Copernicus FICE 2025

Training on
In situ Ocean Colour Above-Water Radiometry towards Satellite Validation

Absolute Radiometric Calibration of field radiometers

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fiducial reference measurements for satellite ocean colour | UNIVERSITY OF TARTU | Brockmann Consult | CNR ISMAR | NPL National Physical Laboratory | EOScience | Venice International University | Programme of the European Union | Copernicus | Implemented by EUMETSAT | NASA

6-20 July 2025
Venice, Italy

NPL National Physical Laboratory

Outline

- Spectral radiometric scale realization
- Reflectance scale realization

- Calibration standards

- Irradiance calibration
- Radiance calibration

SI: Summary

- Identical worldwide
- Century-long stability
- Absolute accuracy

Achieved through:

- Traceability
- Uncertainty Analysis
- Comparison

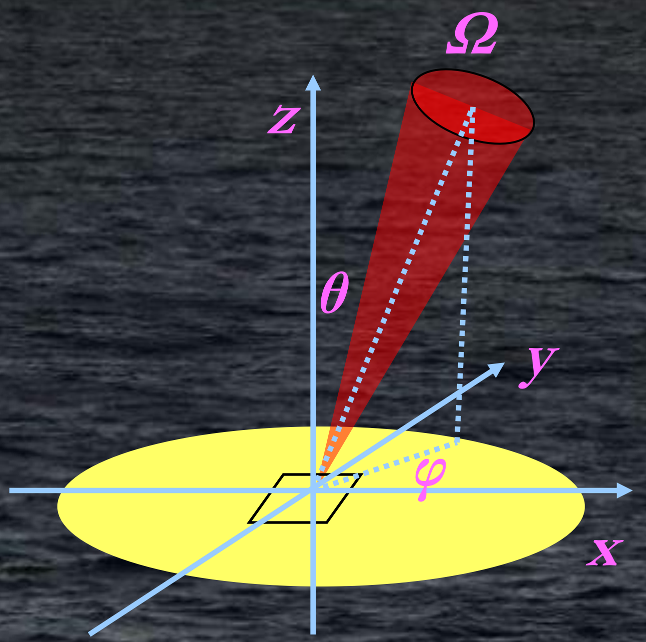
Table 1.1: Radiometric quantities (Palmer & Grant, 2010).

Radiometric quantity	Equation and units	Definition
Radiant Energy	Q [J]	
Radiant Power (radiant flux)	$\Phi = \frac{dQ}{dt}$ [W]	Energy per unit time
Irradiance (radiance incidence)	$E = \frac{d\Phi}{dA_s}$ [Wm^{-2}]	Power per unit area that is incident on a surface Irradiance is measured at the detector
Solid angle	ω [sr]	The plane-angle concept extended to three-dimension
Radiance	$L = \frac{d^2\Phi}{dA_s d\Omega}$ [$Wm^{-2}sr^{-1}$]	Power per unit area and per unit projected solid angle
Radiometric properties of materials		
Reflectance	$\rho = \frac{\Phi_r}{\Phi_i}$	Ratio of reflected power to incident power
BRDF	$f_r(\theta_i, \phi_i, \theta_r, \phi_r) \equiv \frac{dL_r(\theta_r, \phi_r)}{dE_i(\theta_i, \phi_i)} = \frac{dL_r(\theta_r, \phi_r)}{L_i(\theta_i, \phi_i) d\Omega}$ [sr^{-1}]	Differential element of reflected radiance in a specified direction per unit differential element of irradiance, also in specified direction
Transmittance	$\tau = \frac{\Phi_t}{\Phi_i}$	Ratio of the total transmitted flux to the total incident flux
Absorbance	$\alpha = \frac{\Phi_a}{\Phi_i}$	Ration of absorbed power to incident power

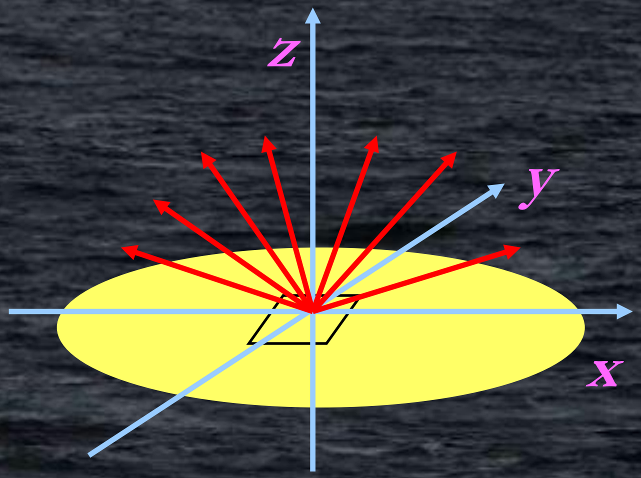
Radiometric quantities: radiance and irradiance

Radiance $L(\varphi,\theta,\lambda)$: power, emitted from the unit area of the source into unit solid angle.
Unit: $W \cdot m^{-2} sr^{-1}$ or $W \cdot m^{-2} sr^{-1} nm^{-1}$

Irradiance $E(\lambda)$: total power, emitted from the unit area.
Unit: $W \cdot m^{-2}$ or $W \cdot m^{-2} nm^{-1}$



$$E(\lambda)=\iint L(\varphi,\theta,\lambda)\,d\varphi\,d\theta$$

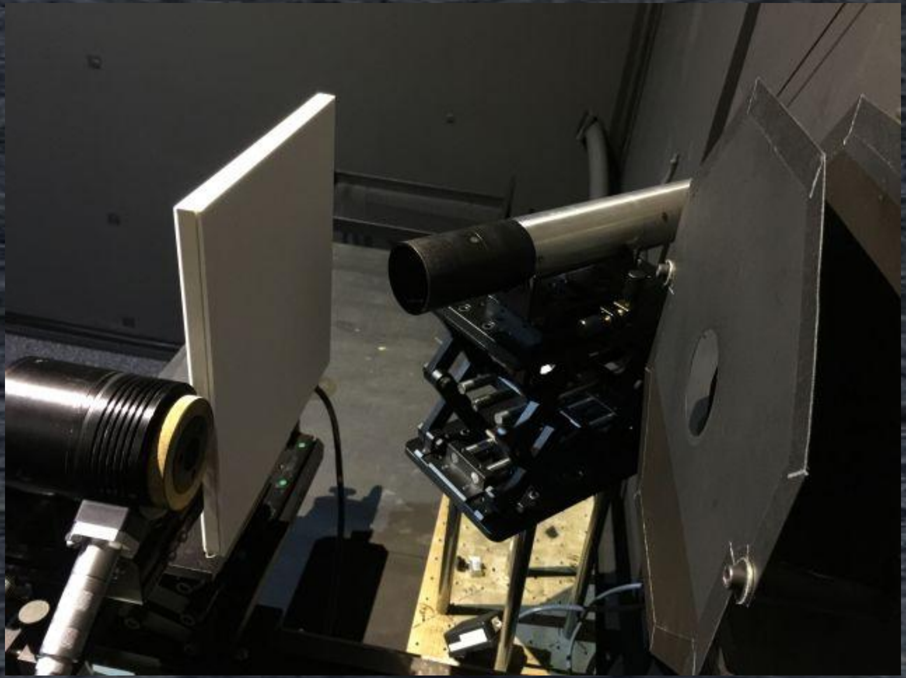


For hemisphere: $\Omega=\iint d\varphi\,d\theta=2\pi\ sr$

Slide in courtesy of I. Ansko, TU

Special case: Lambertian surface

Radiance $L(\varphi,\theta,\lambda)$ does not depend on the polar angles φ,θ:
the surface is perfectly diffuse (e.g. white snow, Sun's surface):
$E(\lambda)=\iint L(\varphi,\theta,\lambda)\,\mathrm{d}\varphi\,\mathrm{d}\theta=\pi L(\lambda)$
Diffuse (Lambertian) targets are widely used for calibration and characterization purposes.

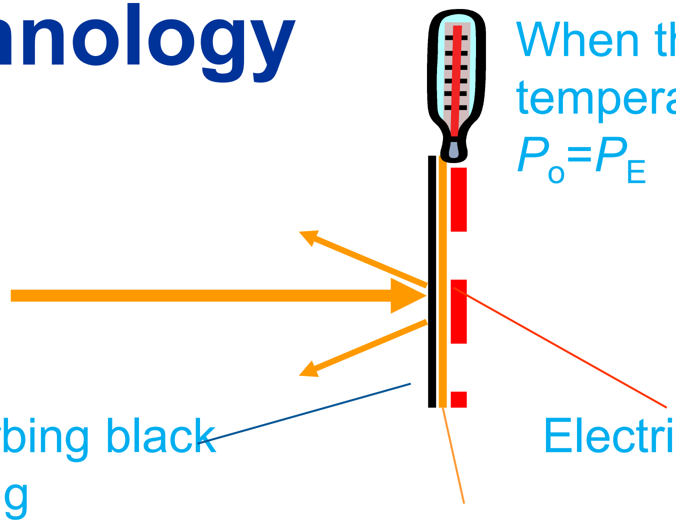


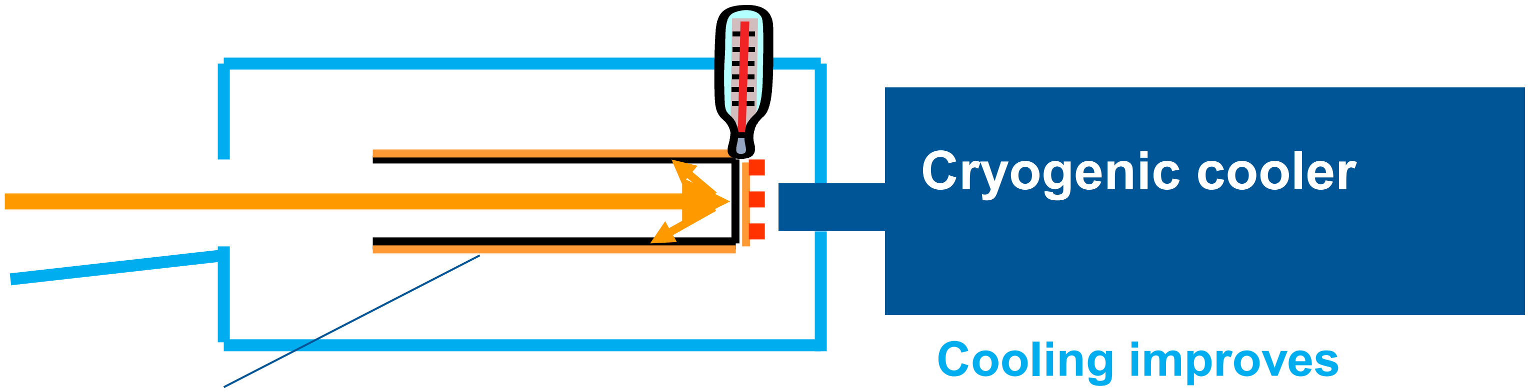
diffuse reflectance target

integrating sphere

Slide in courtesy of I. Ansko TU

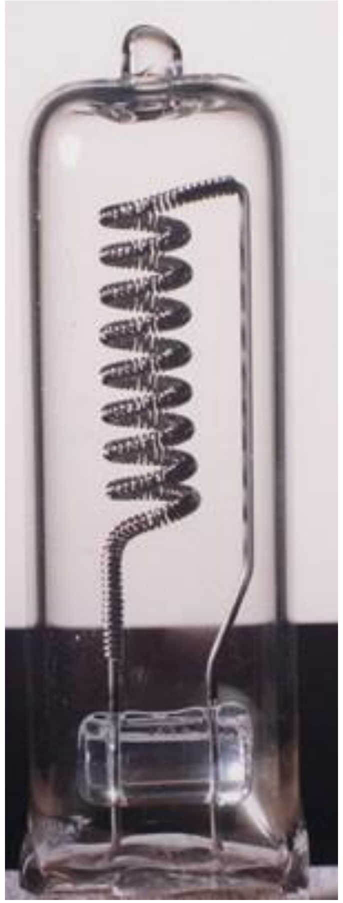
Electrical Substitution Radiometry – a 100 yr old technology

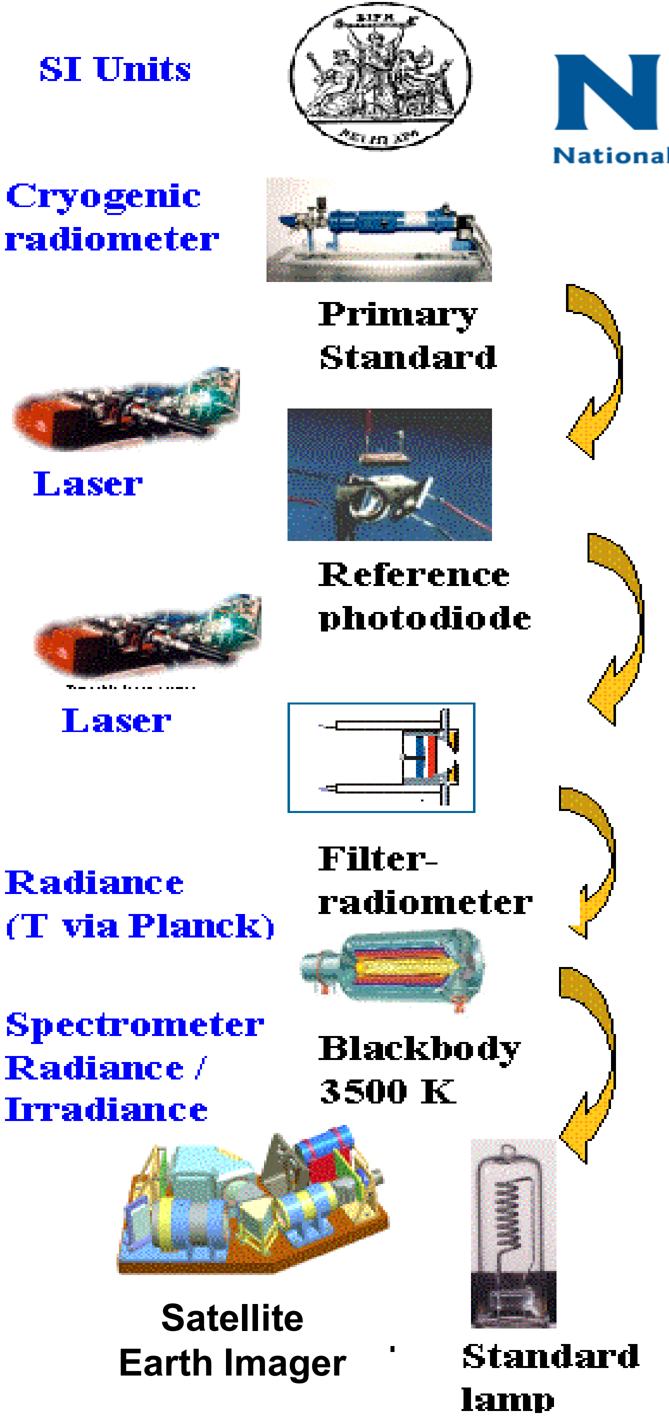




Principle of Cryogenic radiometry

Spectral Radiance and Irradiance





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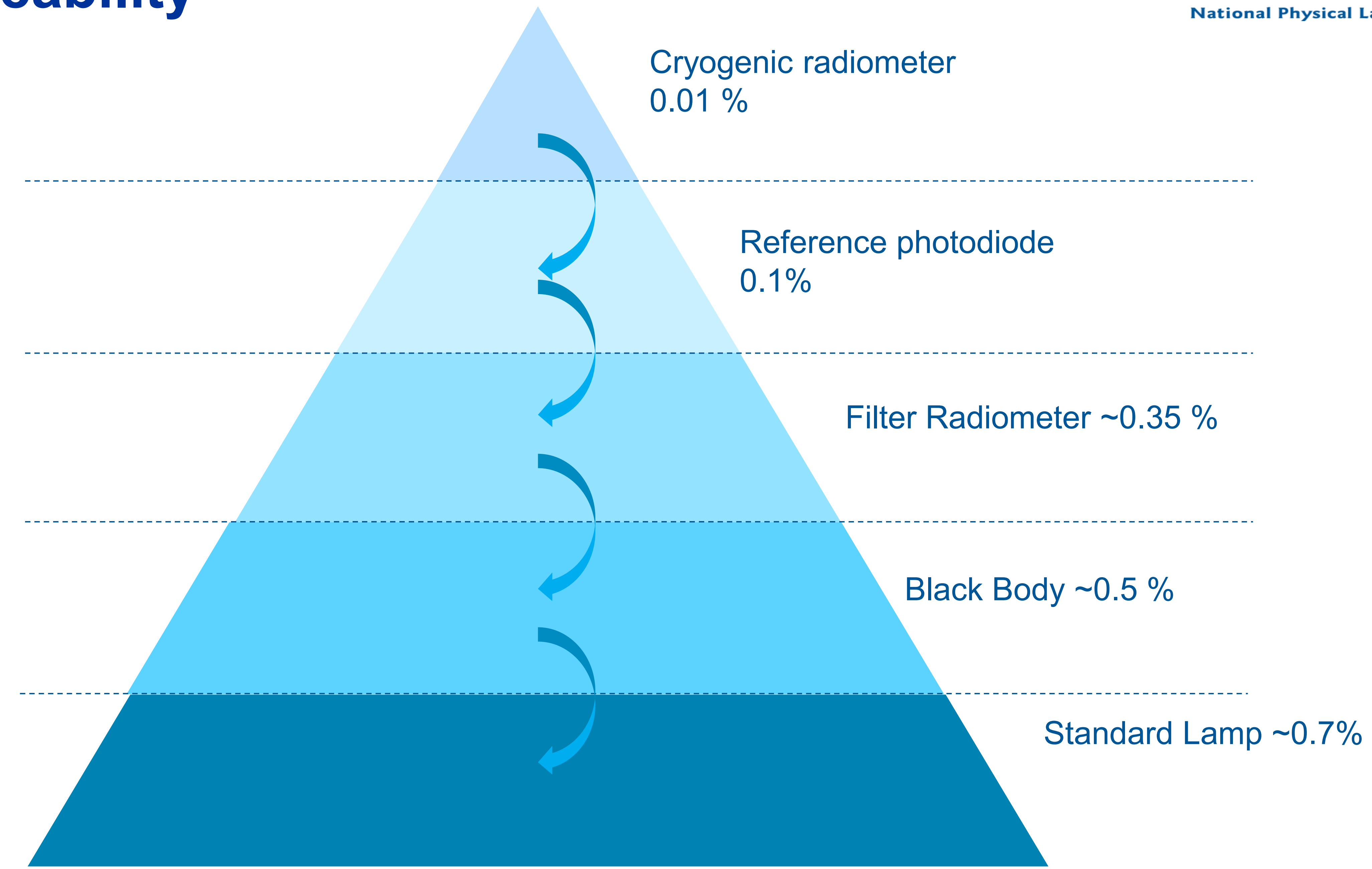
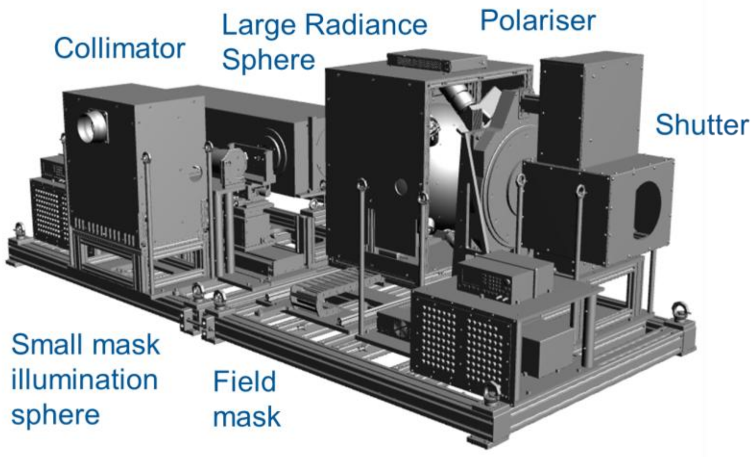
Traceability

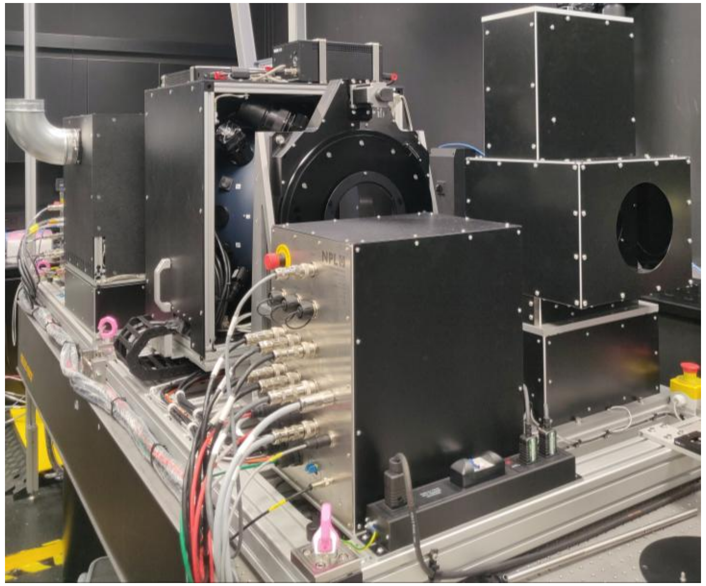


STAR-CC-OGSE

Spectroscopically Tuneable Absolute Radiometric Calibration & Characterization Optical Ground Support Equipmentg

- Cleanroom compatible and transportable system
- Provide geometric (through setup 1) and radiometric (through setup 2) calibration and characterisation of satellites specifically for earth observation purposes
- Both sources allow for the testing in both broadband and monochromatic modes through use of the white light sources in the sphere and connecting a broadly tuneable pulsed laser (260 nm to 2700 nm) via a fibre cable
- Detector-based traceability to the SI primary standard cryogenic radiometer.
- Develop to be compliant for the TRUTHS pre-flight calibration (0.3% k=2) in 2028/2029





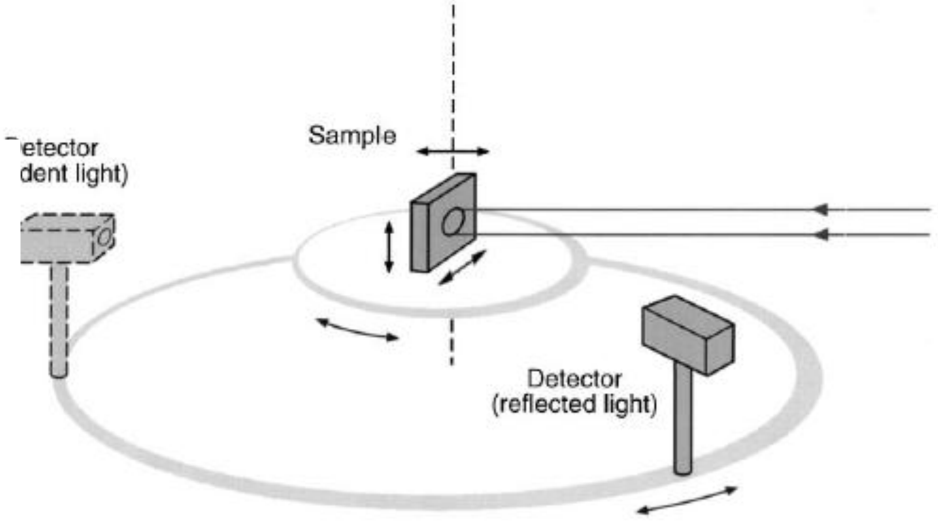
Reflectance scale

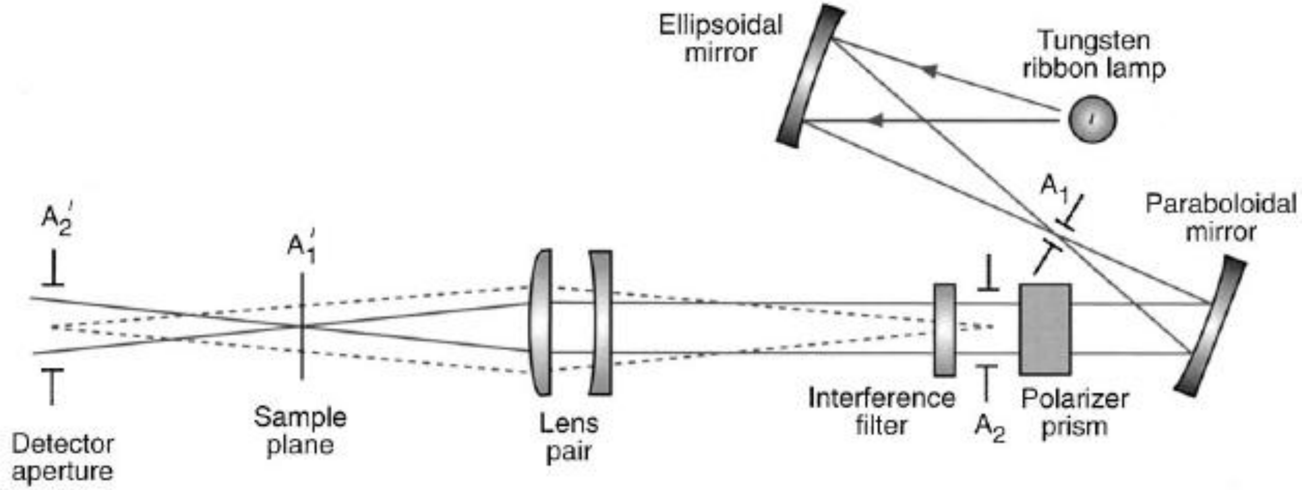
Reference reflectometer

Reference factor Radiance factor

$$BRF(\theta_i,\theta_r,\lambda) = R(\theta_i,\theta_r,\lambda) = \beta(\theta_i,\theta_r,\lambda) = \lim_{\Omega\to 0}\frac{\pi\Phi_r(\theta_i,\theta_r,\lambda)}{\Omega\Phi_i(\lambda)\theta_r}$$

Bidirectional Reference factor

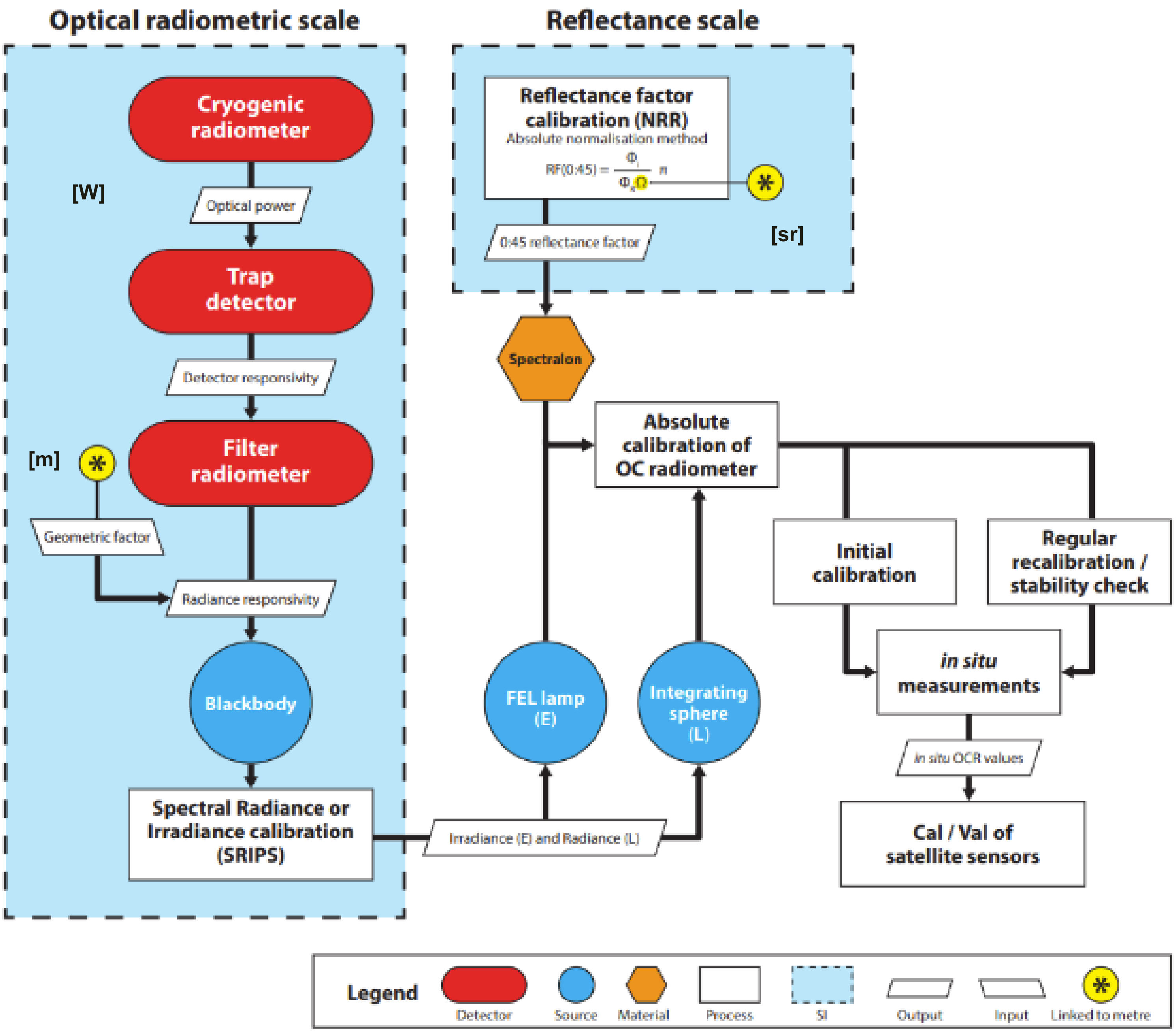




Williams, 1999

SI Traceability

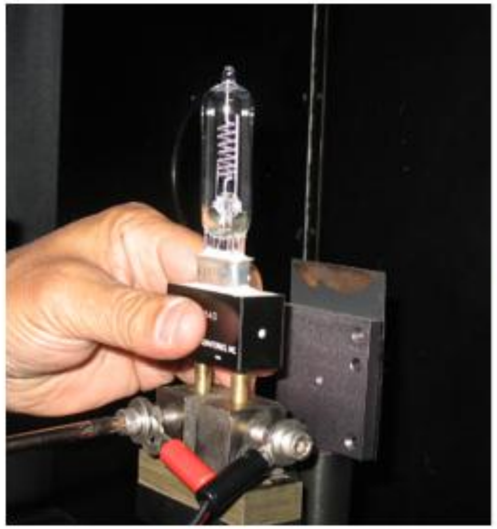
$$W = kg\ m^2\ s^{-3}.$$



Absolute calibration standards

Irradiance standards

- Lamps tungsten-halogen lamp (FEL) 1 kW (~ 3000 K)



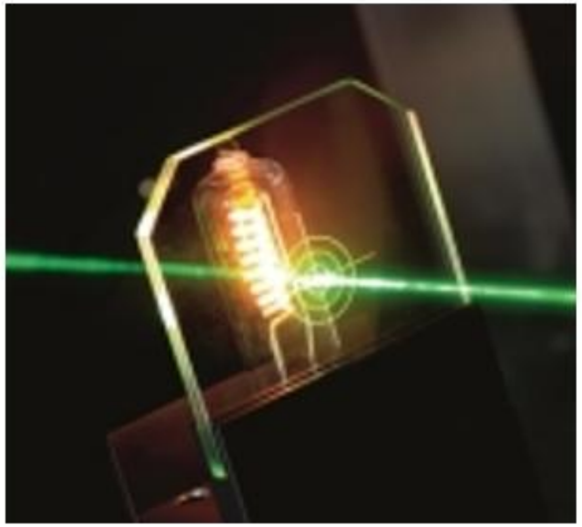
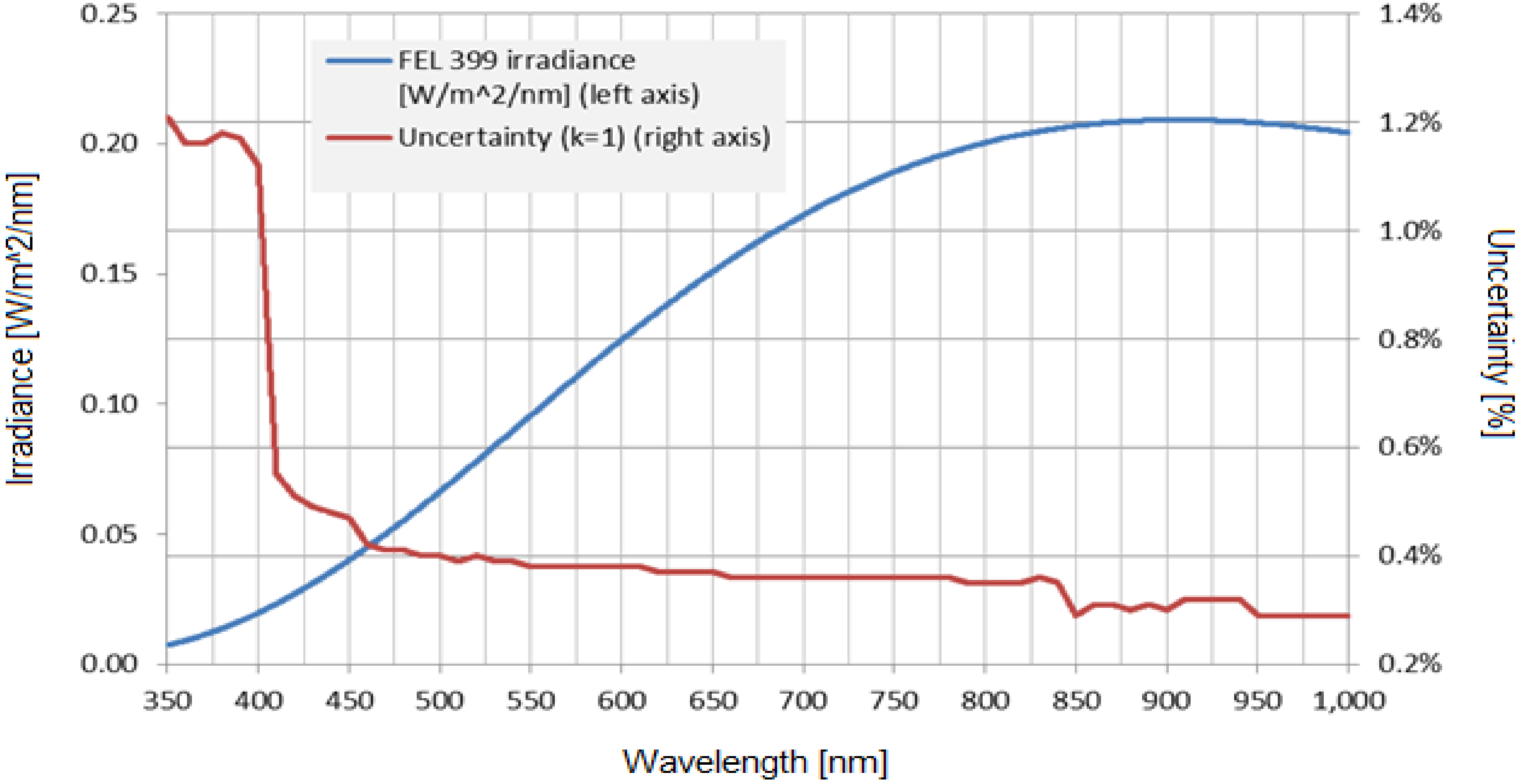


Photo courtesy of Gamma Scientific

Typical FEL irradiance



Calibration

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“operation that, under specified conditions, in a first step, establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication.”

http://jcgm.bipm.org/vim/en/index.html

Calibration Certificate example

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FEL BN-9101-606
ABSOLUTE SPECTRAL IRRADIANCE

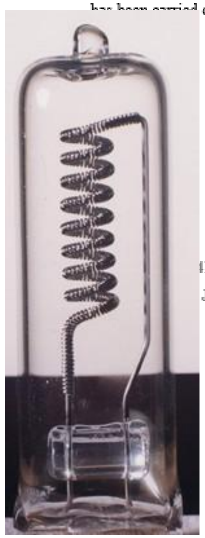
FOR: [redacted]

DESCRIPTION: The lamp was a Gigahertz FEL tungsten halogen filament lamp of no power 1 kW mounted in a lamp holder.

IDENTIFICATION: The number BN-9101-606 was marked on the rear of the lamp base.

DATES OF CALIBRATION: 1 June 2015 to 22 June 2015

The reported expanded uncertainty is based on a standard uncertainty multiplied by a cov factor $k = 2$, providing a coverage probability of approximately 95 %. The uncertainty eval has been carried out in accordance with UKAS requirements.



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July 2015 Signed: (Authorised Signatory)

Name: D Gibbs on behalf of NPLML

MEASUREMENTS

The removable alignment jig was placed vertically in the rear of the lamp mount, with the scratched side towards an alignment laser behind the lamp. The vertical alignment of the lamp in the plane perpendicular to the optical axis was set by placing a spirit level on top of the alignment jig and adjusting the mount so that it was level. The lamp mount was then adjusted so that the light from the laser fell centrally on the jig target and was reflected back along the measurement axis, thus setting the lamp perpendicular to and centred on this axis. The calibration refers to the absolute spectral irradiance at a distance of 0.500 m, measured from the centre of the plate at the front of the lamp mount. The alignment jig was removed before measurements commenced.

The lamp was operated from an actively stabilised dc power supply at 8.100 A. The polarity of the electrical current was as marked on the lamp, it was not changed. The lamp was ramped up and run for 30 minutes before measurements commenced. The voltage was monitored during measurement and is given for checking purposes only.

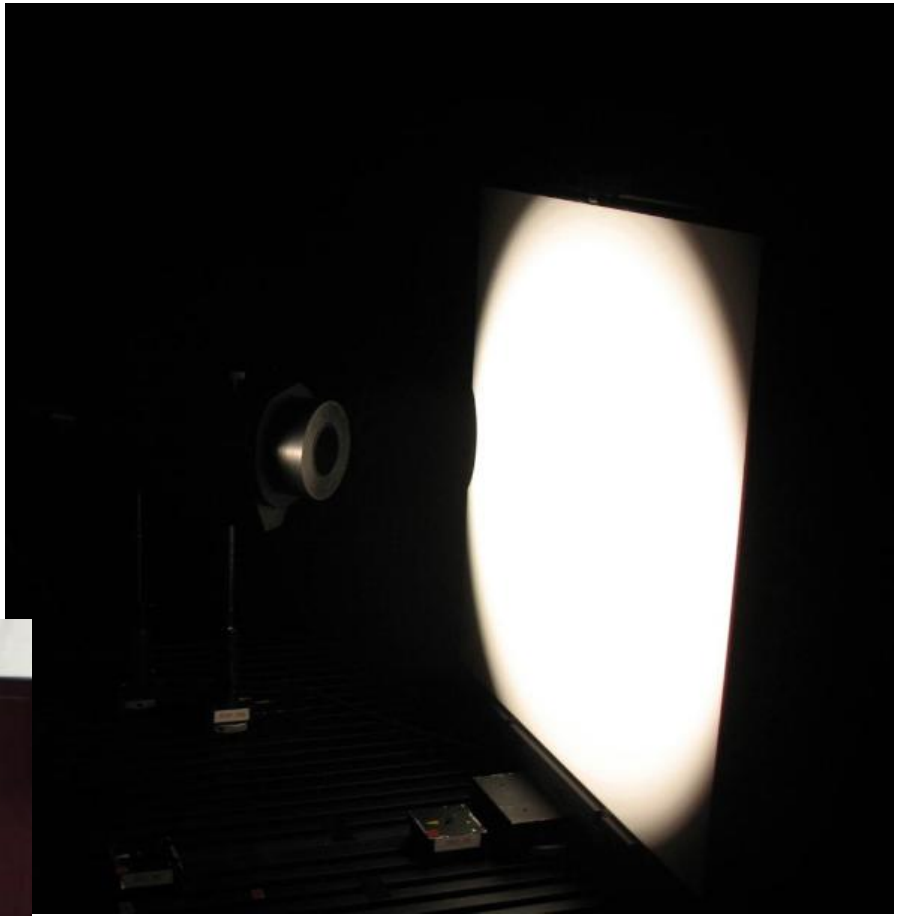
Absolute spectral irradiance values were determined by reference to the NPL_{2010} spectral irradiance scale. The measurements were made using the NPL Spectral Radiance and Irradiance Primary Scales (SRIPS) facility by direct comparison to a radiometrically-calibrated ultra-high temperature, high emissivity blackbody source operated at a temperature of approximately 3050 K.

Spectral irradiance measurements were made over the range 250 nm to 390 nm with an instrument bandwidth of approximately 1.4 nm (FWHM), from 400 nm to 900 nm with an instrument bandwidth of approximately 2.7 nm (FWHM), from 910 nm to 1590 nm with an instrument bandwidth of 4.5 nm (FWHM) and from 1600 nm to 2500 nm with an instrument bandwidth of 9.3 nm (FWHM).

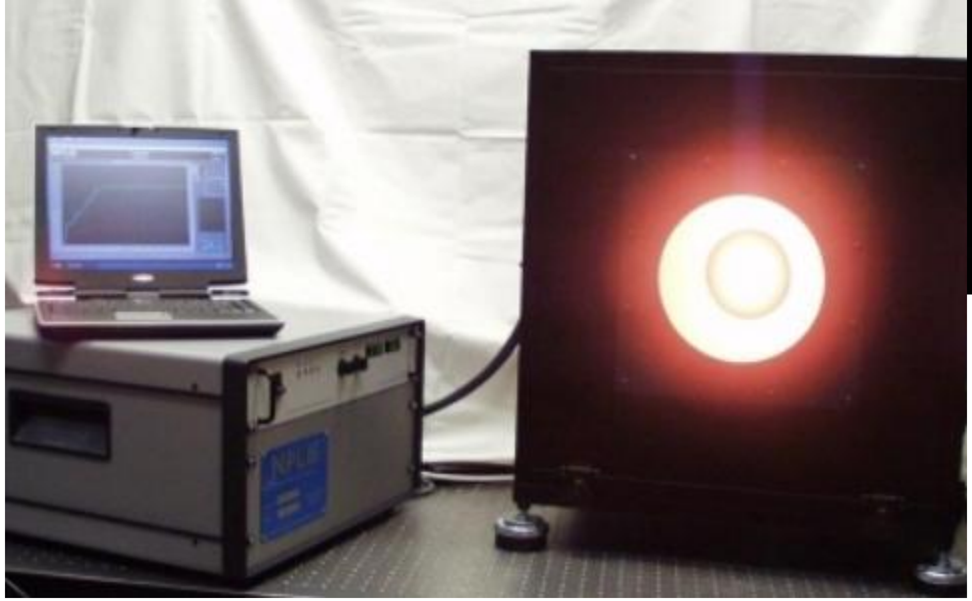
Ambient temperature during measurement was 22 °C ± 3 °C.

Radiance standards

- Lamp –reflectance standard

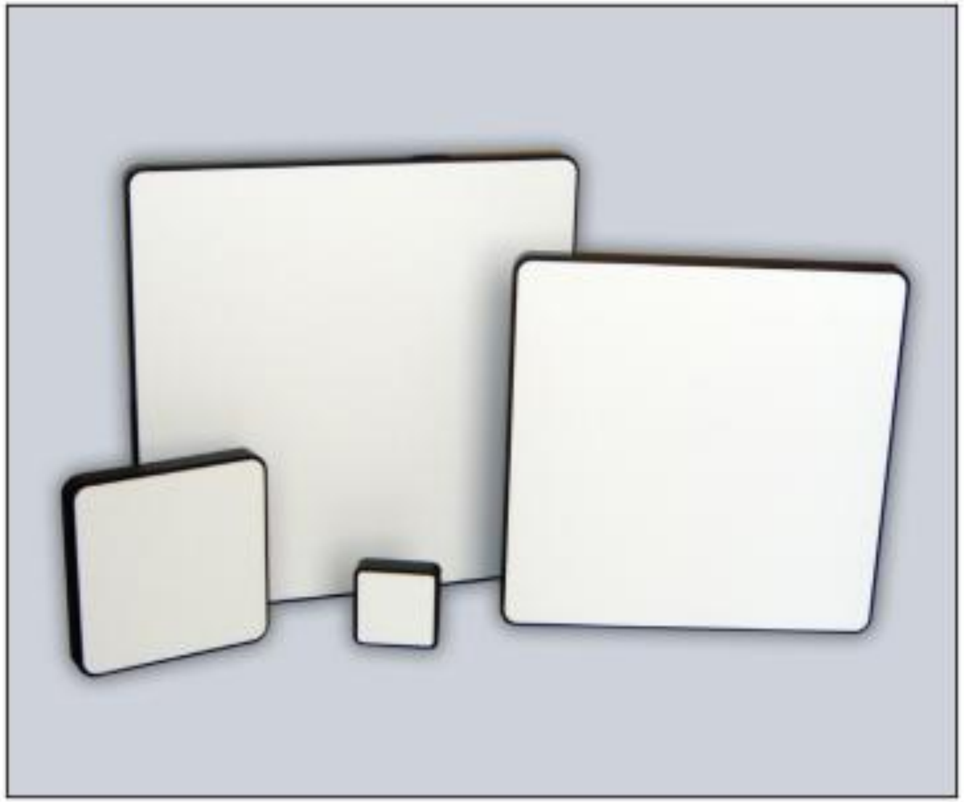


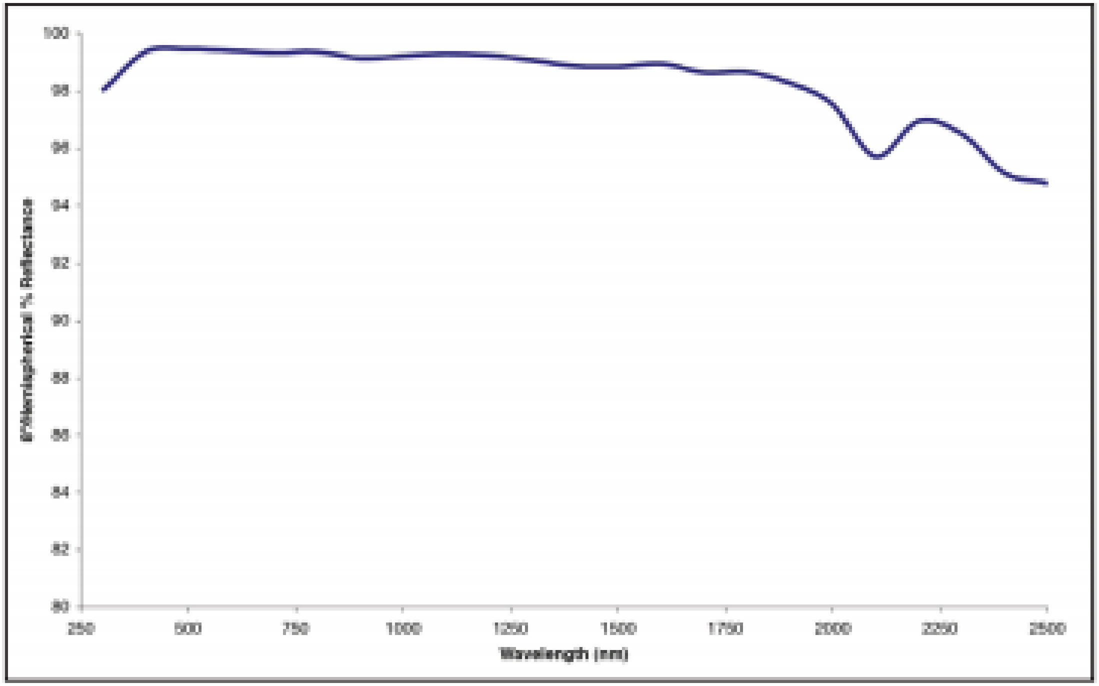
- Integrating sphere



Reflectance Standard

- Spectralon® Diffuse Reflectance Standard

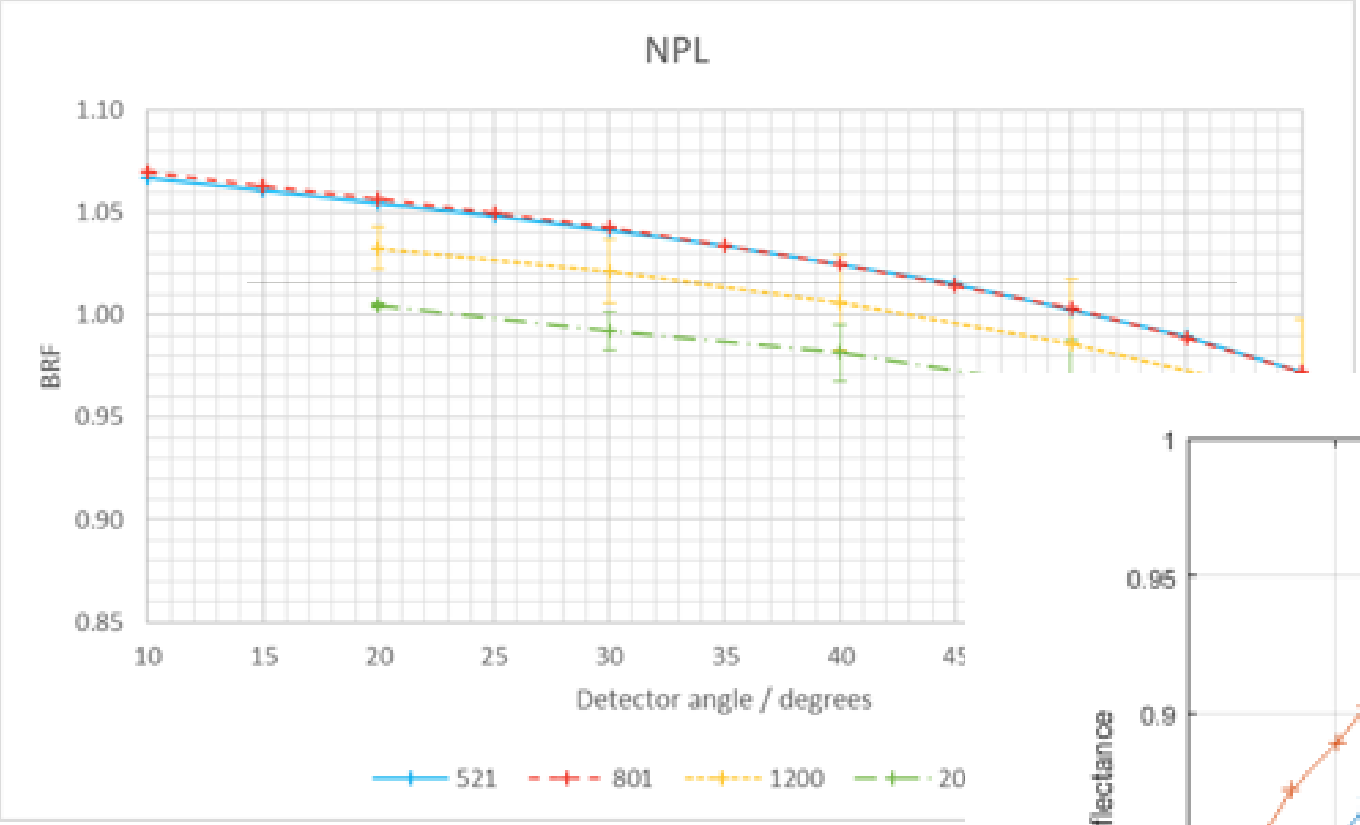


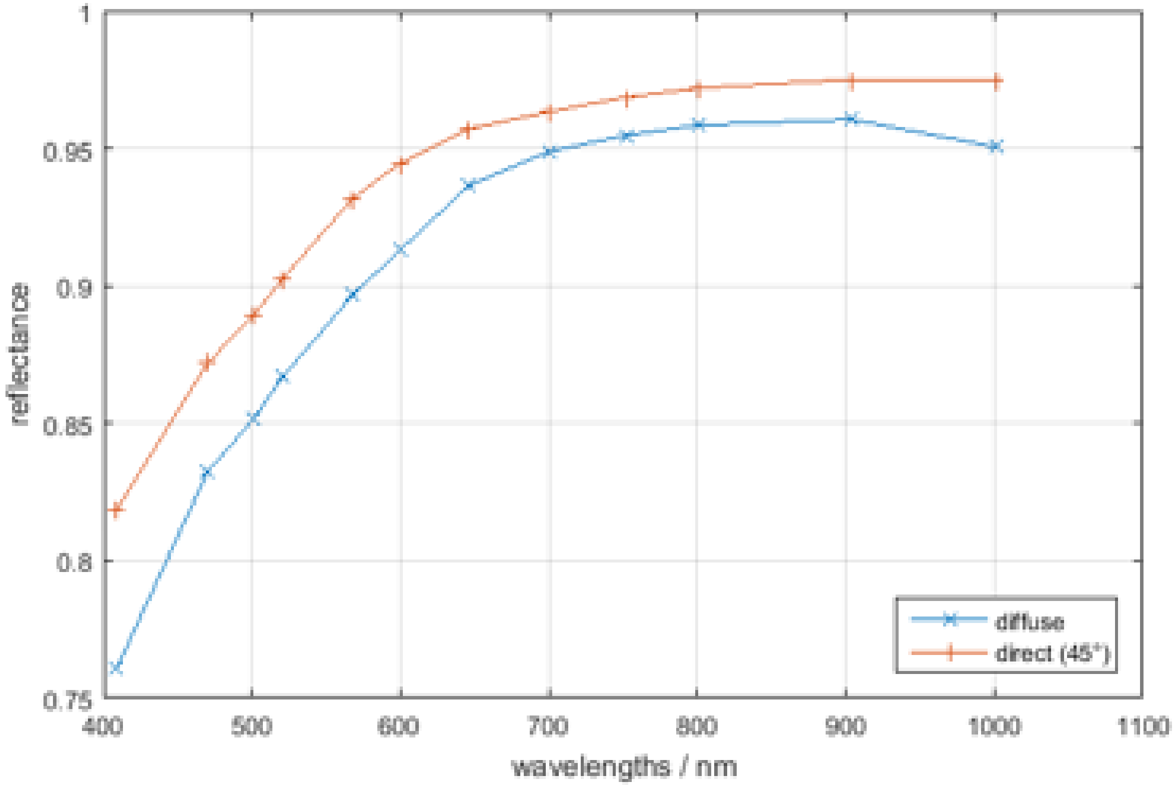


Typical 8° Hemispherical Reflectance SRM-990

https://www.labsphere.com/site/assets/files/1828/spectralon_targets.pdf

Spectralon BRF





Yoon et al. 2009

Calibration certificate example

National Physical Laboratory

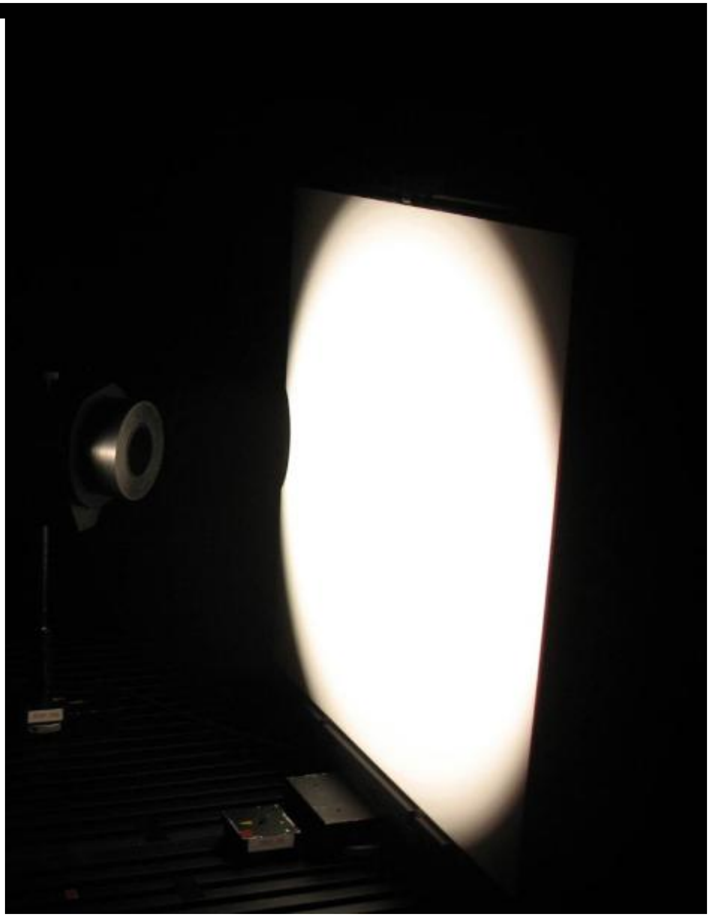
MEASUREMENTS AND RESULTS

A Perkin-Elmer Lambda 900 spectrophotometer fitted with a 0°:45°a radiance factor accessory was used to make measurements in the 0°:45°a geometry. An area 8 mm x 8 mm approximately 165 mm from the bottom and right-hand edges (with respect to the orientation) of the panel were measured. The sample was measured at 5 nm intervals over the spectral range 350 nm to 1000 nm. Measurements were made by substitution with respect to an NPL white standard. The white standard had previously been calibrated on a Perkin-Elmer Lambda 900 spectrophotometer against a master white standard that had previously been measured on the National Reference Reflectometer at NPL [1].

Measurements were made in the symmetrical series: dark, reference, sample, reference, dark. The mean of the two reference scans together with the appropriate dark correction were used in the calculation of the spectral radiance factor values. The sample to master ratios were then multiplied by the master tile data in order to obtain the absolute spectral radiance factor values. Two sets of four measurements were made on separate occasions on the panel, one with the label on the back upright, one with the panel rotated 90 degrees clockwise, one with the panel rotated 90 degrees anticlockwise and one with the label inverted. The values from the four different points on the panel were averaged together to obtain the final values.

The spectral reflectance values are given in Table 1.

The results are traceable to the "NPL - 2007" scale. The results quoted are for a temperature of 23 °C ± 1 °C and are with respect to the perfect reflecting diffuser.



Calibration certificate example

MEASUREMENTS

The radiance standard was positioned with the sphere port vertical and perpendicular to the measurement axis. The unit was operated from the controller provided with the current set to 5.850 A as displayed on the controller. On each occasion of operation the radiance standard was run for at least 15 minutes before measurements commenced. The micrometer was set to 8 for the calibration.

The absolute spectral radiance of the source was measured for a central area of the sphere port not exceeding 18 mm in diameter. Absolute spectral radiance values were measured using the NPL Spectral Radiance and Irradiance Primary Scales (SRIPS) facility by direct comparison to radiometrically-calibrated ultra-high temperature, high emissivity blackbody source operated at a temperature of approximately 2800 K.

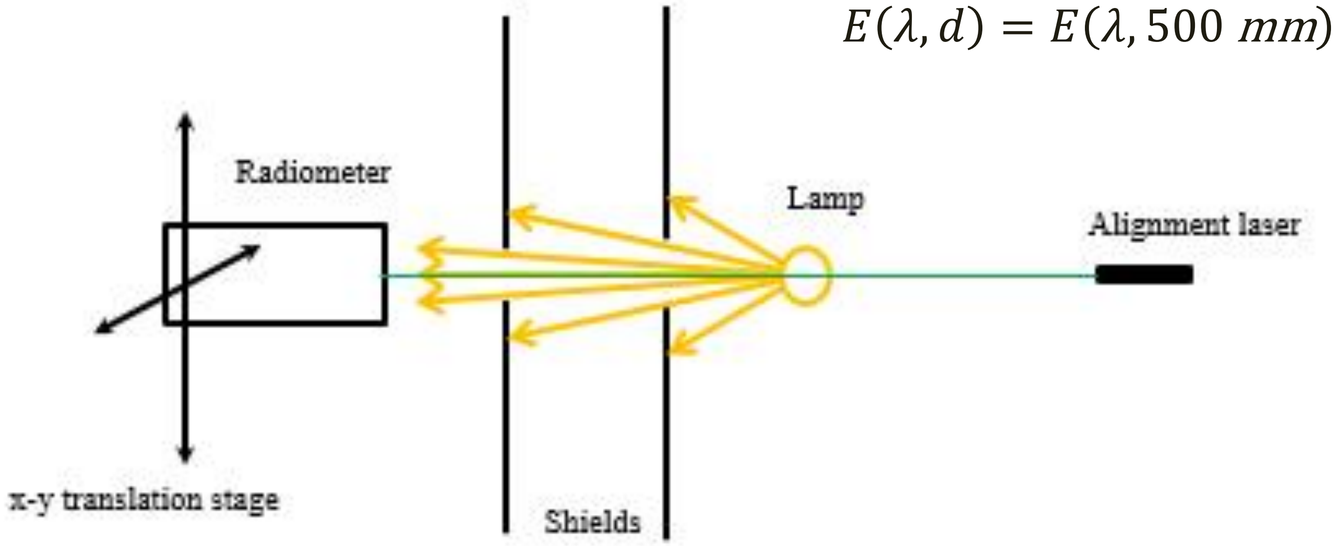
Spectral radiance measurements were made over the range 300 nm to 400 nm with an instrument bandwidth of approximately 2.6 nm (FWHM), from 400 nm to 900 nm with an instrument bandwidth of approximately 5.4 nm (FWHM) and from 850 nm to 2500 nm with an instrument bandwidth of approximately 9.2 nm (FWHM).

Ambient temperature during measurement was 22 °C ± 2 °C.

Absolute radiometric calibration

Irradiance

$$E(\lambda, d) = E(\lambda, 500\ mm)\left(\frac{500\ mm}{d}\right)^2$$



Absolute radiometric calibrations irradiance

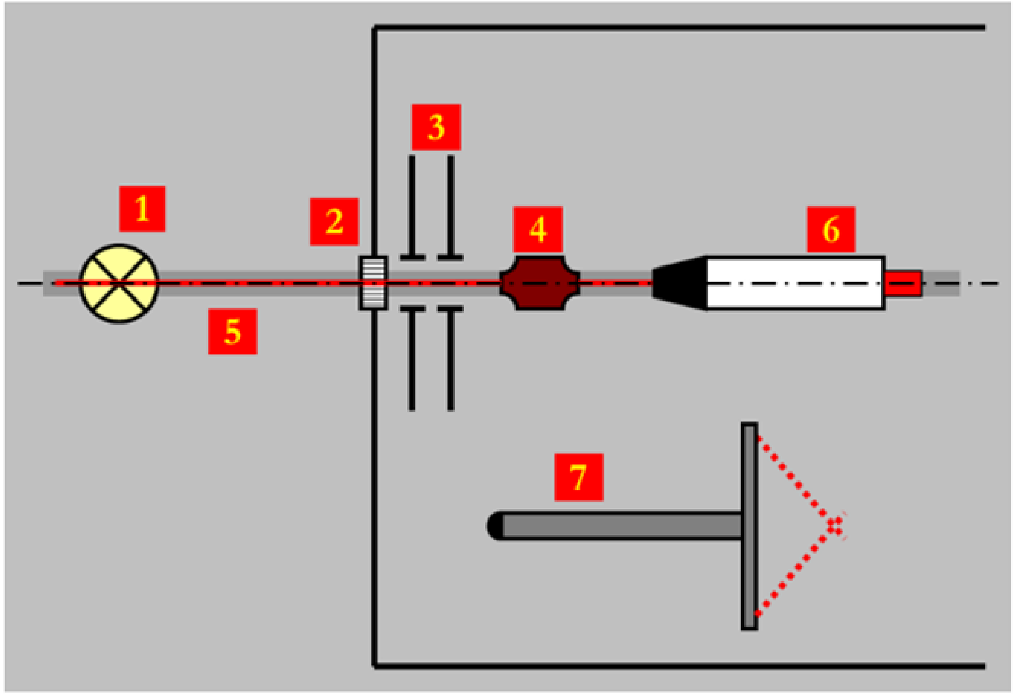
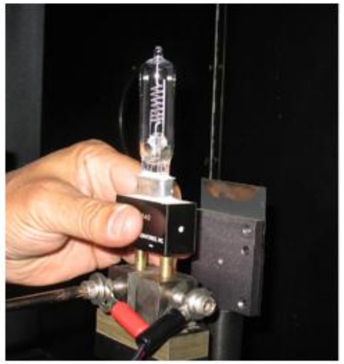


Figure 1.Pilot's (UT) irradiance calibration setup. 1 -FEL lamp; 2 – shutter; 3 – baffles; 4- -alignment laser; 5- optical rail; 6 – radiometer; 7 – contactless distance probe.



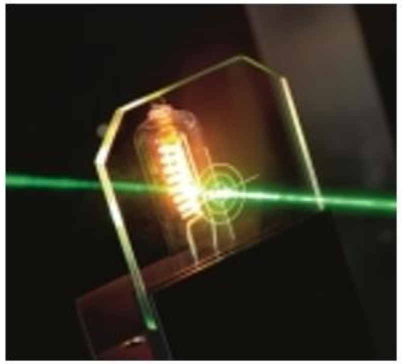


Photo courtesy of Gamma Scientific

Check list

- “Required”, “Highly recommended” and “Preferable”
- To take part in comparison a participant must meet all required points.
- Lack of items “Highly recommended” increases the measurement uncertainty values.
- The “Preferable” category contains non-essential items that would be good to have to speed up or simplify the measurements, however it is possible to make measurements without them.

Absolute radiometric calibrations irradiance

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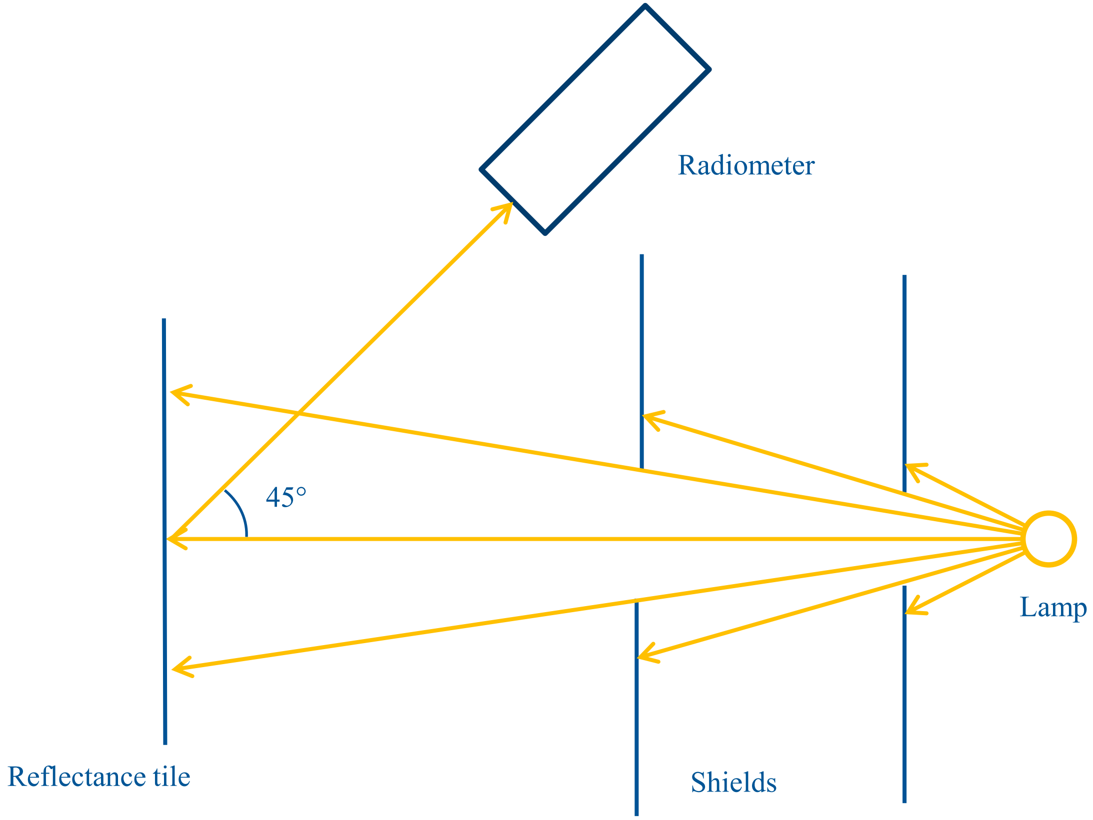
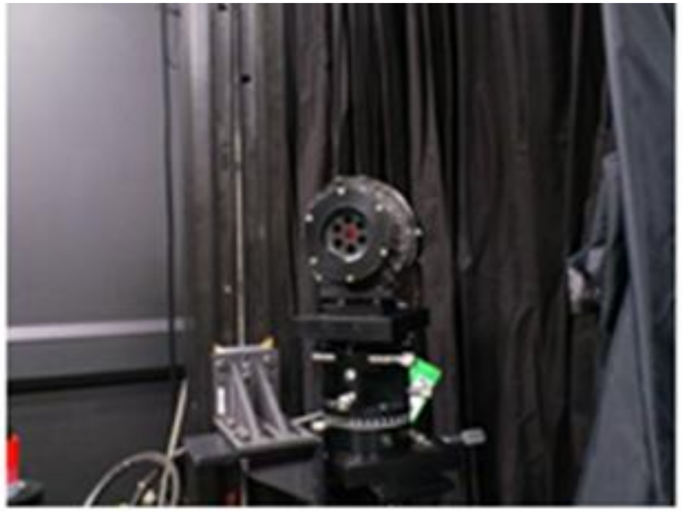
1. R – Optical rail or tale to set up the experiment
2. R – At least two radiometrically calibrated FEL lamps with a burning time less than 50 h since last calibration
3. R – Alignment laser to define the optical axis and align the lamps and the radiometers
4. R – Lamp, radiometer and laser posts. P – Six degrees of freedom lamp and laser mount (to facilitate the alignment)
5. R – Alignment procedure that strictly follows the lamp manufacturer instruction and the lamp calibration instruction (e.g. the reference point for distance measurements is different for every manufacturer of FEL lamp, and the distance setting must be done accordingly to the lamp type),
6. R – Power supply, P – Power supply with a function of automatic rump up/down time
7. Hr – Standard resistor and independent voltmeter readings, P – automatic current and voltage readings with the file output, rather than an operator handwritten notes in a lab book.
8. R – Distance measurement devise, Hr – calibrated measurement stick, P – contactless distance probe
9. R – light shields
10. R – Lab temperature readings (section 7 Harmonisation of laboratory guidelines contain the explanation why this is required)

Radiance

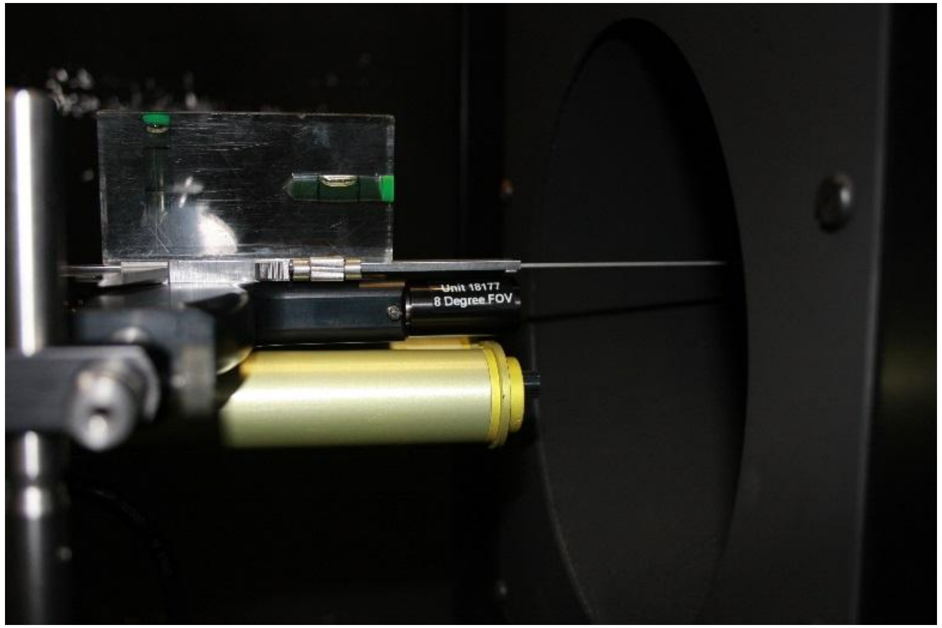
Lamp - tile

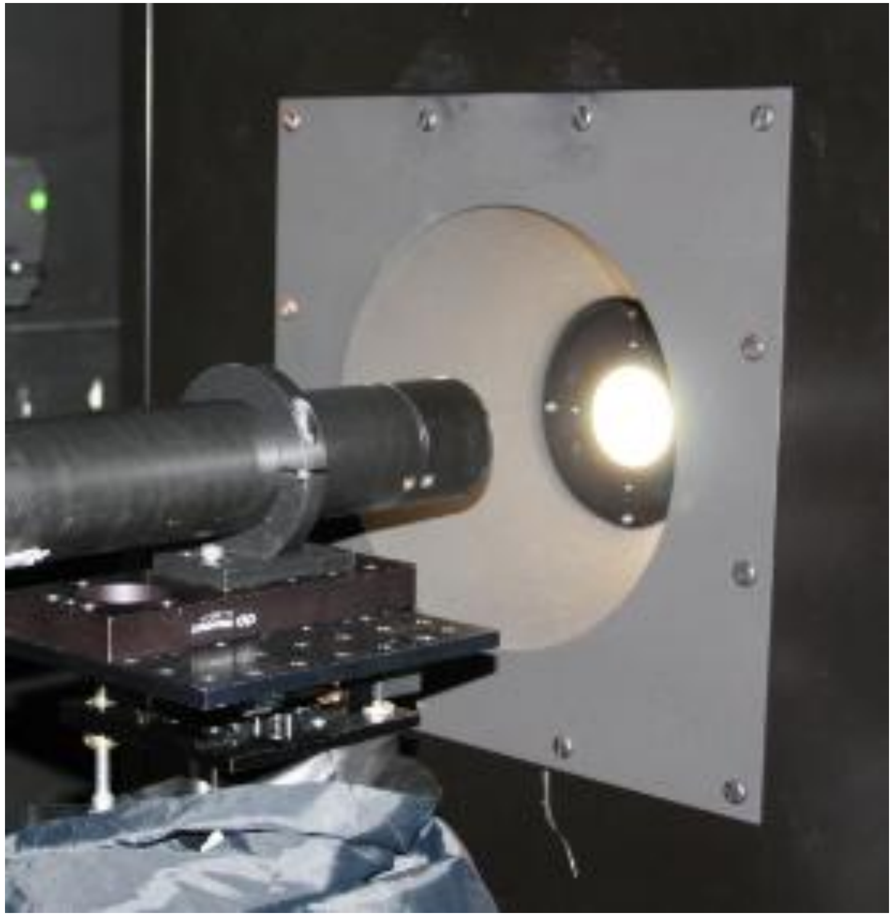




$$L_s = \frac{E_{FEL}\beta_{0:45}}{\pi}\frac{d_{cal}^2}{d_{use}^2}$$

Radiance





Integrating sphere

Absolute radiometric calibrations radiance

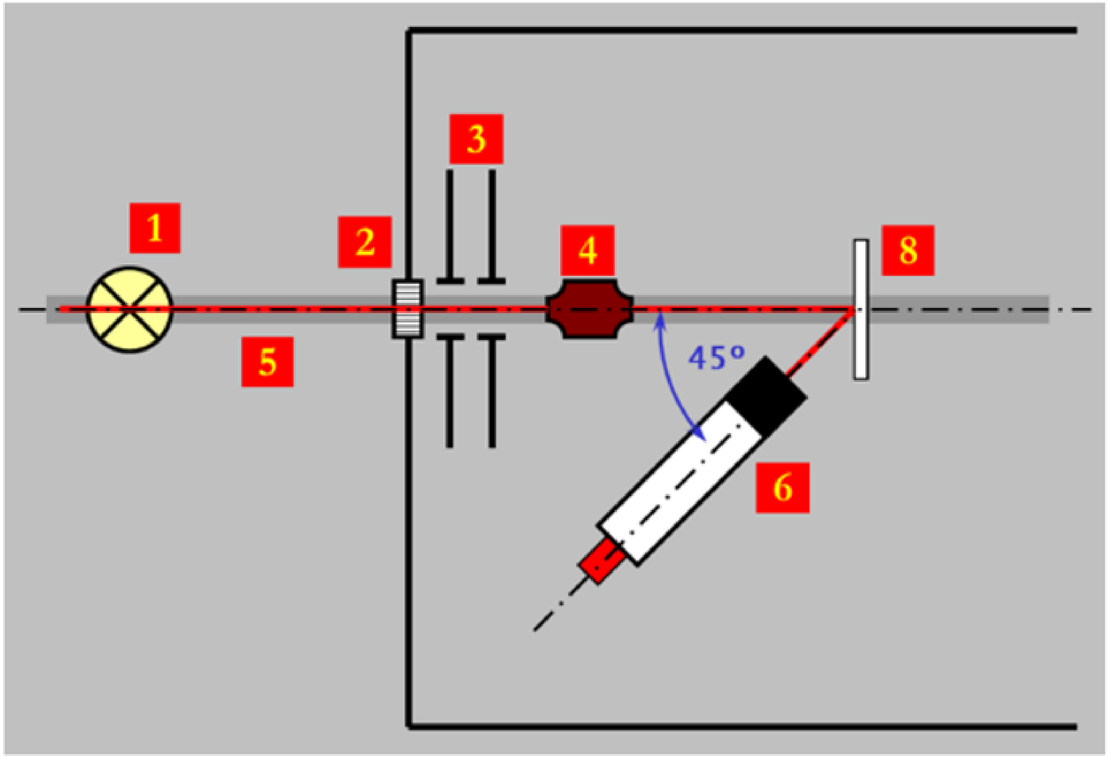


Figure 2. Pilot's (UT) radiance calibration setup. 1 -FEL lamp; 2 – shutter; 3 – baffles; 4- alignment laser; 5- optical rail; 6 – radiometer; 8 – reflectance panel.

Absolute radiometric calibrations radiance

1. R – Any calibrated white pseudo-Lambertian reflectance standard with correction applied to convert the calibration value to 0°:45° geometry for calibration performed at most common and widely available 8°:hemispherical geometry, Hr – Calibrated Reflectance standard with reflectance factor calibration at 0°:45° geometry.
2. P – Mirror with 6 degrees of freedom mount to verify the 45 degrees optical axis
3. R – Lamp filament distance offset. For Gigahertz lamps Hr – lamp filament offset for other lamps types. This is necessary to account for the difference in the plane of the distance setting and actual lamp filament position for measurements performed at any other distance than the default calibration 500 mm.

Laboratory comparison strategy

- Publicly announced open to everybody who holds absolute calibration standards and meet minimum requirements
- Executed as round – robin, so tests each participants in house laboratory capabilities
- With hyperspectral transfer radiometers (thus applying additional conditions during measurements)
- There is no a bad result
- Executed every 3-5 years, for a new players open possibility for a bilateral comparisons

Take home message

- Maintain calibration records of your field instruments (FidRadDB)
- Ensure that calibration are performed regularly ideally once a year (we understand the reality)
- Do your research for the best calibration provider – demand calibration coefficients uncertainty as a part of the service

```
# Correlated color temperature (K)
[LAMP_CCT]
2972.0

# wavelength (nm)       bandwidth (nm)  irradiane (mW/m2/nm)    uncertainty (%, k=2)
[LAMPDATA]
300.00  0.00    1.3604  2.49
310.00  0.00    1.9255  2.12
320.00  0.00    2.6490  1.94
330.00  0.00    3.5525  1.94
340.00  0.00    4.6565  1.93
350.00  0.00    6.0017  1.93
360.00  0.00    7.6133  1.92
370.00  0.00    9.4994  1.92
380.00  0.00    11.6728 1.92
390.00  0.00    14.1421 1.84
400.00  0.00    16.8726 1.77
410.00  0.00    19.9123 1.69
420.00  0.00    23.2544 1.62
430.00  0.00    26.8917 1.55
440.00  0.00    30.8167 1.48
450.00  0.00    35.0184 1.47
460.00  0.00    39.4672 1.47
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THANK YOU