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Recent progress on optical metrology for solid-state lighting at NIST

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SSL products are rapidly penetrating the market

ENERGY STAR

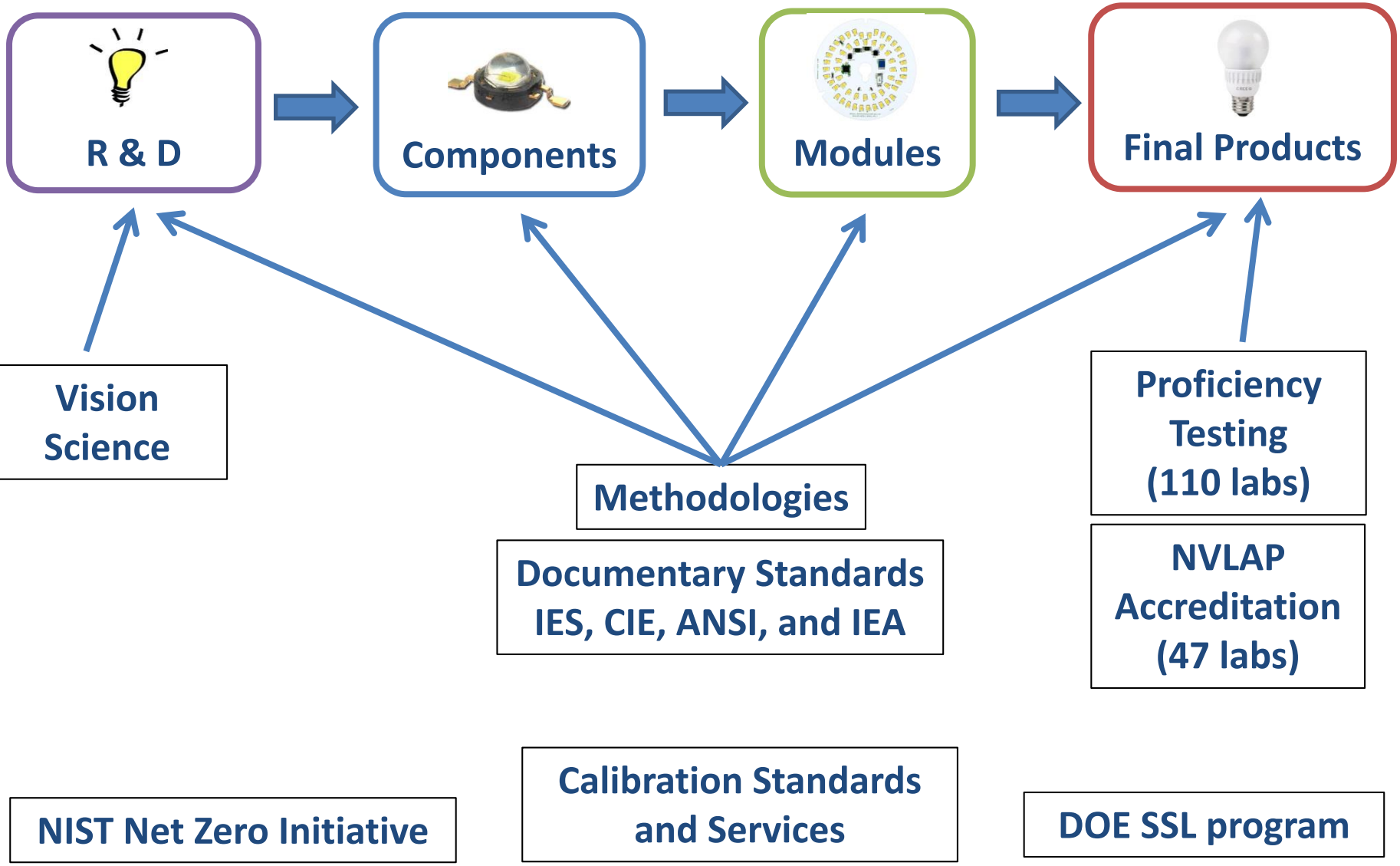
Lighting Facts™
LED Product

Light Output (Lumens)	840
Watts	9
Lumens per Watt (Efficacy)	93
Color Accuracy Color Rendering Index (CRI)	87
Light Color Correlated Color Temperature (CCT)	3100 (Warm White)

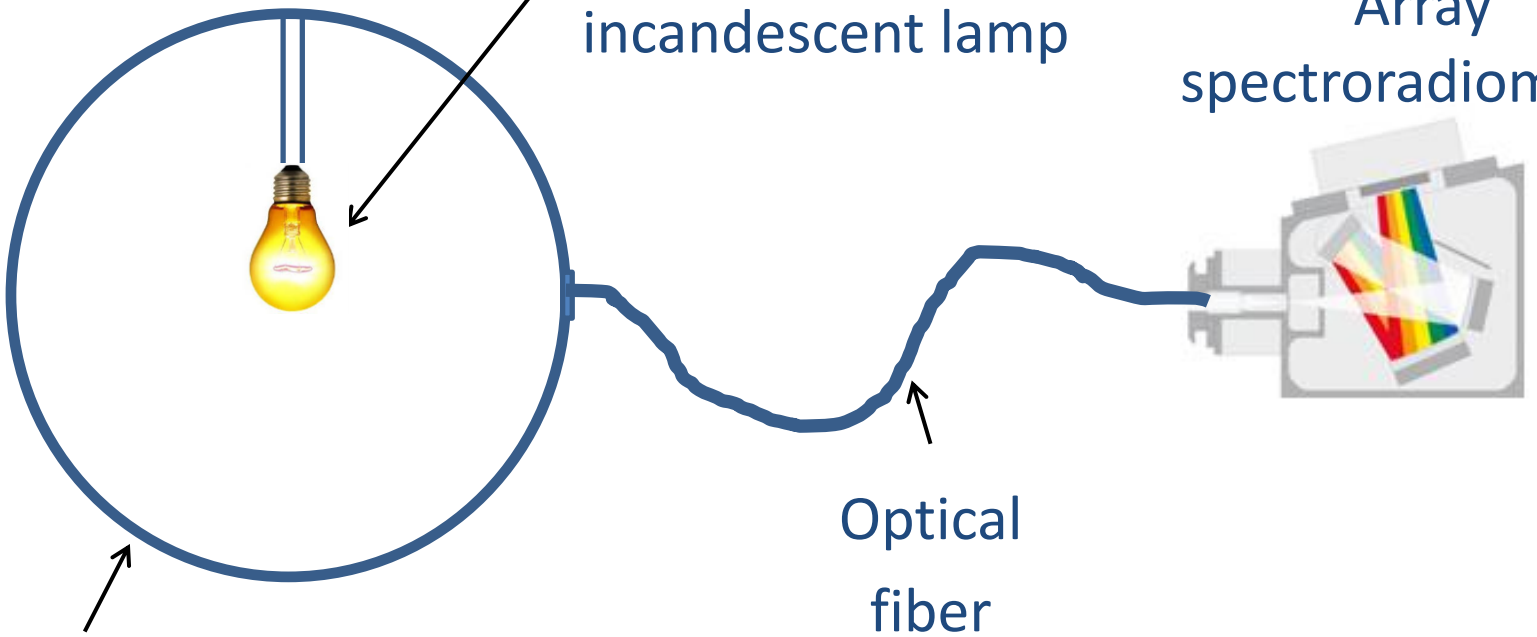
Warm White | Bright White | Daylight
2600K 3200K 4500K 6500K

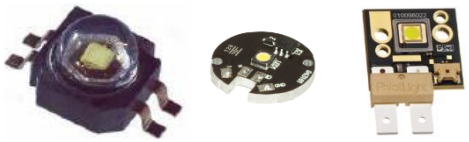
Optical metrology and measurement standards are critical for SSL to avoid market failure.

What do we do for SSL?



A typical SSL measurement system

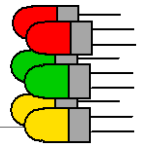


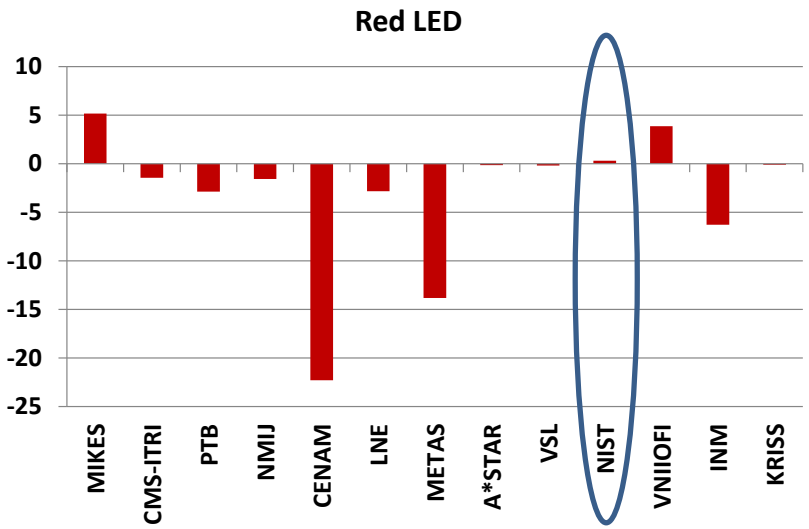


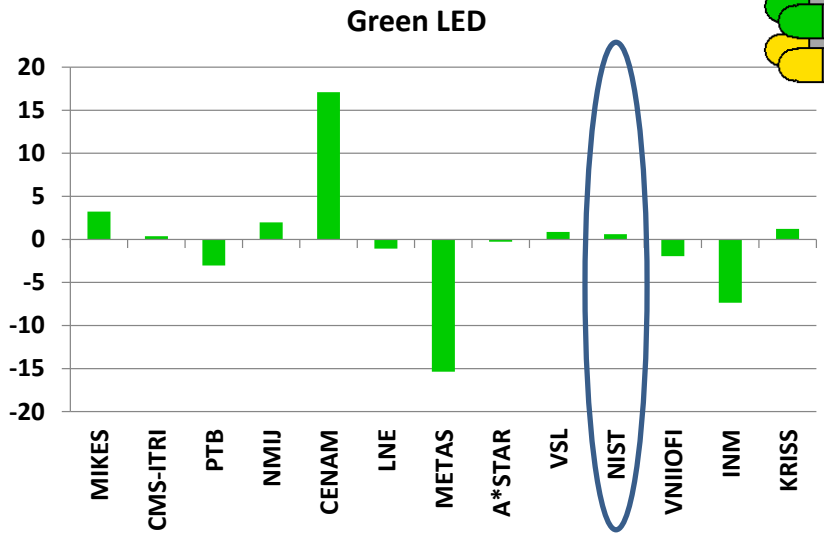
High-power LEDs

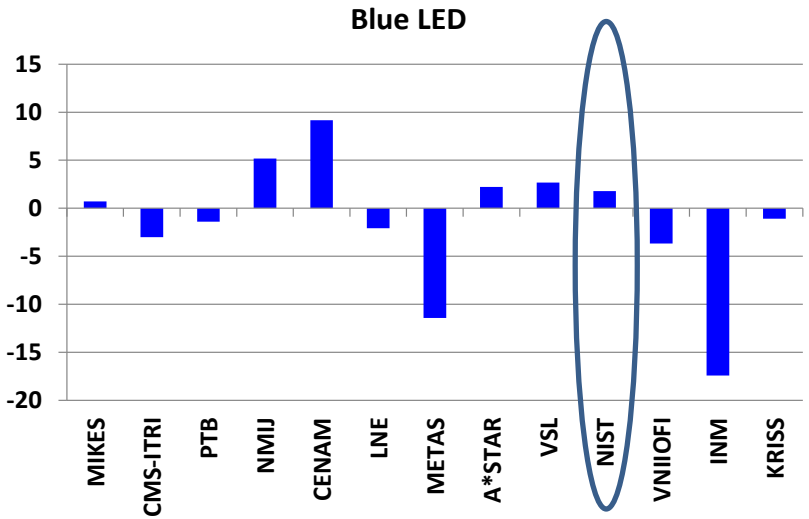
2009 APMP Supplementary Comparison for LEDs

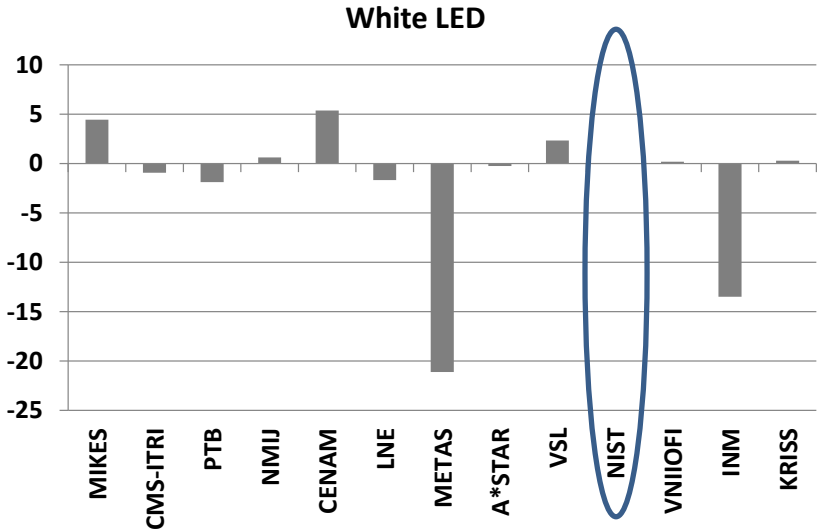
Luminous Flux









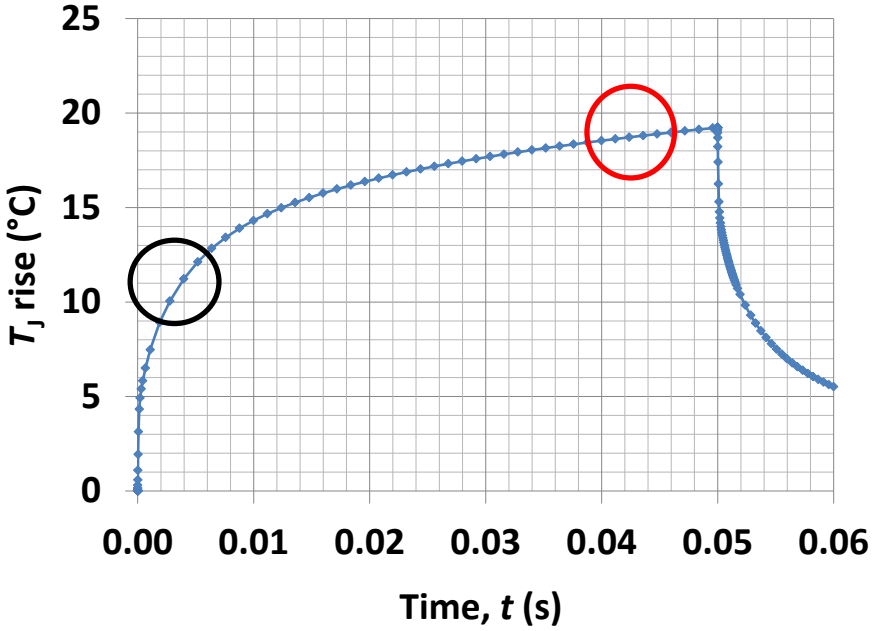


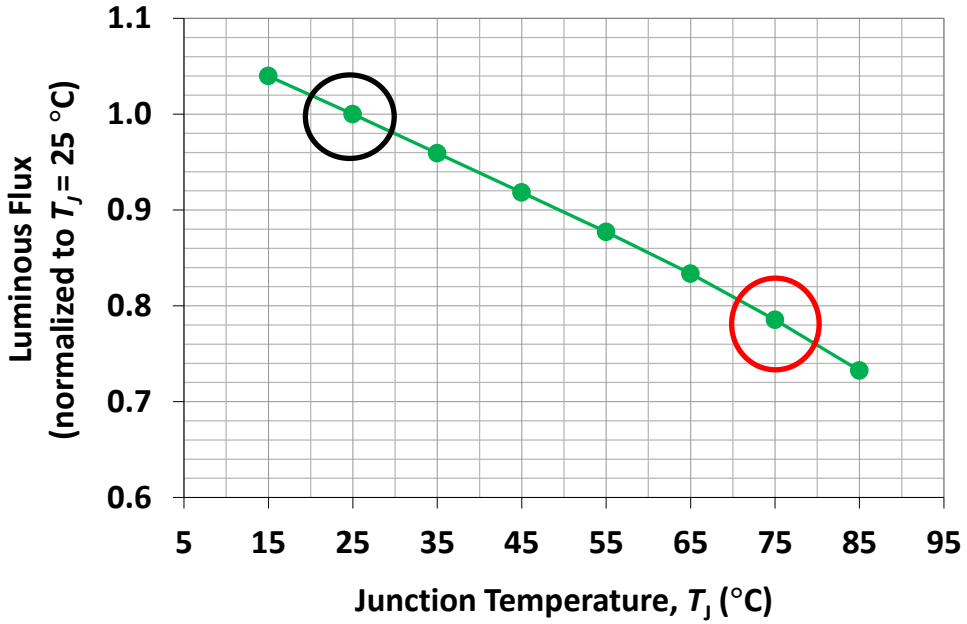
Our research for SSL metrology

1. Develop measurement methods for high-power LEDs.
2. Correct stray light for spectroradiometers.
3. Provide total spectral radiant flux standards for calibration of LED measurement systems.

   - New realization approach for the NIST Candela
   - New detector-based spectroradiometer calibration method.

Thermal issue in measurement of high-power LEDs





Junction temperature, T_J, rises rapidly.
0.1 ms → 1 °C, 1 ms → 4 °C
Acknowledgement to Jeff Hulett

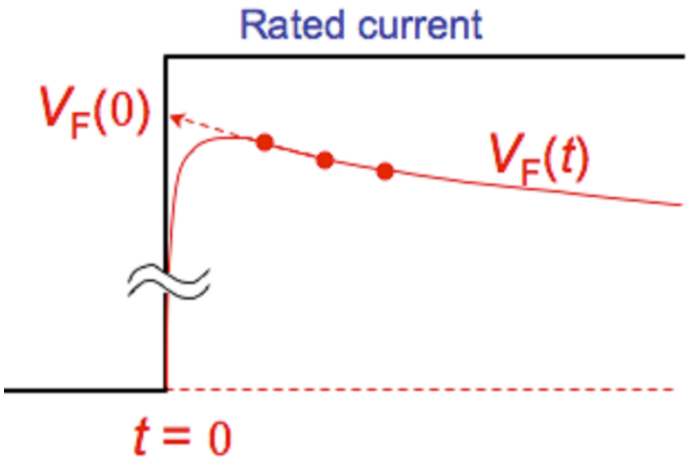
Total flux is very sensitive to T_J.

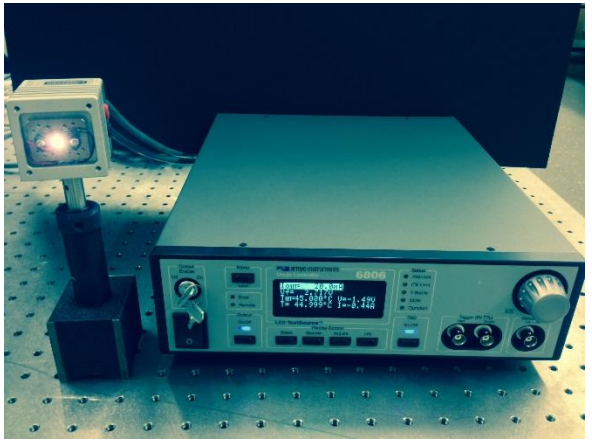
Manufacturer (pulsed mode at 25 °C ambient)

Gap

User (dc mode at a "hot" unknown condition)

Methods for measurement of high-power LEDs





- Junction temperature as the thermal reference.
- Junction temperature is set, not measured.
- Pulse mode and dc mode are equivalent in results.

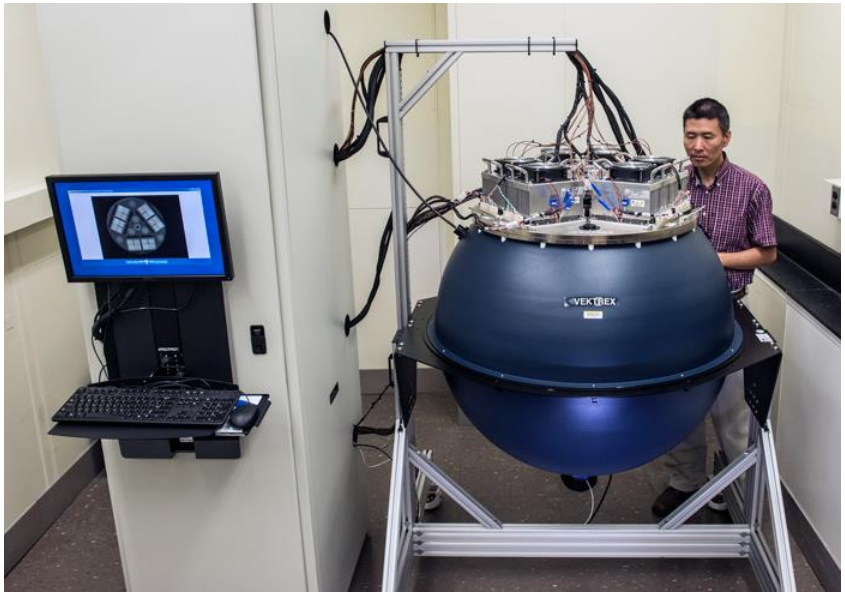
CIE: TC2-63 (Zong) and TC2-76 (Chou)
IES: LM-85 (Ohno) and LM-88 (Zong)

Y. Zong and Y. Ohno, "New Practical Method for Measurement of High-Power LEDs," **CIE x033:2008**, 102-106.

How long do LEDs last?

?

?



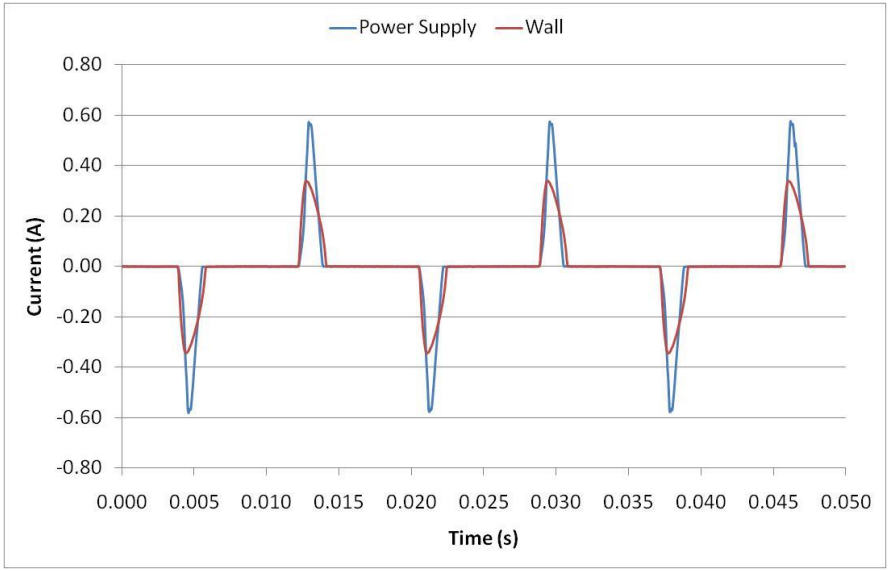
- DOE funded project

- Automated measurements of luminous flux decay & color shift.
- Produces low uncertainty data under real operating conditions
- Enables developing accurate LED lifetime prediction models.

Y. Zong and J. Hulett, “Development of a fully automated LED lifetime test system,” **CIE x037:2012**, 239-245.

Measurement of SSL products -Cameron and Maria

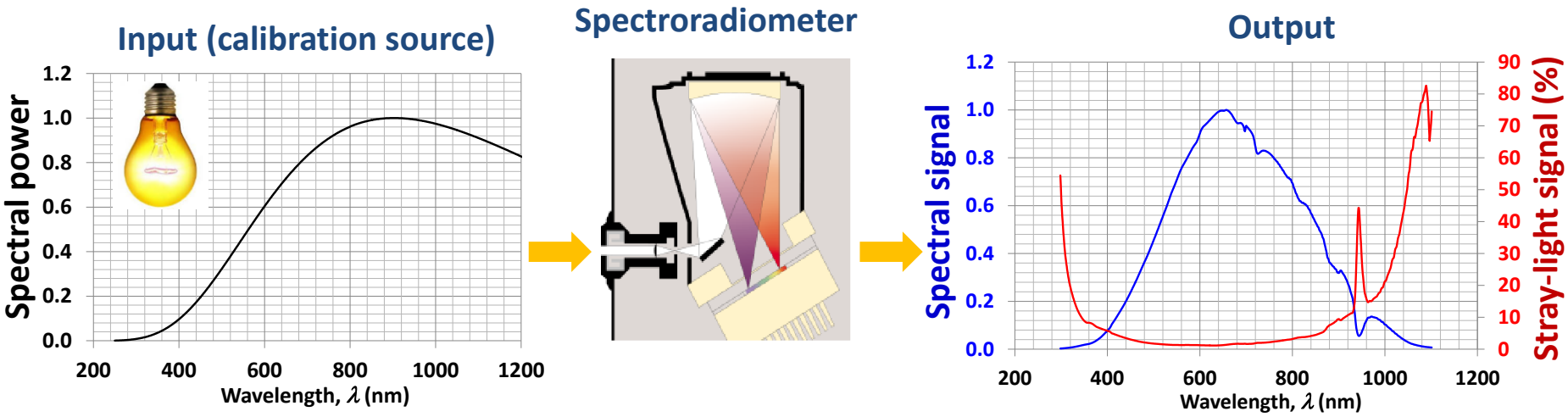
current waveforms of an LED lamp



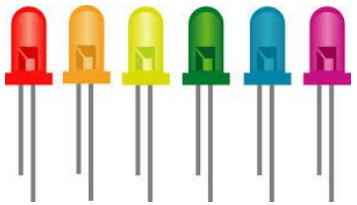
Various drivers/controllers:

- DC
- pulse-width modulated DC
- AC
- feedback controlled output light –smart lighting products

Correct stray light in array spectroradiometers



Stray light is the dominant source of error <u>even</u> with an expensive, 'high-quality' spectroradiometer!



Conventional solutions:

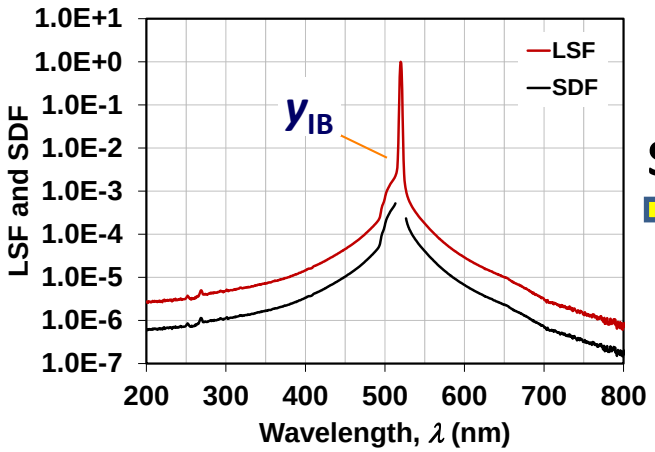
1. Use a double-monochromator.
2. Use many calibration sources.
3. Improve hardware design.

Measurement uncertainty is limited by stray light.

Our method: Correct it mathematically!

Stray-light correction for array spectroradiometers

Line Spread Function (LSF)
Line Distribution Function (SDF)

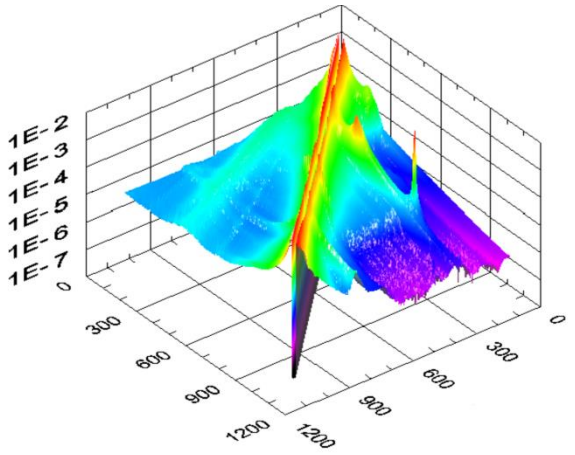


SDF

Building SDF matrix, $D_{n\times n}$
"n" is the total number of pixels

$$\begin{bmatrix} d_{1,1} & d_{1,2} & \cdots & d_{1,J} & \cdots & d_{1,n-1} & d_{1,n} \\ d_{2,1} & d_{2,2} & \cdots & d_{2,J} & \cdots & d_{2,n-1} & d_{2,n} \\ \vdots & \vdots & \cdots & \vdots & \cdots & \vdots & \vdots \\ \vdots & \vdots & \cdots & \vdots & \cdots & \vdots & \vdots \\ d_{i,1} & d_{i,2} & \cdots & d_{i,J} & \cdots & d_{i,n-1} & d_{i,n} \\ \vdots & \vdots & \cdots & \vdots & \cdots & \vdots & \vdots \\ \vdots & \vdots & \cdots & \vdots & \cdots & \vdots & \vdots \\ d_{n-1,1} & d_{n-1,2} & \cdots & d_{n-1,J} & \cdots & d_{n-1,n-1} & d_{n-1,n} \\ d_{n,1} & d_{n,2} & \cdots & d_{n,J} & \cdots & d_{n,n-1} & d_{n,n} \end{bmatrix}$$

Plot of a SDF matrix



$$\mathbf{Y}_{\text{meas, n}\times 1} = \mathbf{Y}_{\text{true, n}\times 1} + \mathbf{D}_{\text{n}\times\text{n}}\ \mathbf{Y}_{\text{IB, n}\times 1}$$
$$\approx [\mathbf{I} + \mathbf{D}_{\text{n}\times\text{n}}]\mathbf{Y}_{\text{true, n}\times 1}$$

$$\mathbf{Y}_{\text{true, n}\times 1} = \mathbf{C}_{\text{n}\times\text{n}}\ \mathbf{Y}_{\text{meas, n}\times 1}$$

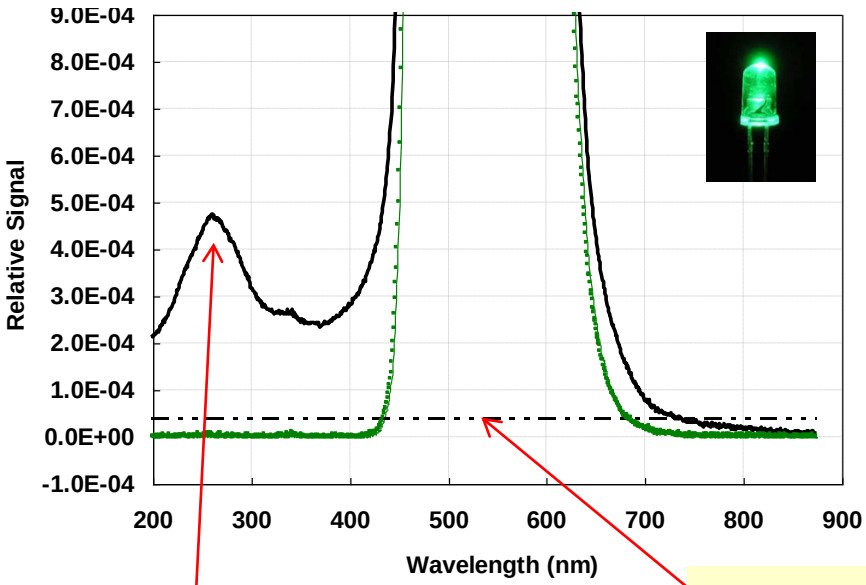
True signals — **Correction matrix (constant)** — **Raw signals**

Yuqin Zong, Steven W. Brown, B. Carol Johnson, Keith R. Lykke, and Yoshi Ohno, "Simple spectral stray light correction method for array spectroradiometers," *Applied Optics*, Vol. **45**, No. 6, 1111-1119. (2006)

- Cited 86 times

Stray-light correction for measurement of LEDs

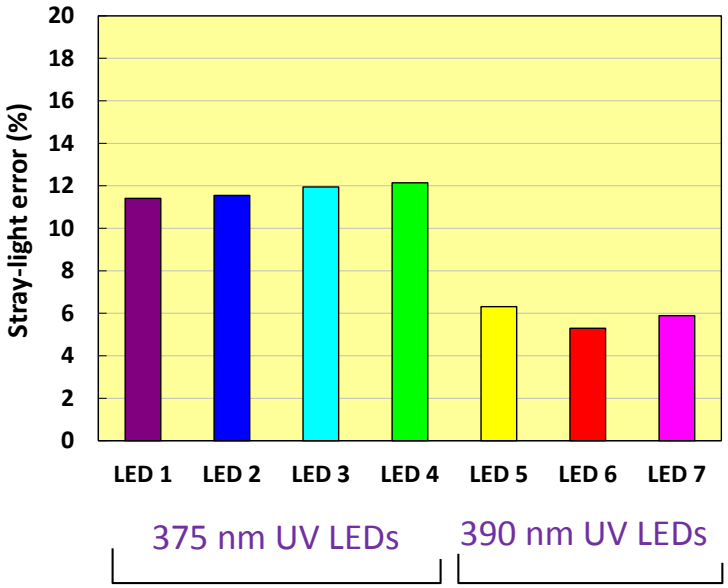
Measurement of a green LED



Stray-light error causes false assessment of UV hazard.

1 bit level, 2 orders of magnitude reduction

Measurement of UV LEDs



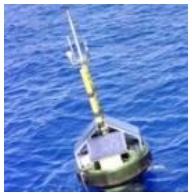
Zong Y., *et al*., Measurement of total radiant flux of UV LEDs, in Proc. CIE, CIE x026:2004, 107–110 (2004)

Correction reduced measurement uncertainty by > 1 order of magnitude for UV LEDs

Applications of the stray-light correction method

- Recommended by the CIE (TC2-51 and TC2-60)
- Adopted by instrument companies

- Other NIST projects
  - STARS, Lunar Irradiance, Color Appearance
  - Simulated Photodegradation via High Energy Radiant Exposure (SPHERE, EL)

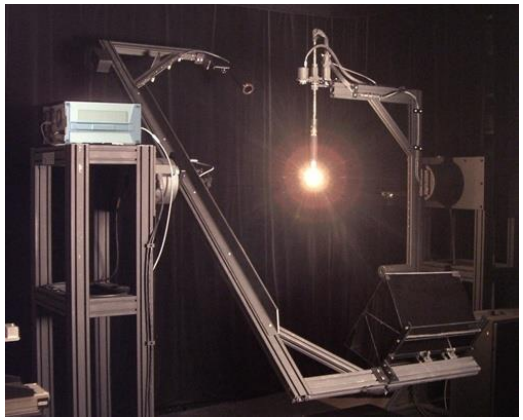


- Remote sensing
  - NOAA's MOBY
  - NATO's Undersea Research Centre
  - NASA's Mars Exploration Rover Mission (planning)

NIST total spectral radiant flux calibration standards

NIST standard lamp

Gonio-spectroradiometer



2.5 m integrating sphere

Based on

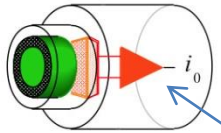
- **Candela scale**
- **Spectral irradiance scale**

Zong Y. and Ohno Y., Realization of total spectral radiant flux scale and calibration service at NIST, in Proc. CIE, July 4-11, 2007, Beijing, China, CIE 178:2007, D2-179 to D2-182. (2007)

New realization approach for NIST Candela

Monochromator power source (Watt)

Photometer

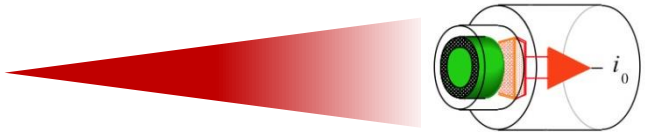


$u_o(\lambda)$ (**V**)

POWER MODE(V/W)
large uncertainty
(0.5 %)

Trans-impedance amplifier

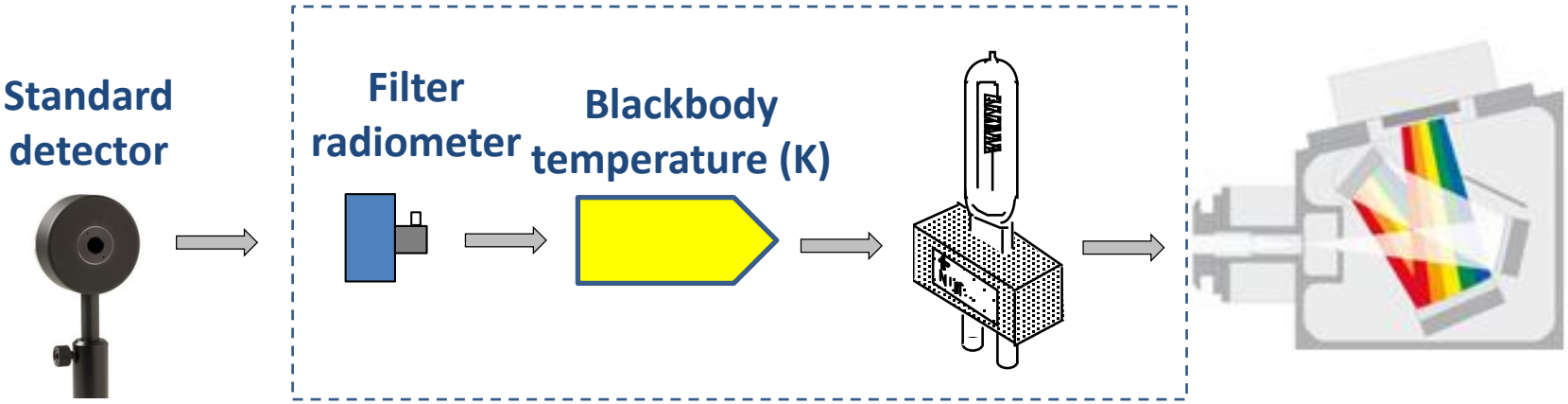
Tunable irradiance source (Watt·m^{-2})



$u_o(\lambda)$ (**V**)

IRRADIANCE MODE
(V/(W·m^{-2}))
low uncertainty
(0.05 %)

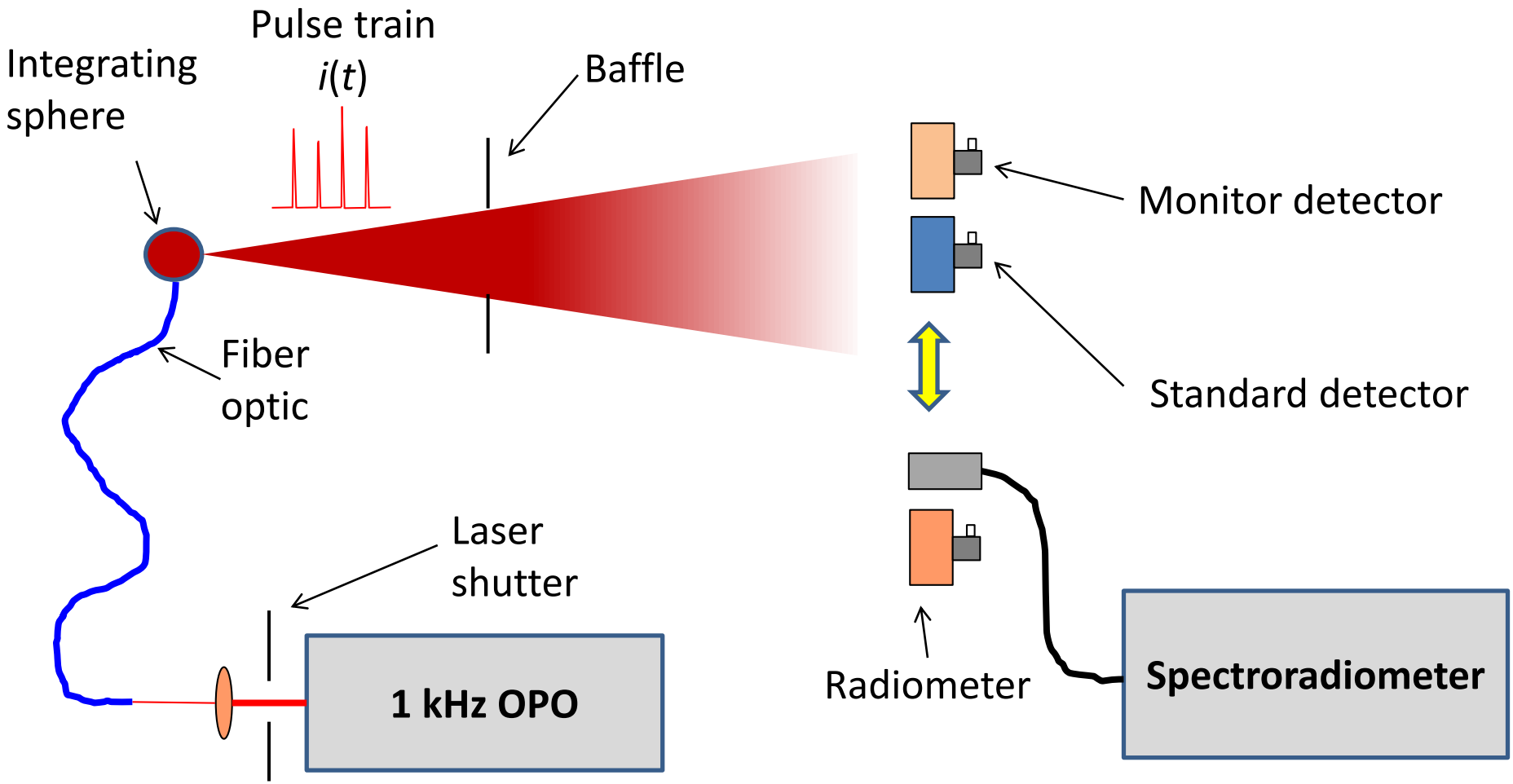
New detector-based spectroradiometer calibration



Conventional lamp-based calibration
Uncertainty (1 %)

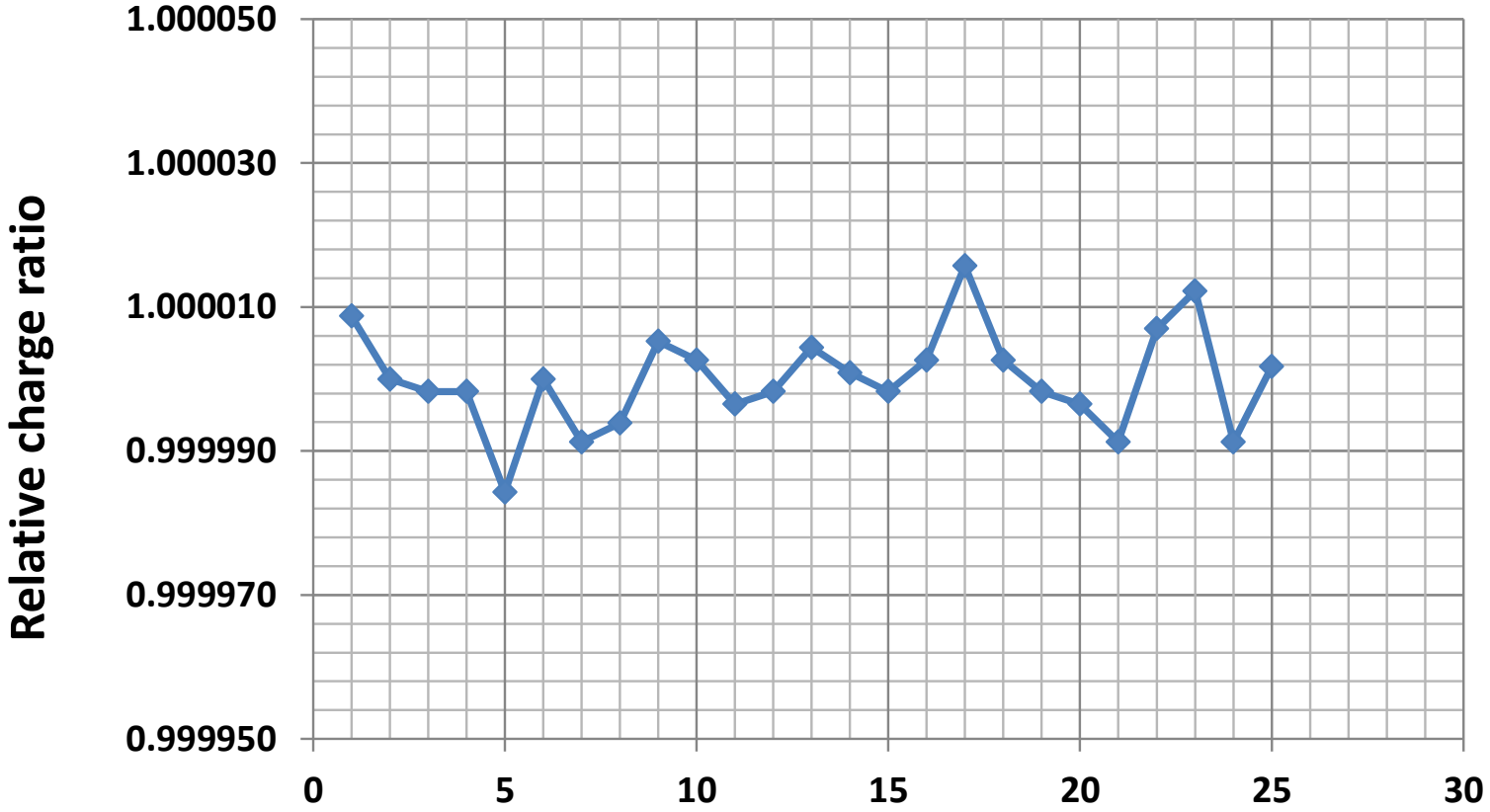
New detector-based calibration using OPO laser
Uncertainty (0.1 %)

Calibration of sensors using tunable kHz OPO



- **Use energy mode (dose) instead of power mode.**
- **Use charge amplifiers instead of trans-impedance amplifiers.**
- **10 ppm repeatability with >20 % laser power fluctuations.**

Measurement repeatability for detector calibration



- **Excellent repeatability ≈ ±10 ppm!**
- **Only 1 s integration time for each measurement**
- **Fluctuation of the pulsed laser (≈ 20 %) does not matter**

Future directions

Optical metrology for UV LEDs

- Many attractive characteristics
- Various applications
- Measurements critical for safety
- Measure high-level of irradiance

Intelligent LED lighting – for energy saving and better light

- Intelligent use and control
- Built-in sensors
- Fully controllable
- Networked
- New measurement and evaluation challenges

Questions and input?

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