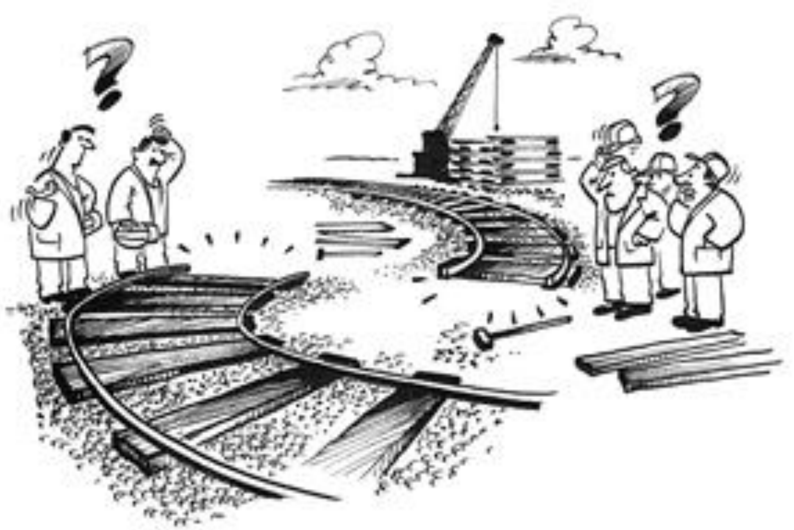
Introduction to traceable radiometric measurements

Agnieszka Bialek
5th April 2017

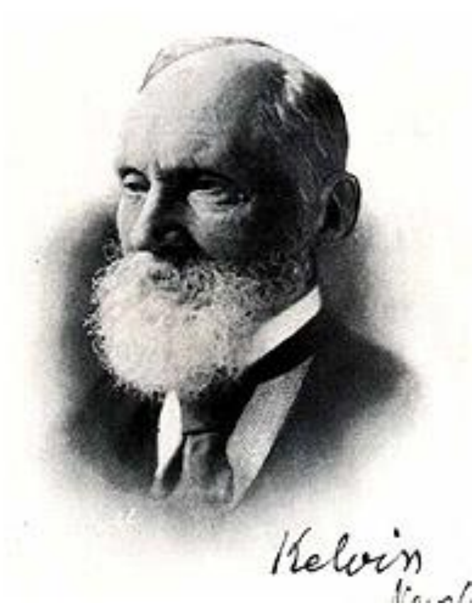
Outline

- SI System of Units and NMIs role
- Principle of radiometric measurement
- Radiometers and calibration



Famous quotes…

When you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind: it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of science.



William Thomson,
Lord Kelvin of Largs (1824 - 1907)

Higgs boson – 1960 idea
CERN 2013 – experiment (tentatively confirmed)

Metrology

[VIM3] 2.2 metrology

science of **measurement** and its application

Notes

NOTE Metrology includes all theoretical and practical aspects of measurement, whatever the **measurement uncertainty** and field of application.

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

International System of Units

The Convention of the Metre:
Created BIPM
the intergovernmental organization through which Member States act together
on matters related to measurement science and measurement standards.

First signed in 1837 in Paris by 17 nations

Now 58 countries members states and 40 associate

http://www.bipm.org/en/about-us/

Pictures in courtesy of BIPM

International System of units

JET'S FUEL RAN OUT AFTER METRIC CONVERSION ERRORS

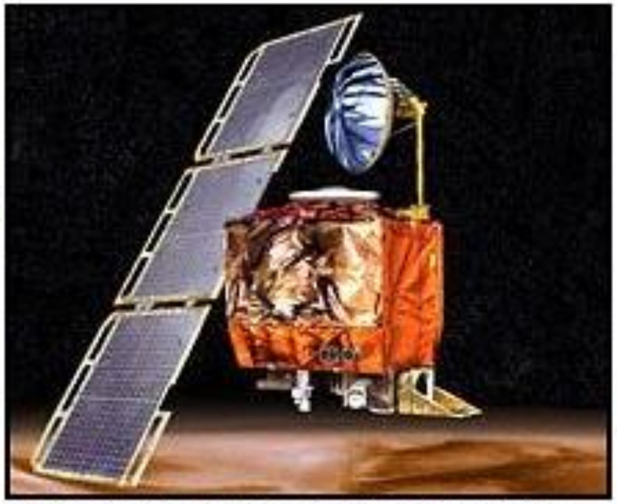
By RICHARD WITKIN
Published: July 30, 1983

Air Canada said yesterday that its Boeing 767 jet ran out of fuel in midflight last week because of two mistakes in figuring the fuel supply of the airline's first aircraft to use metric measurements.

Mystery of Orbiter Crash Solved

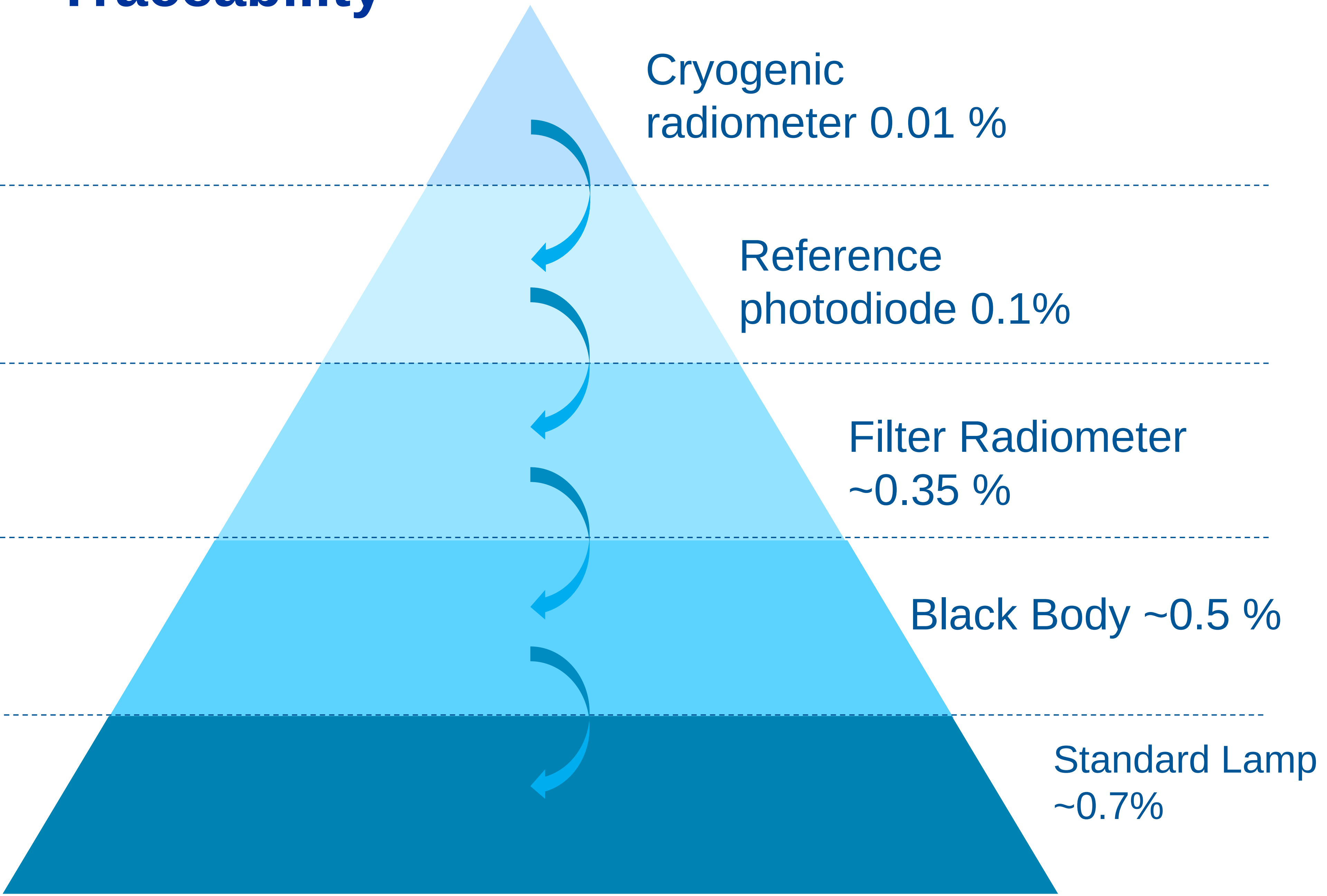
By Kathy Sawyer
Washington Post Staff Writer
Friday, October 1, 1999; Page A1

NASA's Mars Climate Orbiter was lost in space last week because engineers failed to make a simple conversion from English units to metric, an embarrassing lapse that sent the $125 million craft fatally close to the Martian surface, investigators said yesterday.



Scientists do not yet know what caused the Mars Orbiter to crash. (AP)

Traceability



Radiometry

Measurement of optical energy

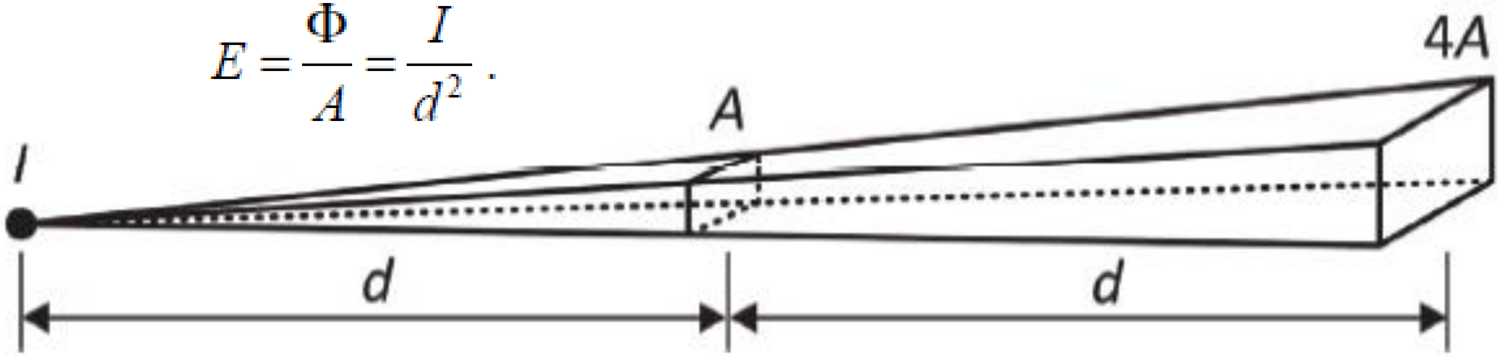
Table 1-1. Radiometric quantities (Palmer J. M. 2010)

Radiometric quantity	Equation and units	Definition
Radiant Energy	$Q\,[\mathrm{J}]$	
Radiant Power (radiant flux)	$\Phi = \frac{dQ}{dt}\,[\mathrm{W}]$	Energy per unit time
Irradiance (radiant incidence)	$E = \frac{d\Phi}{dA_s}\left[\mathrm{W}/\mathrm{m}^2\right]$	Power per unit area that is incident on a surface. Irradiance is measured at the detector
Solid angle	$\omega\,[\mathrm{sr}]$	The plane-angle concept extended to three-dimension
Radiance	$L = \frac{d^2\Phi}{dA_s d\Omega}\left[\mathrm{W}/\mathrm{m}^2\mathrm{sr}\right]$	Power per unit area and per unit projected solid angle.

The Art of Radiometry, Palmer J.M. 2010

Inverse Square Law of Irradiance

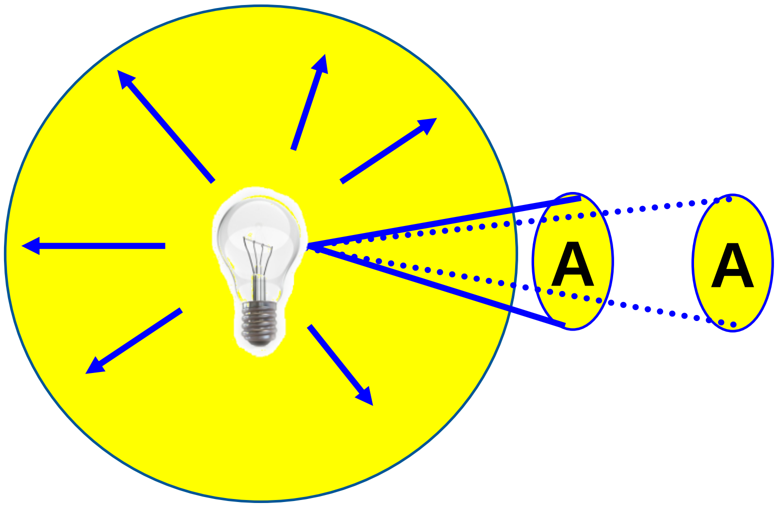
$$E = \frac{\Phi}{A} = \frac{I}{d^2}.$$



Palmer J.M, 2010

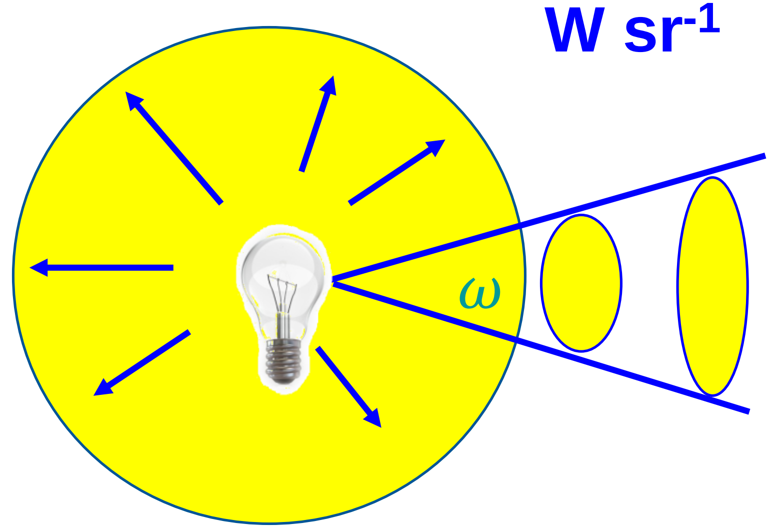
***E* Irradiance**

W m^{-2}



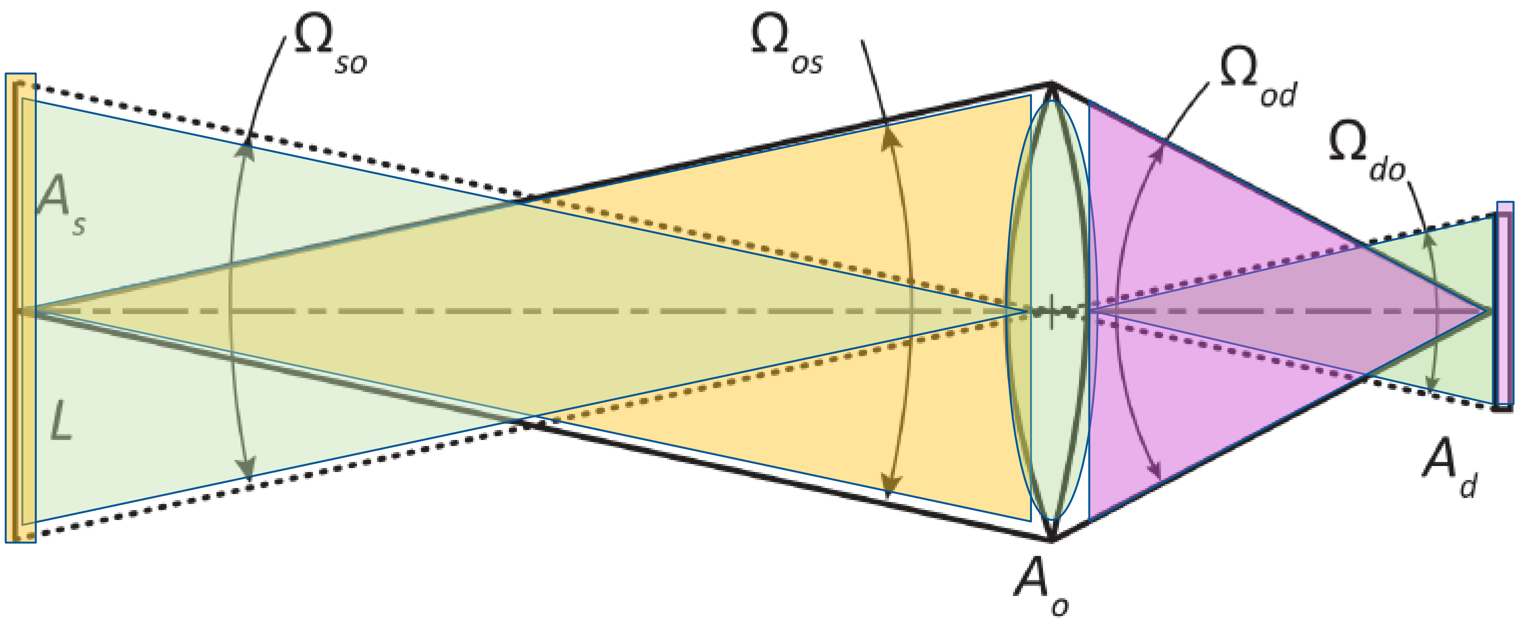
***I* Intensity**

W sr^{-1}



Radiance invariance

- Throughput invariance (étendue) $T = A\Omega$

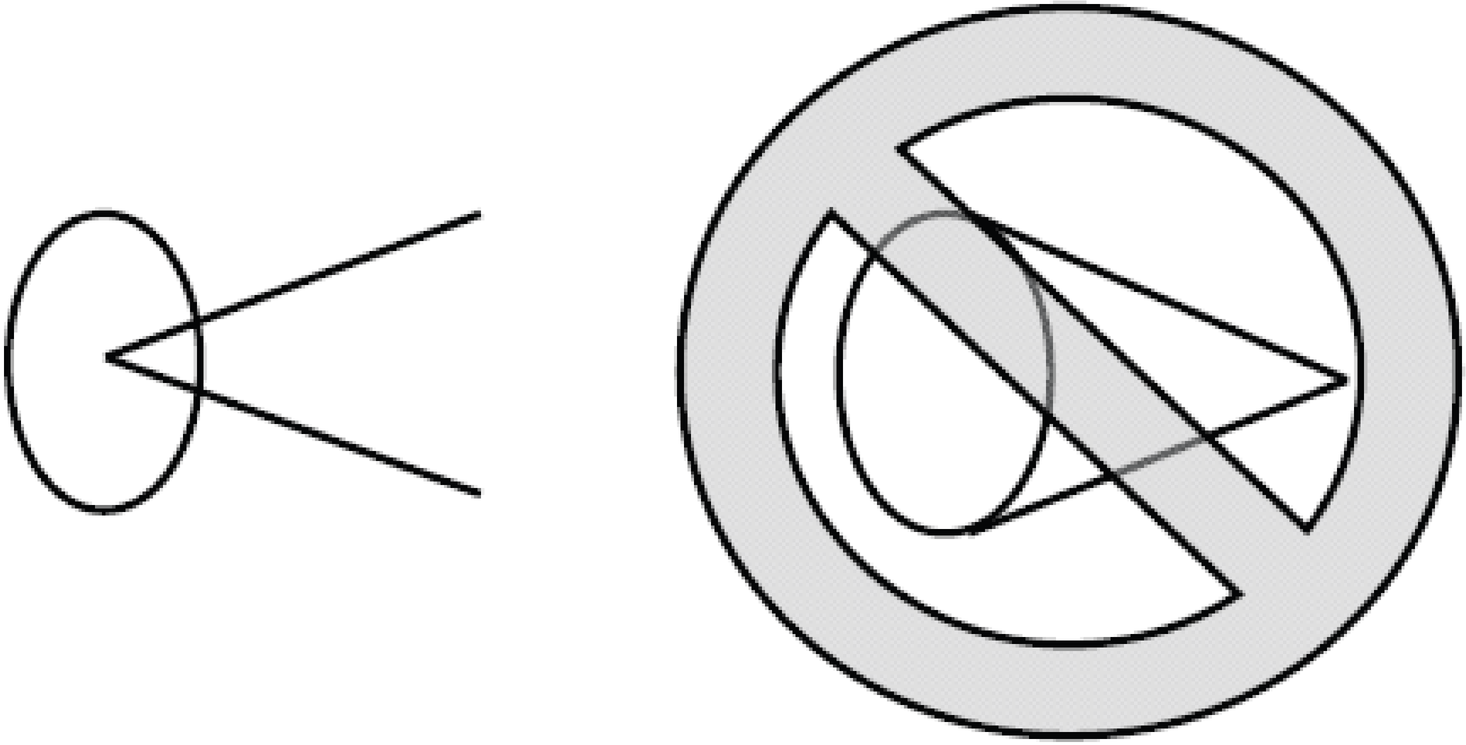


$$A_s\Omega_{os} = A_o\Omega_{so} = A_o\Omega_{do} = A_d\Omega_{od} \ .$$

Assuming lossless beam propagation and no lens transmission

Palmer J.M, 2010

“No ice cream cones” in radiometry



Palmer J.M, 2010

Reflectance ρ and Reflectance factors

We have 9 kinds of reflectance and 9 equivalent reflectance factors.

First defined in 1977 by Nicodemous to simply surface scattering phenomena,

Assumptions:

Geometrical ray optics

A flat surface that is uniformly illuminated

Incident radiance depends only on direction

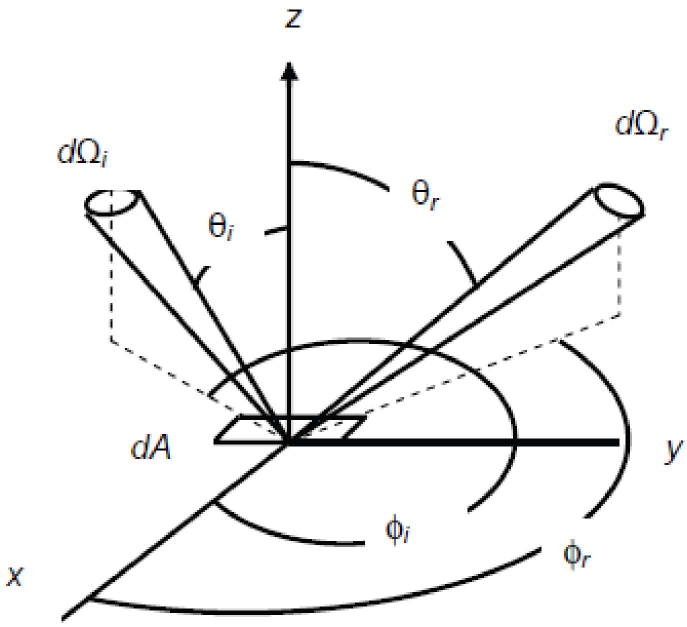
Surface has uniform and isotropic scattering properties

Nicodemous, 1977

BRDF bidirectional reflectance function

Definition

$$f(\theta_{\mathrm{I}},\varphi_{\mathrm{I}};\theta_{\mathrm{R}},\varphi_{\mathrm{R}},\lambda)=\frac{dL_{\mathrm{R}}(\theta_{\mathrm{I}},\varphi_{\mathrm{I}};\theta_{\mathrm{R}},\varphi_{\mathrm{R}},\lambda,E_{I})}{dE_{\mathrm{I}}(\theta_{\mathrm{I}},\varphi_{\mathrm{I}})}$$



Measurement equation

$BRDF=$

$$f_r(\theta_{\mathrm{I}},\varphi_{\mathrm{I}},\theta_{\mathrm{R}},\varphi_{\mathrm{R}},\lambda)=d\rho(\theta_{\mathrm{I}},\varphi_{\mathrm{I}},\theta_{\mathrm{R}},\varphi_{\mathrm{R}},\lambda)=\lim_{\Omega\to 0}\frac{\Phi_{\mathrm{R}}(\theta_{\mathrm{I}},\varphi_{\mathrm{I}},\theta_{\mathrm{R}},\varphi_{\mathrm{R}},\lambda)}{\Phi_{\mathrm{I}}(\lambda)\cos\theta_{\mathrm{R}}\Omega}$$

BRF bidirectional reflectance factor

$$BRF\left(\theta_i\ ;\theta_r,\lambda\right) = BRDF\cdot\pi = \lim_{\Omega\to 0}\frac{\Phi_{\mathrm{R}}(\theta_{\mathrm{I}},\theta_{\mathrm{R}},\lambda)}{\Phi_{\mathrm{I}}(\lambda)\cos\theta_{\mathrm{R}}\Omega}\cdot\pi$$

the ratio of the radiance flux actually reflected by a sample surface to that which would be reflected into the same reflected-beam geometry by an ideal perfectly diffuse standard surface irradiated in exactly the same way as the sample

Perfect "Lambertian" diffuser

- Reflects all radiance equally to all directions

$$\rho = 1$$

$$BRDF(\theta_i, \phi_i, \theta_r, \phi_r) = 1/\pi$$

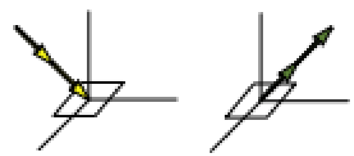
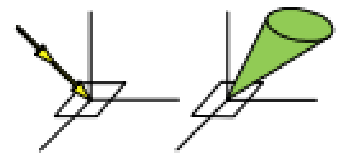
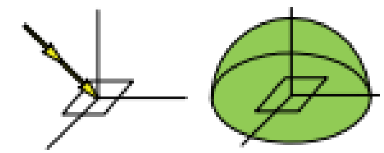
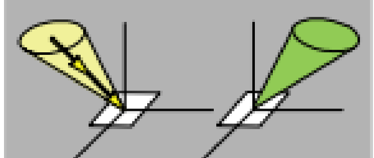
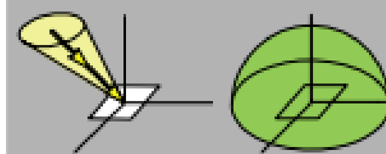
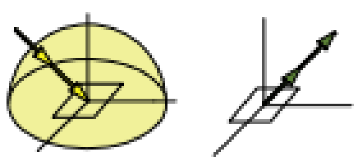
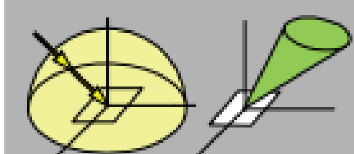
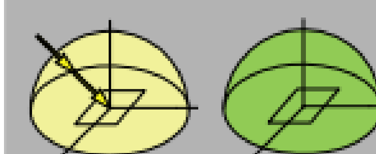
- Lambertian source, radiance is independent of direction

$$L(\theta, \phi) = constant$$

$$I_S(\theta) = I_I \cos(\theta_s)$$

Reflectance configurations

Table 2
Relation of incoming and reflected radiance terminology used to describe reflectance quantities

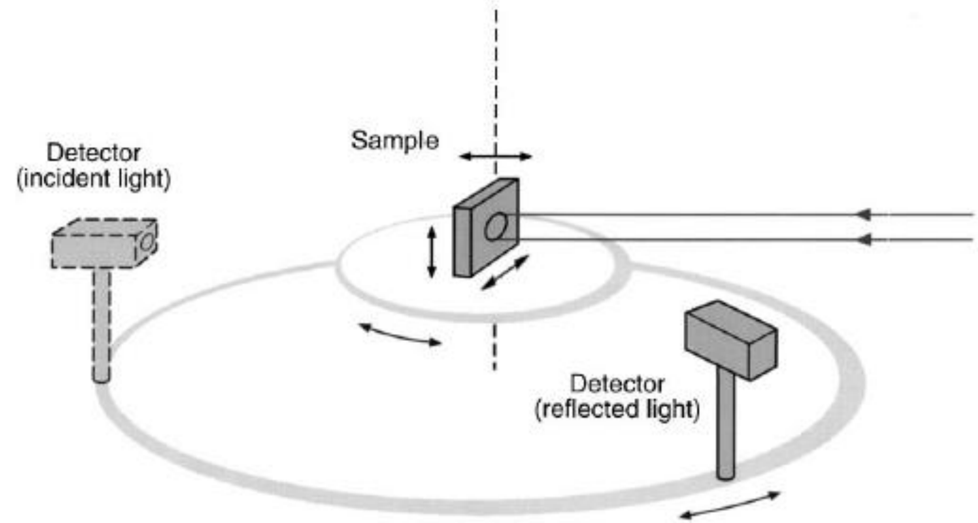
Incoming/Reflected	Directional	Conical	Hemispherical
Directional	Bidirectional CASE 1 	Directional–conical CASE 2 	Directional–hemispherical CASE 3 
Conical	Conical–directional CASE 4 	Biconical CASE 5 	Conical–hemispherical CASE 6 
Hemispherical	Hemispherical–directional CASE 7 	Hemispherical–conical CASE 8 	Bihemispherical CASE 9 

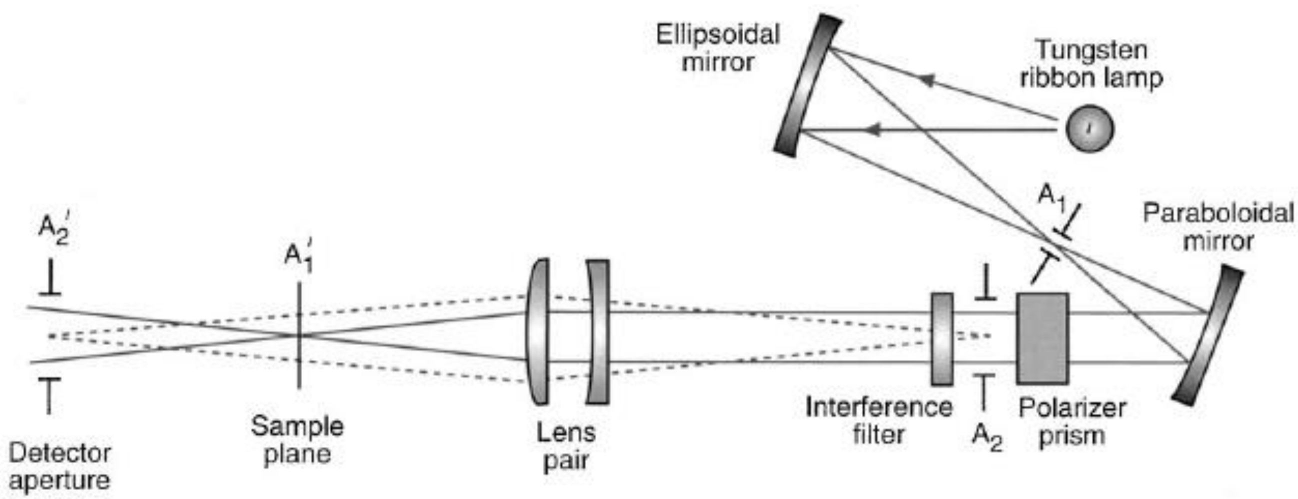
The labeling with 'Case' corresponds to the nomenclature of Nicodemus et al. (1977). Grey fields correspond to measurable quantities (Cases 5, 8), the others (Cases 1–4, 6, 7, 9) denote conceptual quantities. Please refer to the text for the explanation on measurable and conceptual quantities.

From: Schaepman-Strub at all 2006

Reflectance scale

Reference reflectometer





Williams, 1999

Radiometers

- ## Multispectral

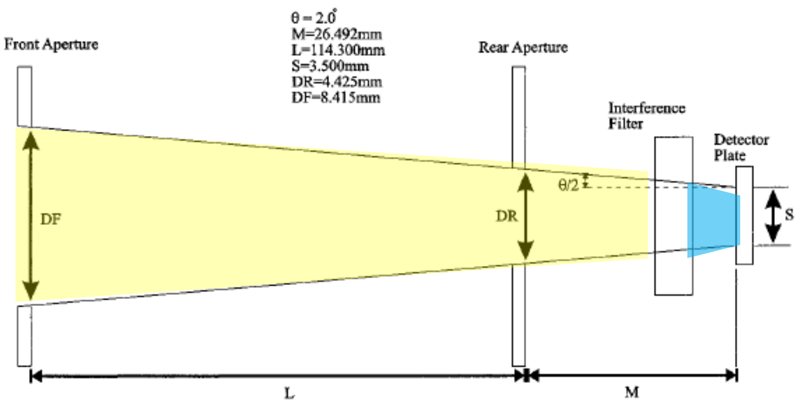
Stable and reliable

Limited spectral information

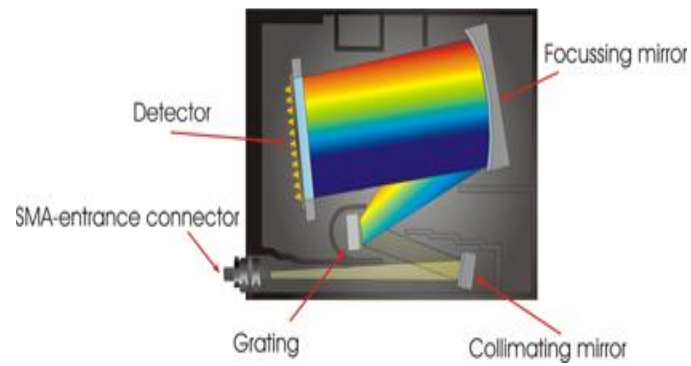
- ## Hyperspectral

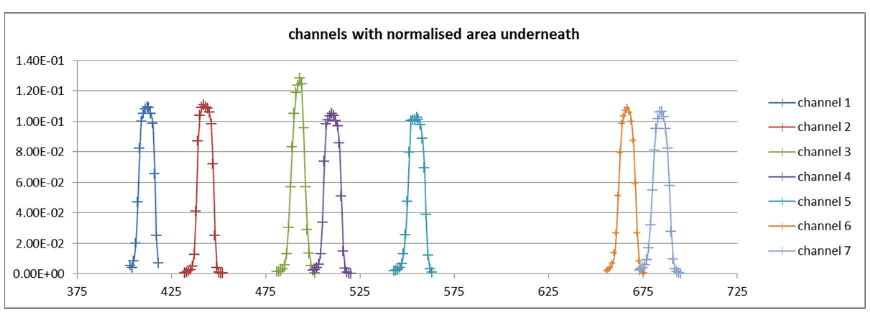
Demanding characterisation necessary !

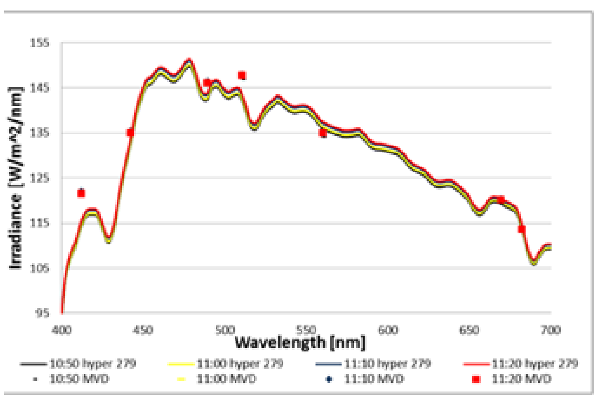
“Full” spectral information



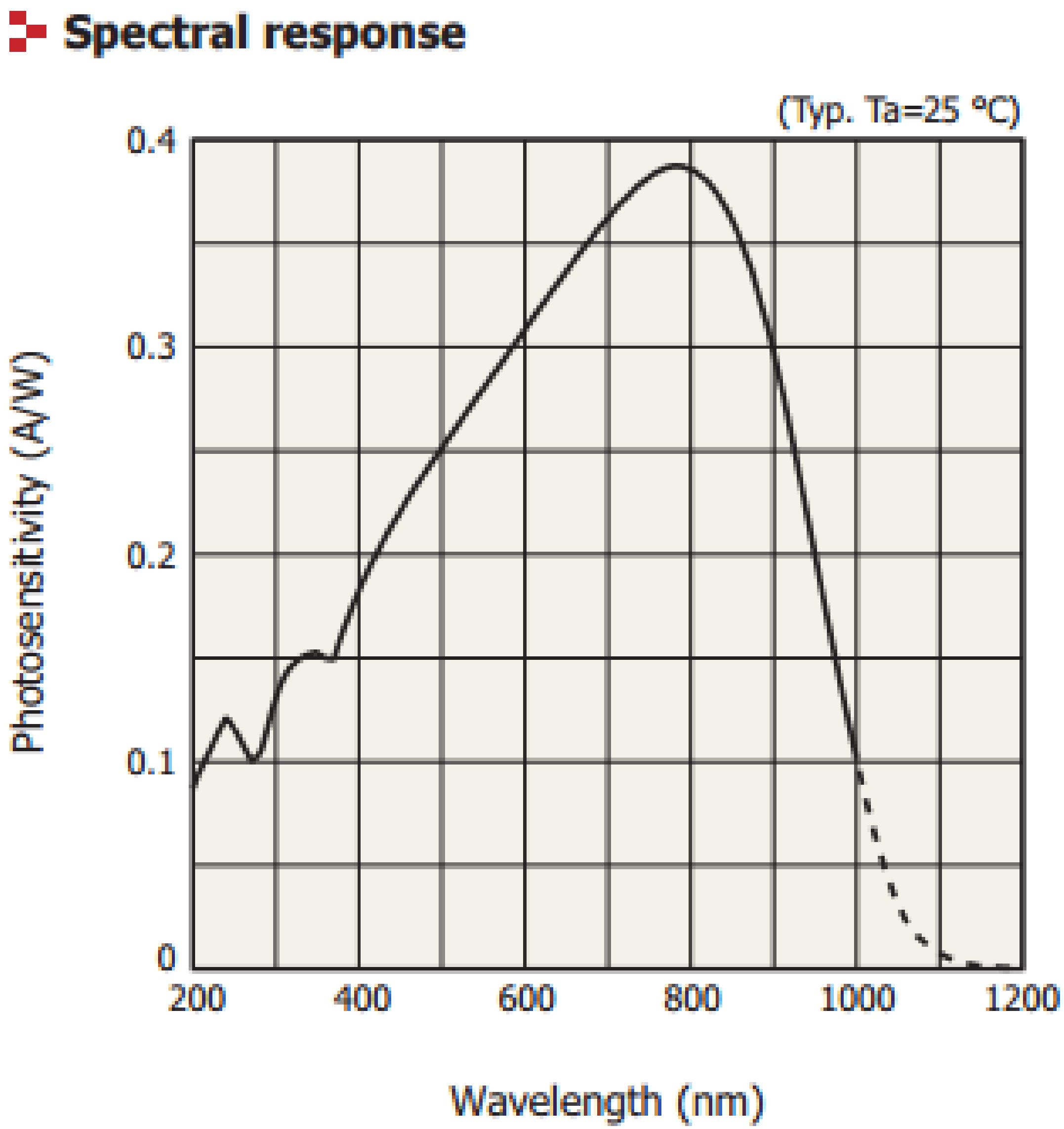
Ehsani et al. 1998





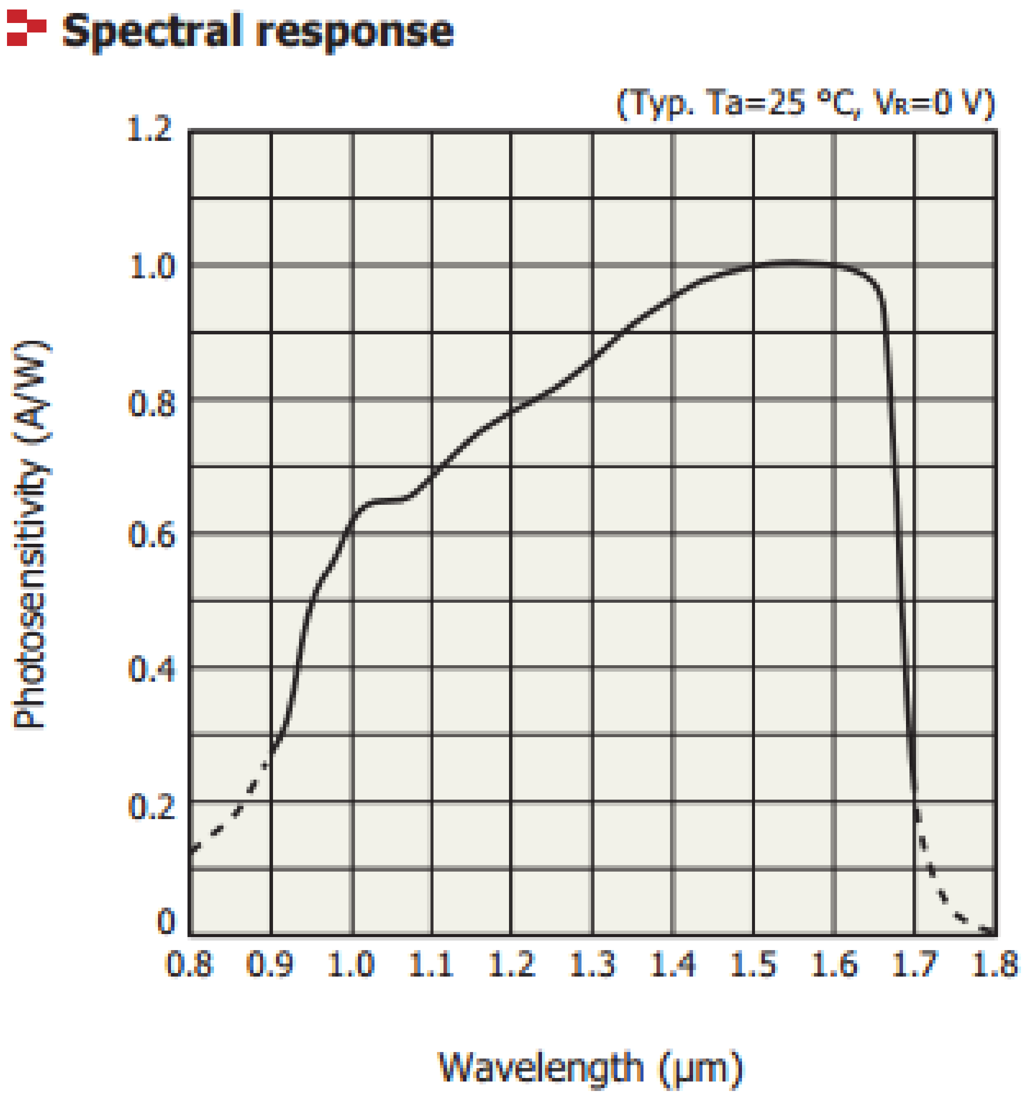


Silicon detector



http://www.hamamatsu.com/resources/pdf/ssd/s12698_series_kspd1084e.pdf/

InGaAs detector



http://www.hamamatsu.com/resources/pdf/ssd/s12698_series_kspd1084e.pdf/

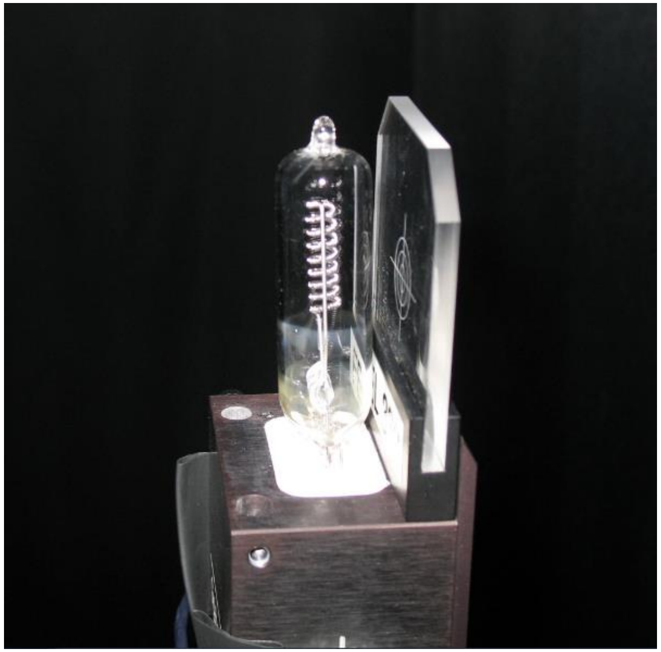
Calibration

"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."

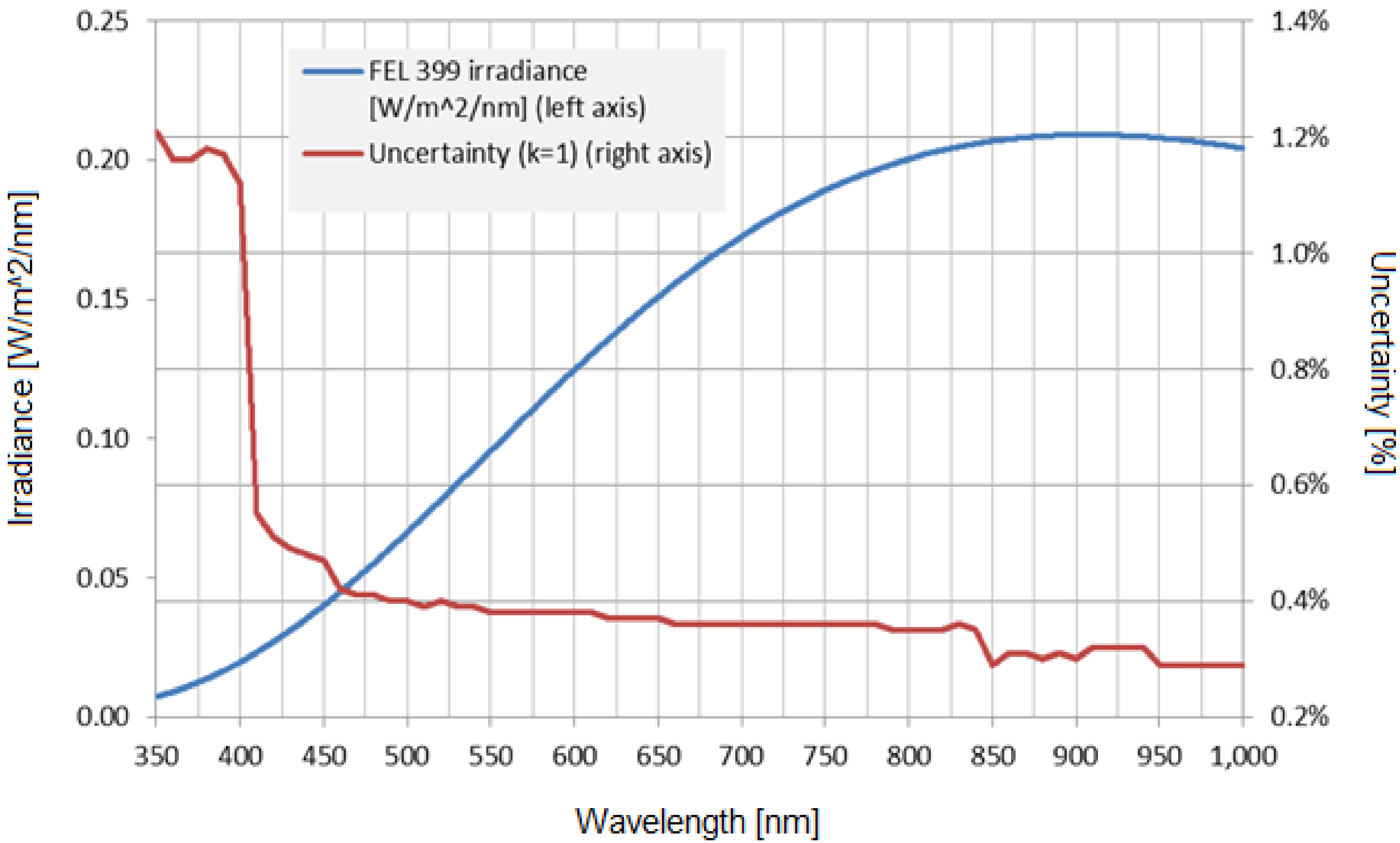
http://jcgm.bipm.org/vim/en/index.html

Irradiance standards

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



Typical FEL irradiance



Calibration Certificate example

FEL BN-9101-606
ABSOLUTE SPECTRAL IRRADIAN

FOR: [redacted]

DESCRIPTION: The lamp was a Gigahertz FEL tungsten hal
power 1 kW mounted in a lamp holder.

IDENTIFICATION: The number BN-9101-606 was marked on the

DATES OF CALIBRATION: 1 June 2015 to 22 June 2015

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

Reference: 2014110132/SIB2-15-1

Date of issue: 2 July 2015 Signed:

Checked by: Name: D Gibbs

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.

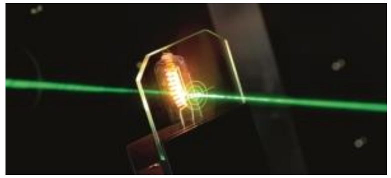
The lamp was operated from an actively stabilised dc power supply at 8.100 A. The polarity of the electrical current was as marked on the lamp, it was not changed. The lamp was ramped up and run for 30 minutes before measurements commenced. The voltage was monitored during measurement and is given for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

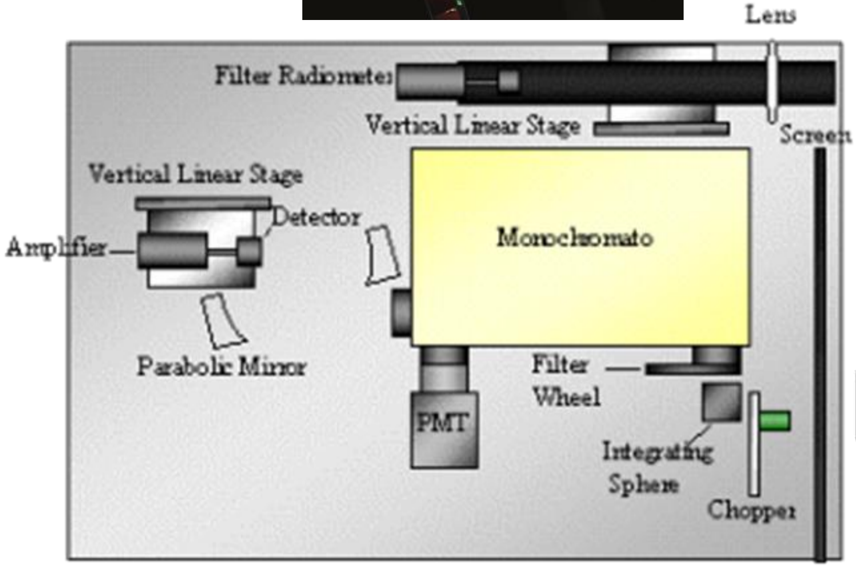
Absolute spectral irradiance values were determined by reference to the NPL_{2010} spectral irradiance scale. The measurements were made using the NPL Spectral Radiance and Irradiance Primary Scales (SRIPS) facility by direct comparison to a radiometrically-calibrated ultra-high temperature, high emissivity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

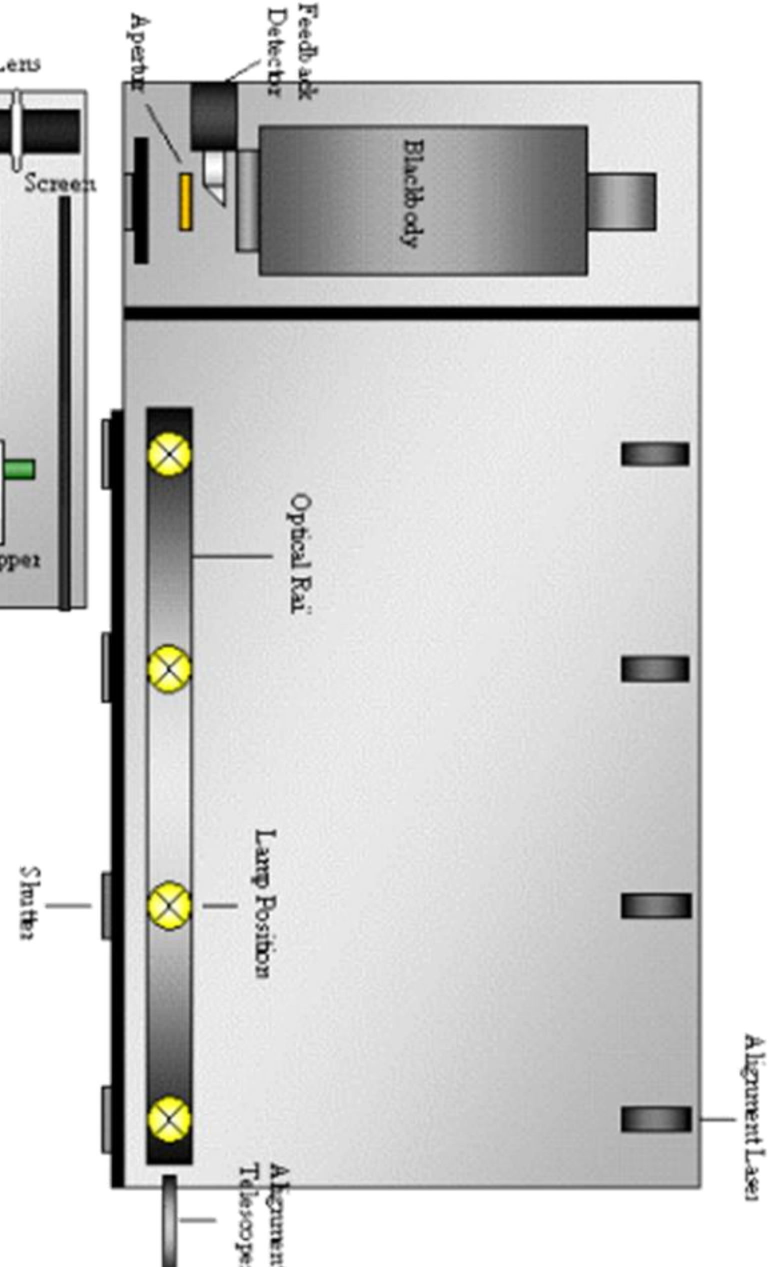
Spectral irradiance measurements were made over the range 250 nm to 390 nm with an instrument bandwidth of approximately 1.4 nm (FWHM), from 400 nm to 900 nm with an instrument bandwidth of approximately 2.7 nm (FWHM), from 910 nm to 1590 nm with an instrument bandwidth of 4.5 nm (FWHM) and from 1600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

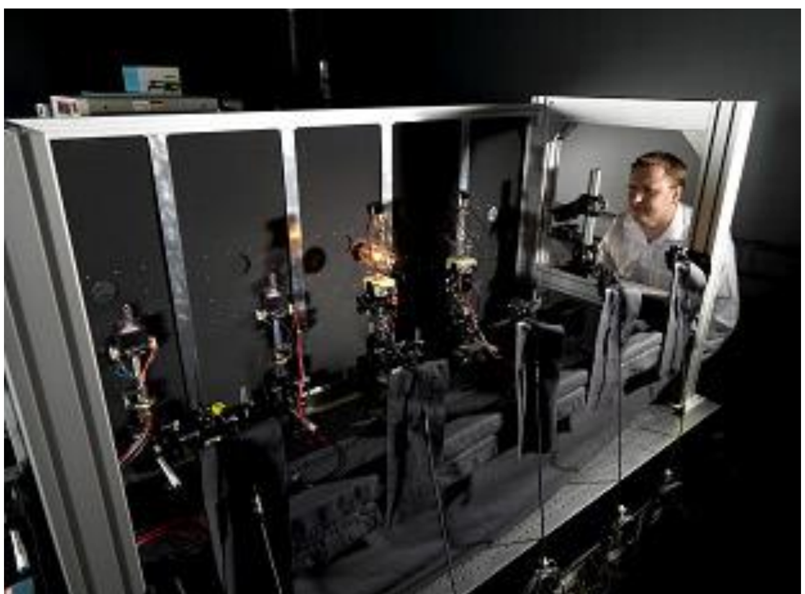
Ambient temperature during measurement was 22 °C ± 3 °C.

Irradiance



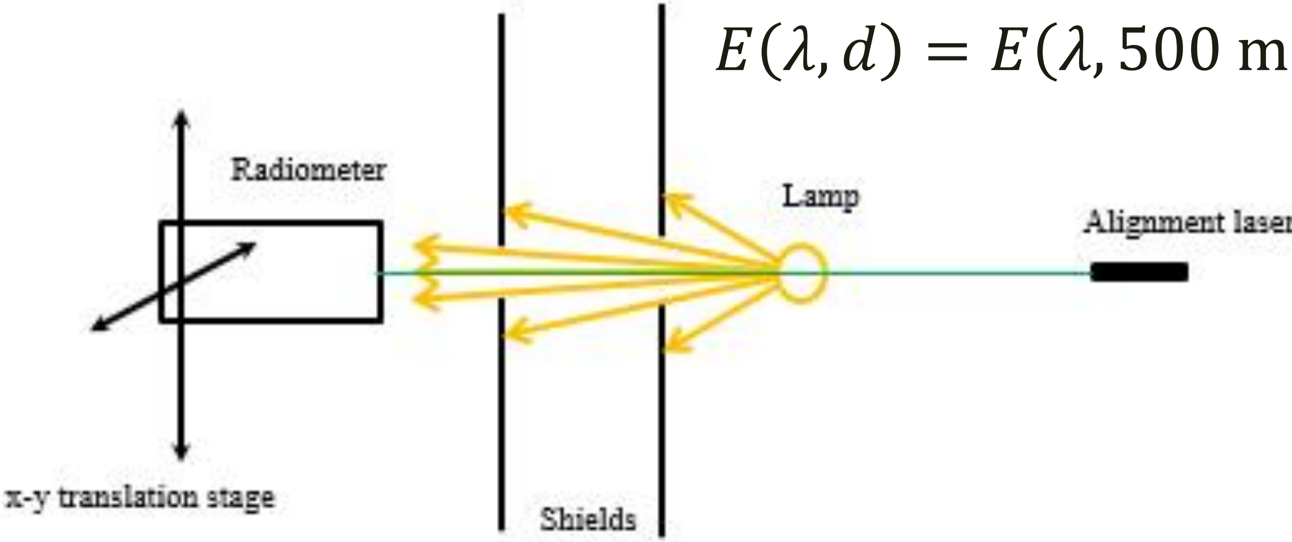

Lens
Filter Radiometer
Vertical Linear Stage
Screen
Vertical Linear Stage
Detector
Amplifier
Monochromato
Parabolic Mirror
Filter
Wheel
PMT
Integrating
Sphere
Chopper


Feedback
Detector
Blackbody
Lamp Position
Shutter
Alignment Laser
Alignment
Telescopes



Irradiance

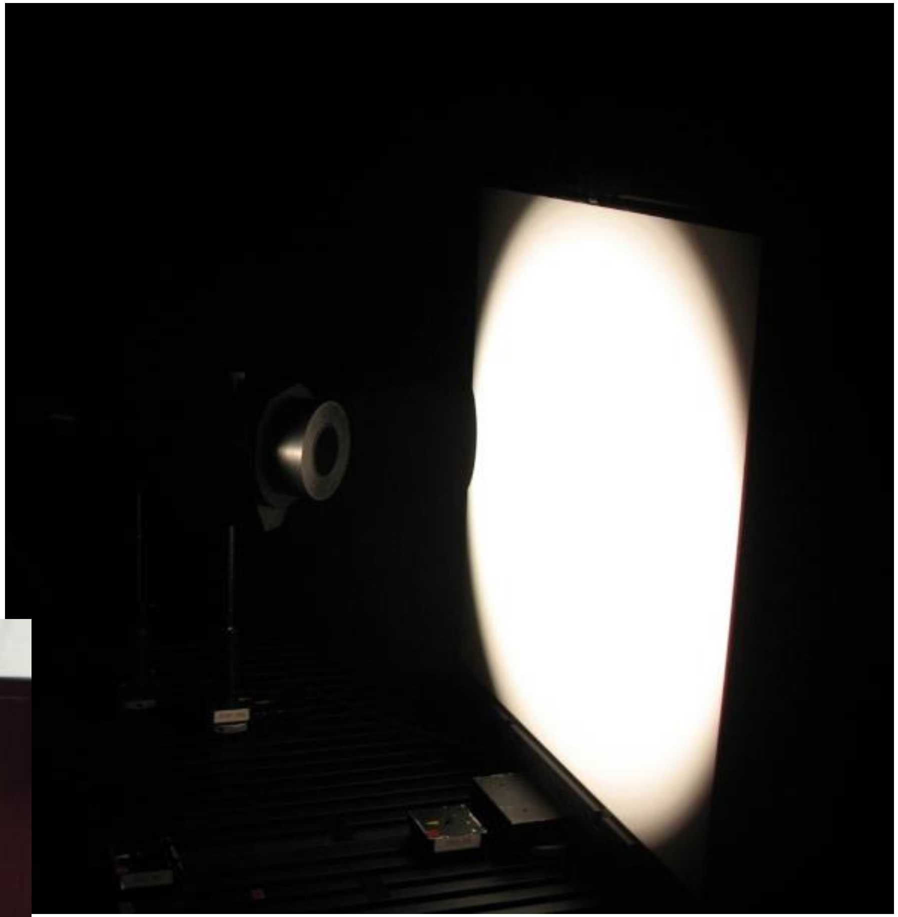
$$E(\lambda, d) = E(\lambda, 500\ \mathrm{mm}) \left(\frac{500\ \mathrm{mm}}{d} \right)^2$$

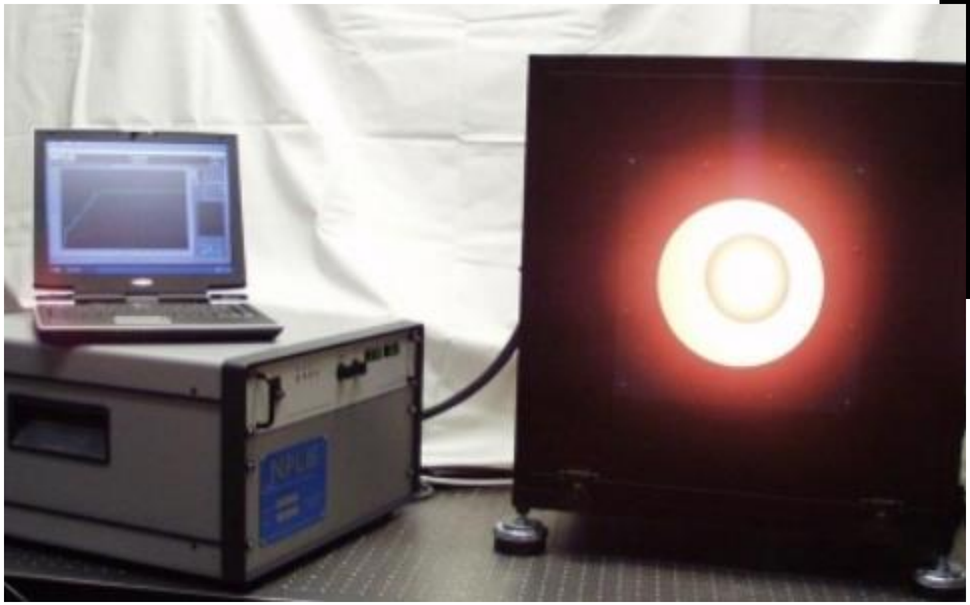


Radiance standards

- Lamp –reflectance standard

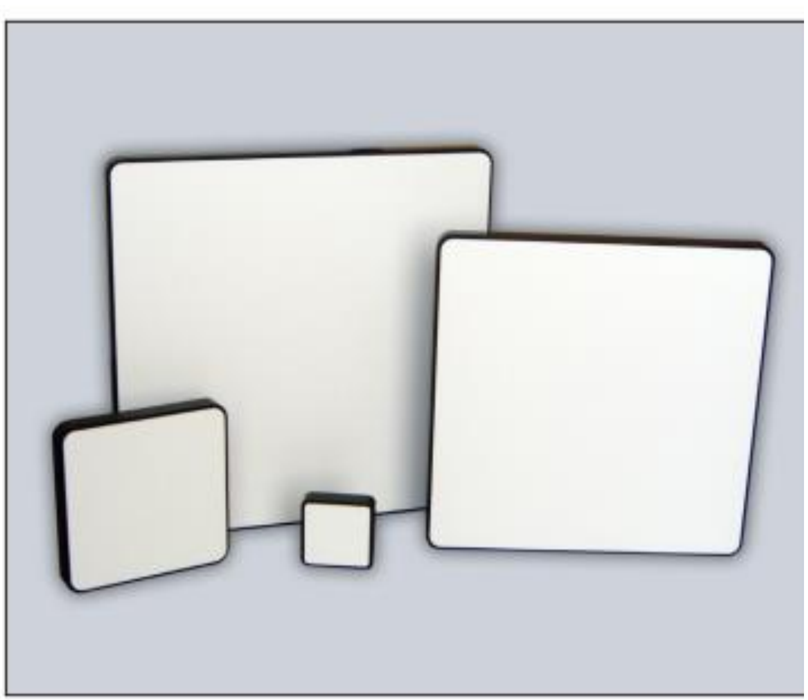
- Integrating sphere

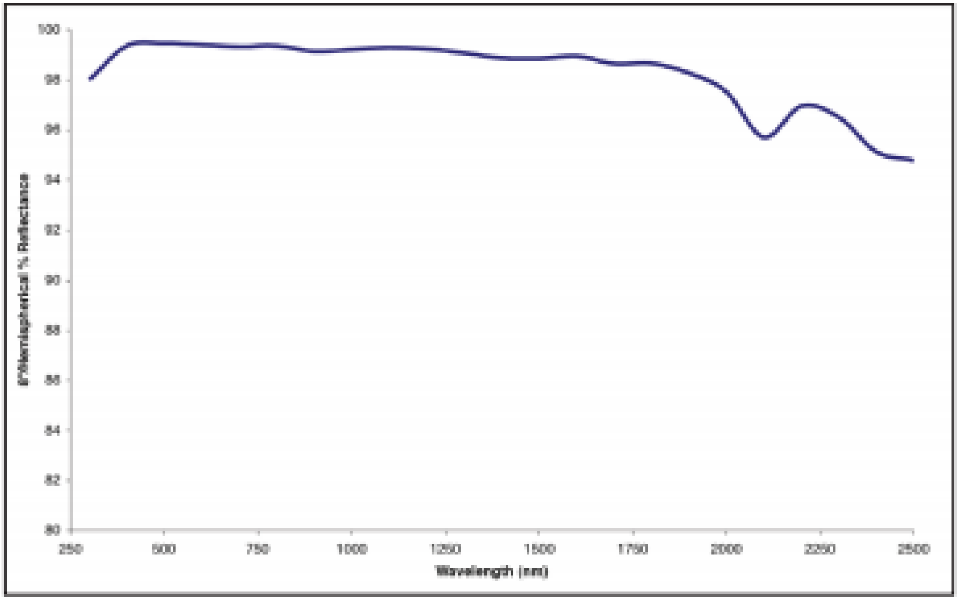




Reflectance Standard

- Spectralon® Diffuse Reflectance Standard

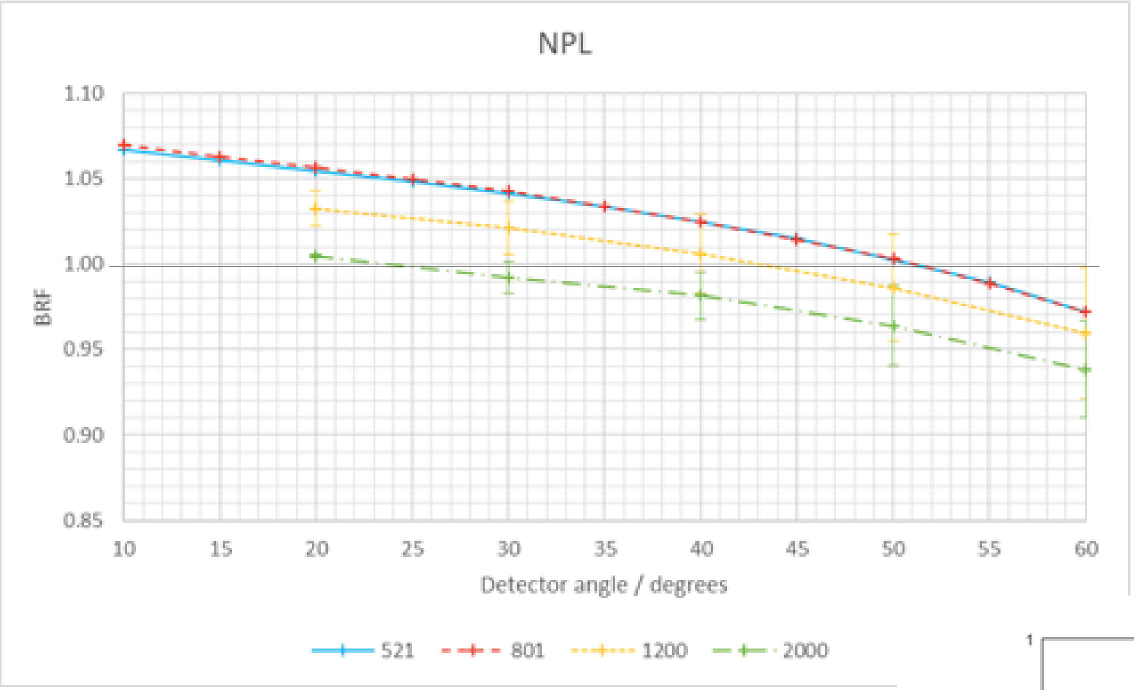


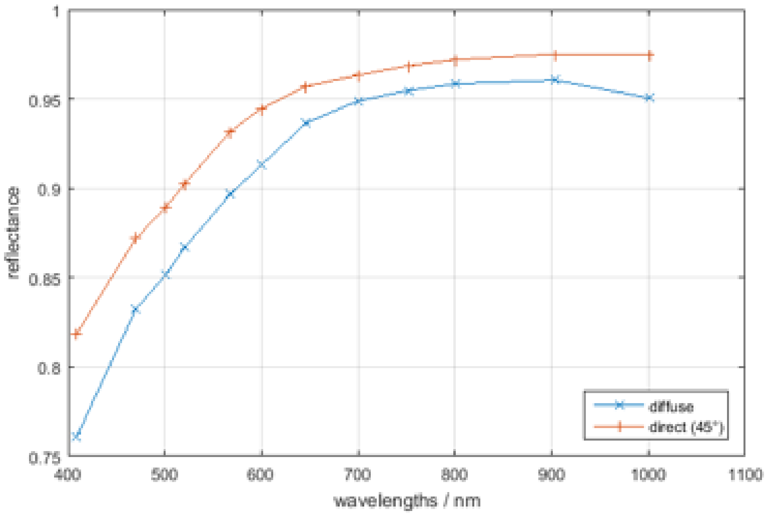


Typical 8° Hemispherical Reflectance SRM-990

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

Spectralon BRF

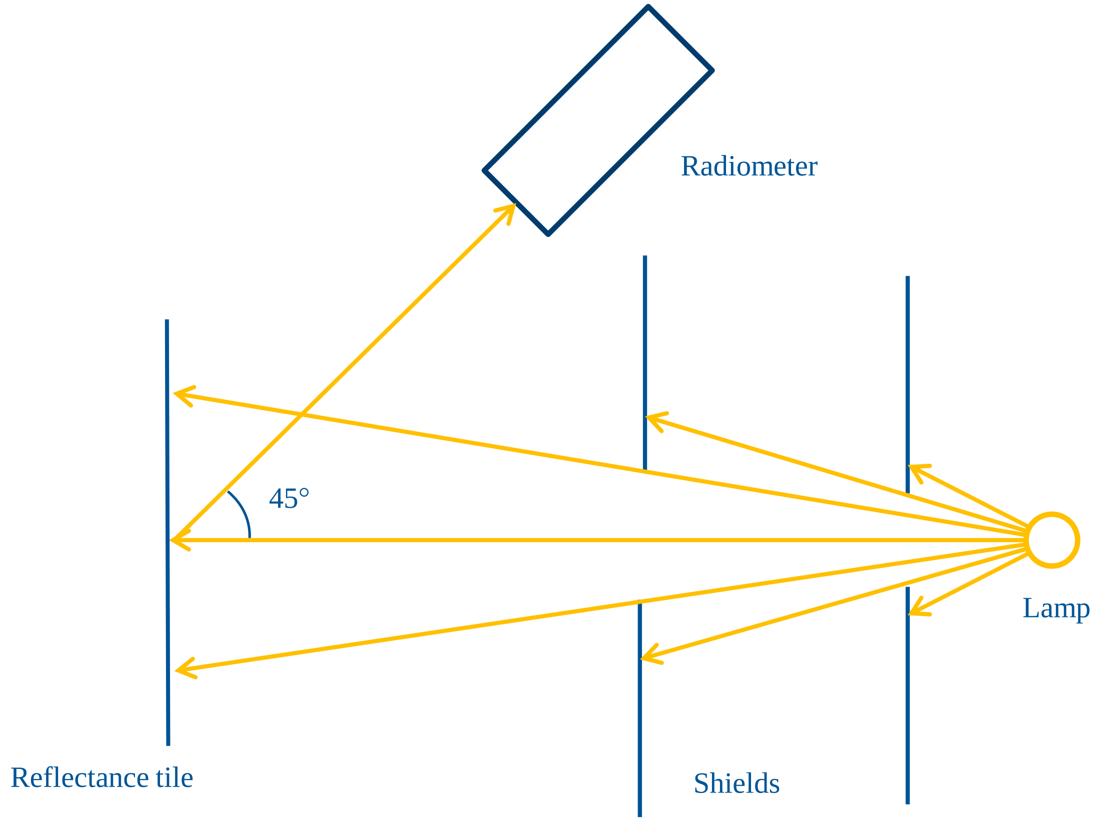


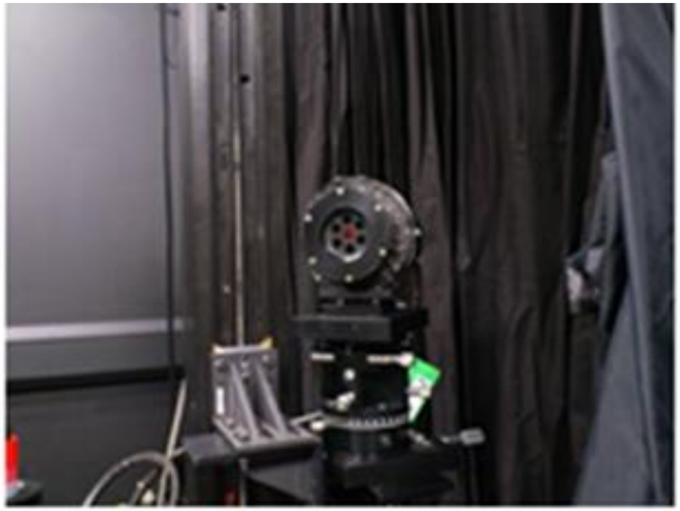


Yoon et al. 2009, ***The Extension of the NIST BRDF Scale from 1100 nm to 2500 nm***

Radiance

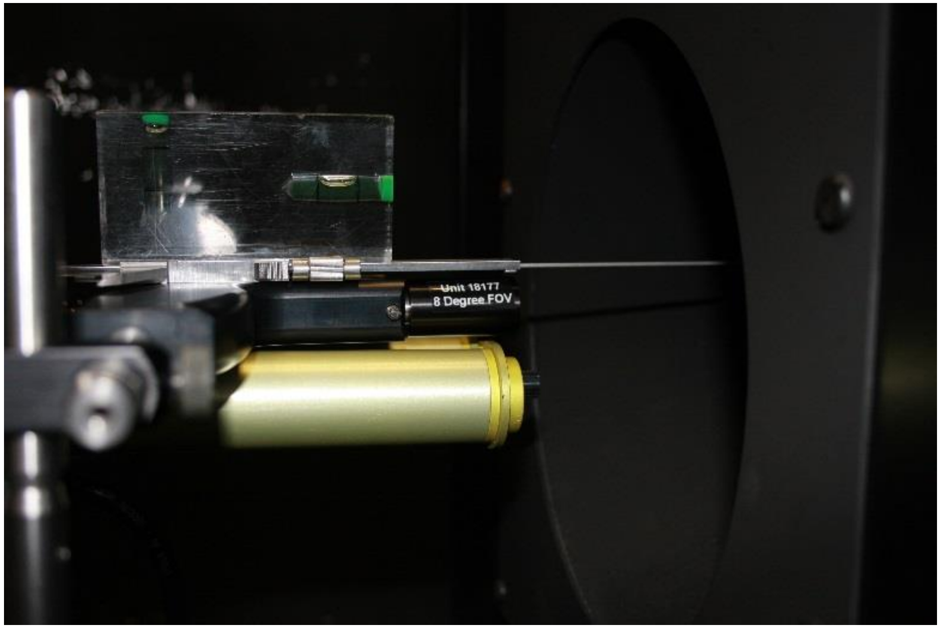
Lamp - tile

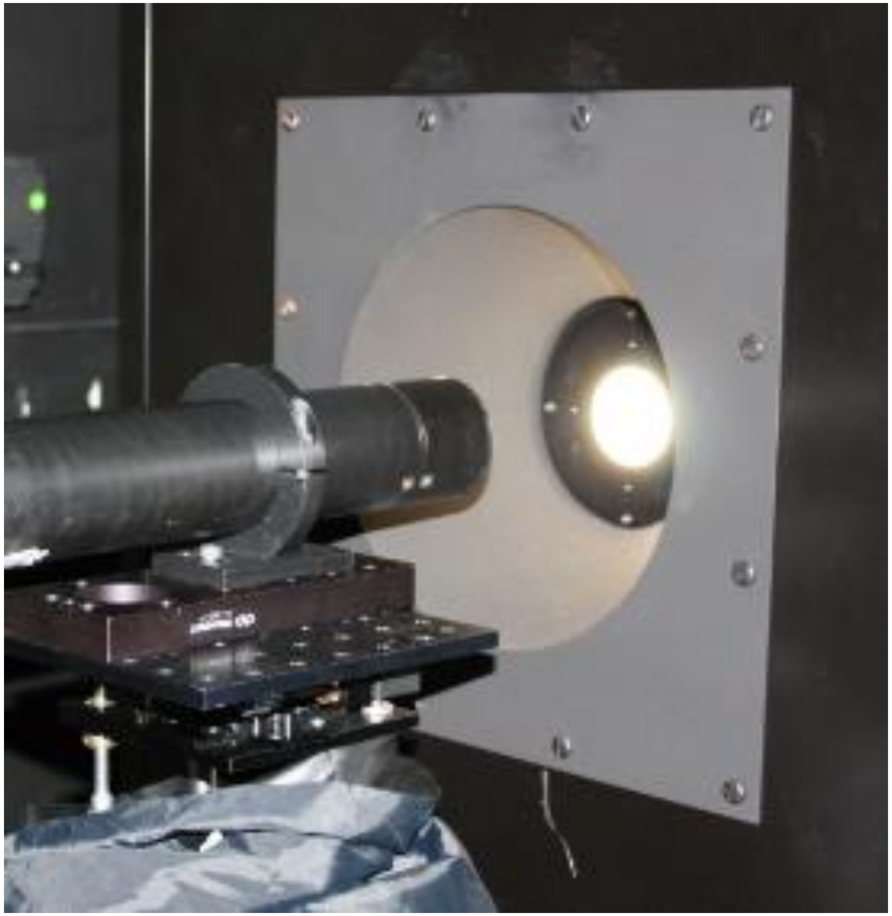




$$L_s = \frac{E_{FEL}\beta_{0:45}}{\pi}\frac{d_{cal}^2}{d_{use}^2}$$

Radiance





Integrating sphere

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.

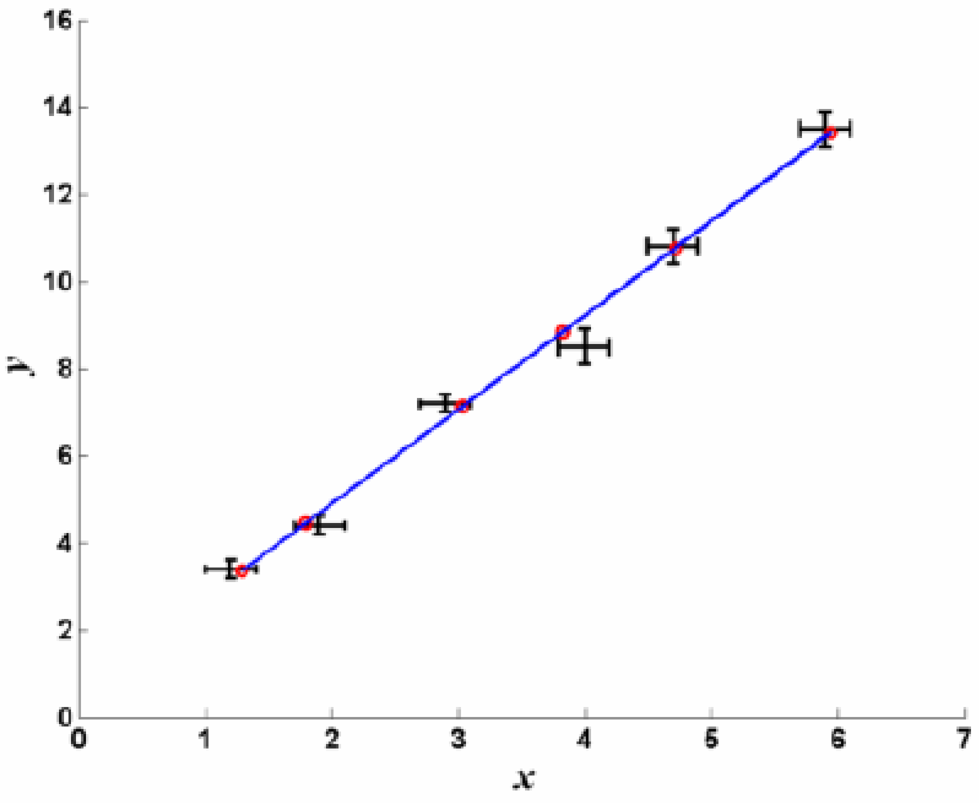
The absolute spectral radiance of the source was measured for a central area of the sphere port not exceeding 18 mm in diameter. Absolute spectral radiance values were measured using the NPL Spectral Radiance and Irradiance Primary Scales (SRIPS) facility by direct comparison to radiometrically-calibrated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

Straight-line calibration function

AERONET radiance calibration uses sphere with
 5 different radiance levels



ISO/TS 28037

http://www.npl.co.uk/science-technology/mathematics-modelling-and-simulation/products-and-services/software-downloads

Calibration fit for purpose

ACCURACY VS COST AND TIME REQUIRED

Above water radiometer system uncertainty

Source	L_{WN}				
	412	443	488	551	667
Absolute calibration	2.7	2.7	2.7	2.7	2.7
Sensitivity change	0.4	0.2	0.2	0.2	0.2
Correction	1.6	2.0	2.8	2.9	1.9
t_d	1.5	1.5	1.5	1.5	1.5
ρ	1.8	1.3	0.7	0.6	2.5
W	1.1	0.8	0.4	0.4	0.4
Environmental effects	3.1	2.1	2.1	2.1	6.4
Quadrature sum	5.1	4.5	4.7	4.7	7.8

Target 3%

G. Zibordi et al., “AERONET-OC: A Network of the Validation of Ocean Color Primary Products”, Journal of Atmospheric and Oceanic Technology, 2009, vol. 26

Calibration fit for purpose

Above water system uncertainties

Source	L_{WN}									
	443	**667**	**443**	**667**	**443**	**667**	**443**	**667**	**443**	**667**
Absolute calibration	**2.7**	**2.7**	**1.4**	**1.4**	**0.7**	**0.7**	**0.3**	**0.3**	**0.0**	**0.0**
Sensitivity Change	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Correction	2	1.9	2	1.9	2	1.9	2	1.9	2	1.9
$\mathbf{t_d}$	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
$\boldsymbol{\rho}$	1.3	2.5	1.3	2.5	1.3	2.5	1.3	2.5	1.3	2.5
W	0.8	0.4	0.8	0.4	0.8	0.4	0.8	0.4	0.8	0.4
Environmental effects	2.1	6.4	2.1	6.4	2.1	6.4	2.1	6.4	2.1	6.4
Quadrature sum	**4.5**	**7.8**	**3.9**	**7.4**	**3.7**	**7.3**	**3.6**	**7.3**	**3.6**	**7.3**

1.05	3.2
3.4	**4.9**

MNIs recommend inter-comparison to ensure and validate the calibration measurements and its uncertainties.

VALIDATION

In- situ inter- comparison

Zibordi et al. 2012

Table 2. Uncertainty budget (in percent) for R_{rs} determined from WiSPER data at selected center-wavelengths.

Uncertainty source	443	555	665
Absolute calibration of $L_u(z,\lambda,t)$	2.8	2.8	2.8
Self- and tower-shading corrections	3.0	1.8	3.2
Absolute calibration of $E_d(0^+,\lambda)$	2.5	2.5	2.5
Environmental perturbations	0.7	0.7	0.8
Quadrature sum	4.9	4.2	5.0

Reference sensor

Table 9. Average values of the absolute of relative percent differences (AD) determined for $R_{rs}(\lambda)$ at the 443, 555 and 665 nm center-wavelengths for the various systems/methods with respect to WiSPER, and combined uncertainties (CU) determined from the statistical composition of uncertainties quantifies for $R_{rs}(\lambda)$ derived from WiSPER and from each other inter-compared system/method. Underlined values indicate AD significantly greater than the computed CU values.

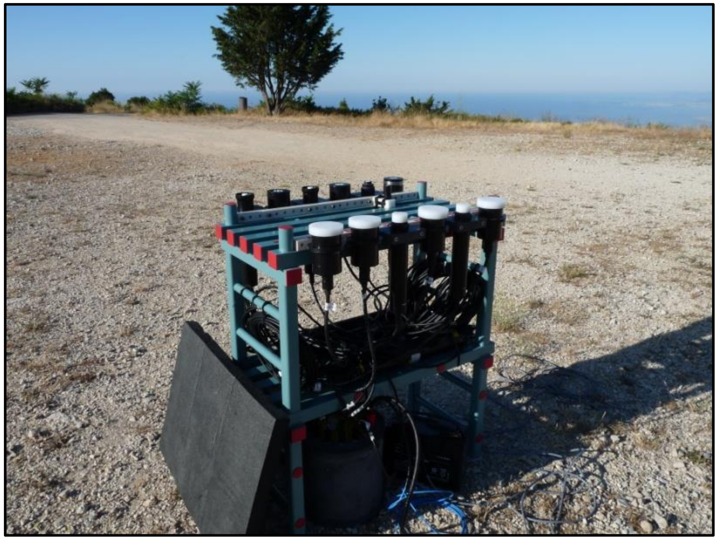
	AD (%)			CU (%)		
λ	443	555	665	443	555	665
TACCS-S	4.5	6.1	$\underline{21.2}$	8.3	8.0	9.3
TACCS-P	8.7	7.8	$\underline{16.1}$	8.4	7.7	8.8
SeaPRISM	5.7	6.0	7.6	6.9	6.0	11.0
TRIOS-B	7.7	2.7	$\underline{11.0}$	8.0	5.5	6.7
TRIOS-E	5.9	3.9	7.2	8.0	5.5	6.7

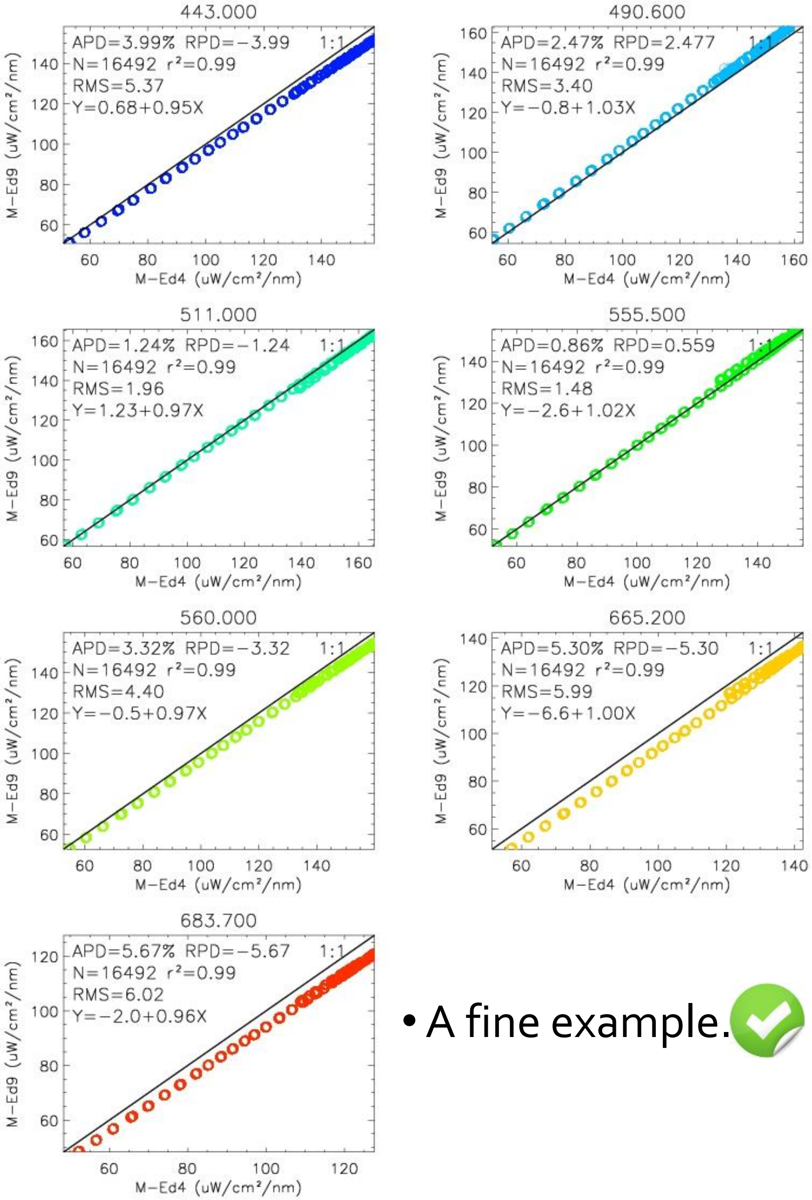
Comparison results

Quality check – Sun inter-comparison

BOUSSOLE EXAMPLE

QA/QC: intercalibration before deployment

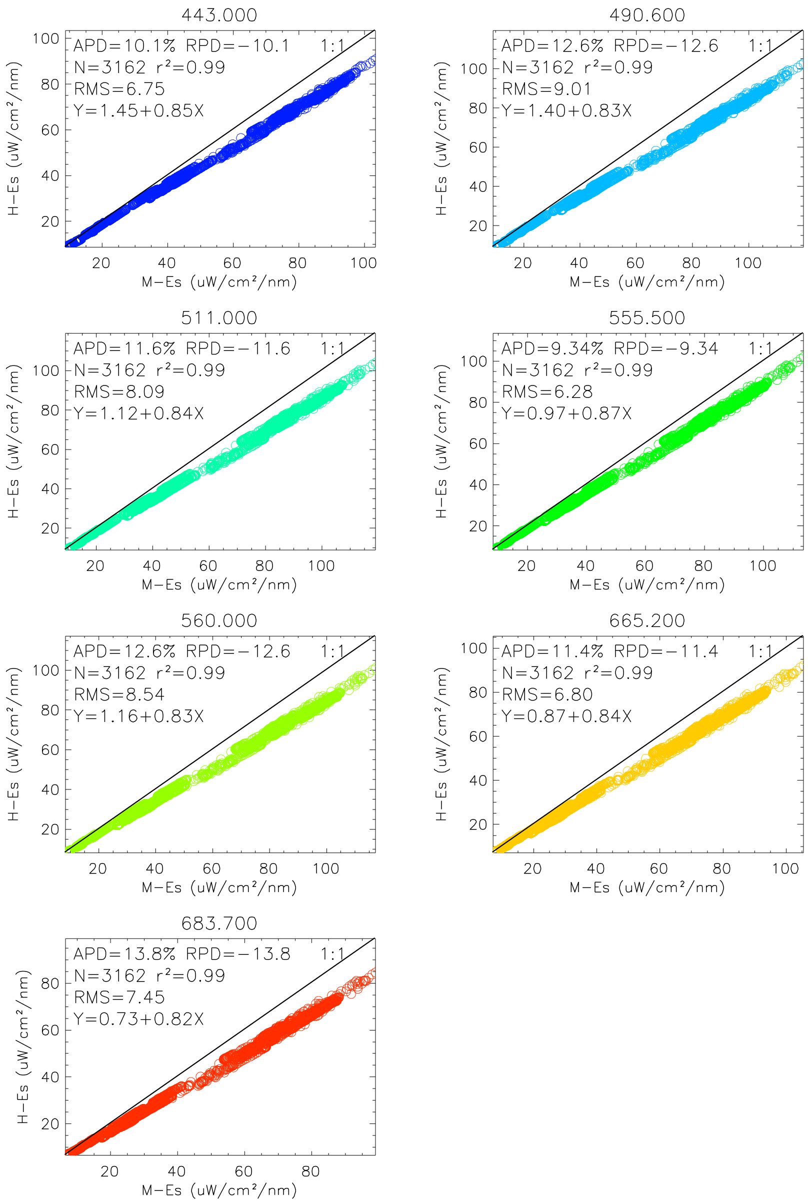


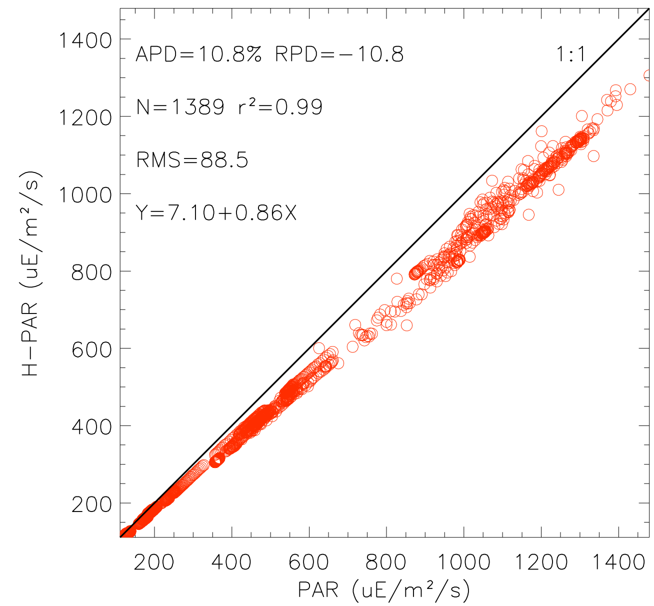


- A fine example.

V. Vellucci

QA/QC: intercalibration before deployment





- A bad example.
- Instrument sent back to factory for verification: collector replacement and recalibration.

V. Vellucci

Why do we have these problems?

Due to other instrument characteristics.

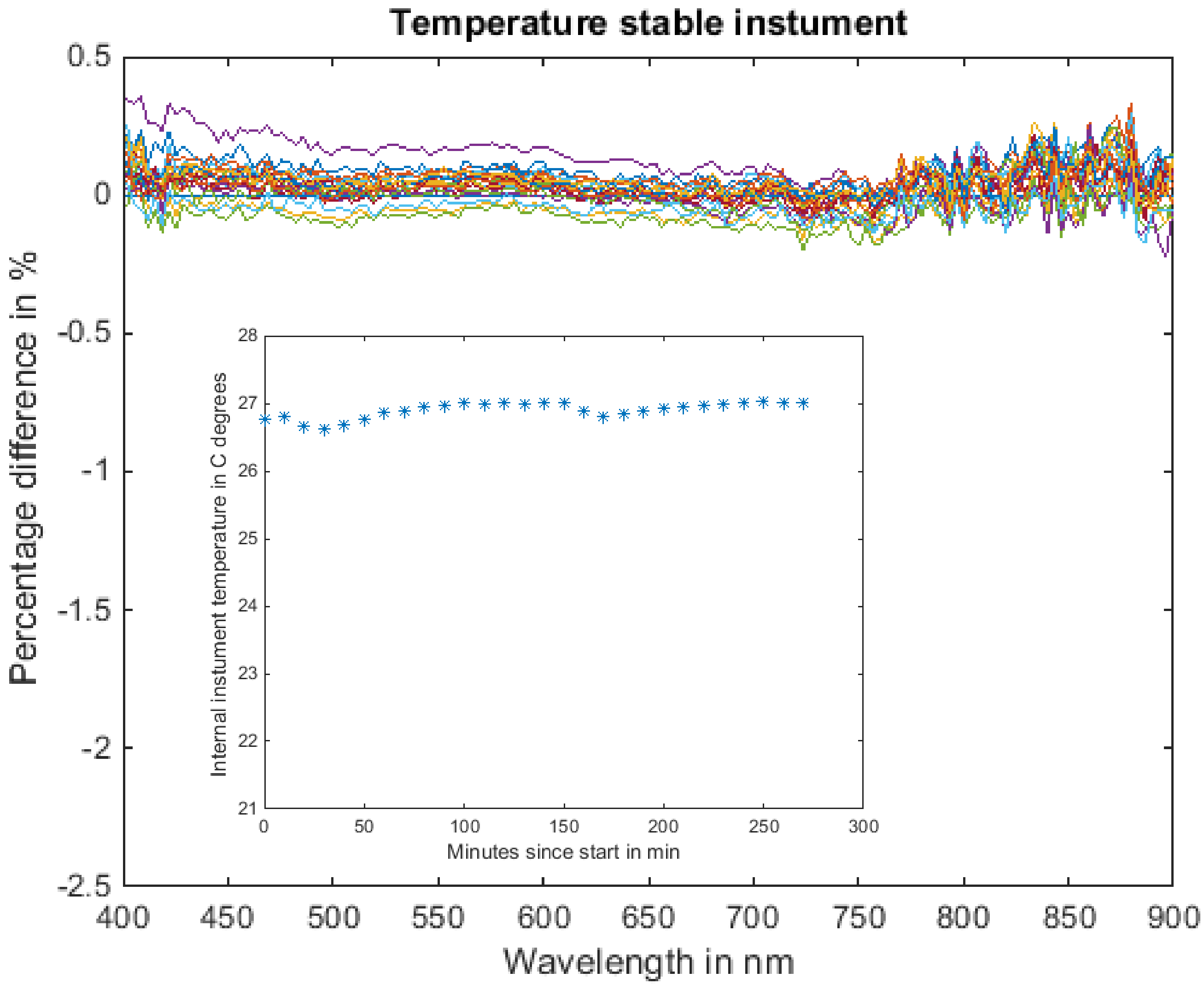
- Stray light, temperature, linearity, cosine response, immersion coefficient

- REMEMBER!

Calibration is valid only *under specified conditions,* (during calibration)

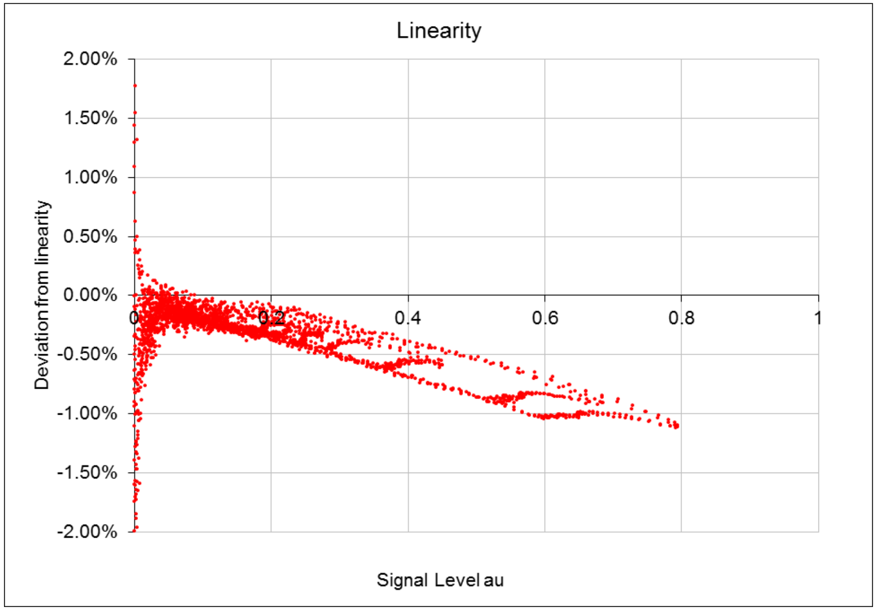
Example results

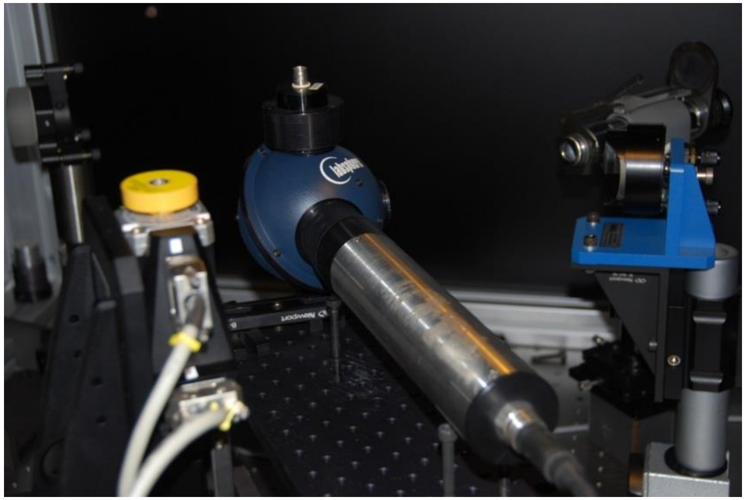
Stability

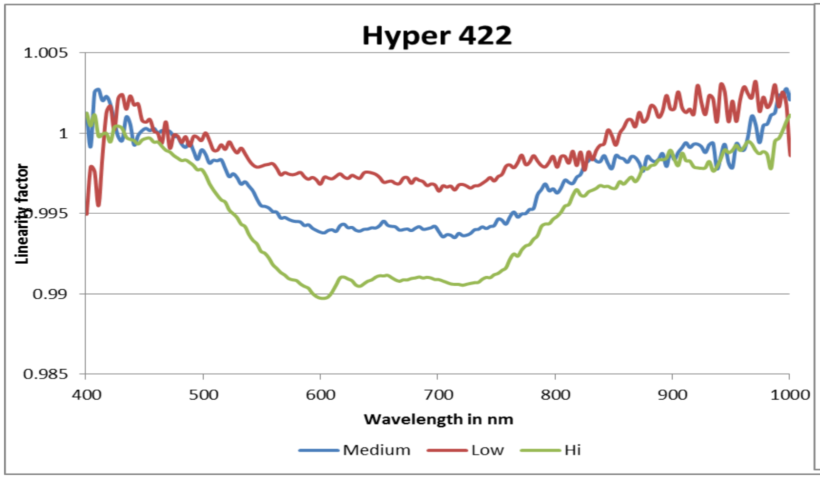


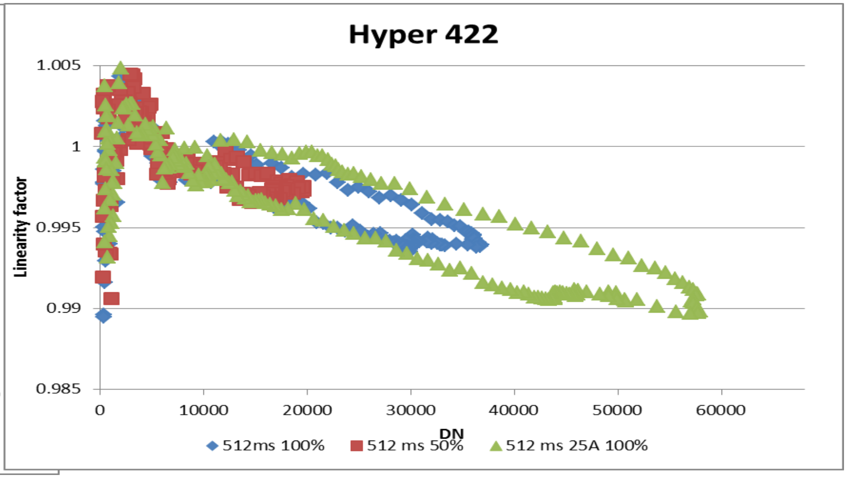
Example results

Linearity





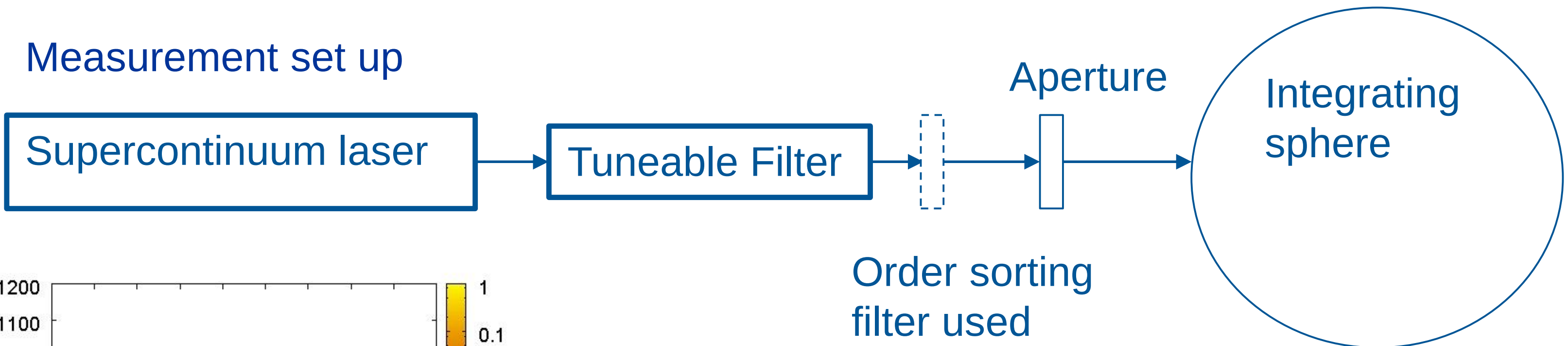


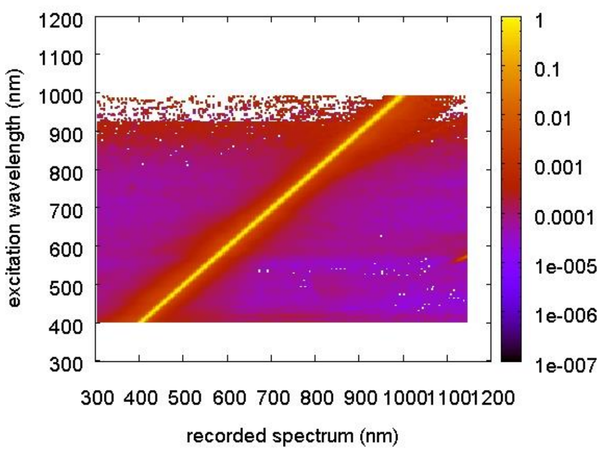


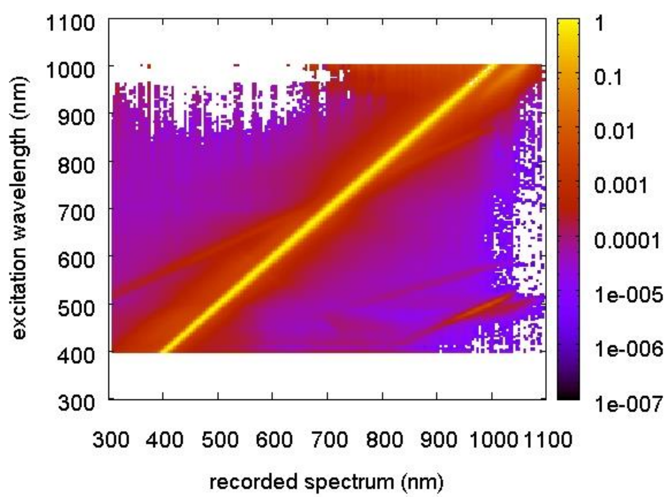
Example results

Stray Light

Measurement set up

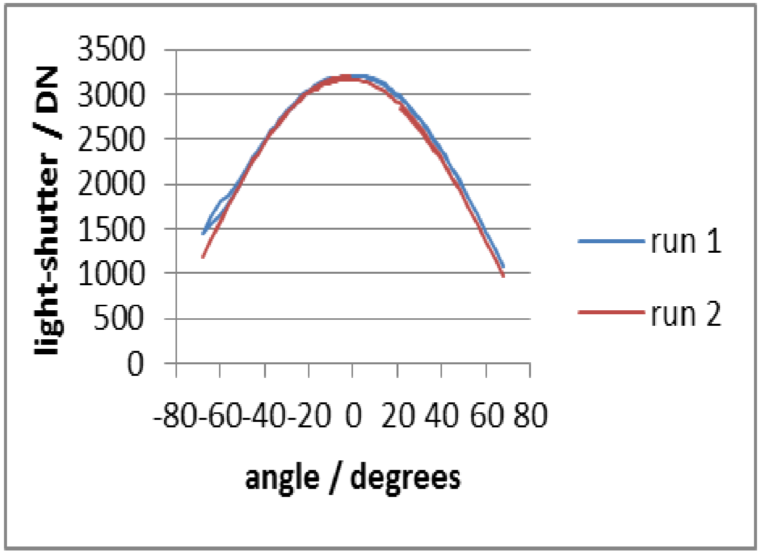


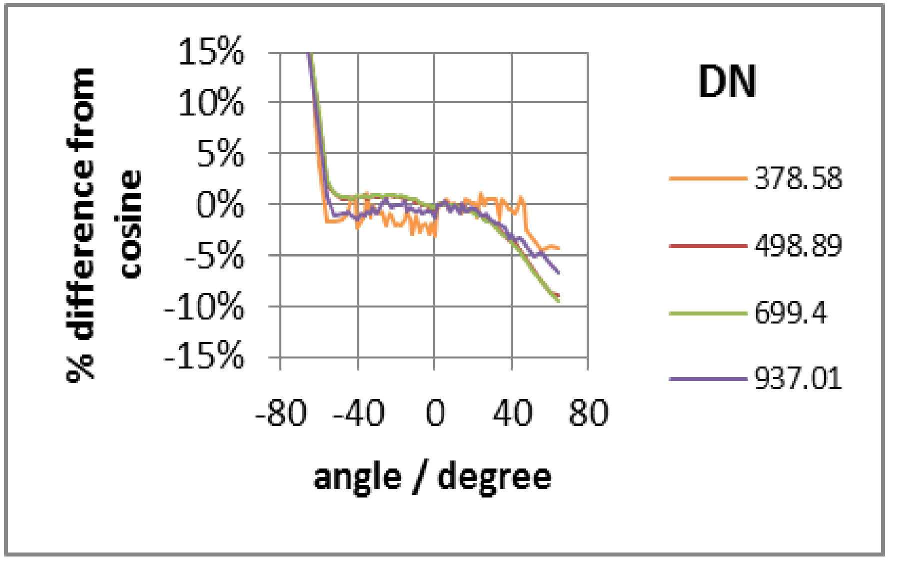




Example results

- Cosine response





Summary

Metrology view

- SI traceability – ensures the valid measurements
- Calibration link instrument output readings to physical values
- SI traceability especially important to radiometry, as these measurements are used calibration and validation of satellite sensors
- Instruments characteristics influence theirs properties and performance

Thank you

National Physical Laboratory

Department for Business Innovation & Skills

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