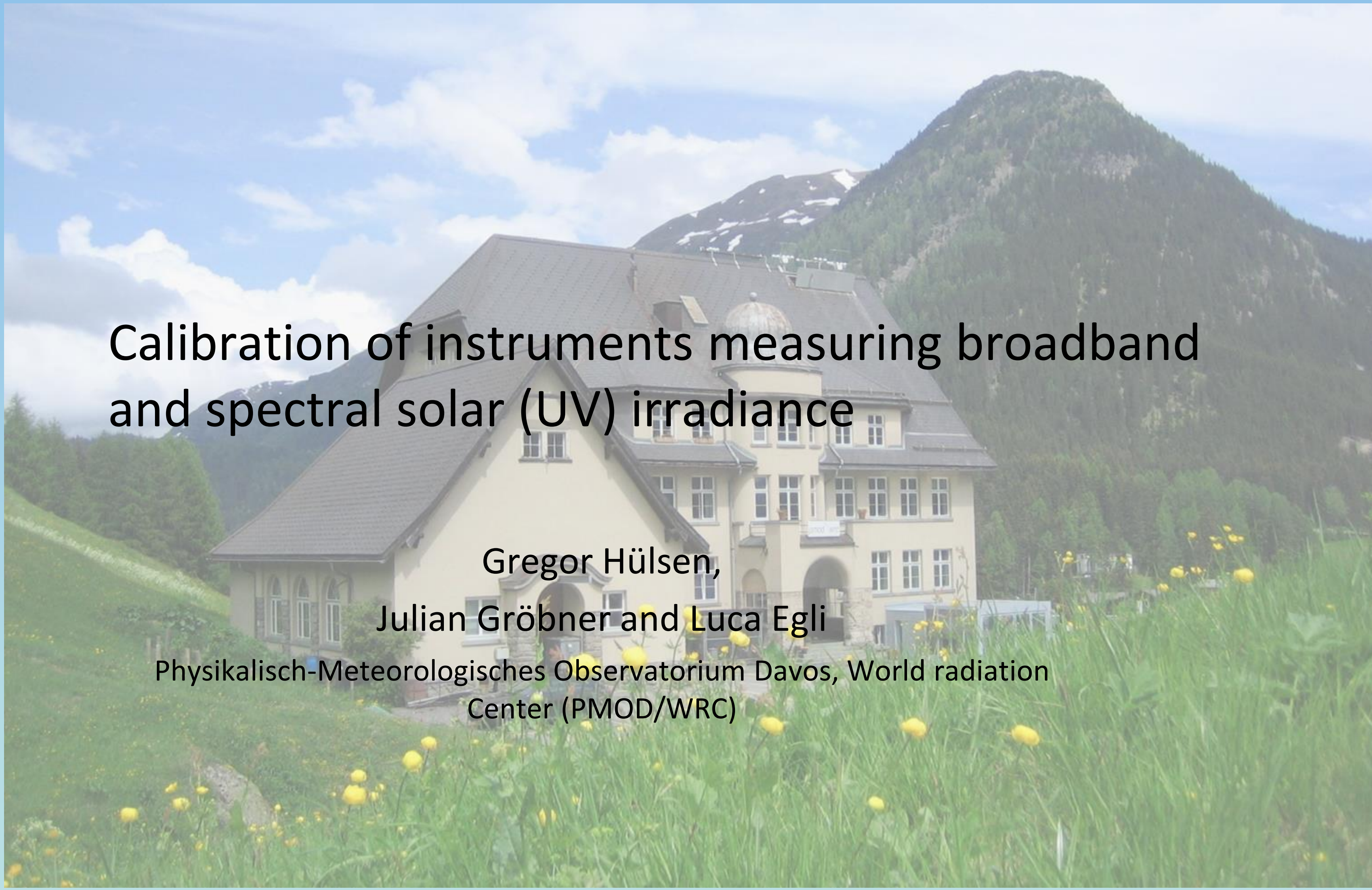

Calibration of instruments measuring broadband and spectral solar (UV) irradiance

Gregor Hülsen,

Julian Gröbner and Luca Egli

Physikalisch-Meteorologisches Observatorium Davos, World radiation Center (PMOD/WRC)

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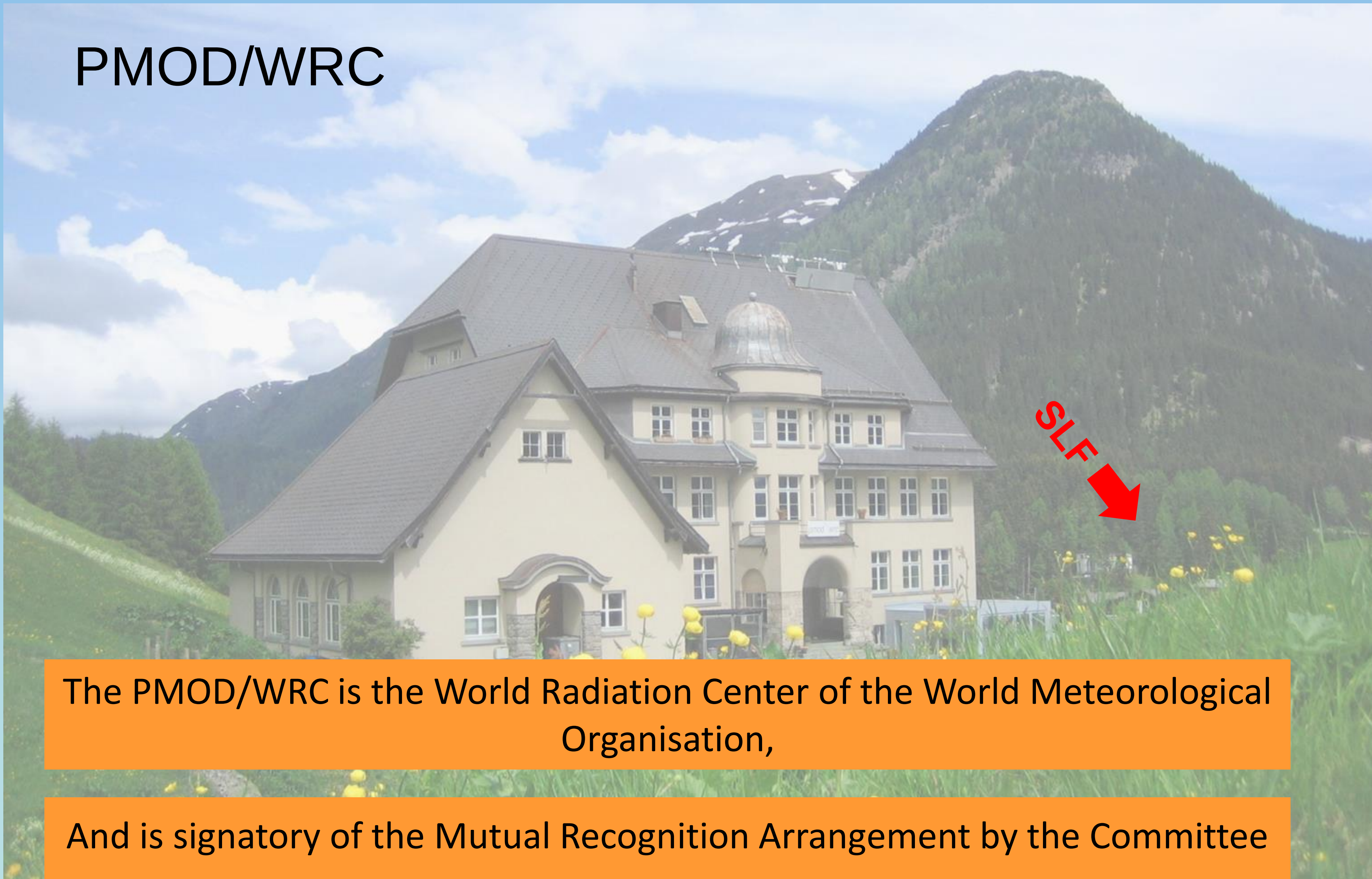
PMOD/WRC



The PMOD/WRC is the World Radiation Center of the World Meteorological Organisation,

And is signatory of the Mutual Recognition Arrangement by the Committee of Weights and Measures (CIPM MRA).

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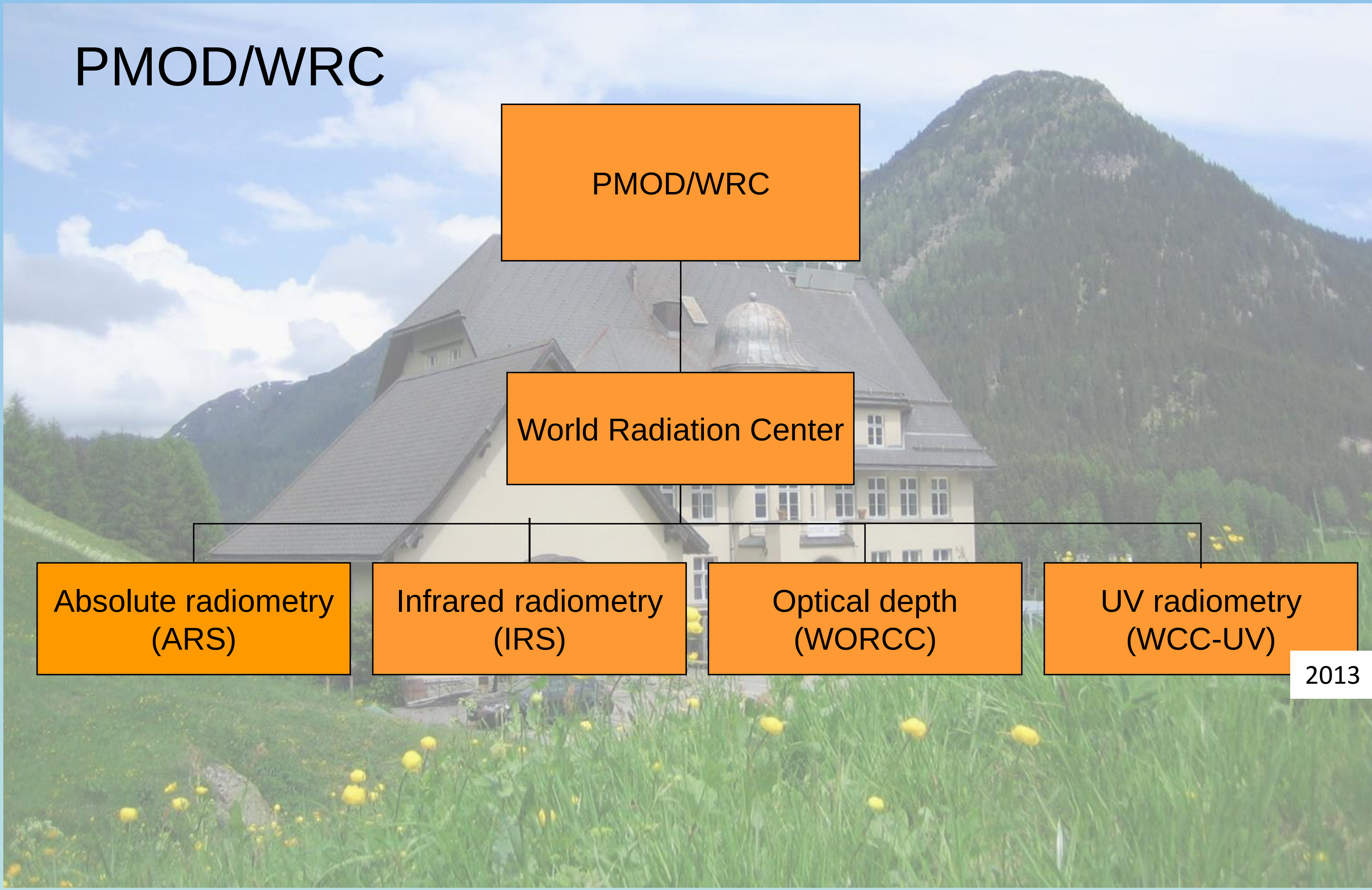

PMOD/WRC
World Radiation Center
Absolute radiometry (ARS)
Infrared radiometry (IRS)
Optical depth (WORCC)
UV radiometry (WCC-UV)
2013

Outline

- What is traceability?
- Calibration and Quality Assurance of
  - Solar Spectroradiometers
  - Broadband Filter Radiometers
- Uncertainty
- Summary

Measuring solar (UV) irradiance

What do we want?

→ Value of solar irradiance in **W**$\mathbf{m^{-2}}$

Who guarantees that **W** is Watt and **m** is meter?

1) We need traceability to the International System of Units (SI).

METAS Federal Office of Metrology

VSL Dutch Metrology Institute

PTB

Aalto University School of Science and Technology

NIST National Institute of Standards and Technology U.S. Department of Commerce

How confident can we be that this value is true ?

2) We also need an Uncertainty and confidence level

Albedo Measurements: “x 2”

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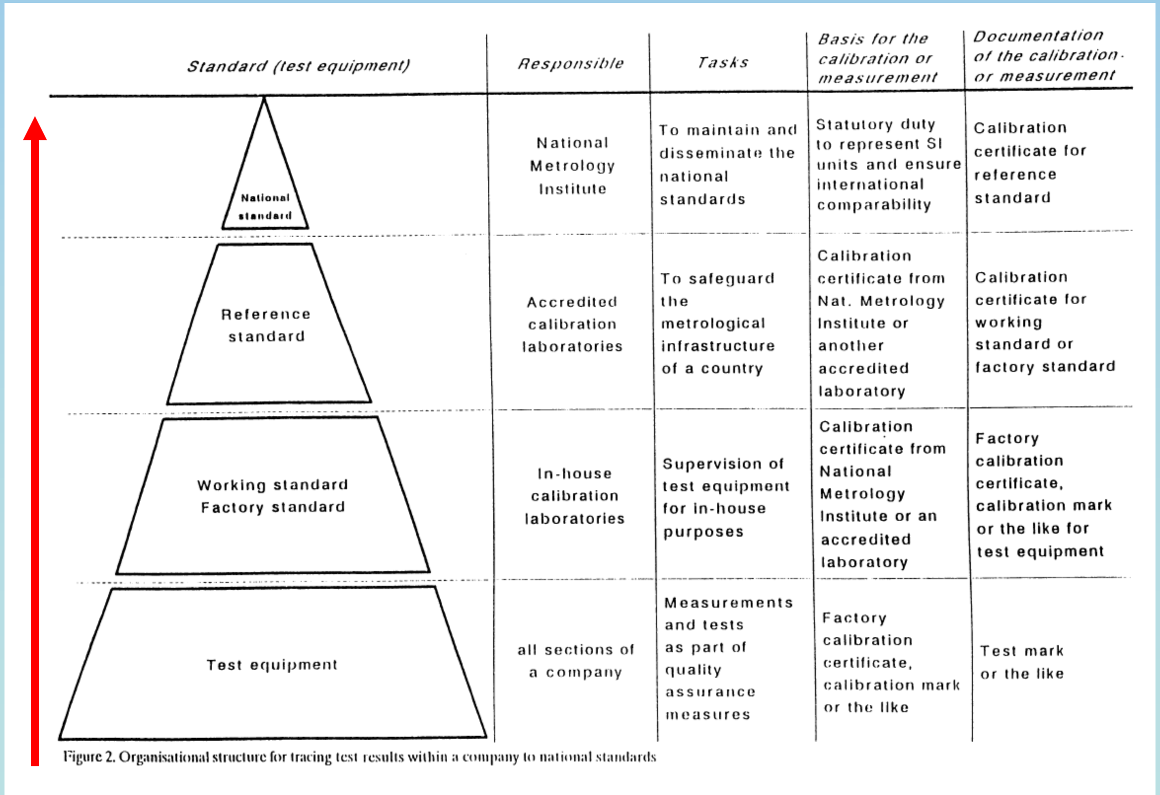
Traceability from a metrologist point of view

2.41 metrological traceability

property of a **measurement result** whereby the result can be related to a reference through a documented unbroken chain of **calibrations**, each contributing to the **measurement uncertainty**

International vocabulary of metrology (VIM),
http://www.bipm.org/utils/common/documents/jcgm/JCGM_200_2012.pdf



Standard (test equipment)	*Responsible*	*Tasks*	*Basis for the calibration or measurement*	*Documentation of the calibration or measurement*
National standard	National Metrology Institute	To maintain and disseminate the national standards	Statutory duty to represent SI units and ensure international comparability	Calibration certificate for reference standard
Reference standard	Accredited calibration laboratories	To safeguard the metrological infrastructure of a country	Calibration certificate from Nat. Metrology Institute or another accredited laboratory	Calibration certificate for working standard or factory standard
Working standard Factory standard	In-house calibration laboratories	Supervision of test equipment for in-house purposes	Calibration certificate from National Metrology Institute or an accredited laboratory	Factory calibration certificate, calibration mark or the like for test equipment
Test equipment	all sections of a company	Measurements and tests as part of quality assurance measures	Factory calibration certificate, calibration mark or the like	Test mark or the like

Figure 2. Organisational structure for tracing test results within a company to national standards

from Traceability of measurement, ILAC-G2: 1994

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Traceability from a metrologist point of view

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property of a **measurement result** whereby the result can be related to a reference through a documented unbroken chain of **calibrations**, each contributing to the **measurement uncertainty**

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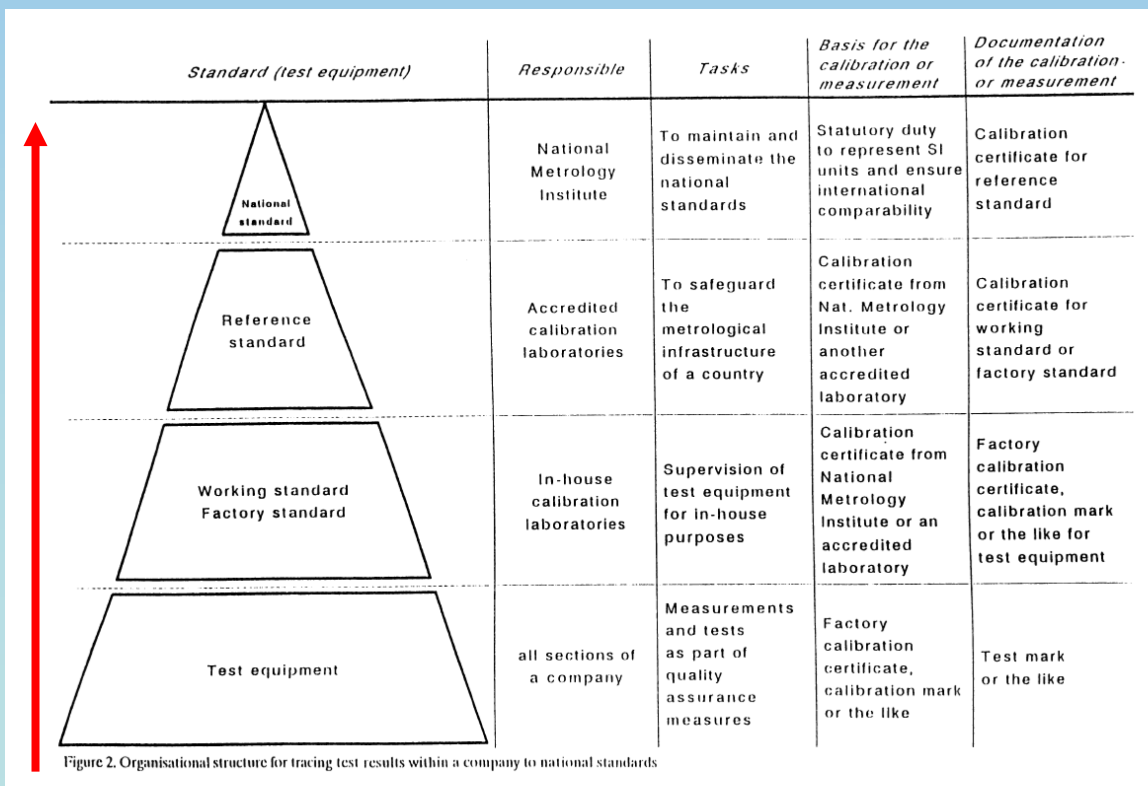

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Test equipment	all sections of a company	Measurements and tests as part of quality assurance measures	Factory calibration certificate, calibration mark or the like	Test mark or the like

Figure 2. Organisational structure for tracing test results within a company to national standards

from Traceability of measurement, ILAC-G2: 1994

Is this sufficient to be traceable??

Transfer Standard from NMI

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Traceability from a metrologist point of view

2.41 metrological traceability

property of a **measurement result** whereby the result can be related to a reference through a documented unbroken chain of **calibrations**, each contributing to the **measurement uncertainty**

What it actually means:

(1) **an unbroken chain of comparisons** going back to stated references acceptable to the parties, usually a <u>national or international standard</u>;

(2) **uncertainty of measurement;** the uncertainty of measurement for each step in the traceability chain must be calculated or estimated according to agreed methods and must be stated so that an overall uncertainty for the whole chain may be calculated or estimated;

(3) **documentation;** each step in the chain must be performed according to documented and generally acknowledged procedures; the results must be recorded;

(4) **competence;** the laboratories or bodies performing one or more steps in the chain must supply evidence for their technical competence (e.g. by demonstrating that they are accredited);

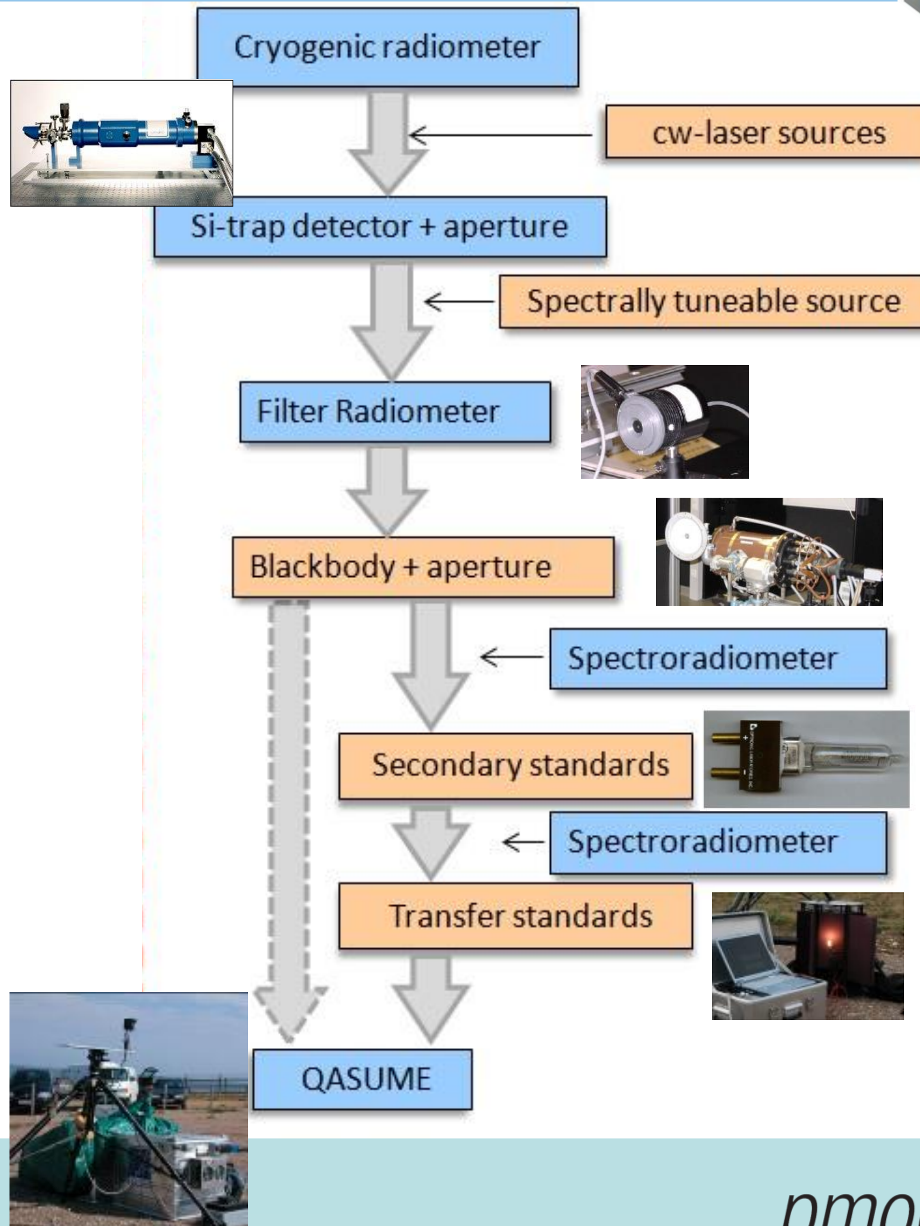
e.g. audit

(5) **reference to SI units;** the chain of comparisons must, where possible, end at primary standards for the realisation of the SI units;

(6) **calibration intervals;** calibrations must be repeated at appropriate intervals; the length of these intervals will depend on a number of variables (e.g. uncertainty required, frequency of use, way of use, stability of the equipment).

from Traceability of measurement, ILAC-G2: 1994

Traceability chain for spectral irradiance $Wm^{-2}nm^{-1}$



Gröbner & Sperfeld, Metrologia, 2006
Hülsen at al., Applied Optics 2016, in Press

QASUME irradiance reference

Based on 7 transfer standards directly calibrated against the primary irradiance normal of the Physikalisch-Technische Bundesanstalt (PTB), in Germany.

PTB

Primary standard PTB

Transfer standard 1000 W FEL lamp

Transfer standard 1000 W FEL lamp

Transfer standard 1000 W FEL lamp

…

WCC-UV/QASUME

Portable QASUME irradiance reference

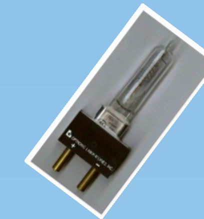
250 W portable lamp

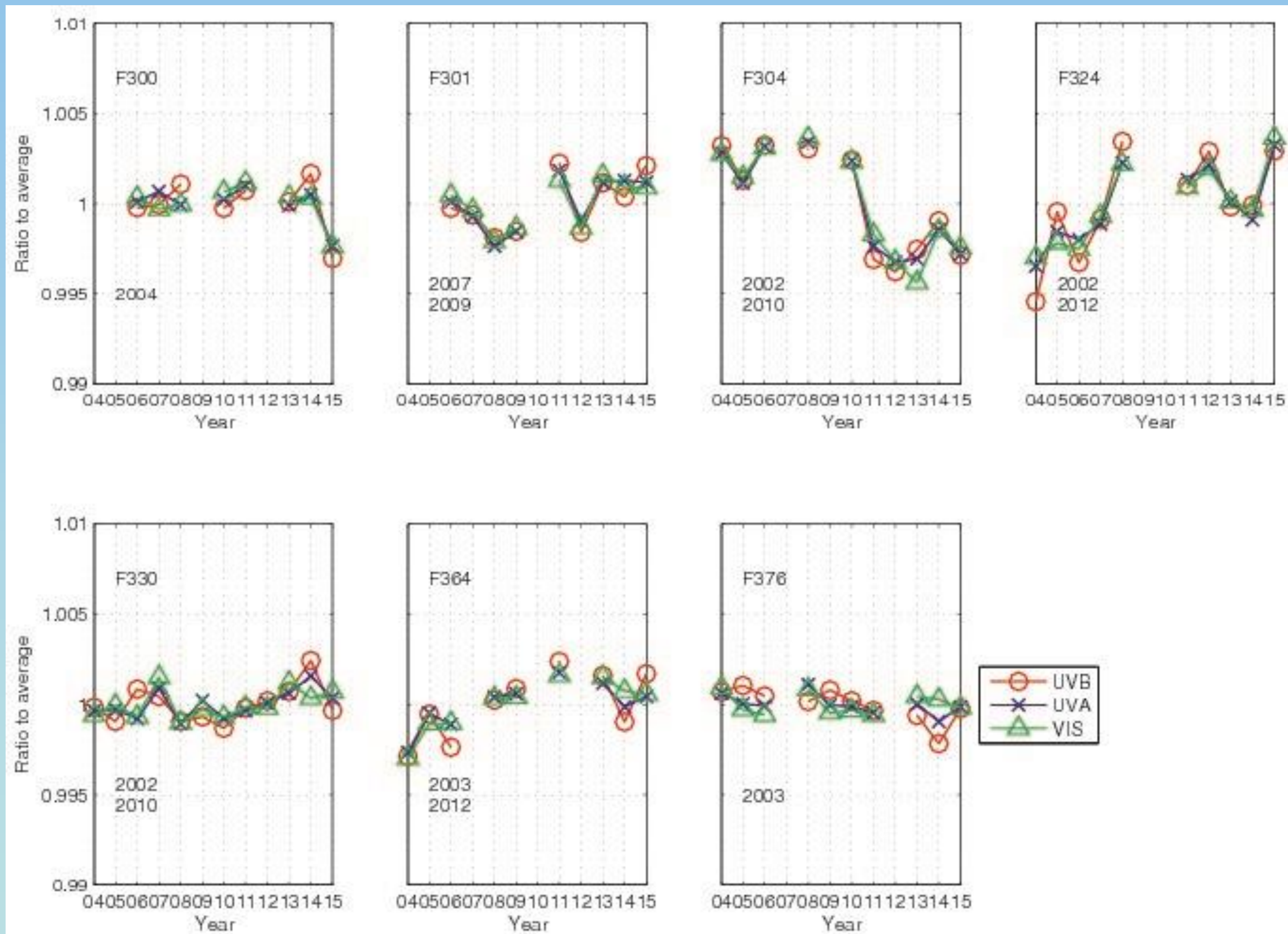
250 W portable lamp

250 W portable lamp

⋮

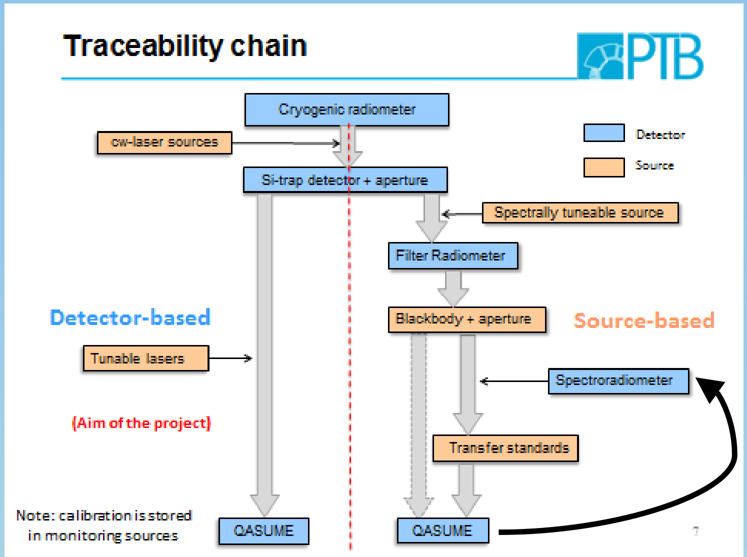
QASUME irradiance reference stability: 2004 to 2015



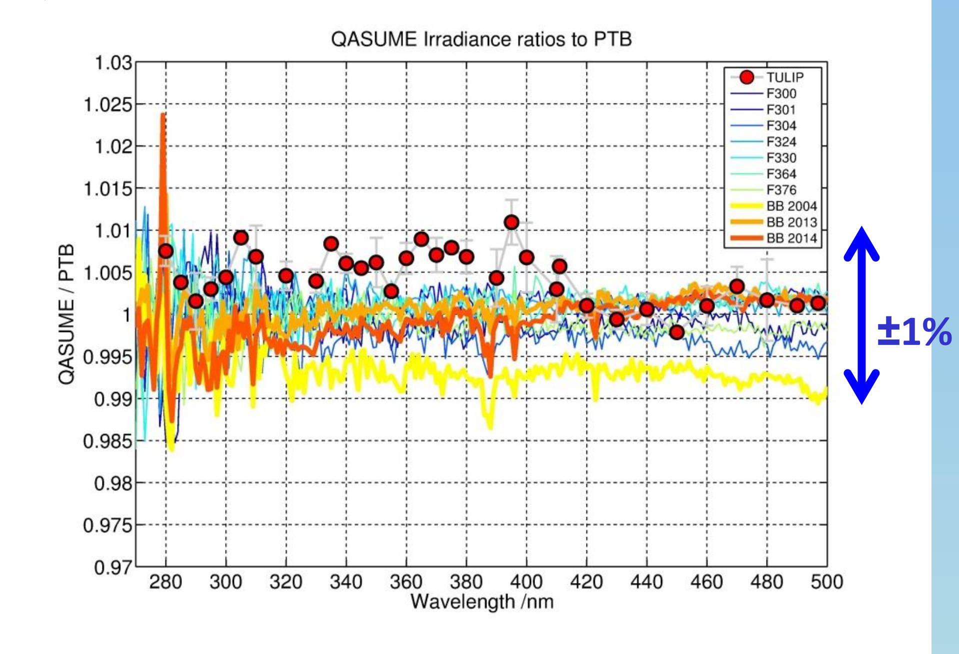


EMRP
European Metrology Research Programme
Programme of EURAMET
The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union

Validation of the QASUME irradiance reference at PTB



QASUME Validations at PTB since 2004



Tuneable Laser facility TULIP

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Quality Assurance of spectral solar (UV) measuremens **«out of the lab»**

A spectroradiometer is calibrated in the laboratory using VERY different sources compared to the solar irradiance.

How can the quality of the solar measurements be verified?

There is only one Method:

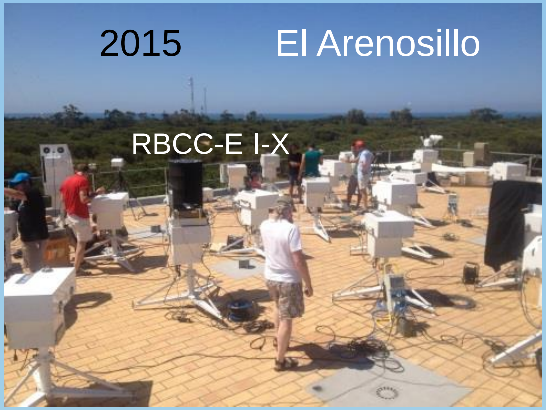
Using a validated reference spectroradiometer and making coincident solar measurements with the test instrument.

European UV Quality Assurance Program

➔ Quality Assurement through intercomparisons (since 2002) and site visits of a designated reference instrument (QASUME)

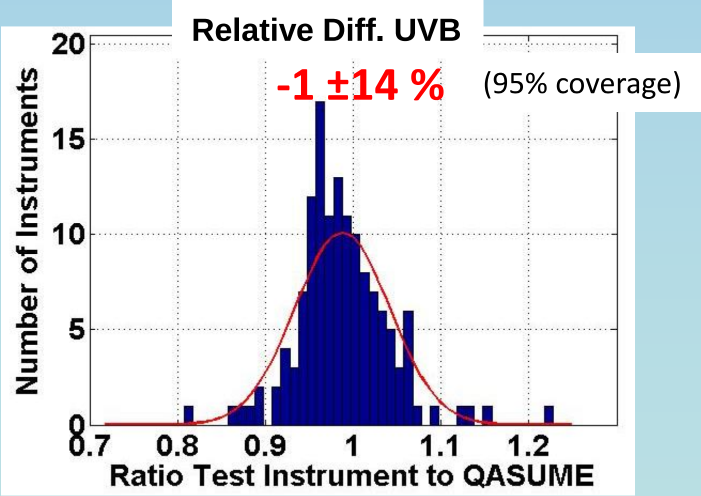
First focused on European stations and ...

... since 2013 worldwide:



QASUME
Age: 15 yr
67 site visits
35 sites
Over 140 spectroradiometer inpercomparisons
1.8 mil km (4.6 ATW)
1.2 mil km (3.0 ATW) EU

QASUMEII since 2015



Gröbner et al., Appl. Opt. 2005
Gröbner et al., Metrologia, 2006

http://www.pmodwrc.ch/euvc/euvc.php?topic=qasume_audit

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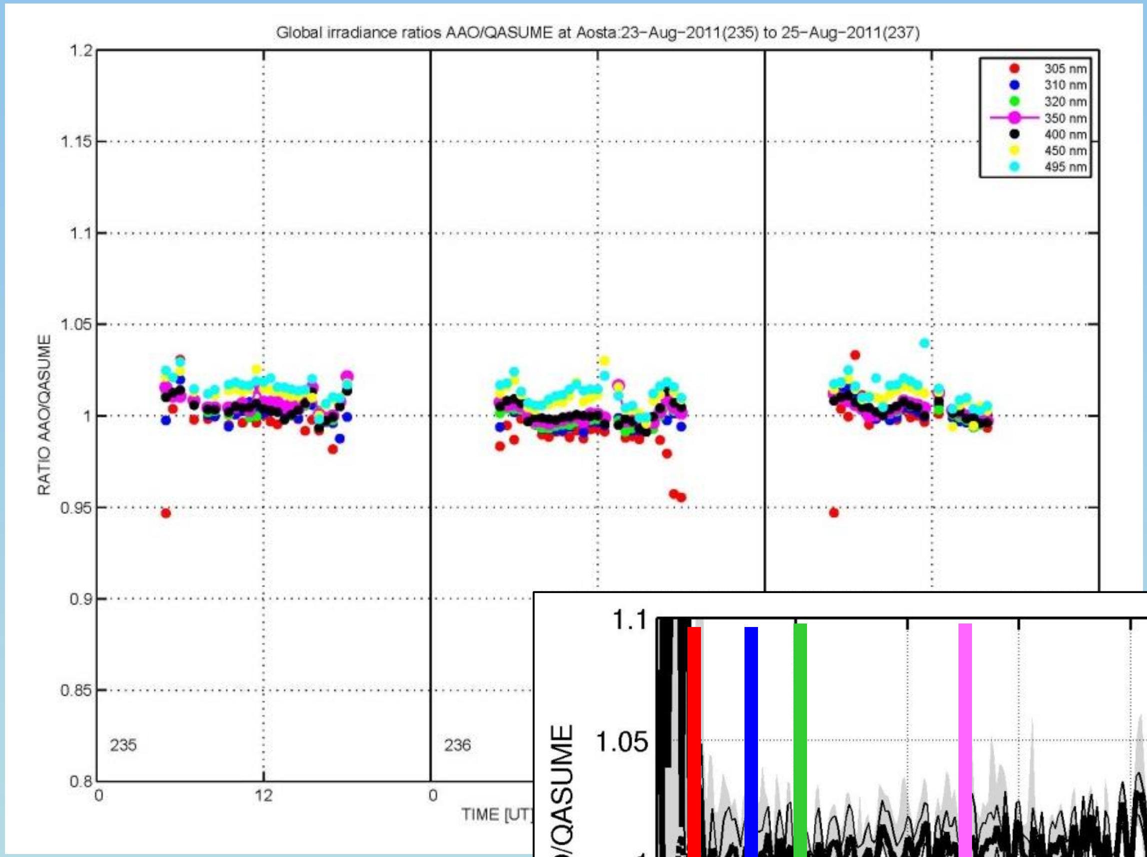
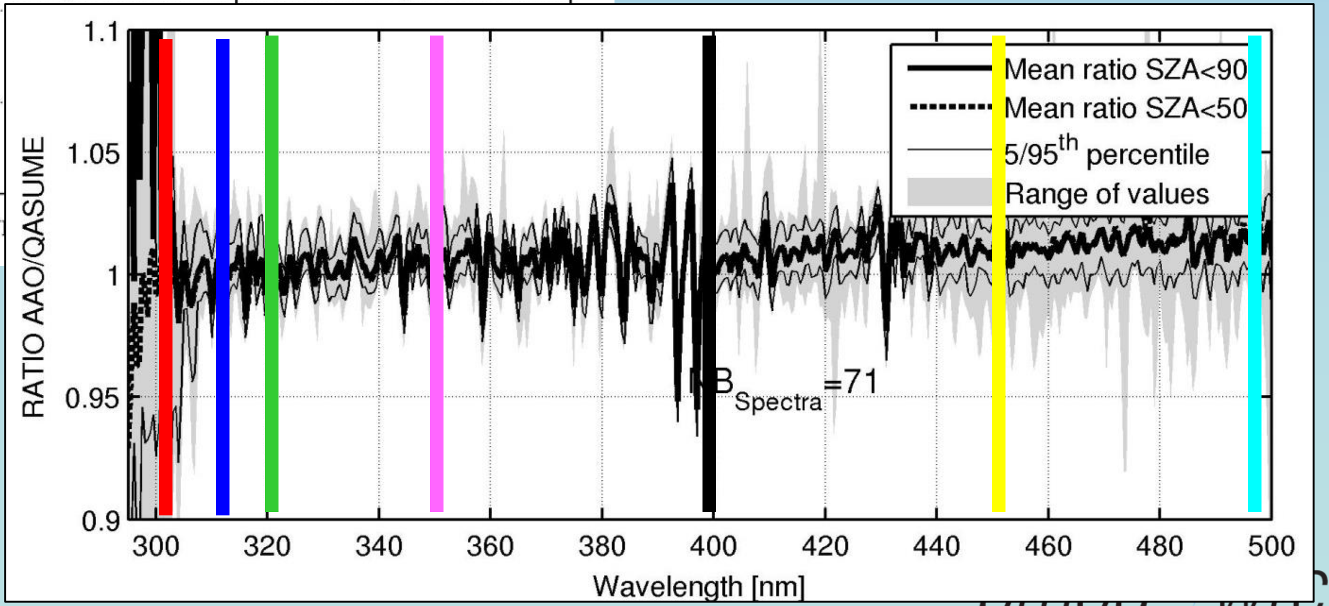
Results – The ideal case

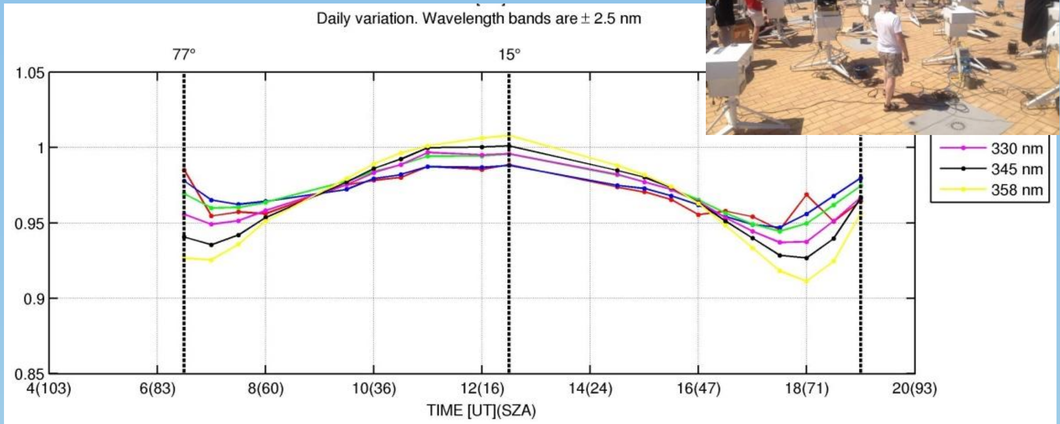




And what we often see…

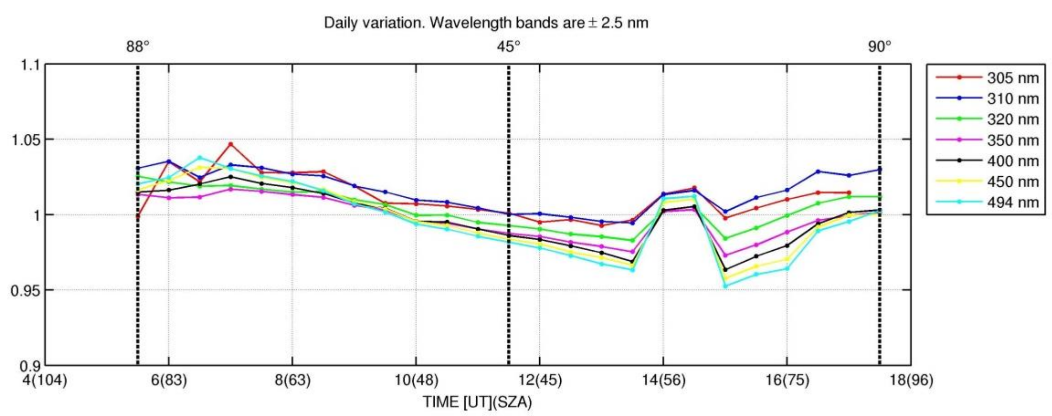
Cosine error

- Visible by the symmetric diurnal change in the ratio of the instrument to the reference
- This error is caused by a non-ideal input optic and is a function of the solar zenith angle and the wavelength.



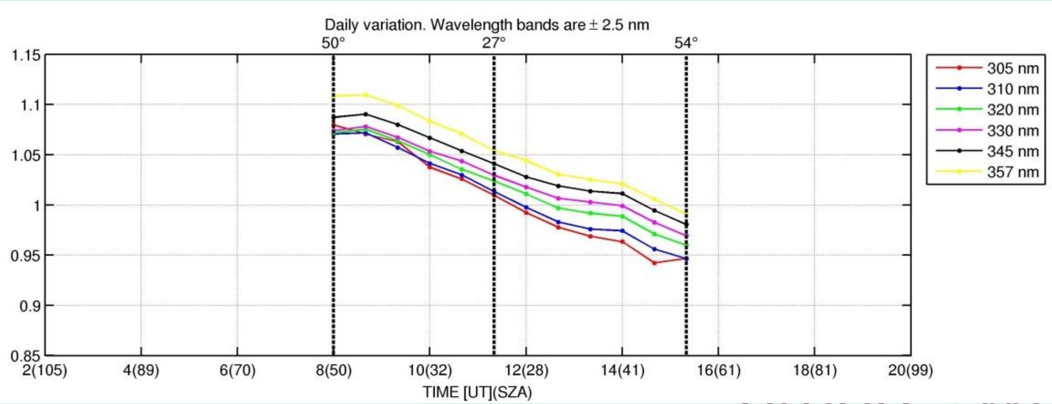
Azimuth error

- Caused by a misalignment of the fiber within the input optic.
- The error could be detected by turning the input optic of the test instrument by 180° for a few scans.

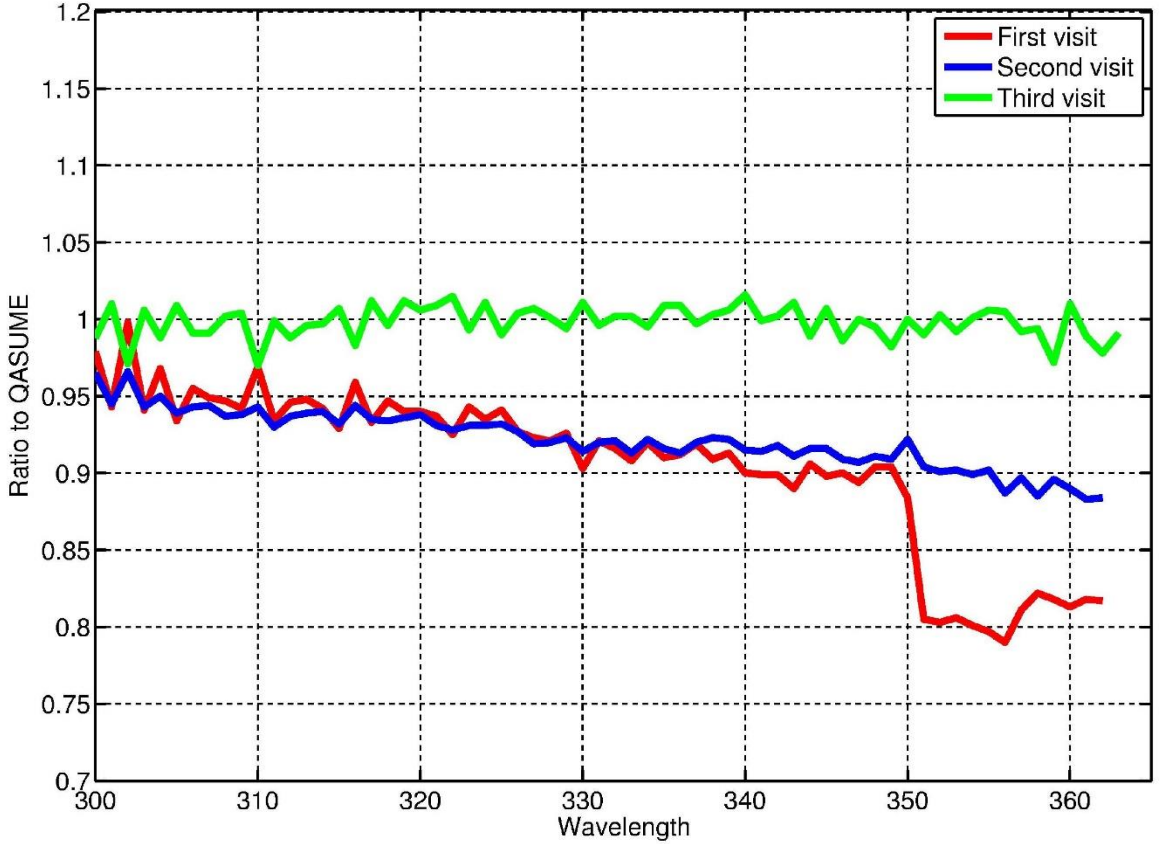


Temperature dependence effect

- Most common for Brewer spectrophotometers.
- A correction algorithm can reduce this diurnal variability.



Improvements due to repeated QASUME site audits



1) First site audit

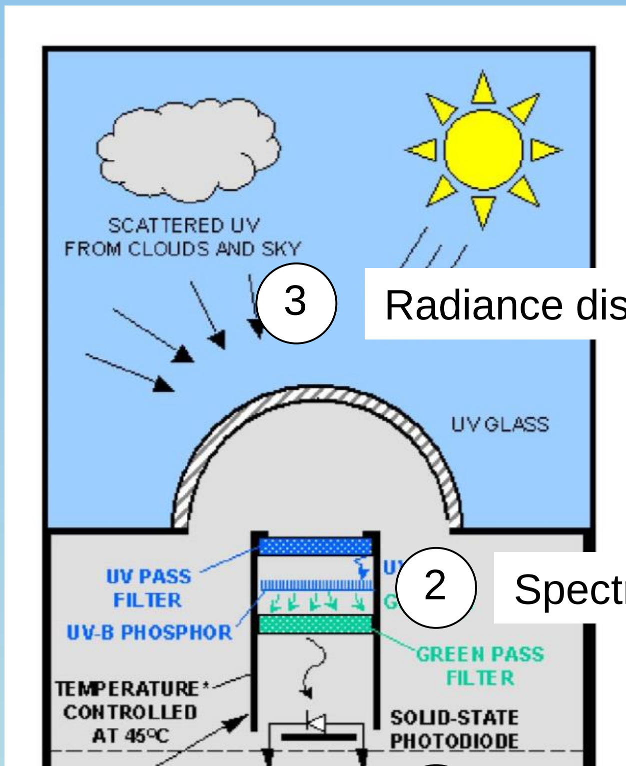
2) Wavelength drive hardware problem corrected

3) Irradiance reference traceable to EUVC+ new entrance optic (shaped diffuser)

Outline

- What is traceability?
- **Calibration and Quality Assurance** of
  - Solar Spectroradiometers
  - Broadband Filter Radiometers
- Uncertainty
- Conclusion

UV broadband filter radiometer



3 Radiance distribution

2 Spectral Responsivity

current 1 Sensitivity

Radiometric equation:

$$E_{CIE} = (U - U_{offset}) \cdot C \cdot f_n(SZA, TO_3) \cdot Coscor$$

1 2 3

Hülsen & Gröbner et al., Appl. Opt. 2007

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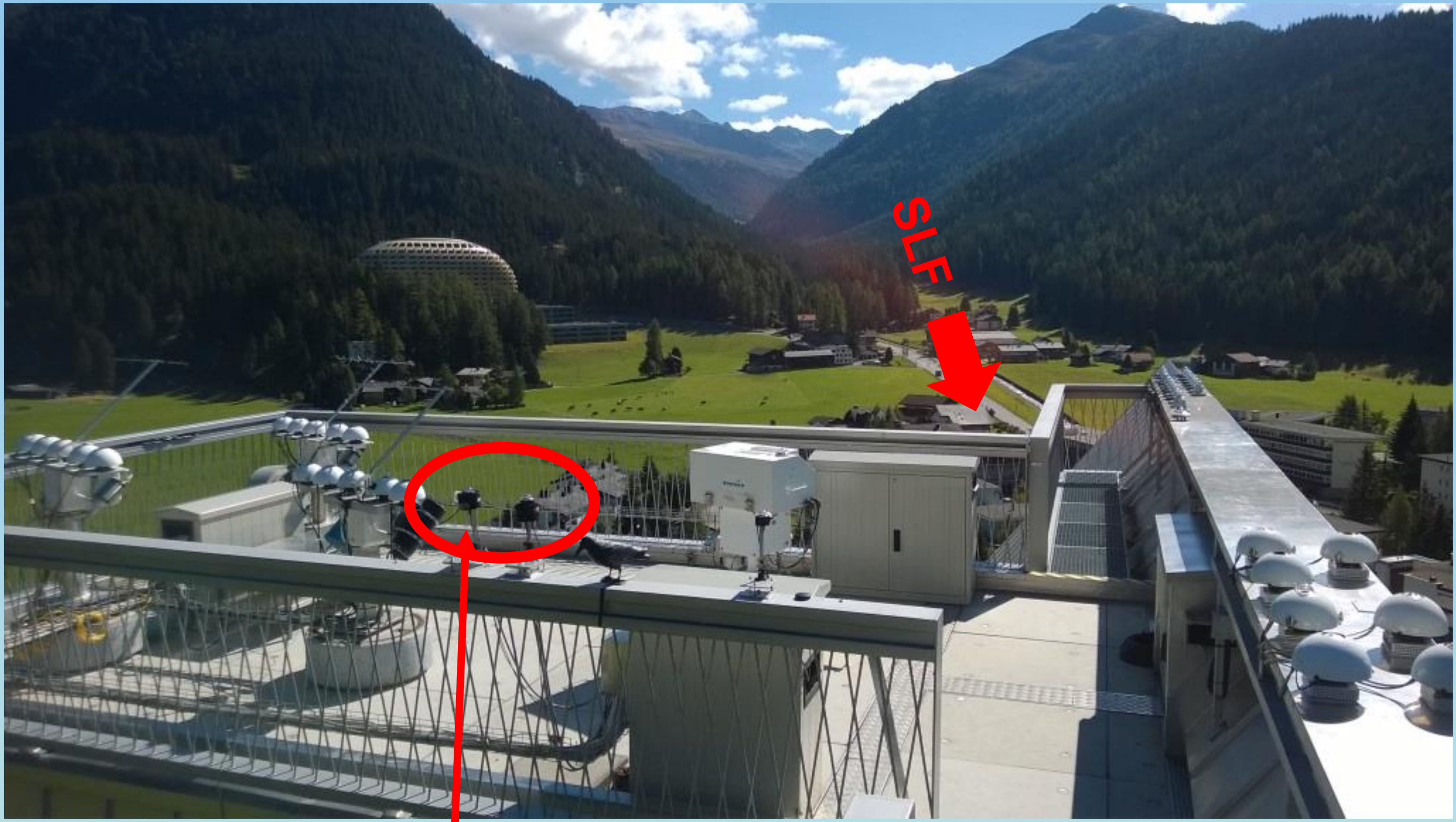
1

Roof Platform of PMOD/WRC



Reference Spectroradiometer

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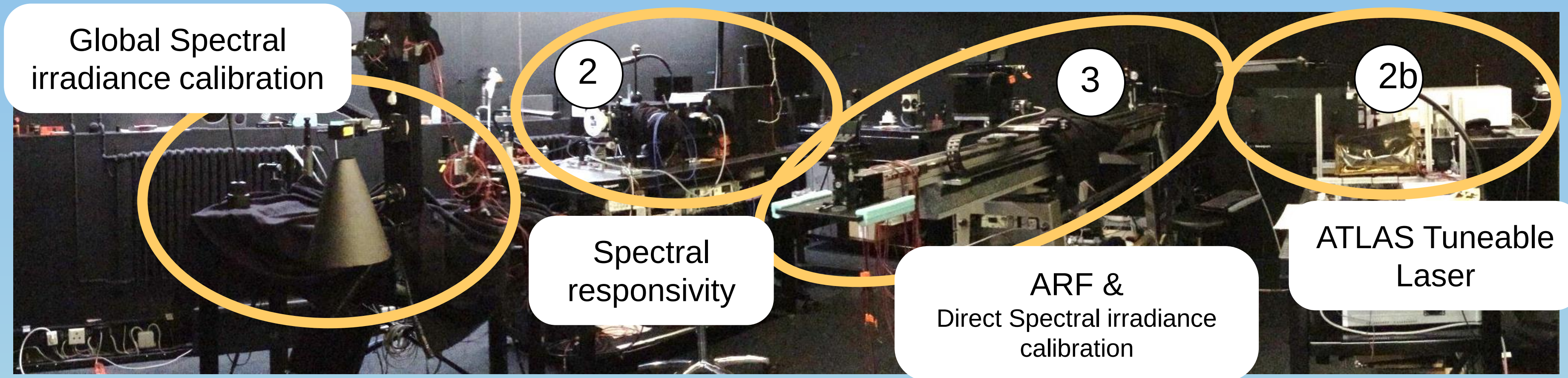
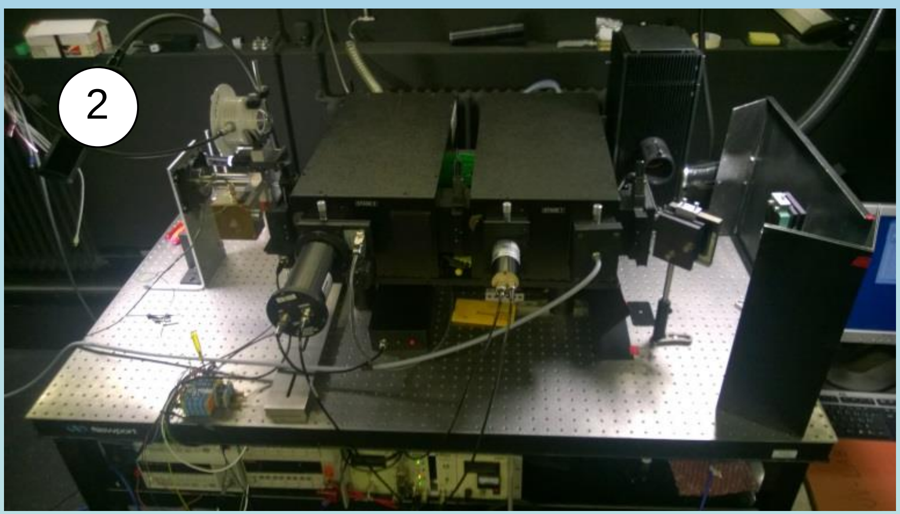
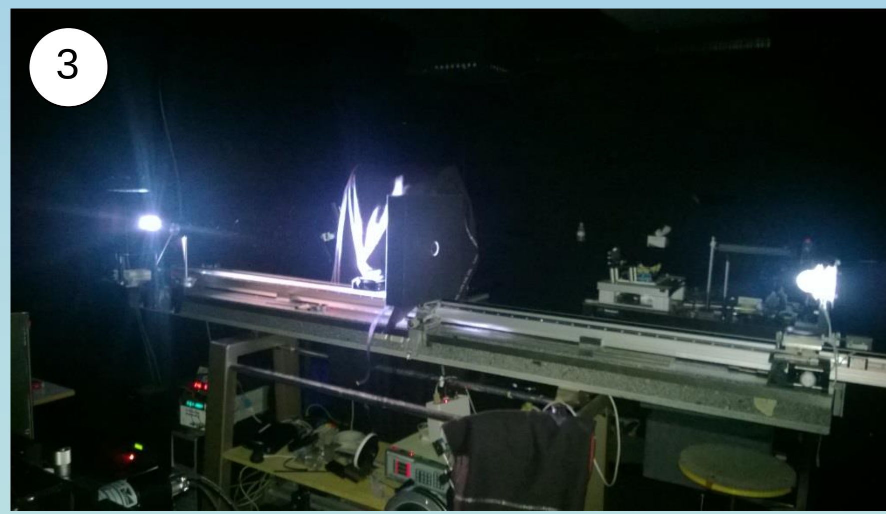
The optical laboratory of PMOD/WRC





Spectral Response Setup



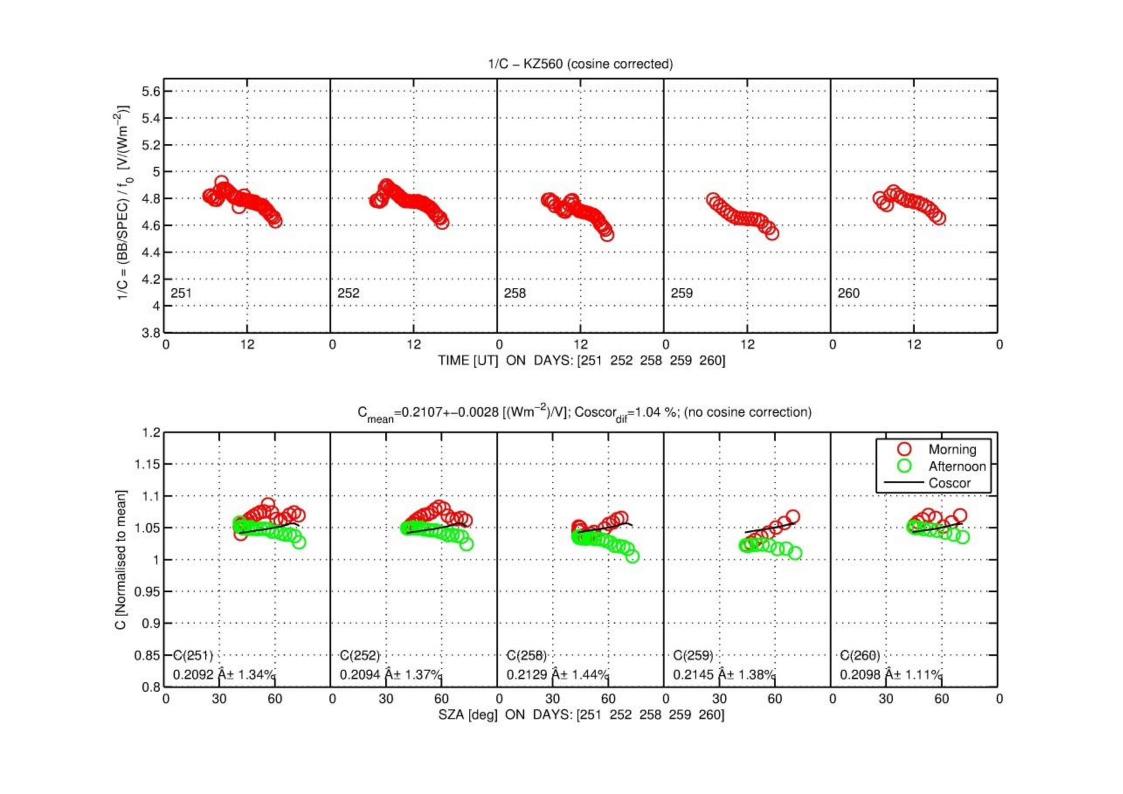
Angular Response Setup

1 Broadband filter Radiometer calibration

$$C_i = \frac{E_D}{U_D - U_{offset}}$$

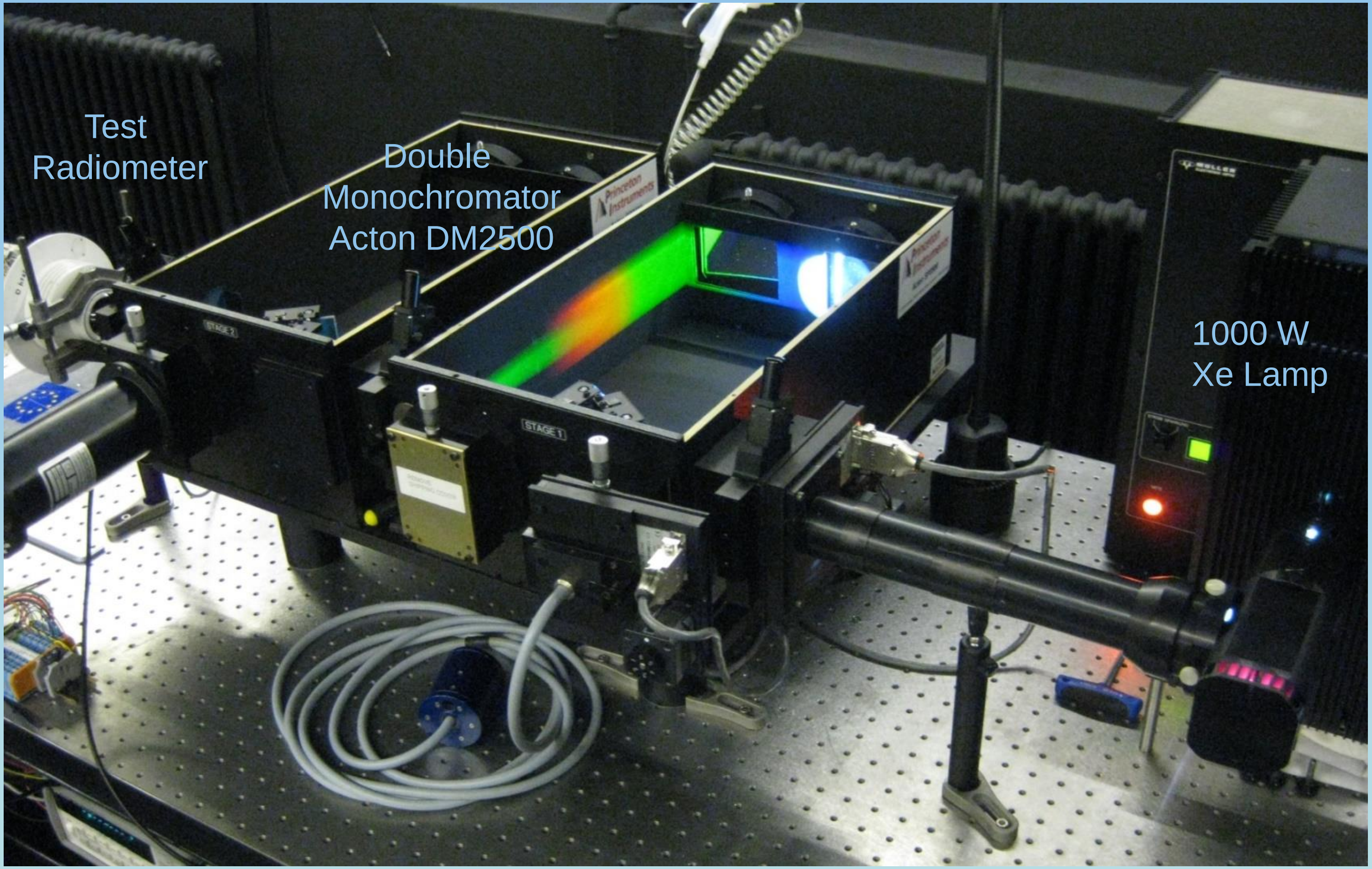
where E_D is the spectral solar irradiance weighted with the instrument spectral response:

$$E_D = \int SRF_{inst}(\lambda) \cdot Spec(\lambda) d\lambda$$



2

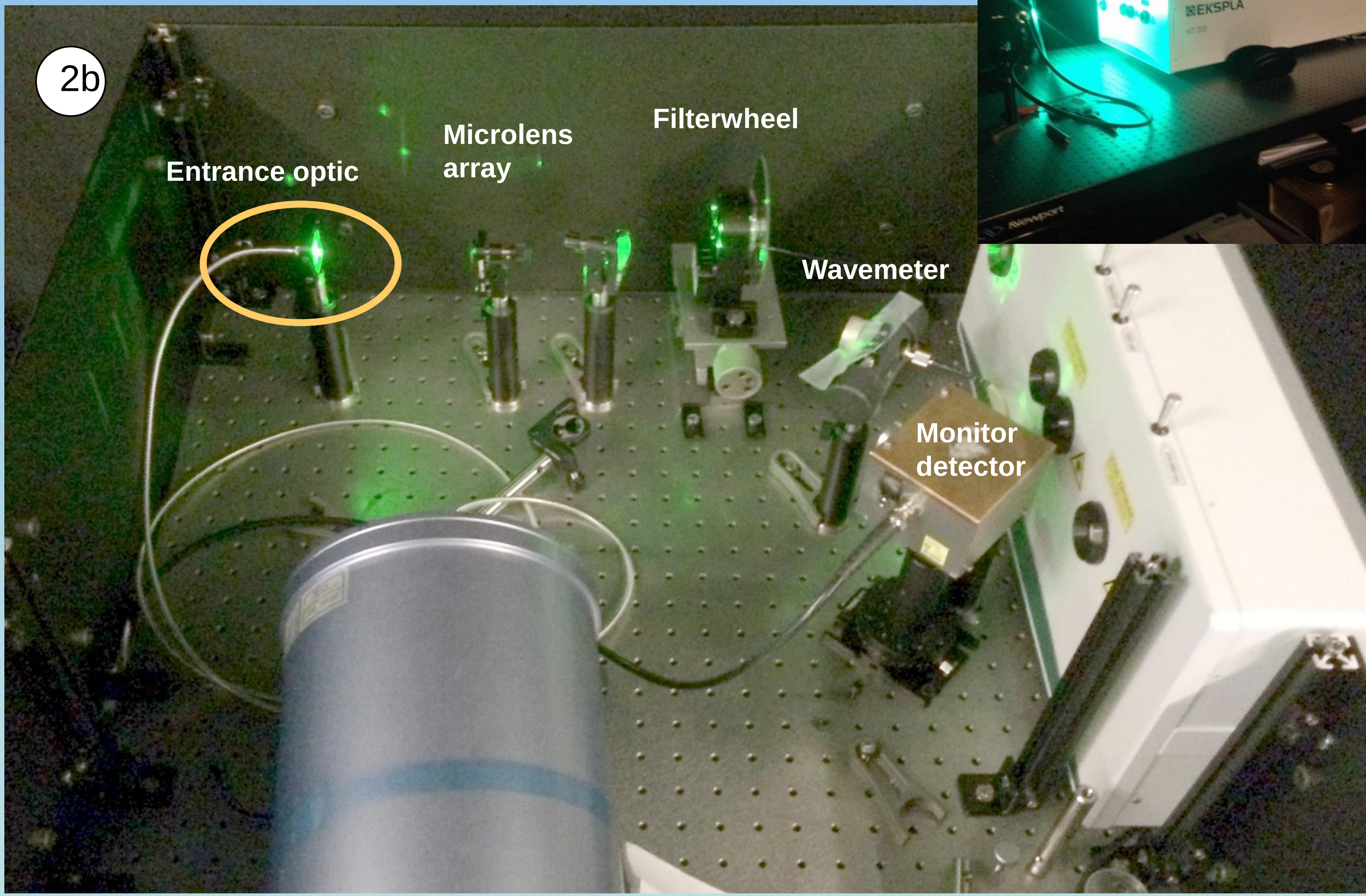
The Spectral Response Facility



Illumination of the radiometer
WL= 250 – 1100 nm

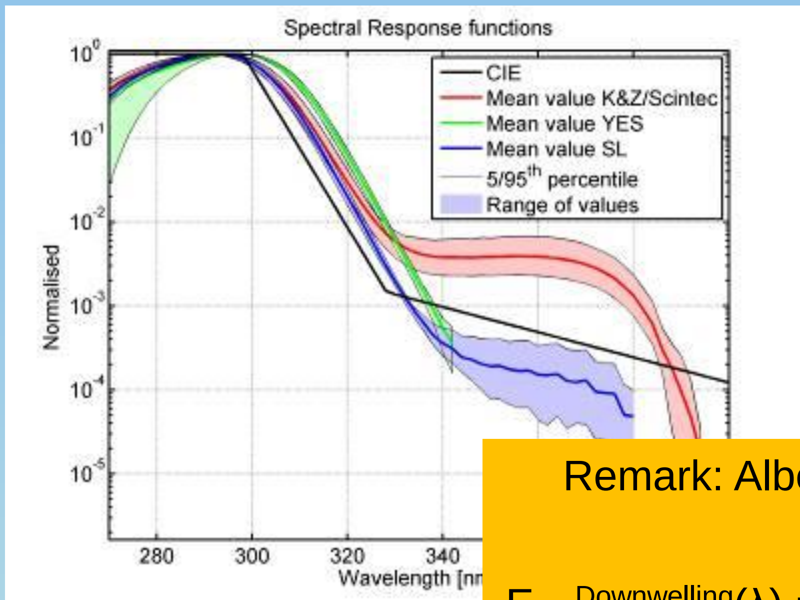
Relative spectral responsivity measurement

ATLAS Tuneable laser facility



The ATLAS project tuneable laser setup from EKSPLA

2 Conversion Function f



The function **f** converts from detector weighted solar irradiance to erythemal weighted irradiance using radiative transfer calculations:

$$f(SZA, TO_3) = \frac{\int CIE(\lambda) E_{rad}(SZA, TO_3, \lambda) d\lambda}{\int SRF(\lambda) E_{rad}(SZA, TO_3, \lambda) d\lambda}$$

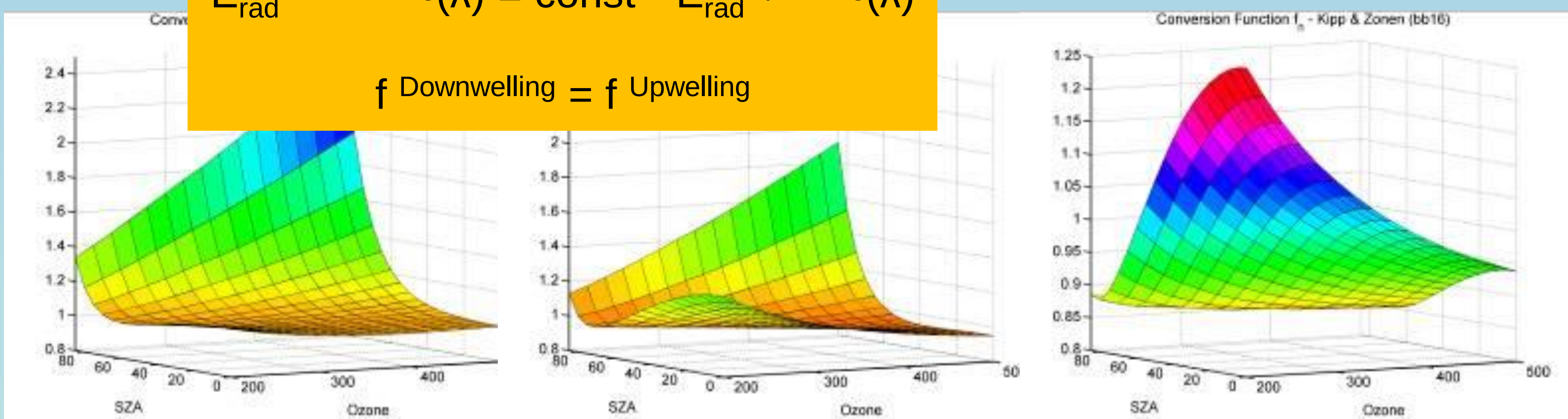
E_{rad} = Set of solar spectra calculated with a radiative transfer model

…ctrum

Remark: Albedo Measurements

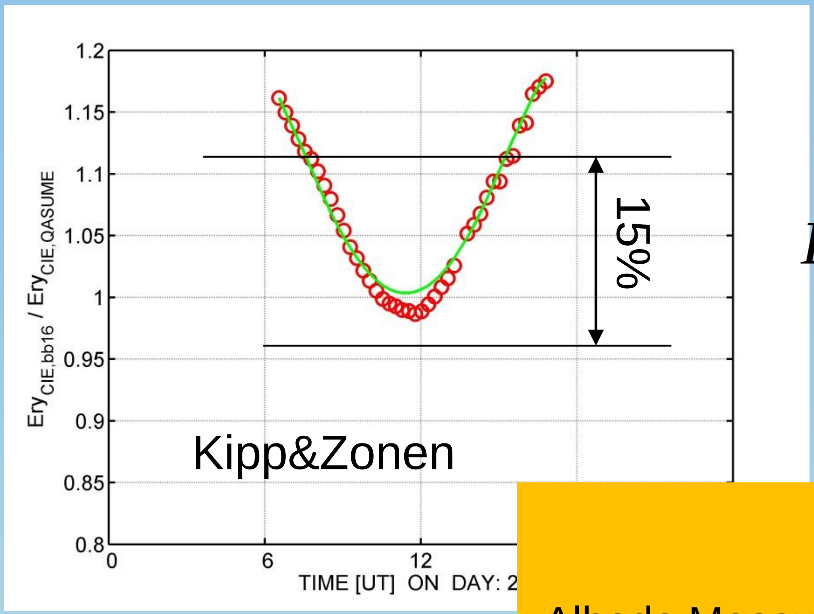
$E_{rad}^{Downwelling}(\lambda) = const * E_{rad}^{Upwelling}(\lambda)$

$f^{Downwelling} = f^{Upwelling}$

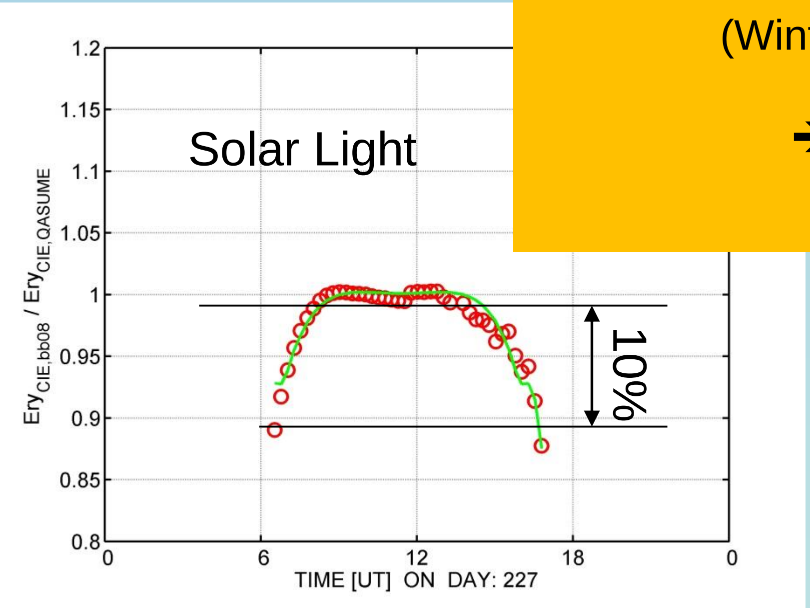


f is normalised at SZA = 40 and TO_3 = 300)

② If the Conversion Function f_n is not used



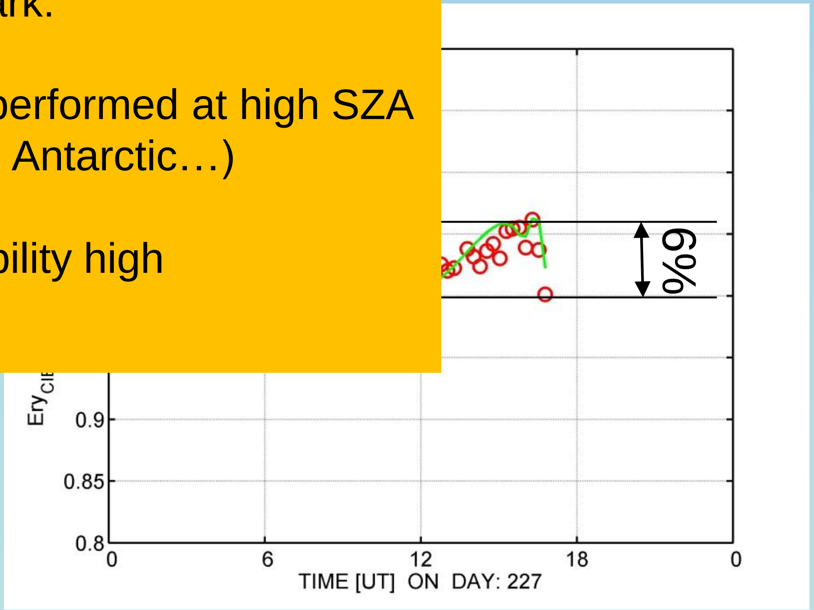
$$E_{CIE} = (U - U_{offset}) \cdot C \cdot f_n(SZA, TO_3) \cdot Coscor$$



Remark:

Albedo Measurements performed at high SZA (Winter, Arctic, Antarctic…)

➔ f_n variability high



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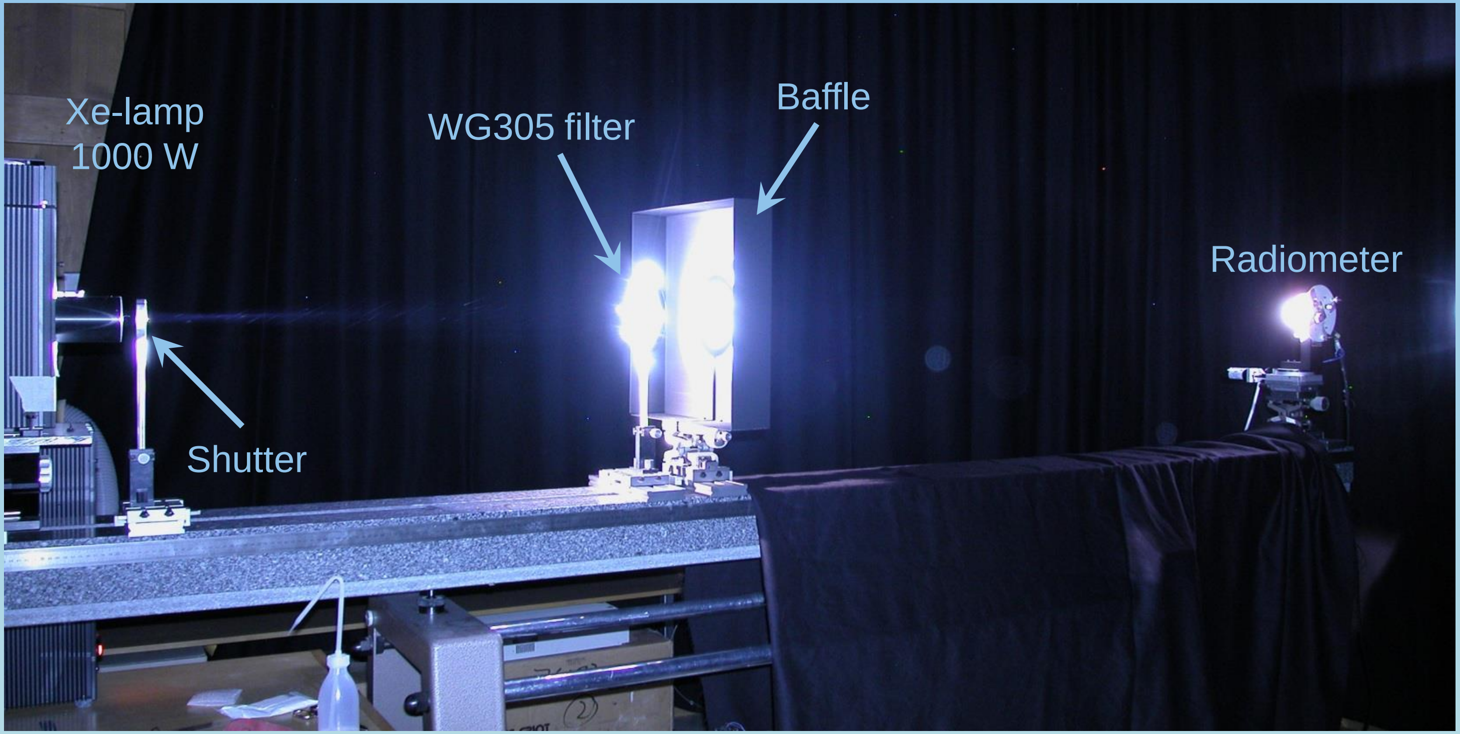
3

The Angular Response Facility



4 characterised planes

Normalisation at normal incidence

Alignment precision: < 0.1°

Homogeneity of the light in the 25×25×25mm^3 cube around the centre of the radiometer: < ± 1%

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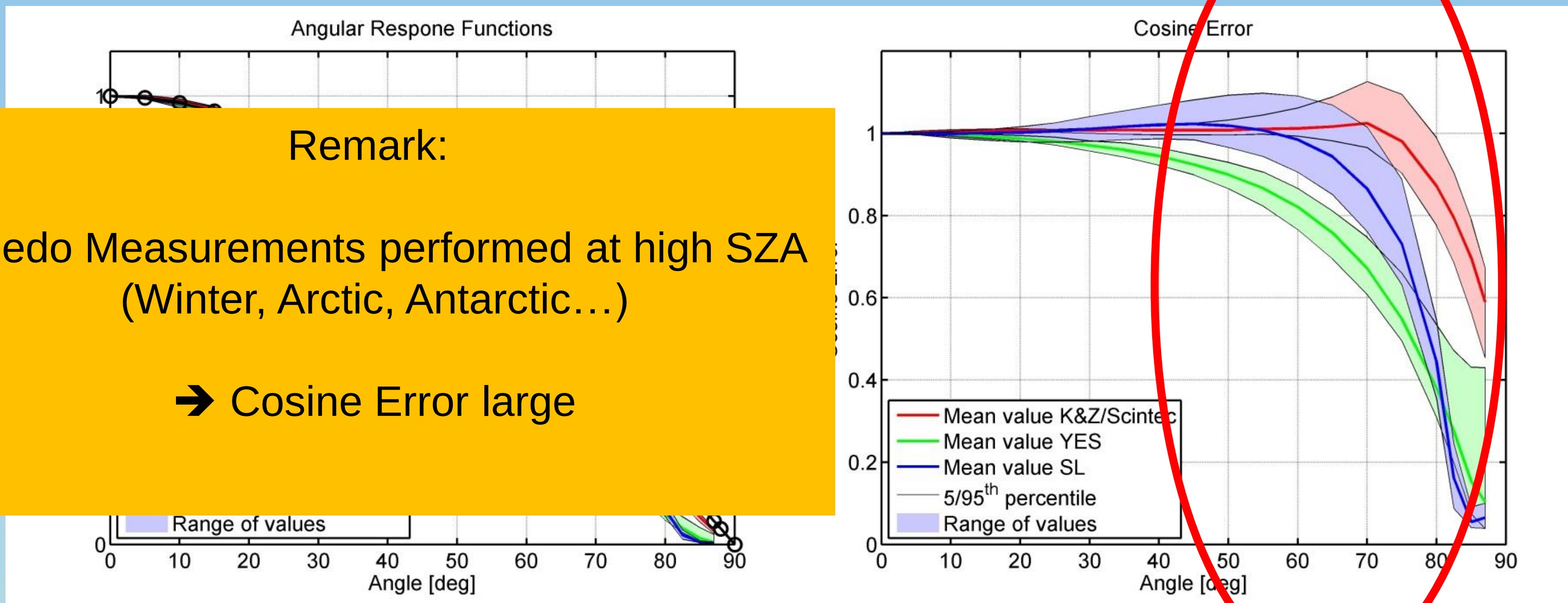
3

Angular Response Function of various Instrument types with Cosine Diffusers



Remark:

Albedo Measurements performed at high SZA (Winter, Arctic, Antarctic…)

➔ Cosine Error large

The expanded relative uncertainty (k = 2):
Less than 4 % for zenith angles smaller 80°

Cosine error = Deviation from ideal cosine response

Input Optic for UV➔VIS➔IR

1) Diffuser Material become transparent for longer wavelength
2) Integrating spheres

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1

Cosine Correction Function

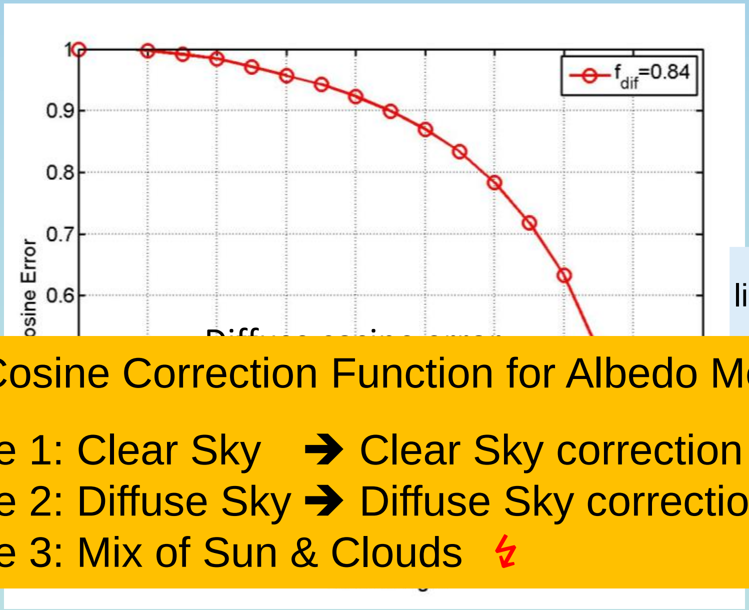
Principle

From the laboratory measurements of the angular response function ARF(Θ), we determine:

1) Diffuse cosine error f_{dif}
2) Clear sky global cosine error factor f_{glo} using radiative transfer calculations

$$f_{dif} = 2 \cdot \int_0^{pi/2} ARF(\theta)\sin(\theta)d\theta$$

$$f_{dir} = ARF(\theta)/\cos(\theta)$$



libRadtran

$$f_{glo} = f_{dir}\frac{E_{dir}}{E_{glo}} + f_{dif}\frac{E_{dif}}{E_{glo}}$$

➔ Cosine Correction Function for Albedo Measurements

Case 1: Clear Sky ➔ Clear Sky correction ➔ Downwelling Instrument ✓
Case 2: Diffuse Sky ➔ Diffuse Sky correction ➔ Upwelling Instrument ✓
Case 3: Mix of Sun & Clouds ϟ ➔ **Not needed** ✓

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Calibration of a Spectroradiometer for global (UV) irradiance measurements

- Angular response of entrance optic (diffuser)
- Spectral responsivity
- Wavelength dispersion relation
- Spectral resolution
- Temperature dependence
- Linearity
- Long-term stability
- Straylight from other wavelength with higher intensities (e.g. VIS and IR)
- …
- …

Calibration of a Spectroradiometer for global (UV) irradiance measurements

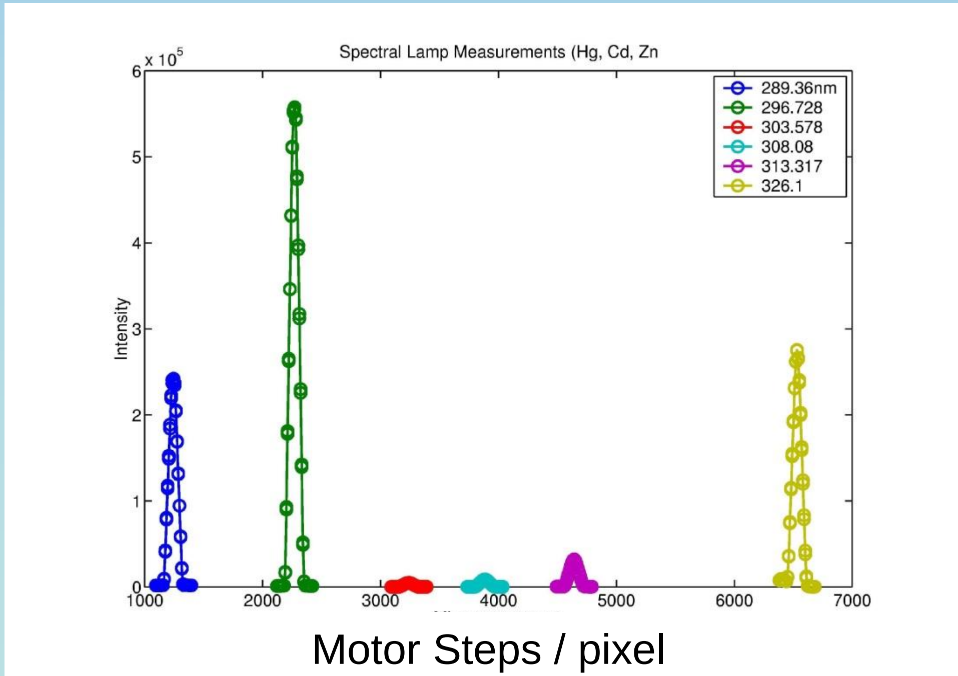
- Angular response of entrance optic (diffuser)
- Spectral responsivity (Lamp Calibration)
- Wavelength dispersion relation
- Linearity
- Straylight from other wavelength with higher intensities (e.g. VIS and IR)
- Spectral resolution
- Temperature dependenceLong-term stability
- …
- …

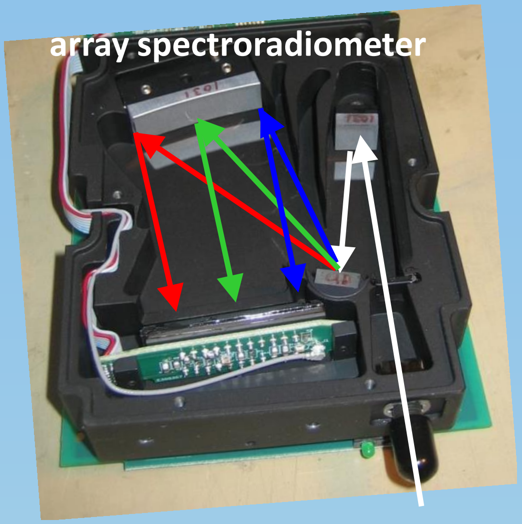
Wavelength scale calibration

The wavelength scale is usually determined from measurements of discrete spectral lines from spectral discharge lamps (for the UV: Mercury, Cadmium, Zinc, Indium)

A smooth function (polynomial) is used to describe the relation between the grating angle / detector pixel and the wavelength of each spectral line.

$$\lambda = f(motorsteps / pixel)$$





Emission lines:

Mercury	289.360 nm
	296.728 nm
	334.148
Cadmium	313.317
	326.105
	340.365
	349.995
Indium	293.263
	303.936
Zinc	310.836
	303.578
	328.233

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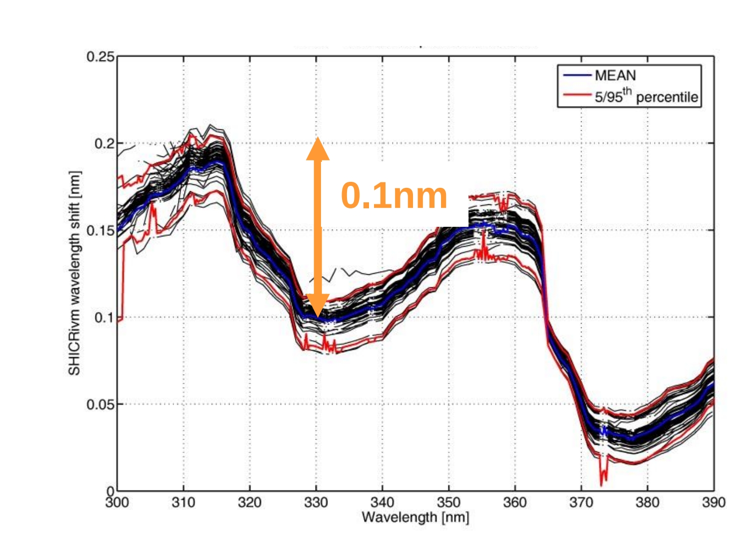
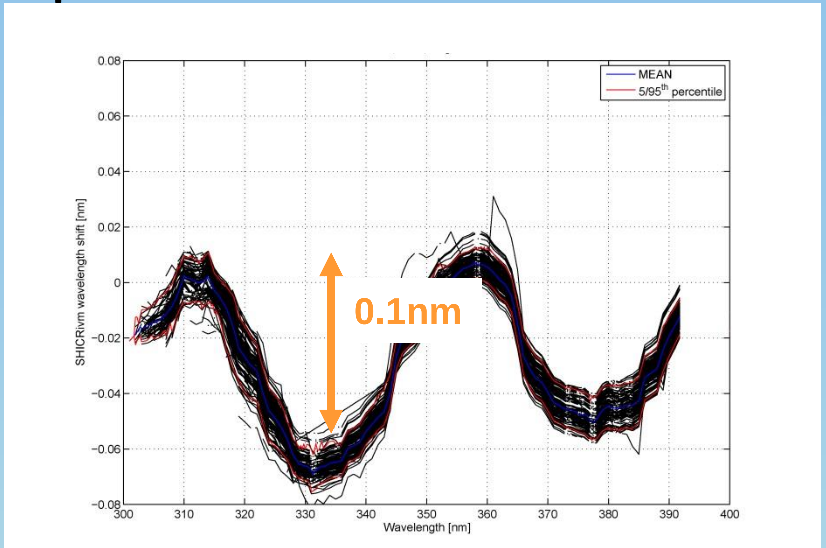
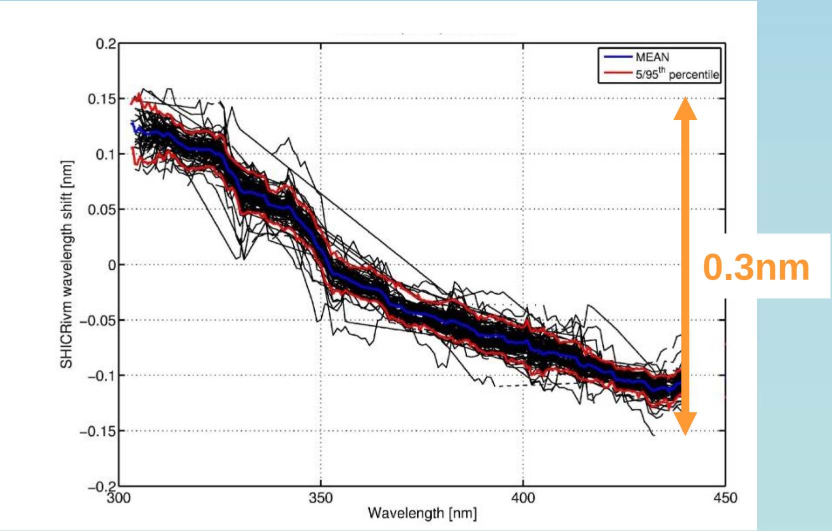
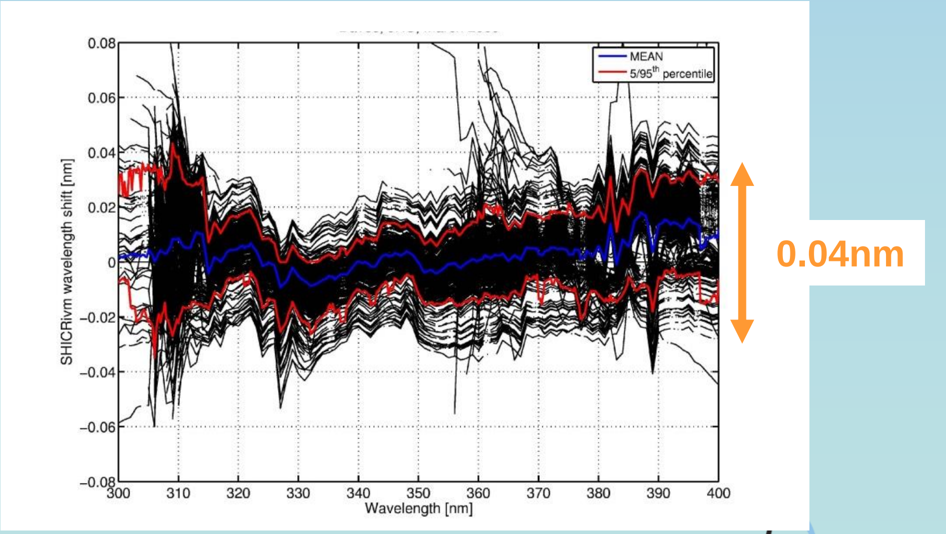
Spectral wavelength error relative to the Fraunhofer lines of the solar spectrum









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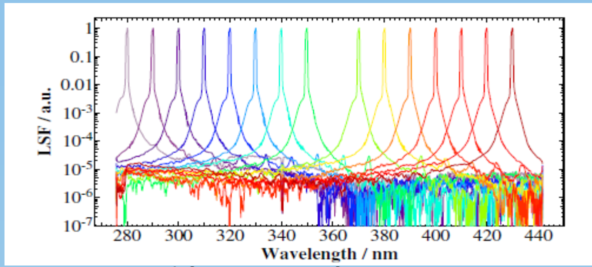
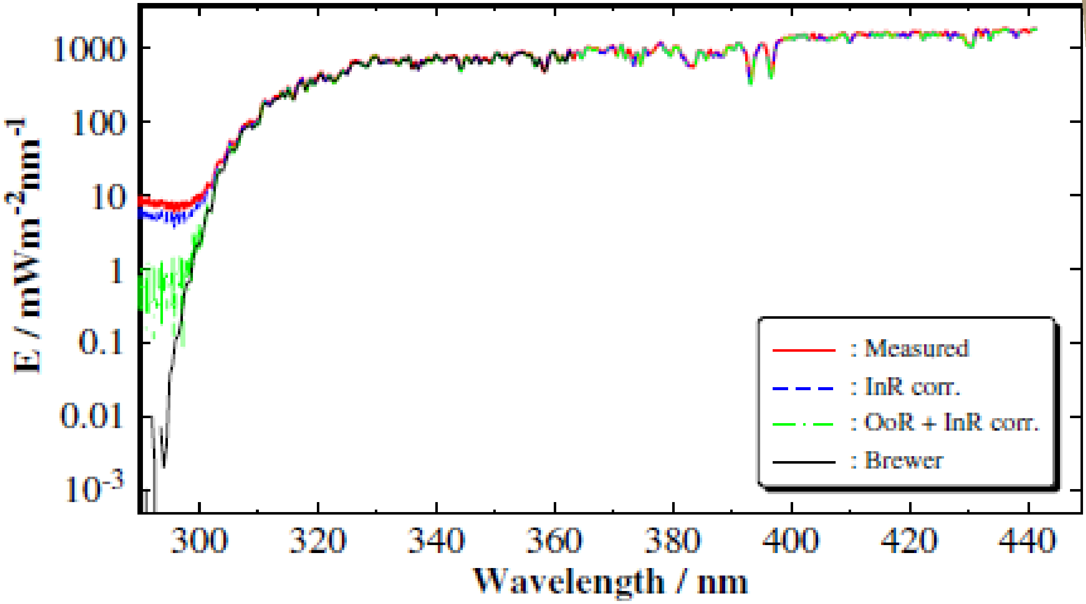
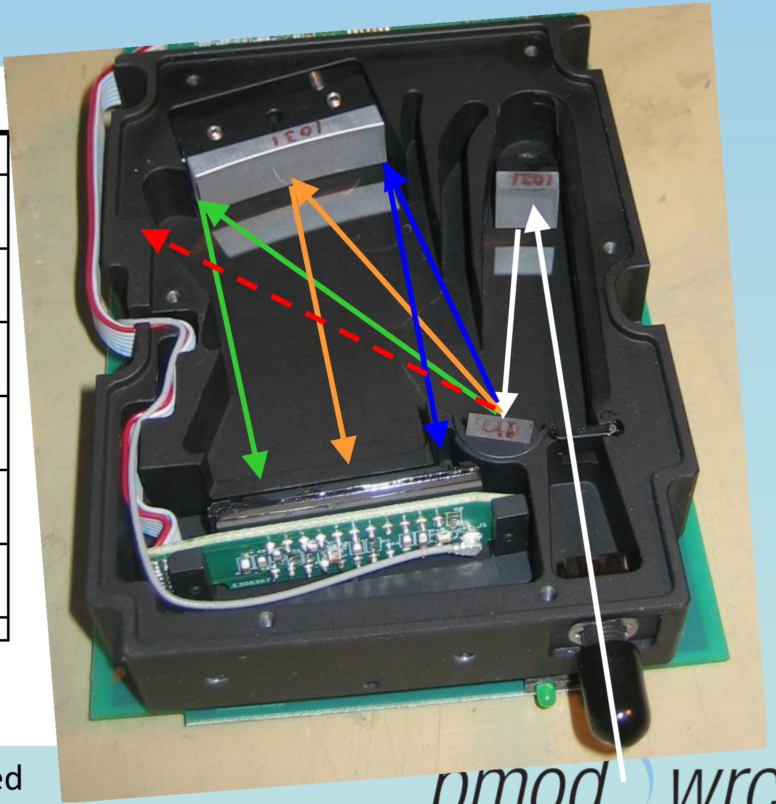
Stray light correction

- For array spectroradiometer
- Stray-Light correction using **tuneable laser setup**
- In-range and out-range correction
- Factor 10 improvement of spectral solar UV irradiance measurements



Line-Spread functions of array spectroradiometer





Solar Spectrum without (red) and with (green) stray light correction applied

pmod wrc

Outline

- What is traceability?
- Calibration and Quality Assurance of
  - Solar Spectroradiometers
  - Broadband Filter Radiometers
- **Uncertainty**
- Conclusion

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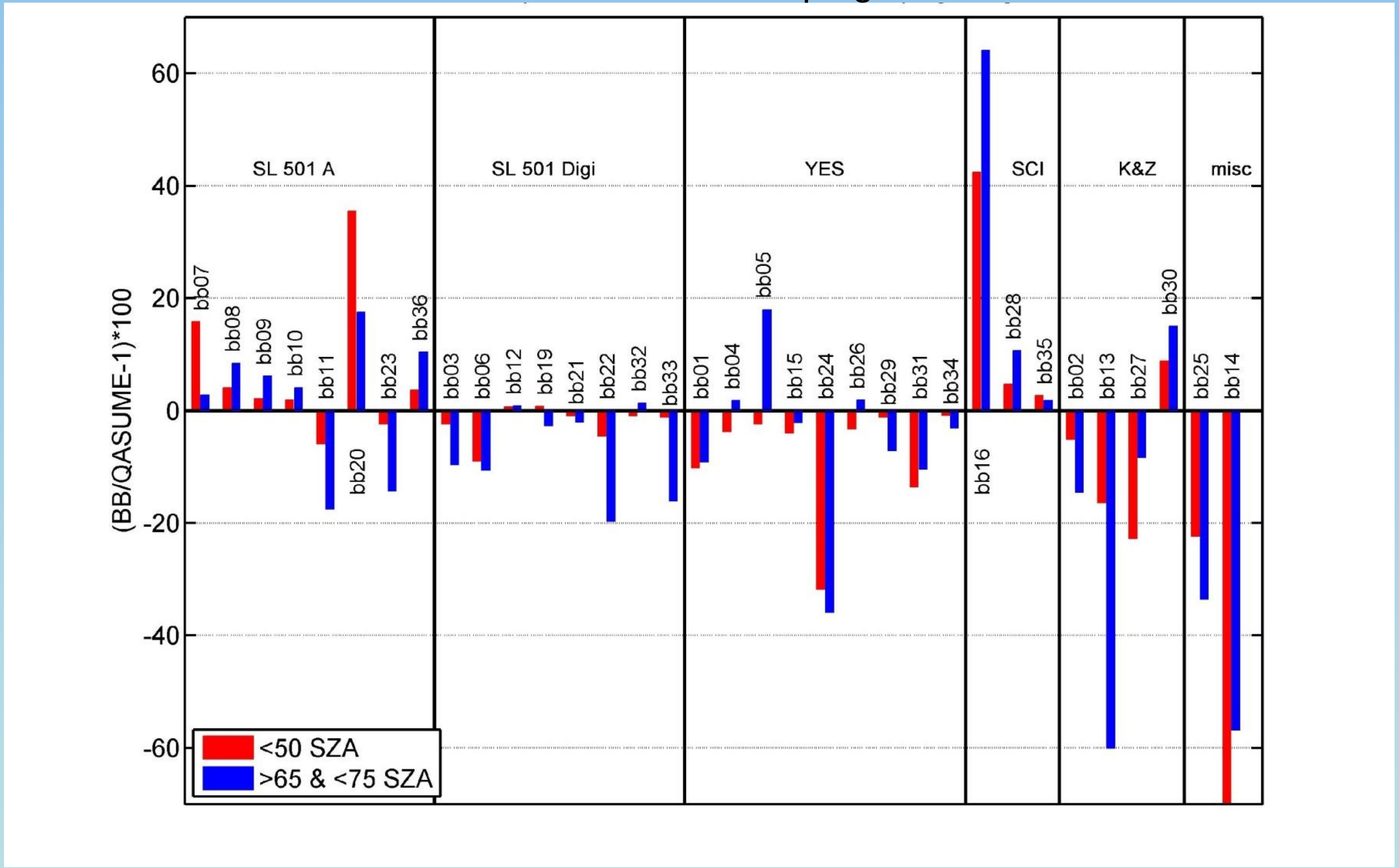
Uncertainty Budget 2016

Uncertainty Parameter	Relative Std Uncertainty %	
	QASUME	QASUMEII
Radiometric calibration	0.55 (before 1.8)	
250 W lamp stability (one year)	0.10 (±0.25%/√2)	
Nonlinearity ... From PMT or PC	0.25	0.17
ND filter transmission	n/a	0.3 (1% full scale, 0.5/√3)
Stability	0.6 (diurnal var. 2%, 1/√3)	0.20
Temperature Dependence, Entrance optic (-0.11%/K)	0.2 (Temp-Stability ±3 K result in 0.33/√3)	
Angular Response (Clear Sky)	1.2 (full scale 4.2%, 2.1/√3) 0.7 (**SZA<65°**) 0.6 (full scale 2.2%, 1.1/√3) (**wl<350nm**)	0.6 (full scale 2%, 1/√3)
Angular Response (Overcast)	0.6 (full scale 2.2%, 1.1/√3)	0.3 (full scale 1%, 0.5/√3)
Repeatability (std noise) (wl>=310nm)	0.2	0.2
Repeatability (std noise) (wl=300nm, SZA=75°)	3.5	3.5
Wavelength shift (after matSHIC) Δwl=0.02 nm	0.1, 0.5 at wl=300 nm	
Combined Uncertainty	1.5 (overcast, SZA<65°: 1.1)	1.0 (overcast, SZA<65°: 0.8)
Expanded Uncertainty (k=2)	3.1 (overcast: 2.2)	2.0 (overcast:1.6) (before 4.8)
Expanded Uncertainty (k=2) 300 nm	7.4	7.3

Hülsen at al., Applied Optics 2016, in Press

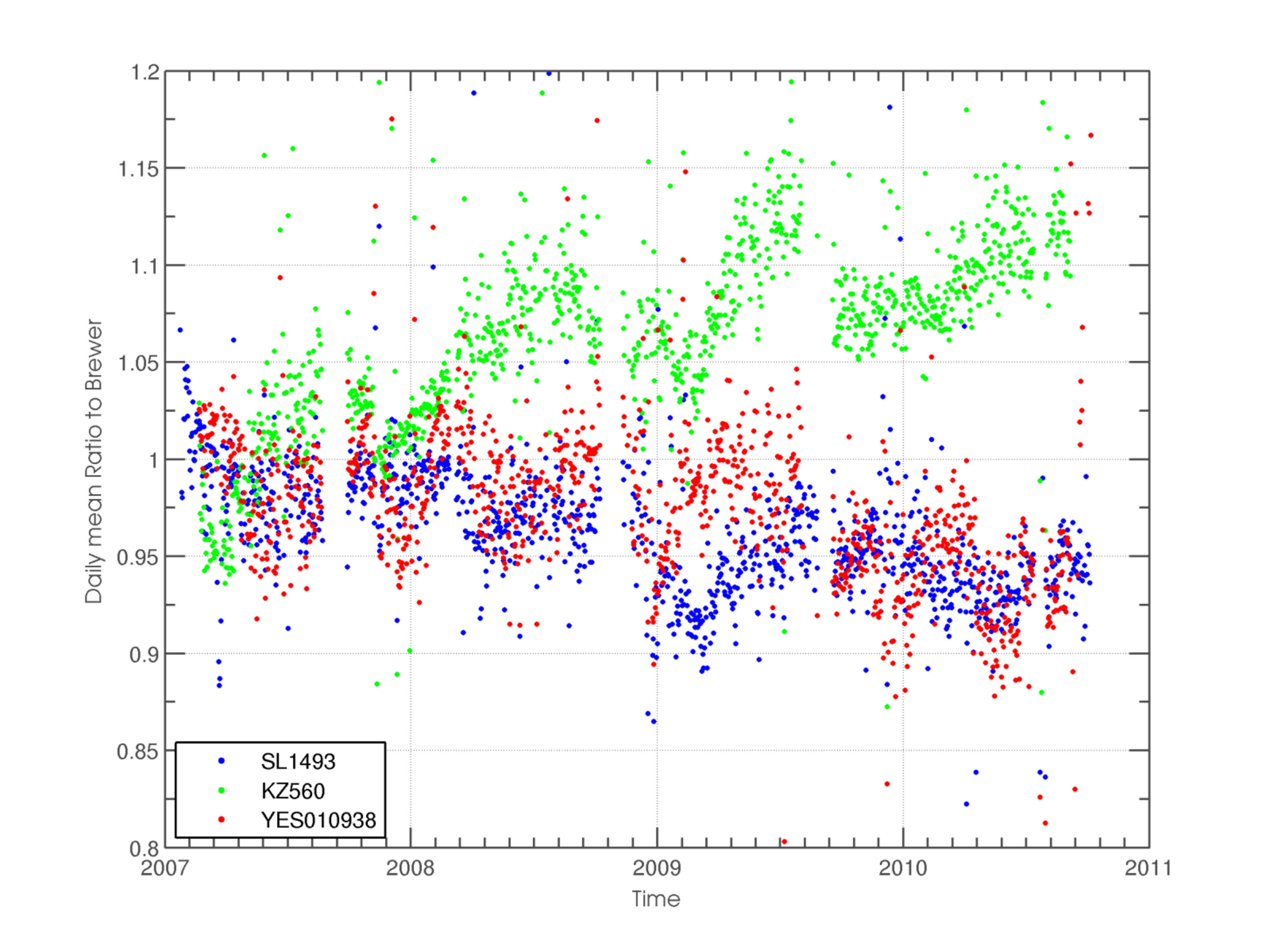
Broadband filter Radiometers Comparison

The PMOD/WRC-COST 726 Campaign – Juli 2006



Report at: www.cost726.org
ftp.pmodwrc.ch/pub/publications/PMOD_COST726_BBreport.pdf

Broadband Long Term Stability

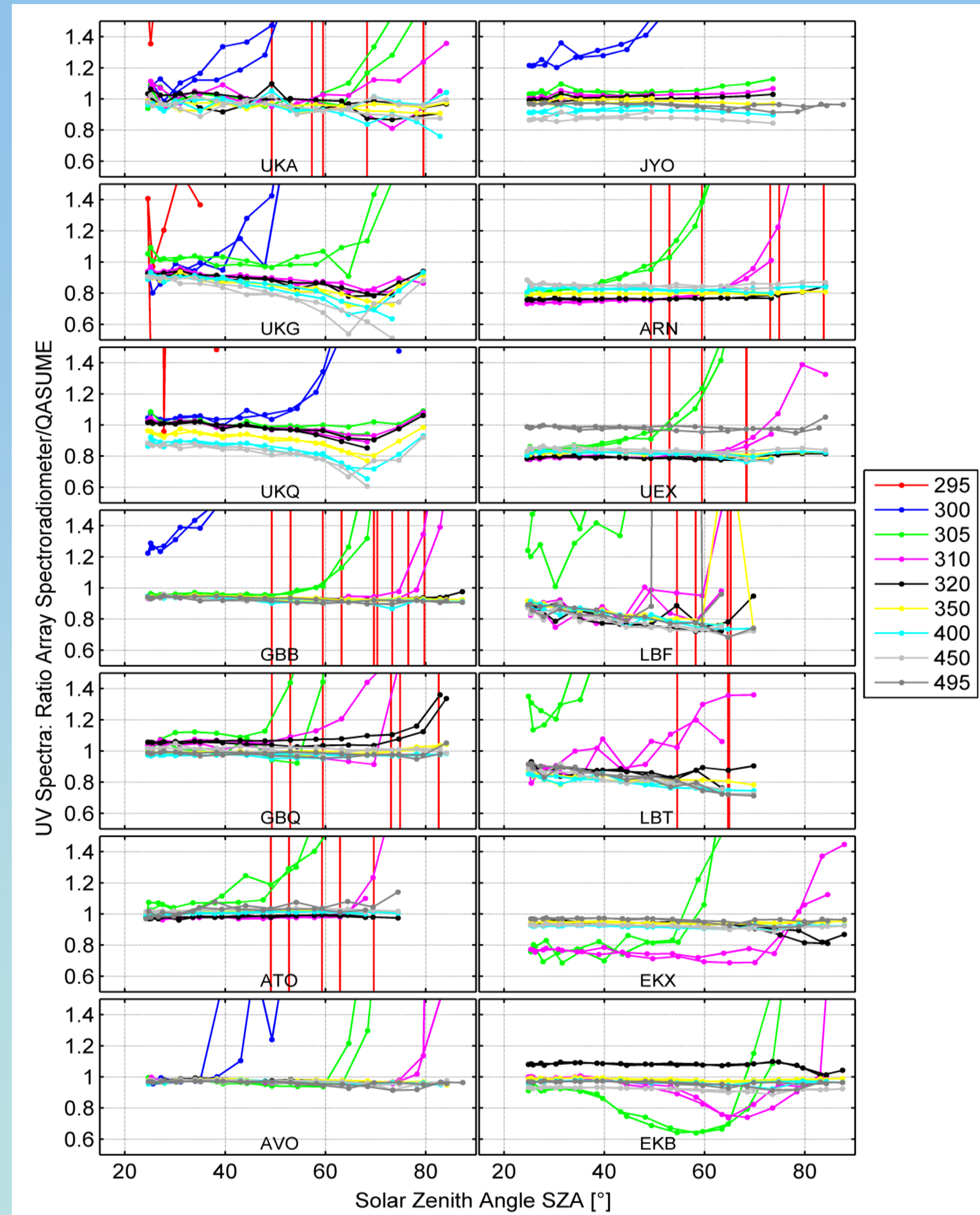


Solar UV Intercomparison

Davos, 7-16 July 2014:

Comparison with the portable reference spectroradiometer QASUME

- **Comparison** on the PMOD/WRC Roof
- **19** Solar UV instruments
- **14** Array Spectroradiometers from 7 countries



Objective:
<5% between
295 nm and **500 nm**
for sun measurements

Summary

To obtain reliable solar (UV) measurements:

1) Calibrate regularly
2) Know your Uncertainties
3) Document your procedures
4) Validate your measurements
5) Take part in Intercomparisons

e.g. become traceable !!!