A stray light corrected array spectroradiometer for complex high dynamic range measurements in the UV spectral range

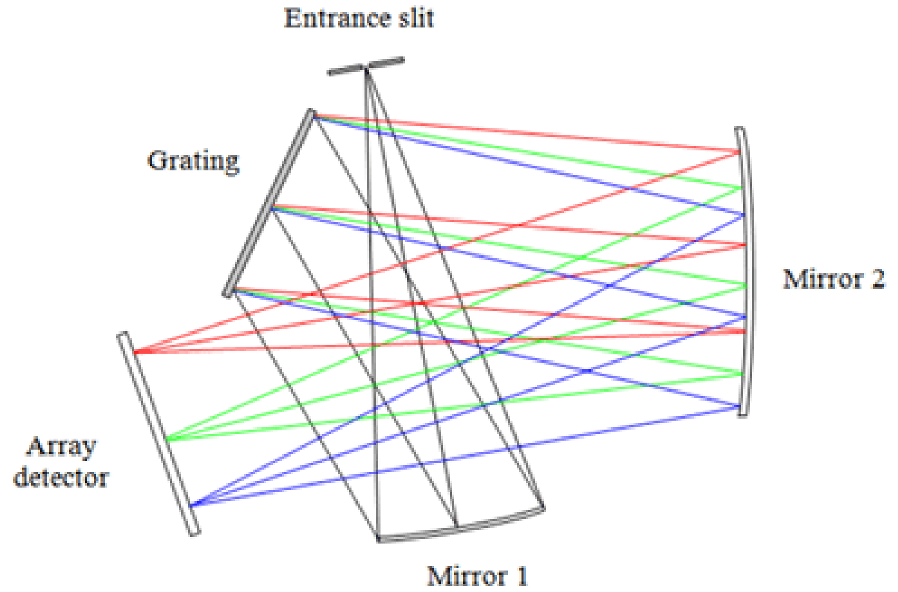
Mike Clark Gigahertz-Optik GmbH

m.clark@gigahertz-optik.de

Array spectroradiometers

Array spectrometers – used extensively in spectroscopy and optical radiation applications

- Fast measurements
- Solid state
- Cost effective
- Flexibility



Gigahertz-Optik

Array spectroradiometers – entrance optics

Spectroradiometer - instrument for measuring <u>radiometric quantities</u> in narrow wavelength intervals over a given spectral region. (CIE definition)

Entrance optic determines what radiometric quantity can be measured e.g. :-

Calibration standard → **Entrance optic** — **Spectrometer**

Cosine diffuser

Spectral irradiance

W/(m² nm)

Integrating sphere

Spectral radiant flux

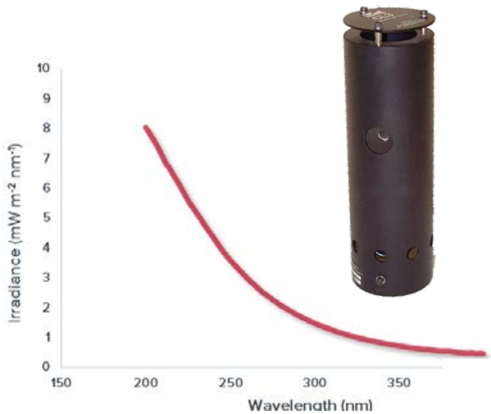
W/nm

F.O.V. optic

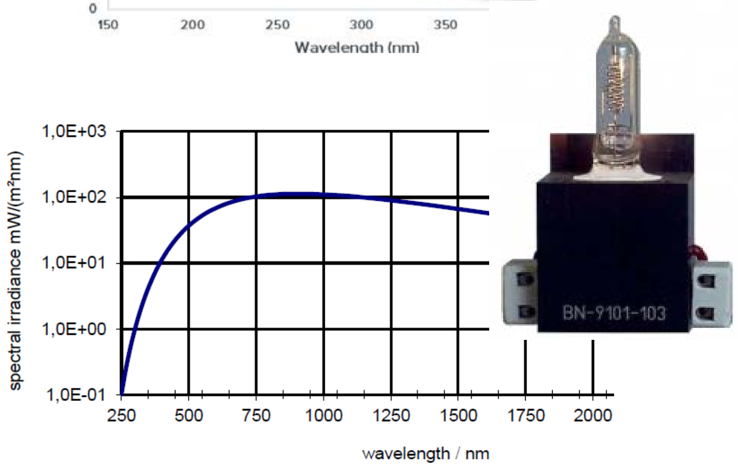
Spectral radiant intensity

W/(sr nm)

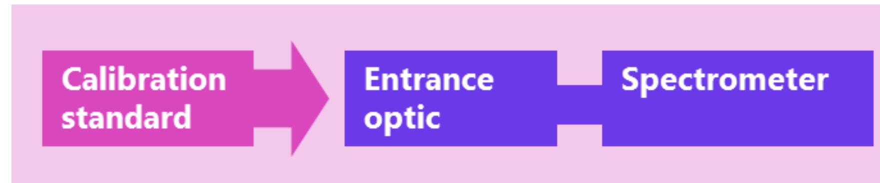
Array spectroradiometers - calibration



30W D2



1000W FEL

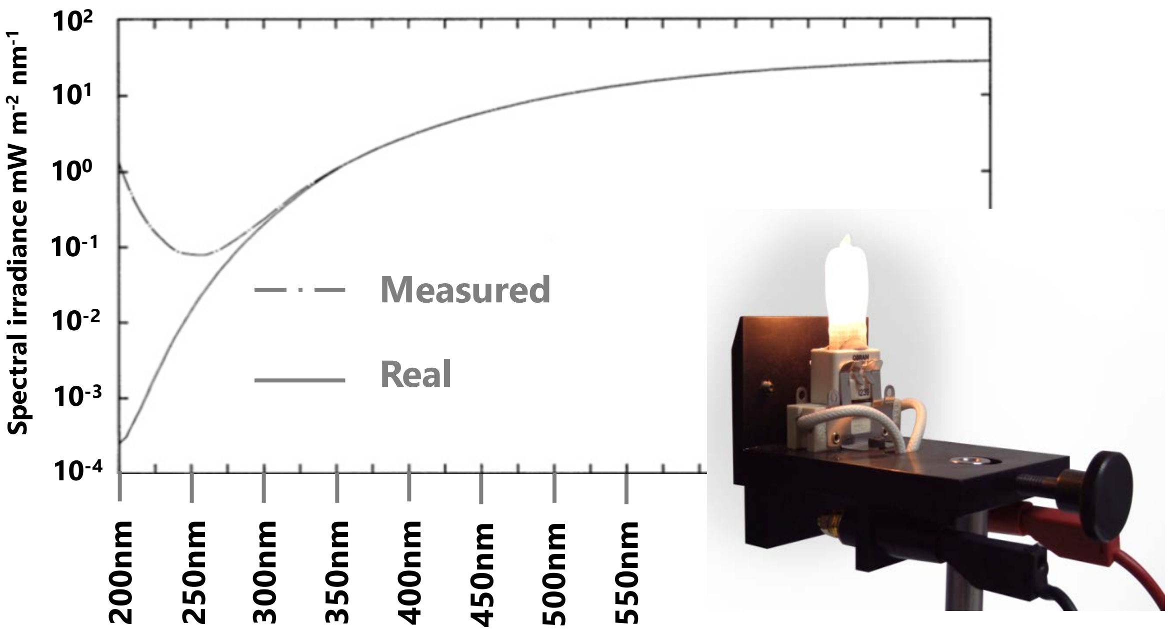


Tungsten halogen and deuterium lamps commonly used – but both have their limitations

Calibration source needs to be suitable for required radiometric quantity and entrance optic

What is Stray light?

Stray light is signal that is detected during a spectroradiometer measurement in addition to the real signal.



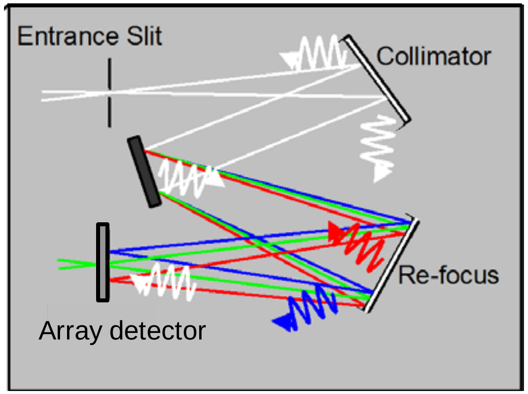
The amount of stray light in a measurement strongly depends on the light source and the spectrometer itself.

Gigahertz-Optik

Stray light causes

Possible causes of internal stray light:

- Scatter from the diffraction grating
- Reflections and scatter from 0th order
- Higher orders of diffraction
- Double diffraction
- Scatter from imperfect mirrors
- Inter-reflections between optical components
- Diffuse reflections within housing
- Optically over-filling entrance aperture
- Fluorescence



Gigahertz-Optik

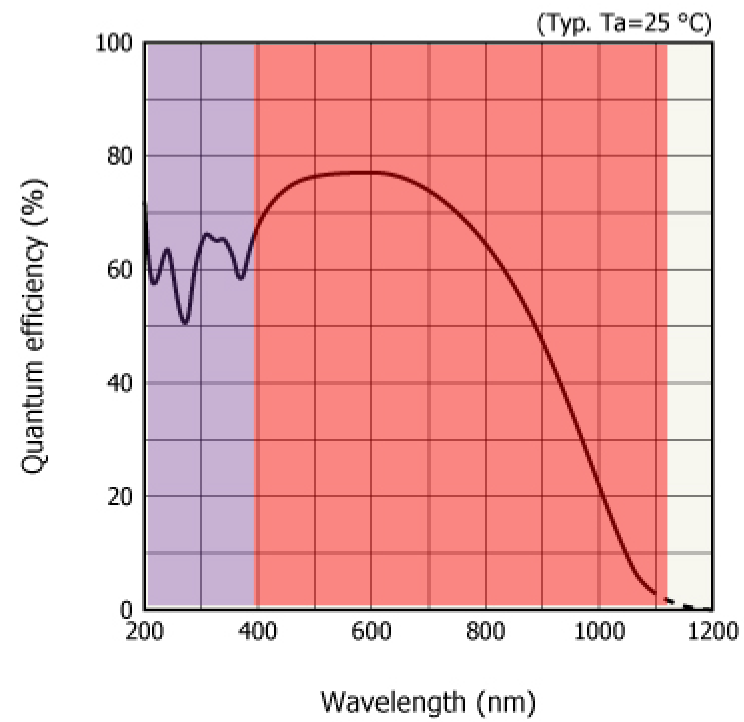
‘Out of Range’ stray light

Each pixel in an array detector is sensitive to all wavelengths in the detector’s range

Back-thinned CCDs can offer good efficiency in UV 200-400nm

Conventional detector technologies (Si-based) have high responsivity well beyond UV

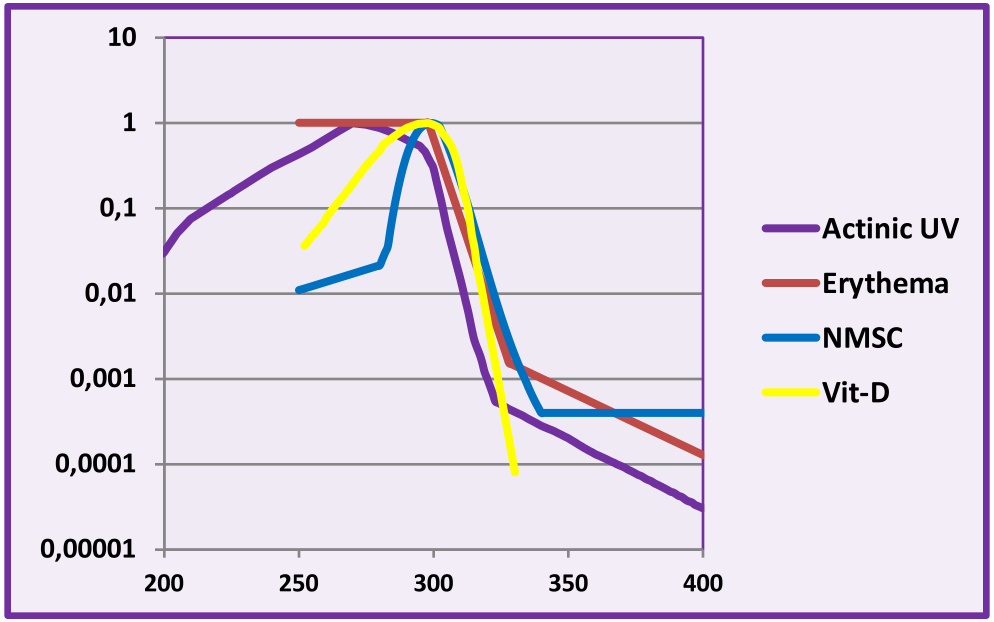
Results in ‘Out of Range’ stray light

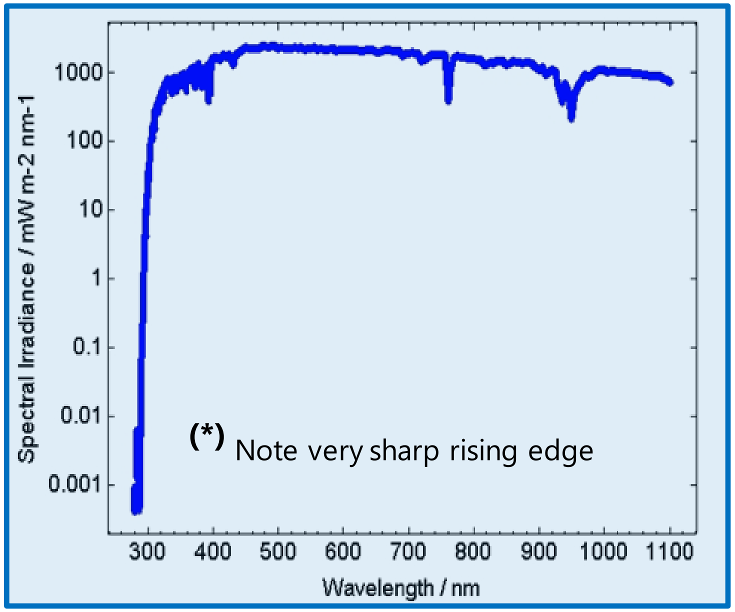


Significance of stray light for UV measurements

Biological action spectra have wide dynamic ranges

Common sources e.g. sunlight (*) relatively high proportion of visible + NIR radiation





Calibration factors inversely proportional to responsivity

Therefore, stray light component increasingly significant in deep UV

Gigahertz-Optik

Double monochromators

Double monochromators often specified as reference instruments

B.1.1 Double monochromator: Recommended instrument

The measurement of a source for the purpose of hazard classification requires accuracy during calibration and testing. The detector's broad spectral response and high spectral resolution required to provide accurate weighting leads to stringent requirements for out-of-band stray light rejection. .....
The ratio of out-of-band energy to pass-band energy at 270 nm for tungsten or tungsten-halogen calibration lamps should be smaller than 10^{-4}. The double monochromator is the only instrument that provides the needed selectivity, and it is recommended for hazard measurements involving UV and visible radiation. It is recognized that monochromator systems introduce limitations in convenience and speed. Use of a single monochromator in the UV or visible spectrum **should be used only if comparable results to that from a double monochromator can be obtained**. ....

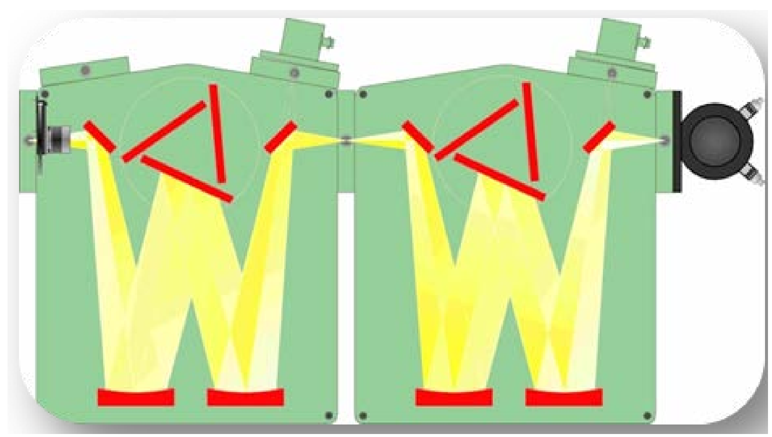
NORME INTERNATIONALE — CEI
INTERNATIONAL STANDARD — IEC
62471
CIE S 009:2002
Première édition
First edition
2006-07

Sécurité photobiologique des lampes et des appareils utilisant des lampes

Photobiological safety of lamps and lamp systems

Two monochromators in series, first acts as a pre-filter. Limited stray light enters second monochromator.

Mechanical scanning.



Single element detectors only (e.g. PMT)

No array detector meaningful at exit of double.

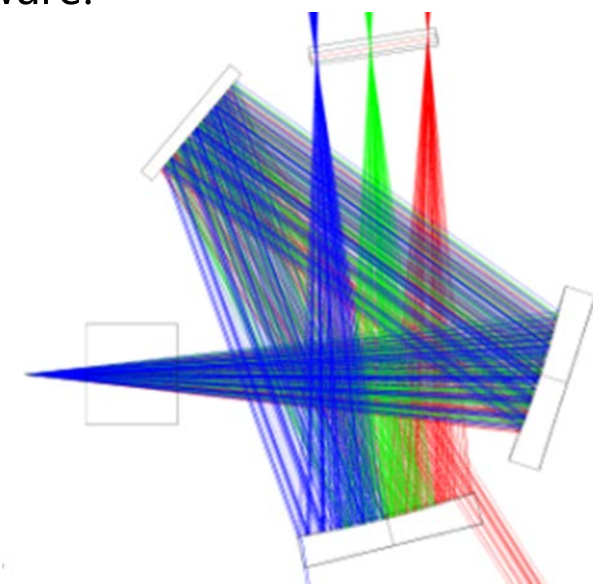
Stray light suppression in array spectroradiometers

Good optical design
e.g. use of optical simulation raytracing software.

Diffraction grating
e.g. holographic grating cf. ruled grating

Optical component selection
e.g. mirror surface quality

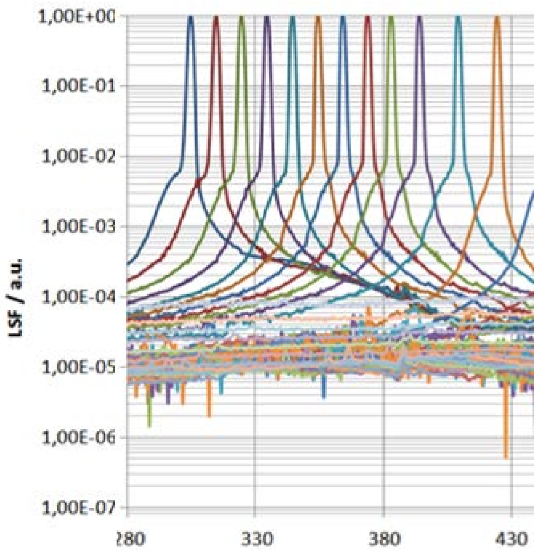
Instrument housing design
e.g. materials used, size, shape



Gigahertz-Optik

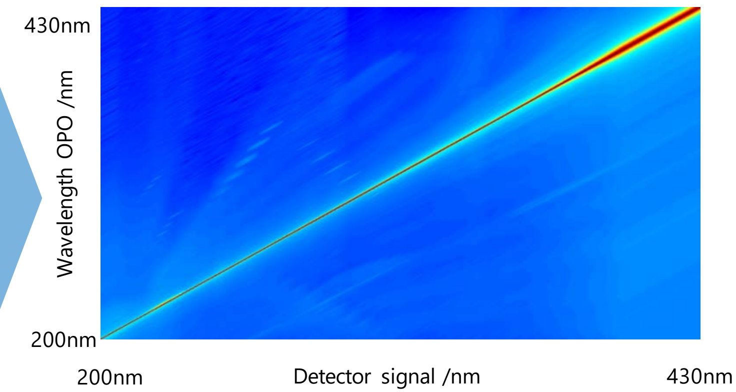
Mathematical corrections

Tuneable lasers (OPOs) enable spectrometers to be characterized at any wavelength.



LSF of spectroradiometer measured using an OPO

Line Spread Functions (LSF) form a signal distribution function (SDF) characterization matrix of the spectrometer.



LSF matrix representation

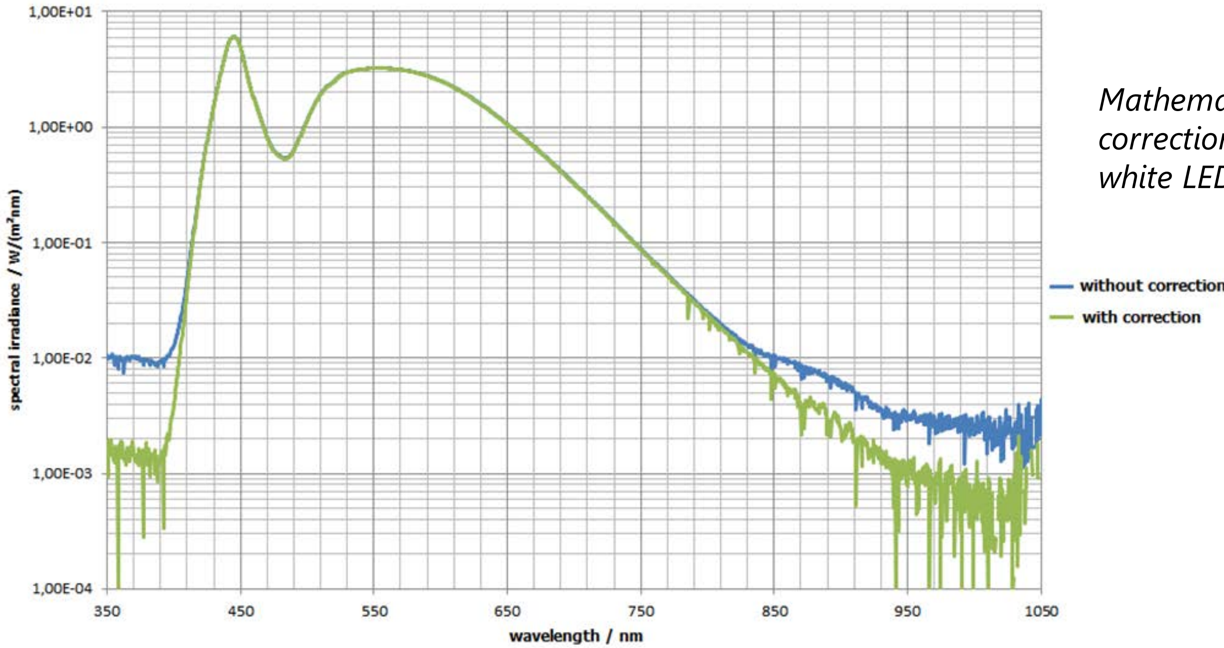
The SDF data and the measurement data from the light source under test enable the use of mathematical correction methods according to (Zong *et al.*, 2006) or (Nevas *et al.*, 2012).

Zong Y, Brown S W, Johnson B C, Lykke K R and Ohno Y 2006 Simple spectral stray light correction method for array spectroradiometers Appl. Opt. 45 1111-9

Nevas S, Wübbeler G, Sperling A, Elster C and Teuber A 2012 Simultaneous correction of bandpass and stray-light effects in array spectroradiometer data Metrologia 49 S43

Stray light matrix correction

Possible to reduce stray light by between 1 and 2 orders of magnitude

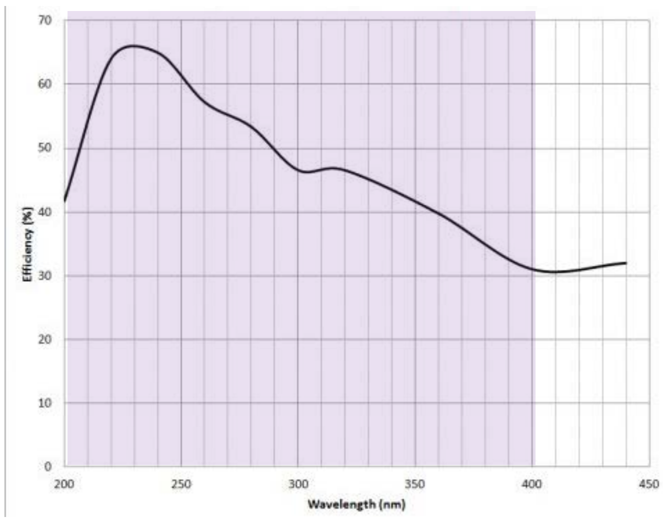


Mathematical stray light correction applied to a white LED measurement

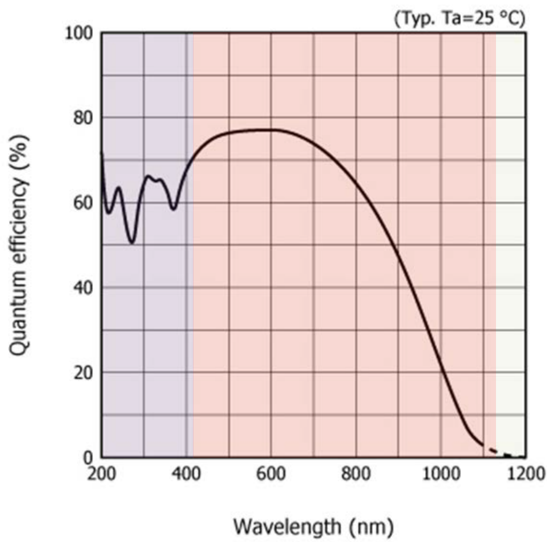
- ➢ Mathematical correction must be performed for every measurement
- ➢ An OPO is required in order to perform the measurements precisely
- ➢ Spectroradiometer must be stable (time and temperature) for SDF matrix to work
- ➢ Small wavelength shift is very significant w.r.t. stray light matrix

Limitations of mathematical corrections

Optimum stray light suppression requires the LSFs to be measured over the entire spectral sensitivity range of the detector



Holographic grating 1800g/mm 230nm blaze



Back-thinned CCD

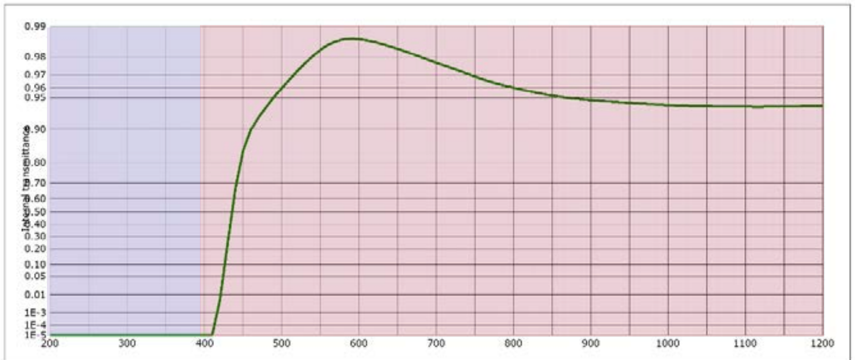
UV optimised grating (e.g. 200 nm to 400 nm) only permits a minor part of the stray light to be corrected

Stray light beyond 400 nm (Out of Range, OoR) cannot be corrected with this method!

Use of filters

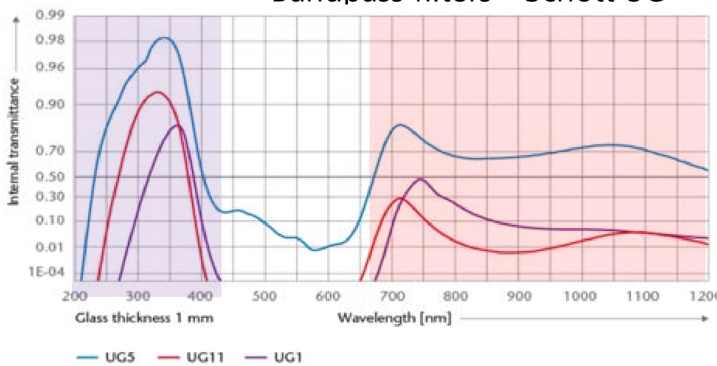
Use of long-pass filter (e.g. Schott GG435) determines OoR stray light during calibration.

But subsequent measurements likely to have different stray light

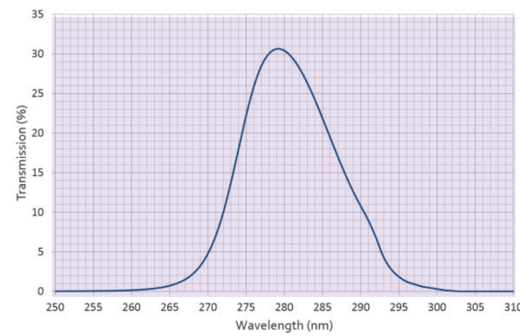


Long-pass filter – Schott GG435

Bandpass filters – Schott UG



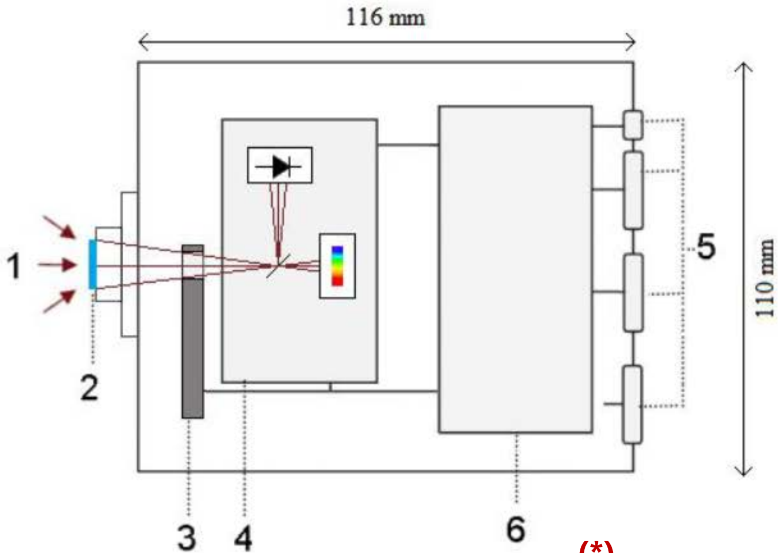
Interference bandpass filters



Bandpass filters can significantly reduce potential for stray light – akin to first half of a double monochromator

Perfect bandpass filters not available (e.g. out of band transmission, narrow and low passband transmission)

BTS2048-UV-S stray light corrected spectroradiometer



1. Optical radiation
2. Cosine diffuser
3. Filter wheel
4. BiTec sensor (*)
5. Electrical connectors
6. Microprocessor for data processing and communication

BTS2048-UV-S

(*) BTS technology

Integral photodiode (SiC) + CCD spectrometer

https://www.gigahertz-optik.de/en-us/service-and-support/knowledge-base/bts-technology/

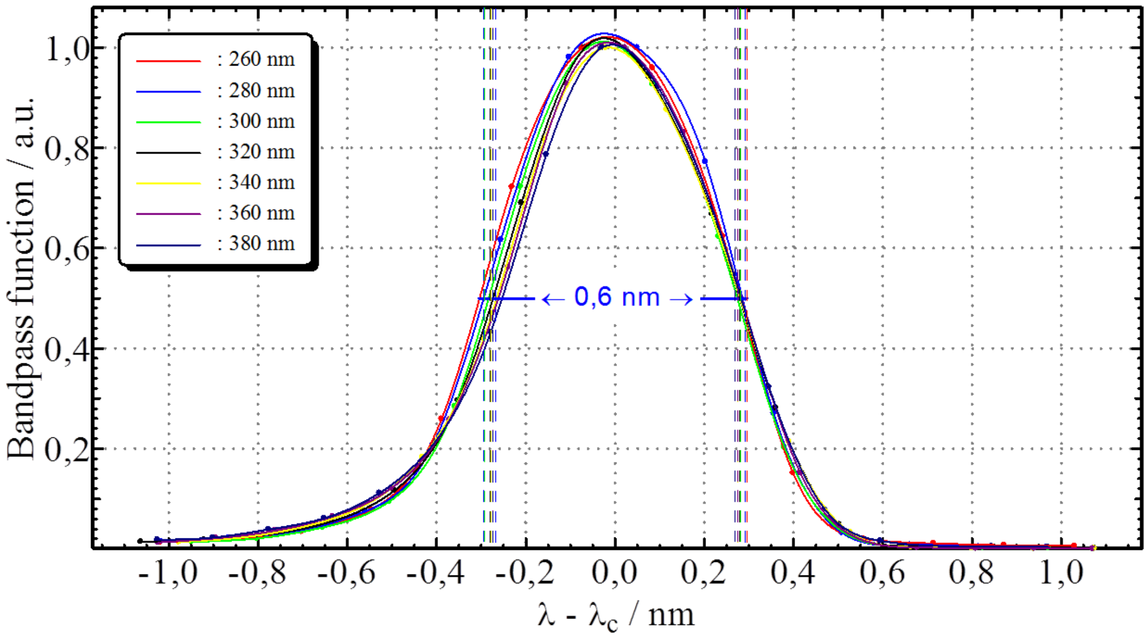
A miniaturized filter wheel holds a set of up to 6 different optical bandpass and long-pass filters.

Optimized stray light-reduced spectra result from the smart combination of sub-measurements.

Integration time	2 µs - 60 s
Spectral range	(190 - 430) nm
Optical bandwidth	0.8 nm
Pixel resolution	~0.13 nm/Pixel
Number of pixels	2048
Chip	Back-thinned CCD chip, 1stage cooled
ADC	16bit (25 ns instruction cycle time)
Dynamic range	>9 Magnitudes
Peak wavelength	± 0.05 nm
Band-pass correction	mathematical online
Linearity	completely linearized chip >99.6%

PTB characterization of BTS2048-UV-S

Device characterization undertaken by PTB
e.g. wavelength accuracy, radiometric accuracy, linearity, stray light rejection, bandpass function, etc.



Bandpass function around centroid λ_c for different wavelengths with bandwidth (FWHM, dashed lines) indicated.

Gigahertz-Optik

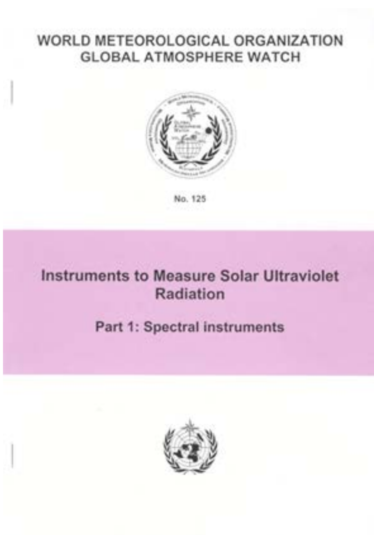
BTS2048-UV-S-WP Solar irradiance measurements

Measurement of solar radiation in UV-B is particularly challenging – conventionally the domain of double monochromators

Therefore, a good quality test!

Ozone Hole was first announced in a paper by British Antarctic Survey's Joe Farman, Brian Gardiner and Jonathan Shanklin, which appeared in the journal Nature in May 1985.

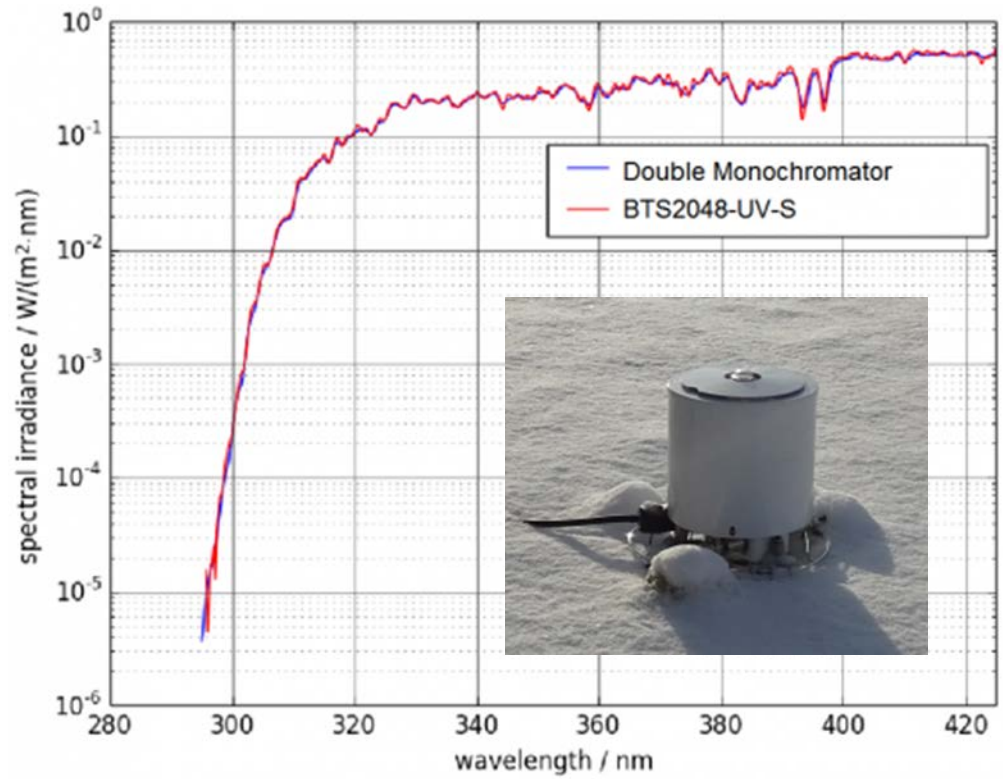
Instrument specification requirements developed in 1990's.


WORLD METEOROLOGICAL ORGANIZATION
GLOBAL ATMOSPHERE WATCH

No. 125

Instruments to Measure Solar Ultraviolet Radiation

Part 1: Spectral instruments



Comparison of a solar measurement with BTS2048-UV-S-WP and a double monochromator illustrates the high dynamic range of the stray light corrected array spectroradiometer

TOC inter-comparison Izaña

Total Ozone Measurements Inter-comparison at Izaña Tenerife, Sep 12th – 30th, 2016
Izaña Atmospheric Research Center in conjunction with World Radiation Center (PMOD-WRC)

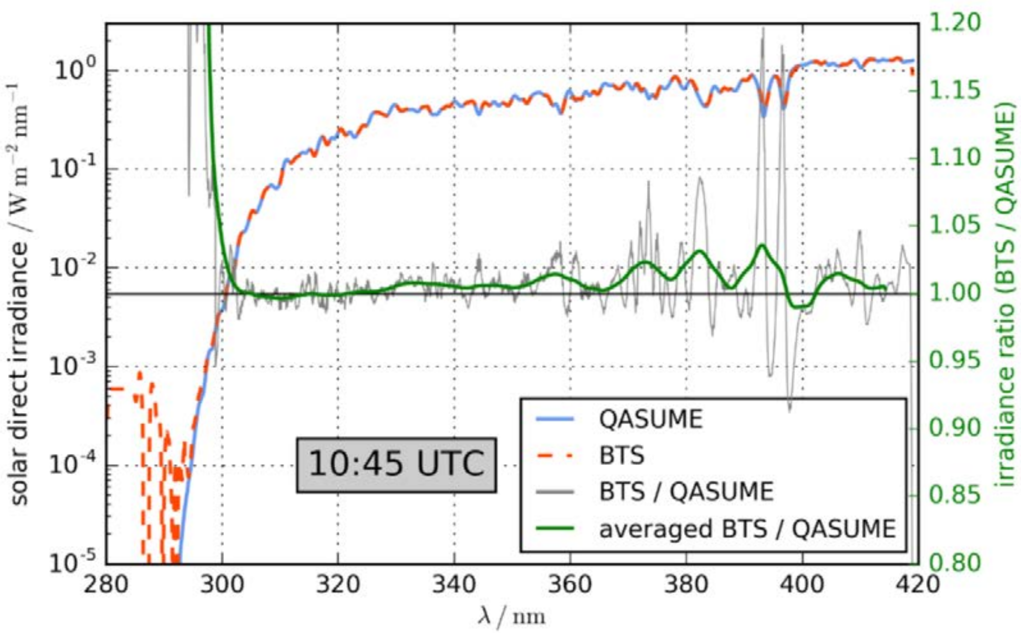
BTS2048-UV-S mounted on a solar tracker

Ground-based spectroradiometer measurements of direct solar UV irradiance can be used to determine the Total Ozone Column (TOC) by applying the Beer-Lambert law in conjunction with the known absorption characteristics of ozone over the 290-350nm wavelength range. Suitable modelling is required to minimise the influences of other atmospheric attenuators [1].

[1] Vaskuri, A., Kärhä, P., Egli, L., Gröbner, J., and Ikonen, E.: Monte Carlo method for determining uncertainty of total ozone derived from direct solar irradiance spectra: Application to Izaña results, Atmos. Meas. Tech. Discuss., https://doi.org/10.5194/amt-2017-403

Gigahertz-Optik

TOC inter-comparison measurement results



Adaption of an array spectroradiometer for total ozone column retrieval using direct solar irradiance measurements in the UV spectral range

Ralf Zuber[1], Peter Sperfeld[2], Stefan Riechelmann[2], Saulius Nevas[2], Meelis Sildoja[2], and Gunther Seckmeyer[3]

[1]Gigahertz-Optik GmbH, 82299 Türkenfeld/Munich, Germany
[2]Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, 38116 Braunschweig, Germany
[3]Leibniz Universität Hannover, Institute of Meteorology and Climatology, Germany

https://doi.org/10.5194/amt-2017-240

The measured spectra and integral values showed good agreement to the results of the double mono-chromator based QASUME **(*)** reference system.

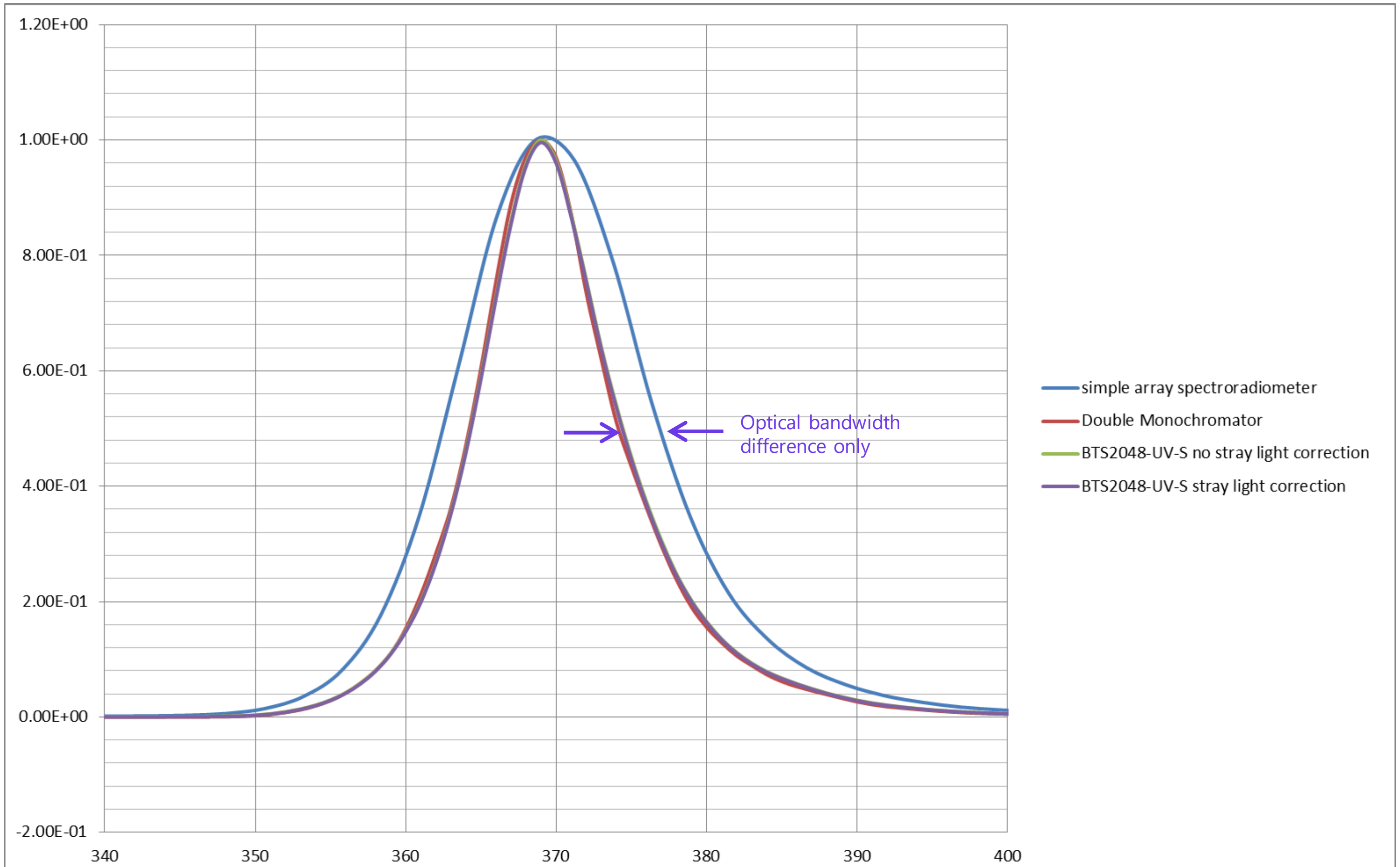
The performance (stray light suppression, absolute radiometric precision and wavelength precision) was proven by calculating the total ozone column from direct solar measurements

The results showed deviations of the TOC of less than 1.5 % to other well established instruments.

(*) QASUME - transportable reference spectroradiometer for Quality Assurance of Spectral Ultraviolet Measurements in Europe

UV LED measurement

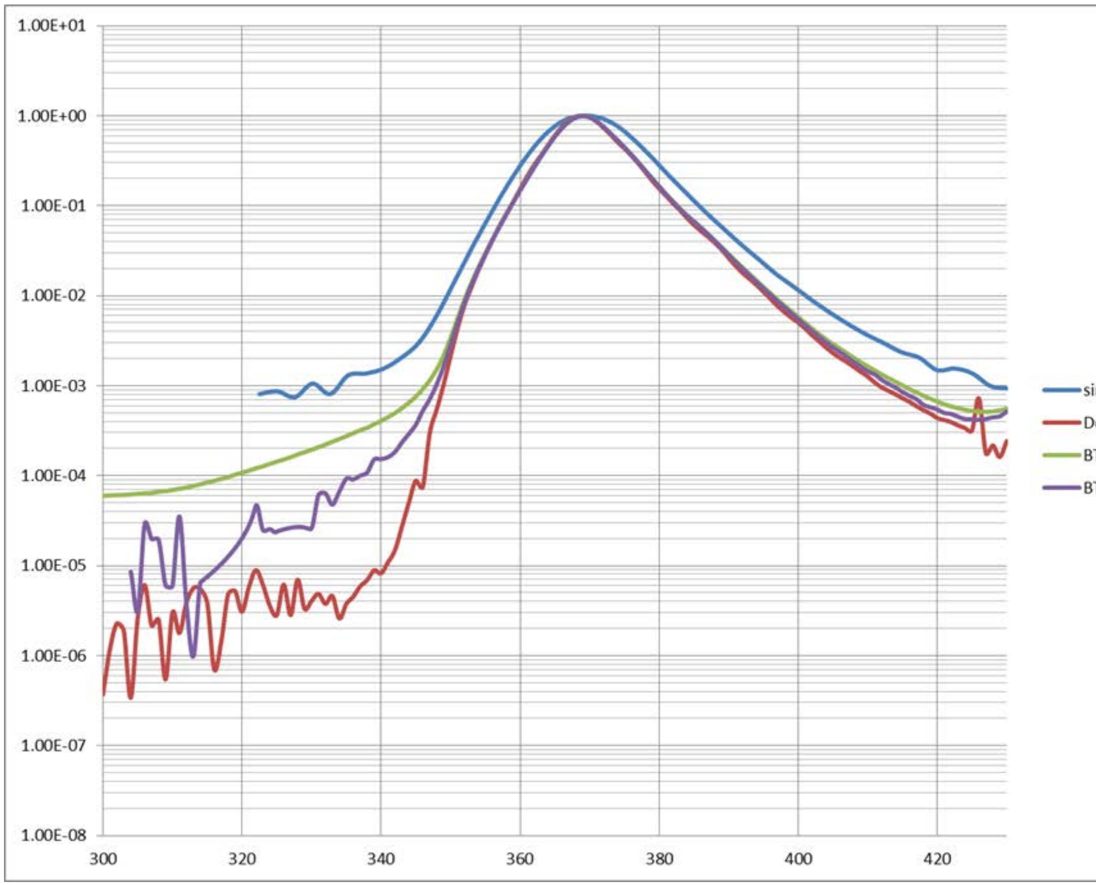
Is stray light correction needed for ‘simple’ routine measurements of UV LEDs?



Gigahertz-Optik

UV LED measurement

The need for stray light suppression varies depending on application.



BTS2048-UV-S
BTS2048-UV

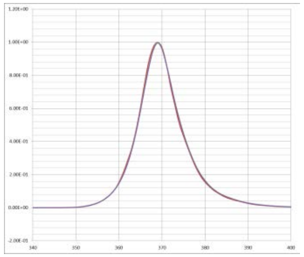
Proven UV performance - applications

Solar measurements – excellent stray light suppression, dynamic range and linearity is absolutely essential.

Photobiological safety measurements
excellent stray light suppression, dynamic range and linearity is absolutely essential
e.g. for IEC EN 62471 and 2006/25/EC

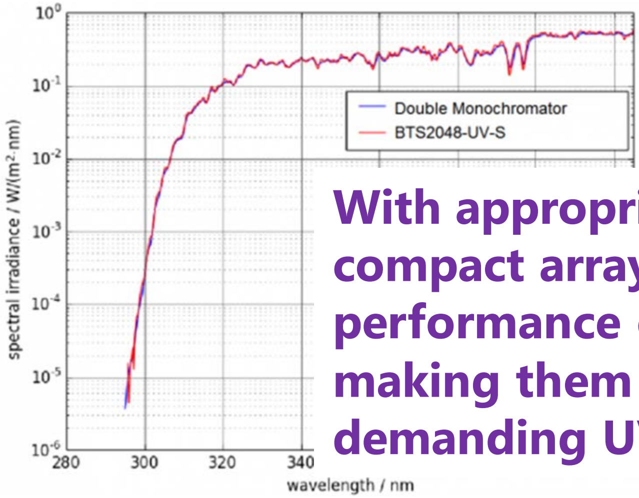
High power UV measurements i.e. UV curing and disinfection / water treatment - high dynamic range and linearity required as typical calibration sources have comparably low spectral power

BTS2048-UV-S with fibre coupling option



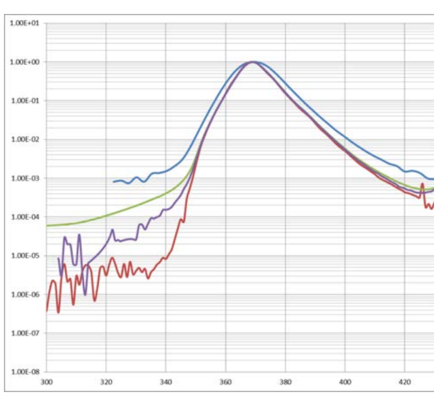
UV LED measurements – excellent reference instrument, highest accuracy, suitable in presence of 'external' stray light (e.g. room light)

Conclusion



With appropriate stray light suppression techniques, compact array spectroradiometers can match the performance of traditional double monochromators making them suitable for many of the most demanding UV spectroradiometry applications.

Their compactness and robustness offers new levels of speed, convenience and flexibility.



They are well suited for use as reference grade instruments as well as providing accuracy and reliability for more routine measurements.

Thank you for your interest and attention

Mike Clark m.clark@gigahertz-optik.de

Acknowledgements

Gigahertz-Optik GmbH
r.zuber@gigahertz-optik.de
www.gigahertz-optik.com

Physikalisch-Technische Bundesanstalt
peter.Sperfeld@ptb.de
www.ptb.de