
  - High thermal conductivity
    - 15 °C/W & 8 °C/W ($T_{Junction}$ to $T_{Solder\ Point}$)
  - Single color

Absolute Radiometry

- Electrical Substitution LED Source
  - Limited spectral extent of optical output



Design Goals

- Room Temperature → no condensation
- No optical surfaces → no transmission corrections
- Steady state (DC) operation → minimize fluctuations
- Accurate electrical measurements
  - Four contact voltage sense
  - 0.1 % Resolution
- Accurate heat flow measurements
  - Minimize heat loss
  - 0.1 % Resolution
  - Equivalent for each source
- Equal currents → equivalent lead heating
- Minimize time constant

Design Goals

- Electrical Substitution LED Source
  - Heat quantified by resistor's input power
  - Optical output equals electrical input minus heat lost

$$W_{OPT} = W_{ELE} - W_{HEAT}$$

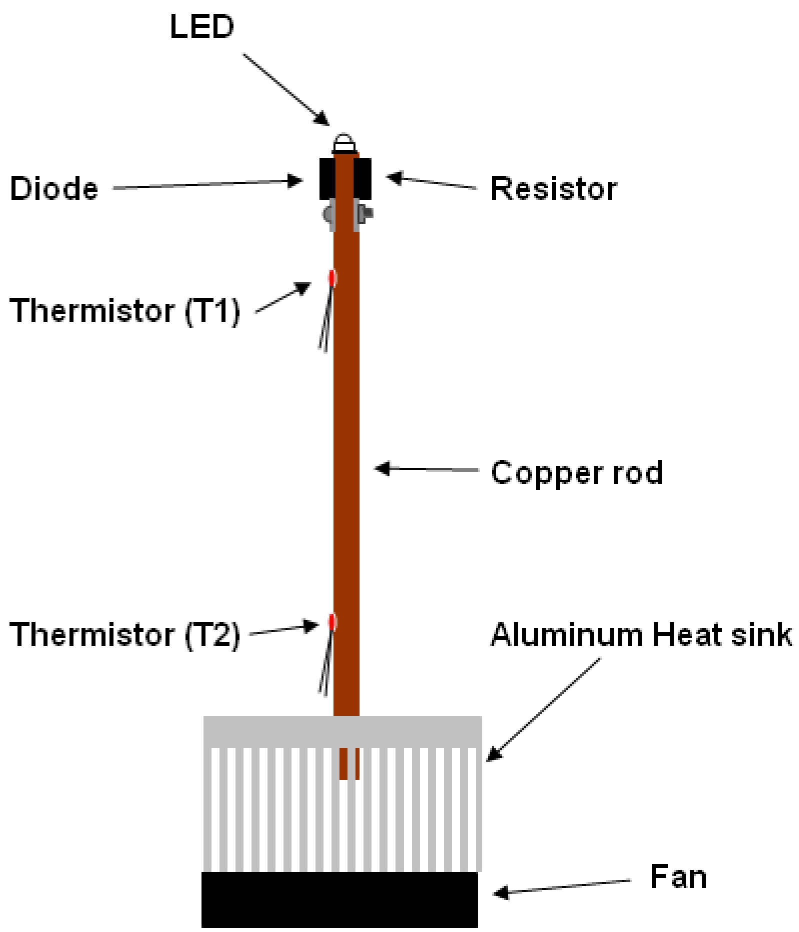
$$W_{OPT} = V_{LED} \cdot I_{LED} - Q_{LED}$$

$$W_{OPT} = V_{LED} \cdot I_{LED} - (\Delta W / \Delta T)_{Res} \cdot \Delta T_{LED}$$

$$W_{OPT} = V_{LED} \cdot I_{LED} - V_{Res} \cdot I_{Res} \qquad \text{when } (\Delta T_{Res} = \Delta T_{LED})$$

$$W_{OPT} = (V_{LED} - V_{Res}) \cdot I \qquad \text{when } (I_{Res} = I_{LED})$$

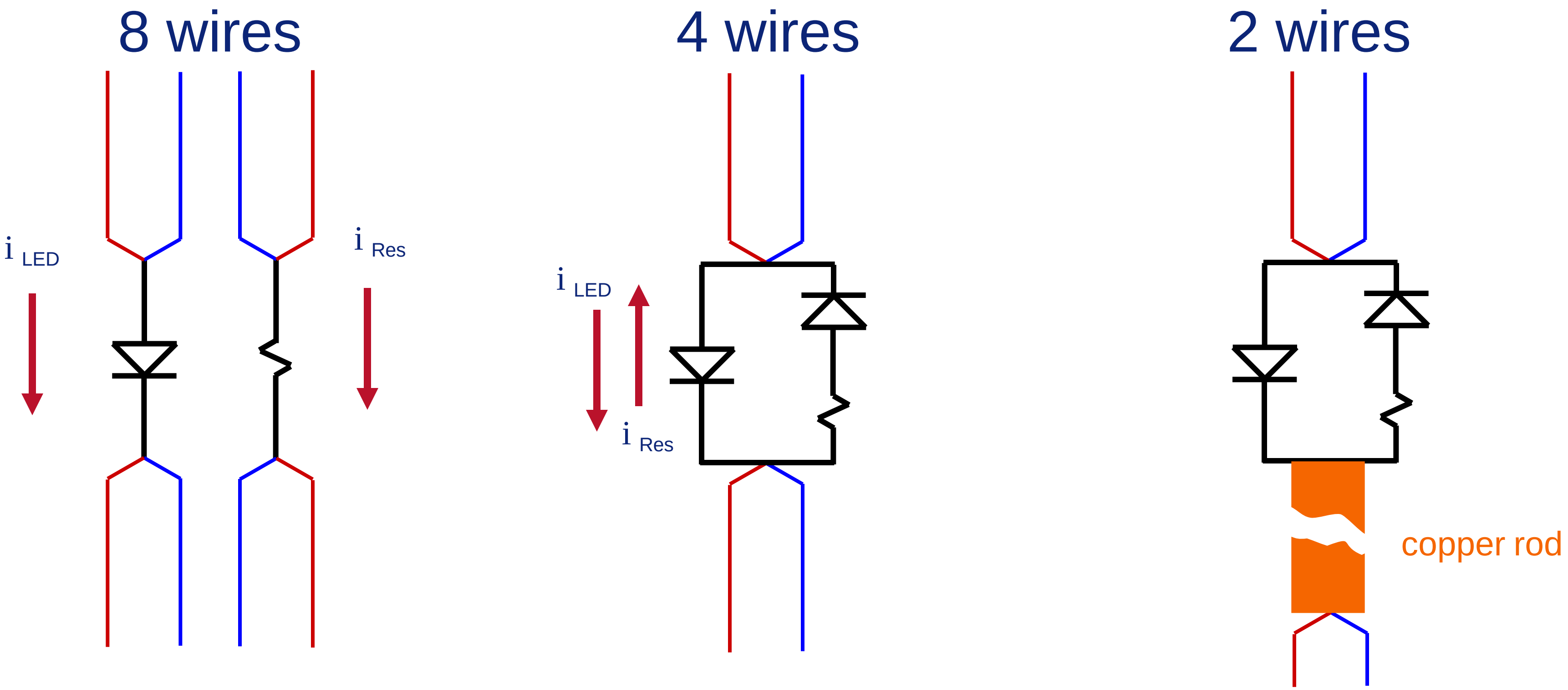
Proof of Concept - Design



Fiberglass insulation is not shown

Proof of Concept - Design

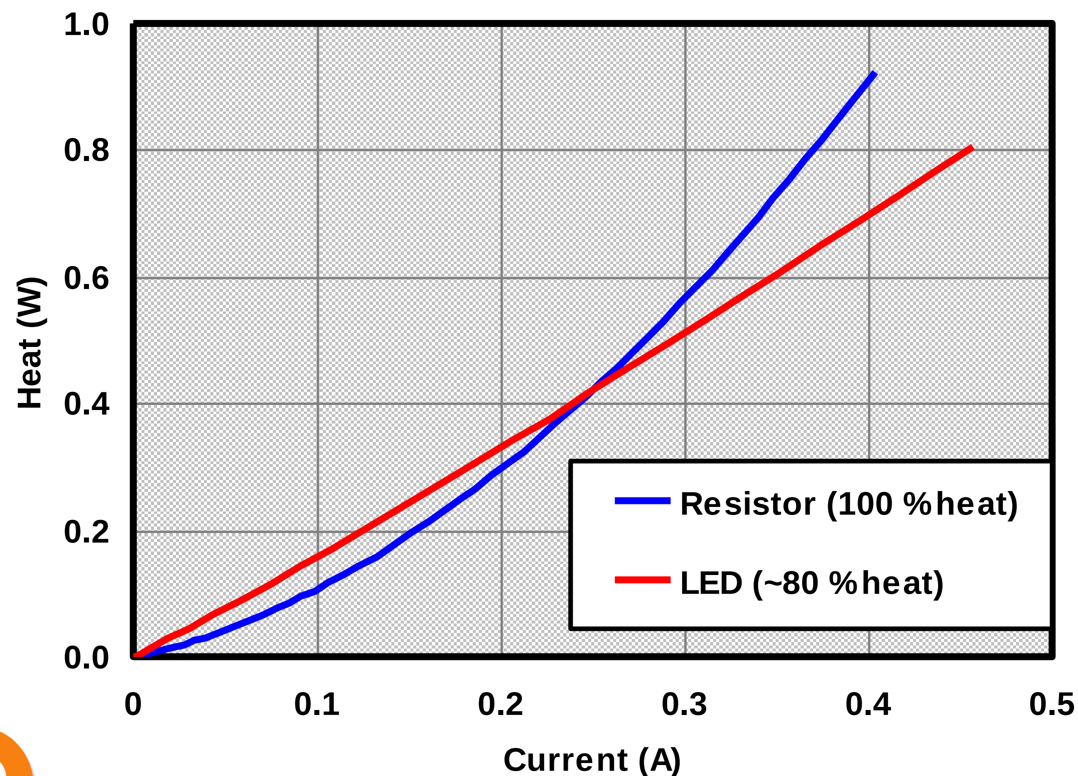
- Wire connections are heat sinks and sources and not part of the calculations



Current Supply Voltage Sense

Proof of Concept - Design

- A resistance value is chosen so that the LED and resistor have the same heat flow at a current within the LED's normal operating range.



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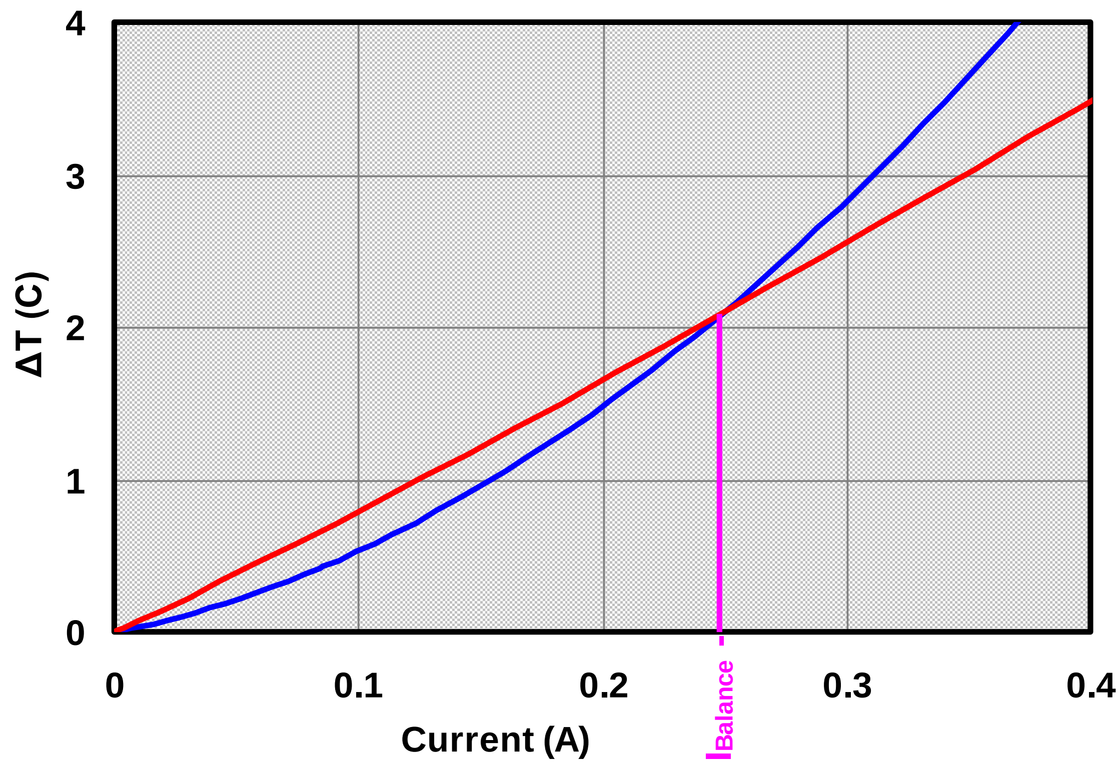
Proof of Concept - Design

- Find the one current ($I_{balance}$) with the same temperature rise (ΔT) for both the LED and the resistor

- Determine electrical input power for resistor and LED

$W_{Opt} = W_{LED} - W_{Res}$



Proof of Concept - Design

- Design
  - Off the shelf parts
    - LED Red efficiency > 20 % CREE XR7090RD
    - Diode 25 amps 400V TO-220
    - Resistor 3.9 ohm 35 watt TO-220
    - Thermistors 5K ohm type MS95
    - Heat Sink CPU cooler Aluminum with 12 V fan
    - Copper rod 0.25" diameter
    - Thermal paste Omegatherm type OT-201
    - Solder Sn 60 % - Pb 40 % Kester 44
  - Common instruments
    - Keithley 2000s Voltage & Current
    - Keithley 2700 Thermistor Monitor
  - Hand fabrication

Devices used identified for reference only

Proof of Concept – Results

- Electrical Substitution LED Source
  - Typical values Red 632 nm

	LED	Resistor-diode
Voltage	2.096 V	1.655 V
Current	0.2430 A	0.2430 A
T1	27.831 °C	27.831 °C
T2	25.827 °C	24.826 °C
ΔT	2.004 °C	2.004 °C
Input Power	0.5094 W	0.4021 W
Output Power	0.107 W	

Proof of Concept – Results

- Disagreement with NIST calibration -0.3 % to +0.2 %
- Settling time 15 minutes
- Similar results were found for a second device using a blue LED

Proof of Concept – Analysis

- Electrical Substitution Detector Issues (corrections)
  - Reflectance losses (absorption < 100 %)
  - Electrical leads remove heat through conduction and add heat from ohmic heating
  - Temperature distribution differs between radiation and electrical heating
  - Stray radiation heating of thermal reservoir
  - Broad spectral response
  - Diffraction and aperture size errors

Proof of Concept – Uncertainty (k=1)

Electrical Measurements	0.02 %
Temperature Measurements	0.05 %
Conduction Losses	0.04 %
Convection Losses	0.02 %
Radiation Losses	0.21 %
Total Uncertainty	**0.22 %**

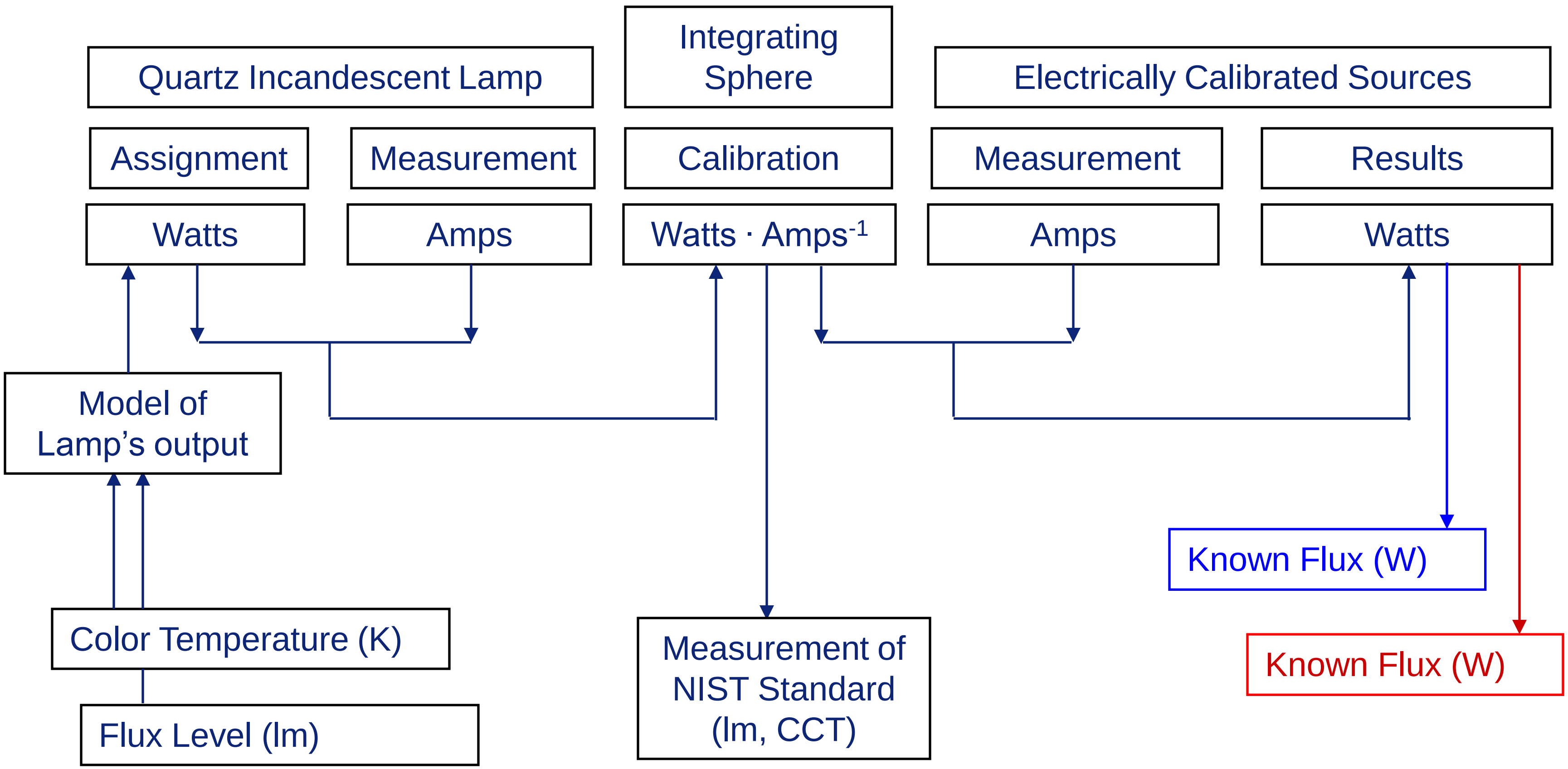
Per ISO Guide to Uncertainty

Total Flux Realization - Method

1. Determine self absorptions in an uncalibrated sphere
2. Uncalibrated spectral measurements in units of current for red and blue Electrical Substitution Sources and quartz incandescent lamp
3. Model the lamp's spectral output
4. Calculate calibration from model of the lamp
5. Apply calibration to red and blue sources
6. Adjust model (level & temperature) to match known outputs

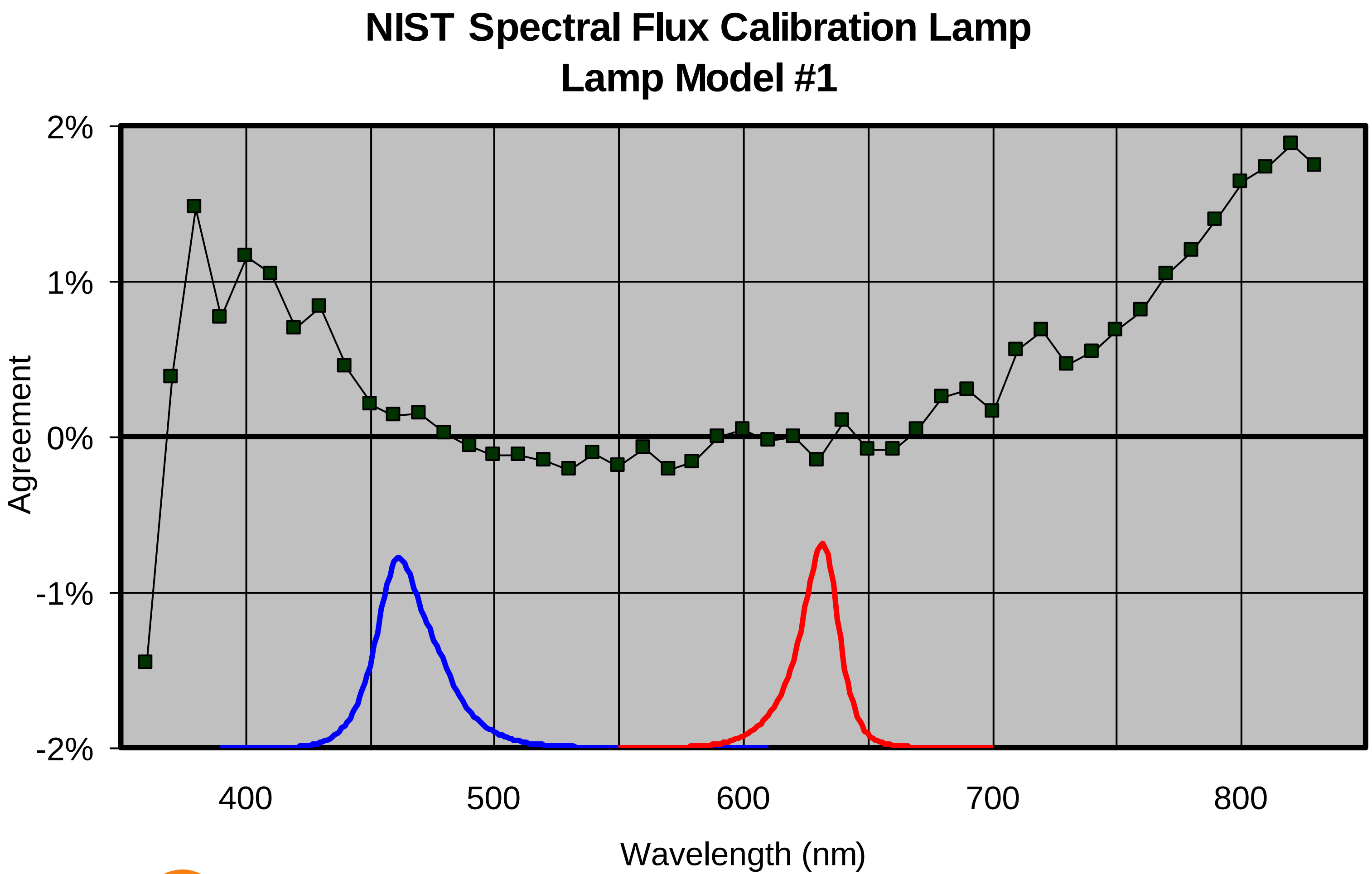
- Measure a NIST calibration standard lamp

Total Flux Realization - Method

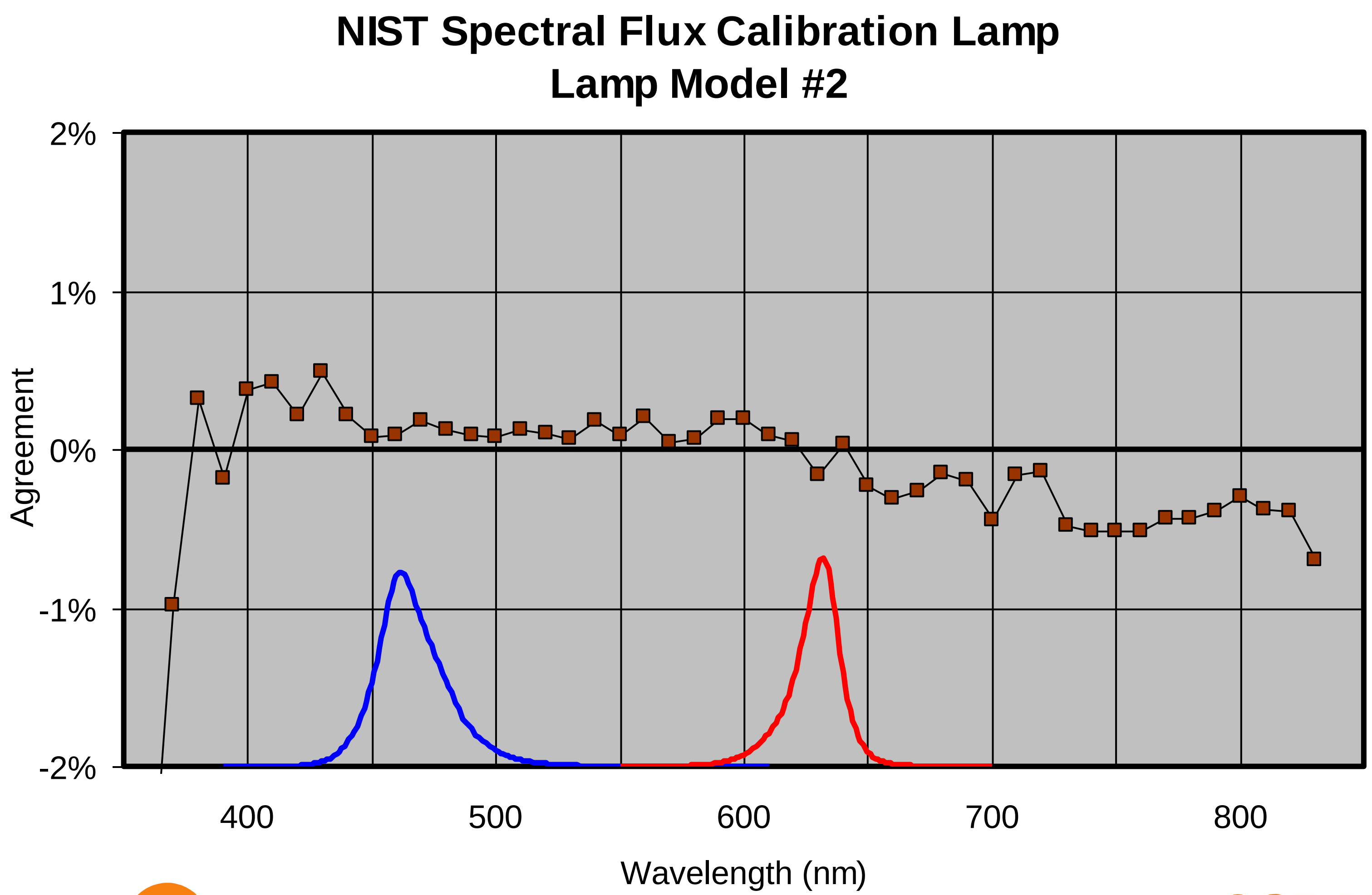


Note : Spectral characteristics are ignored for clarity

Total Flux Realization - Results



Total Flux Realization - Results



Total Flux Realization - Method

- Models of incandescent lamp output

  - Model #1 (Naive Model)
    Planck's Equation for Blackbody Emission
    $$c_1 / (\lambda^5 \cdot e^{c_2/\lambda T} - 1)$$
    Two adjustable parameters T & c_1

  - Model #2 (Incandescent Lamp Model)
    Blackbody Emission times the emissivity of tungsten to a power
    $$c_1 / (\lambda^5 \cdot e^{c_2/\lambda T} - 1) \cdot \varepsilon_W(T, \lambda)^{0.5}$$
    Two adjustable parameters T & c_1

Total Flux Realization - Results

- NIST Spectral Flux Calibration Lamp
  65 Watt hard glass halogen

Level agreement with NIST	0.1 %	lumens
Color agreement	3 K	CCT

LED Calorimetry for Lumen Realization

- Sphere calibration for total flux
- Low cost ($50 per device $4K instruments)
- Controllable uncertainties < 0.5%
- Calibration through electrical chain vs. optical
- One step vs. seven steps (HACR ... Gonio-Spec.)
- Stability of lamp or LEDs is not required

Improvement Suggestion

- Matched emitters, one with opaque coating
  - Balance IR losses
- LED held to ambient temperature
  - Reduce IR losses
- Reduce thermal difference/distance between the LED and the resistor at the die level
  - Match IR losses
- Shorter, thinner heat path to reduce settling time
- Laser Diode in a Dewar with output via optical fiber