FINAL PUBLISHABLE JRP REPORT

JRP-Contract number	ENV03
JRP short name	SolarUV
JRP full title	Traceability for surface spectral solar ultraviolet radiation
Version numbers of latest contracted Annex Ia and Annex Ib against which the assessment will be made	Annex Ia: V1.2 Annex Ib: V1.2
Period covered	From 01 08 2011 to 31 07 2014

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Report Status: PU Public

EMRP
European Metrology Research Programme
Programme of EURAMET

The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union

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1 Executive Summary

This project has made significant improvements in spectral global solar ultraviolet measurements that will ensure homogeneous worldwide measurements of solar UV radiation by decreasing the uncertainty of the world reference spectroradiometer, improving the characterization of array spectroradiometers, establishing a new portable UV reference spectroradiometer and developing new technologies, methods and software for for applications in the solar UV end-user community responsible for environmental and human health protection.

The Problem

The reliable quantification of UV radiation at the Earth's surface requires accurate measurements of spectral global solar UV irradiance in order to understand long-term trends in this parameter. The observation and understanding of the long-term trend is essential mainly for human health protection for the next decades. An increase in surface UV radiation could substantially increase additional non-melanoma and melanoma skin cancers and more than a million of more cases of yearly cataracts worldwide. In prevention of some deceases UVB has beneficial health effect due to vitamin D production in human body.

In order to support health protection agencies and national atmosphere observation institutes, array spectroradiometers provide cost effective alternatives for spectral irradiance measurements. To ensure the quality of array spectroradiometers, the instruments need to be characterised using a costly infrastructure typically only available at NMI laboratories. The end-user community observing the long-term trends has not the experience and the infrastructure to thoroughly characterise their array spectroradiometers.

The Solution

The project, coordinated by the World Calibration Center for UV radiation (WCC-UV), operated on the behalf of the World Meteorological Organization (WMO) by SFI Davos, has developed new devices, guidelines, and characterization methods in order to provide support and improved traceability of solar UV measurements to the end-user community by:

- Establishing an improved traceability chain for spectral global solar UV measurements by reducing the state-of-the-art uncertainties in solar UV measurements provided by the end users from ca. 5% to 3%, nearly a factor 2 improvement;
- Developing new techniques for the end–users to correct spectral stray light, non-linearity and provide software tools for bandwidth and wavelength homogenization and uncertainty evaluation;
- Developing new array spectroradiometers with improved stray light suppression and new devices for characterizing array spectroradiometers for wavelength dispersion relation and non-linearity as well as performing an absolute field calibration;
- Performing an international intercomparison campaign with participants from the end-user community to offer training and access to the methods and devices developed in this project in order to decrease the uncertainty of solar UV measurements performed at monitoring sites across Europe.

The Impact

The project results represent important improvements towards more reliable measurements of solar UV radiation and harmonising the European and World network of UV monitoring sites. This activity will be continued after the end of the project by the WMO-World Calibration Center for UV radiation, which has coordinated this project. Following specific impacts has been made by the project:

- Reduced uncertainty of the primary reference spectroradiometer QASUME, which will provide improved traceability to UV monitoring stations and thereby better understanding of decadal UV changes,
- Developed stray-light and bandwidth correction methods for characterised array spectroradiometers, which allow the use of these robust and cost-effective instruments for UV exposure studies with known uncertainties,
- Developed global input optics and solid state detectors, to significantly decrease the measurement uncertainties of spectroradiometers from the end-user community,
- Creation of CMCs for characterization and calibrations services at NMI level such as spectral stray light or nonlinearity.
- Significantly increased awareness among the user-community of the necessity of a thorough characterisation of array spectroradiometers before they are used for solar UV measurements.

2 Project context, rationale and objectives

Context

The quantification of UV radiation at the Earth's surface requires accurate measurements of global solar spectral UV irradiance in order to understand long-term trends in this parameter. Monitoring long term trends is important for climate observations and specifically for human health protection. UV-B is of great biological importance because photons in this region may damage deoxyribonucleic acid (DNA) molecules and some proteins of living organisms."A 10% increase in surface UV radiation could cause an additional 300,000 non-melanoma and 4500 melanoma skin cancers and between 1.6 million and 1.75 million more cases of cataracts worldwide every year. On the other hand, UVB is essential for the synthesis of vitamin D in the human body, which has beneficial health effects and helps in prevention of some diseases." (http://www.who.int/uv/uv_and_health/en/index.html). Long-term trends in surface UV solar radiation due to general atmospheric induced changes (termed global dimming and global brightening), have demonstrated long-term changes of the order of 2 % per decade over Europe. These changes are currently explained by changes in the transparency of the atmosphere (aerosols) and possibly long-term changes in clouds (cloud fraction and cloud opacity). The effects on UV radiation have not yet been quantified due to the difficulty of observing these small changes over such long time scales. Future changes in UV radiation due to atmospheric changes are expected to be of the same order of magnitude and require measurements with uncertainties of around 2 % to 3% to detect such decadal changes.

The current knowledge on spectral solar UV radiation is limited to very few places worldwide where spectral solar UV monitoring instruments are located. Large-scale deployment of such instruments is limited by the required manpower and infrastructure to guarantee an adequate level of uncertainty. UV monitoring at additional locations is required to better understand the relationship between UV radiation and its influencing factors and to validate radiative transfer models and satellite-derived UV estimates.

The main instruments to measure solar UV are currently scanning spectroradiometers. These instruments measure the solar irradiance spectrum sequentially, which requires several minutes of scanning time. The interpretation is thus rendered difficult in the case of fast varying atmospheric conditions (e.g. clouds). Also, the slow scanning speed does not allow fast sampling rates, limiting the number of measurements available per day.

Array spectroradiometers have not been widely used for solar UV measurements so far. Currently available array spectroradiometers are not suitable for solar UV measurements without complex correction methodologies due to the large dynamic range of the solar UV radiation between 300 and 400 nm and the significant stray light contamination of these instruments.

Both types of instrument require technologies providing stray light rejection of at least 10^{-6} to reliably sample the whole solar UV spectrum between 300 nm and 400 nm. Furthermore, due to the large decrease in UV radiation below 330 nm over many orders of magnitude, wavelength accuracies of better than 0.05 nm are required to reach nominal uncertainties of 2% in the wavelength range 300 nm to 400 nm. Furthermore, a high dynamic range of the detector over at least five orders of magnitude is necessary to cover the wavelength range between 300 nm and 400 nm.

Fourier Transform Spectroradiometers (FTS) hold the promise of recording solar UV spectra within a very short time span (typically less than 1 minute) and with a wavelength uncertainty below 0.02 nm due to the very nature of their measurement process,

Objectives

The project aimed to shorten the detector based traceability chain of the solar UV measurements to the SI unit and reduce the associated transfer uncertainties e.g. for the portable reference spectroradiometer known as 'QASUME' to provide traceable solar UV irradiance measurements with an uncertainty of 2 %. This is essential to unambiguously quantify decadal changes in solar UV radiation due to the expected changes in the global climate system. The project further aimed to support the use of cost-effective array spectroradiometers in UV monitoring networks, where significant progress is needed in the characterisation of these devices. Therefore, new technologies, characterisation techniques and post-correction methods were needed to determine, physically reduce and then correct the stray light, linearity, and wavelength scale of array spectroradiometers.

Specifically, following four scientific and technical issues were addressed to achieve the main objectives introduced above:

1. Improving spectral irradiance traceability of spectroradiometers:
   - Upgrading and expanding an existing tuneable laser suite, to enable the absolute calibration of spectroradiometers from 280 nm to 400 nm,
   - Development of compact, robust, portable and stable UV LED-based monitoring sources that are suitable for field use,
   - Development of a transfer standard based on a compact laser-induced high-flux UV source, suitable for field calibrations.
2. Improving array spectroradiometer characterisation:
   - Development of a guide for measuring solar UV spectra using array spectroradiometers and a guide for uncertainty estimation in array spectroradiometer measurements of solar UV spectra,
   - Development of an algorithm/methodology for stray light correction for in-range and out-of-range radiation contributions and an algorithm/methodology for bandwidth and wavelength correction methodology applied to solar spectra. Then development of user friendly software that incorporates the two algorithms,
   - Development and evaluation of two devices for wavelength scale characterisation and three methods for determining linearity of array spectroradiometers.
3. Improving the QASUME reference UV spectroradiometer:
   - Improvement of the existing QASUME UV spectroradiometer, with new global entrance optics,
   - Development of a new solid-state detector as a replacement for an existing photomultiplier,.
   - A feasibility study on weather a Fourier-Transform spectroradiometer can be used for solar UV irradiance measurements.
4. Investigating the suitability of new technologies for solar metrology:
   - Development of a UV hyperspectral imaging camera for spectral sky radiance measurements and optimised global entrance optics (optimised diffuser design) for solar UV irradiance measurement,
   - Development of two prototype UV array spectroradiometers array spectroradiometers physically reducing stray light using 1) micro-mirror devices and 2) band-pass filters. Prototypes are manufactured and tested.

The activities performed in this project aggregated the effort from seven European NMIs and two designated institutes for optical quantities and for solar irradiance respectively. The individual metrological capacities of each NMI was efficiently used to address the objectives of the project.

This project built on existing commercial instrumentation developed for industrial and laboratory use which were applied to environmental research (solar UV measurements). The specifications required for use in research grade instrumentation required significant improvements in reliability and radiometric characterisations. These were only possible through innovative approaches from the project-partners composed of NMIs and experts in the field of solar UV research.

Furthermore, the REG-Researchers, acknowledged experts in solar UV research, considerably strengthened the potential of this JRP and provided the dissemination of the project results to the UV research community through their prominent role in the user community.

Stakeholders and researchers involved in solar UV research participated in activities of this JRP. Specifically, workshops and conference sessions were organised to inform the solar UV research community of the activities within this JRP. In addition, direct involvement in this JRP were made available to researchers owning array or similar fast-scanning spectroradiometers to characterise their instruments and participated at a measurement intercomparison with the new reference spectroradiometer. This involvement provided a direct exchange of expertise between the solar UV community and the metrological developments of this project.

3 Scientific and technological results and foreground

3.1 Improving spectral irradiance traceability of spectroradiometers

A) Traceability using tuneable laser source

One of the main goals within the project was to realise a completely detector-based traceability chain allowing a calibration of the spectral responsivity of the SFI Davos portable solar UV world reference QASUME against a reference detector with the help of wavelength-tuneable lasers (Figure 1, left side). The motivation to follow this traceability route was shortening the traceability chain to the primary standard of optical power, the cryogenic radiometer, and, thus, reducing the associated uncertainties and validating the spectral irradiance realisation using two independent methods. The shortening of the traceability chain required the expertise of both PTB and SFI Davos.
In order to enable this calibration scheme, however, a uniform and quasi monochromatic radiant field with sufficiently high irradiance is required. Within the framework of the SolarUV project, the wavelength-tuneable laser facility at PTB, TULIP, was upgraded by mode-locked fs-pulsed lasers and prepared for the operations throughout the solar UV spectral rage, 280 nm to 400 nm, and beyond. To enable irradiance-mode calibrations at the TULIP facility in the UV spectral range, a laser monochromator has been set-up and an active stabilisation for the laser power has been implemented. Additionally, a beam conditioning unit providing a spatially homogeneous and depolarised field qualified for calibrations in the irradiance mode has been developed. The traceability to the primary standard for radiant power, the cryogenic radiometer of PTB, is provided by silicon trap detectors built and characterised for this purpose and is available for further studies. The transfer to irradiance responsivity has been realized using a radiometric aperture with calibrated area.

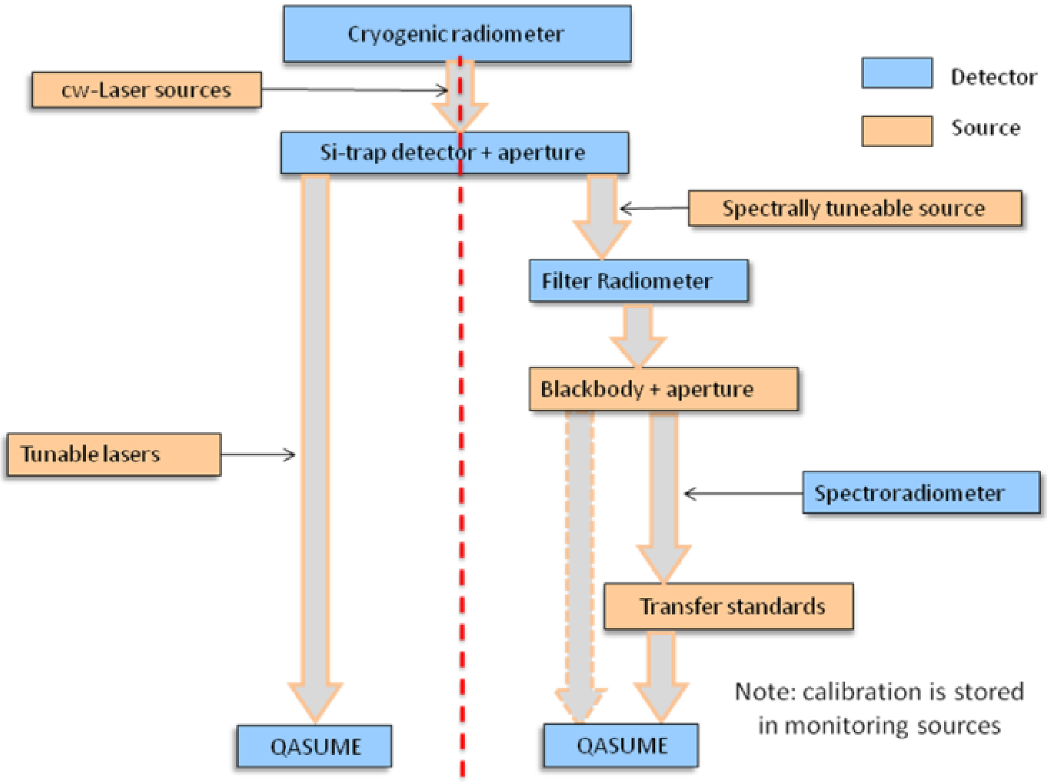


Figure 1: *Traceability chain for the calibration of the reference spectroradiometer QASUME: it can be realised by means of calibration sources as shown to the right from the vertical line or by using a calibrated detector and wavelength-tuneable lasers.*

In collaboration with the World Calibration Center (WCC-UV) for solar UV measurements, SFI Davos, two measurement campaigns involving both the calibration of QASUME spectroradiometer at the TULIP facility against the trap detectors and a direct irradiance measurement of the primary standard of the spectral irradiance of PTB, a high temperature blackbody, were arranged in spring of 2013 and of 2014. The second campaign was used to sort out systematic effects observed in the behaviour of QASUME spectroradiometer during the laser-based calibrations of the first campaign. Results of the second calibration campaign are summarized in Figure 2. The agreement within the source and detector based calibrations was within 1 %, i.e. within the estimated uncertainty of the detector based calibrations. The major uncertainty contributions were estimated to be caused by the QASUME spectroradiometer itself and the monitoring scheme.

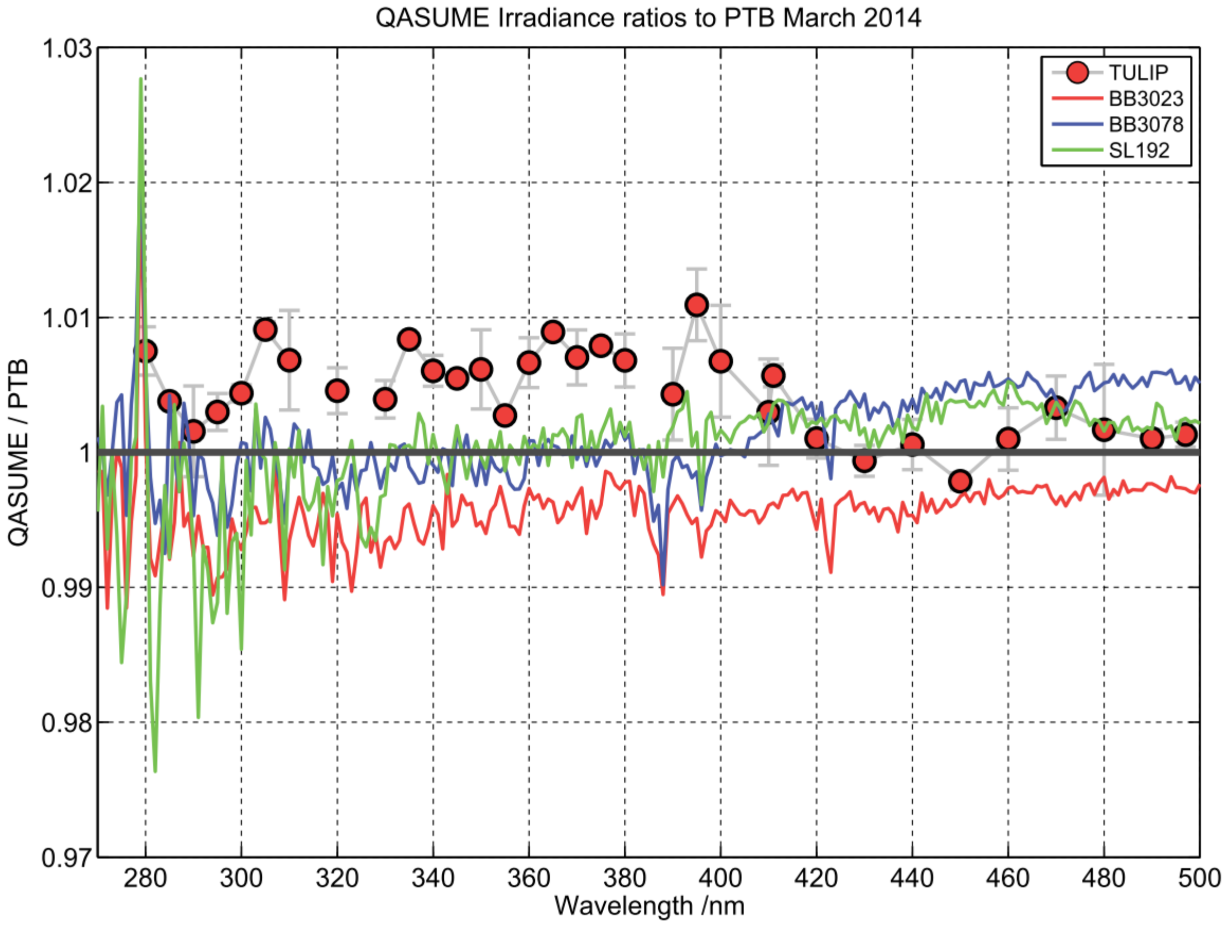


Figure 2: *Ratio of irradiances measured by the QASUME and those provided by PTB. The measurements compared irradiance of the laser field at the TULIP facility (filled circles) and irradiance of the blackbody radiator at two temperatures as well as of an FEL-type lamp (solid lines).*

Summary: Objective achieved:The joint research between PTB and SFI Davos scientifically confirmed the reliability and stability of QASUME as the standard for portable solar UV measurements and revealed that the traceability chain can be shortened using the TULIP tuneable laser source. The radiometric uncertainty of the QASUME calibration could be decreased by nearly a factor of three, from about 4% to now 1.5%. Beyond the state of the art, the investigated detector based new traceability chain may be used for calibration of further reference spectroradiometers measuring solar UV.

B) UV-LED Portable Reference

Instruments measuring solar UV irradiance are generally not stable enough in time intervals between calibrations carried out in the laboratories and the solar measurements in the field. Therefore, they typically need to be often recalibrated, also in the field. State-of-the-art is that their stability is monitored using compact low-power tungsten-halogen lamps. These are fragile and their stability is affected by aging and transportation. To overcome these limitations, a more robust monitoring technique based on UV light emitting diodes (LEDs) was required and has been developed within the project in joint efforts between PTB, EJPD, VSL and SFI Davos.

In the first stage of the project, commercially available UV-LEDs covering the solar UV spectral range, 280 nm to 400 nm, have been selected and characterized at PTB and EJPD with respect to their temporal stability, generated irradiance levels and spectral properties. The investigations revealed that the commercially available UV-LEDs after certain operating times can reach the temporal stability required for building a monitor source. The operating time needed to reach the required stability, i.e. radiant flux drifts at the level of 0.05 %/h, was found to depend on the specific LED device and especially its wavelength. I.e. the shorter the UV-LED peak wavelength, the stronger drift was generally observed for the irradiance of the LED and the longer operating times were typically needed to reach a stable enough operation mode. The spectral properties of the UV-LEDs, i.e. peak wavelengths and spectral power distributions, remained in principle constant despite drifting irradiance levels. At the end of these studies, a set of 10 pre-aged LEDs covering the whole spectral range from about 270 nm to 460 nm was selected with the verified drift of their spectral irradiances being at the level of about 0.05 %/h. These LEDs were built into a monitoring source that was designed in collaboration between PTB, EJPD and SFI-Davos and built by PTB. The design of the UV-LED source implemented a concept of mounting the source directly on the entrance optics of a spectroradiometer in a reproducible way. Here, the unfunded partners CMS and KIPP provided technical specification of their diffusers used with the solar UV spectroradiometers. To ensure the compatibility with both types of the entrance optics, an interchangeable flange was constructed. All UV-LEDs in the monitoring source are temperature controlled to 25^{o} C within ± 0.01^{o} C by a thermo-electrical cooler (TEC). The current flowing through the LEDs is 20 mA and controlled within ± 0.07 µA. The temperature and the electrical current flowing through the LEDs need to be accurately known and controlled in order to have stable and reproducible radiant flux of the device irradiating the entrance optics of the spectroradiometers. In addition to the precision current supply and TEC controller, the monitor source system included also a DMM with a multiplexer card so that the voltage drop across every single LED and the temperature of the copper block hosting the LEDs could be continuously monitored during its operation. The UV-LEDs monitor system, including the electrical instrumentation, was fitted in a standard ZARGES case for an easy transportation.

SFI-Davos has tested the UV-LED monitoring source under different operating conditions in the laboratory and the field. The new monitor source was used side to side with the compact halogen lamp portable calibrator and the reference QASUME spectroradiometer in the measurement campaigns in La Reunion, France from 8 to 17 April, 2013 and in El Arenosillo, southern Spain from 10 to 19 June 2013. The performance of the system is summarized in Figure 3 and shows agreement with the current portable system to within 1%.

In addition to its intended use as spectral irradiance calibration device, it can also be used for wavelength stability checks, using the spectral structure of the UV-LED device. The dual use of the system was not part of the original task and was found to be very valuable in detecting wavelength shifts during calibration of the order of a few 10 ppm.

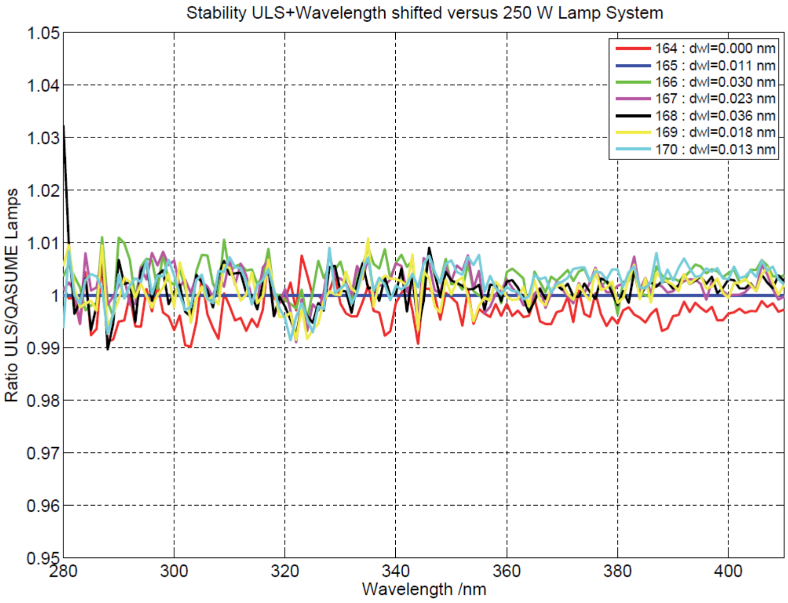


Figure 3: *Stability of the UV-LED-based source with respect to the portable 250 W tungsten-halogen lamp system.*

Summary: Objective achieved: In collaboration with the different project partners, the suitability of UV-LED for portable spectroradiometer calibrations was shown. Beyond the state of the art, the new light sources were tested for stability and the ability for field applications. The developed unit may be promising to be up-taken by a commercially interested manufacturer to provide a new dual calibration device for calibration of the absolute irradiance and calibration of wavelength.This duel use of a standard lamp would be a new devices beyond the state of the art. However, so far no commercial product is realized.

C) Laser Driven Light Source (LDLS)

To find an alternative solution to UV-LED for the problem of field calibration of spectroradiometers described above, a second technology was investigated using the expertise of the different project partners.
In the last few years a new class of laser-driven plasma sources has been made available for the radiometry community. These sources generate a broadband spectrum, with high irradiance levels, particularly appealing in the 280 – 400 nm wavelength range which makes them of special interest for calibration of spectroradiometers for measurements of the UV component of solar radiation.
Within this project we have investigated the possibility of using a commercially available Laser-Driven Light Source (LDLS), by Energetiq, as a spectral irradiance calibration tool for spectroradiometers (Figure 4). The Laser Driven Light Source (LDLS) is a broad-band source, characterized by a nearly flat spectral emission, ranging from about 170nm to 2100nm (Figure 4). This is very useful, especially for the ultraviolet part of the electromagnetic spectrum, since typically in that region of the spectrum current spectral irradiance standards (such as 1000 Watt halogen lamps) show a large spectral irradiance drop while the LDLS can offer higher irradiance levels. This supports the solar UV community to determine the responsivity of instruments with better accuracy and precision, leading, in turn, to improved determination of the amount of ultraviolet radiation. The light source has been partly modified in order to make it more suitable for the goal of the project (development of a transfer standard based on a compact laser-induced high-flux UV source, suitable for field calibrations, see Figure 4). The source clearly shows a strong potential, providing much more radiation than standard lamps used so far. Additionally, in this project we have tested the feasibility of using these new types of sources as field tool. In particular during the final Intercomparison in July 2014 in Davos, Switzerland 15 end-user instruments from stakeholders, collaborators and project partners were successfully characterized to enable an improved calibaration of the end-users devices. The collaboration within the project supported the ability of LDLS as a new portable reference. Furthermore it should be pointed out that the main advantage of

the LDLS as a real portable transfer standard is the characteristics of the low sensitivity with respect to uncertainties in the determination of the distance between source and the instrument.

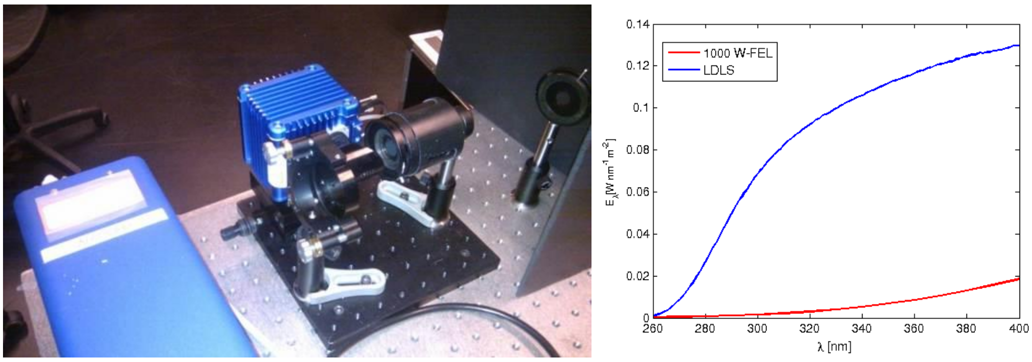


Figure 4: *A LDLS modified LDLS source and its increased spectral irradiance level (right panel, blue line) in the ultraviolet region of the electromagnetic spectrum when compared to a standard halogen lamp (right panel, red line).*

Summary: Objective achieved: As aimed to improve the spectral irradiance traceability, a new field calibration device (transfer standard) based on a new type of radiation source (LDLS) was modified and characterized to be used in a free-beam configuration for field calibrations of spectroradiometers measuring global irradiance. The work within this project and due to the collaboration with the different partners showed firstly that the LDLS is sufficiently stable to be used as a portable standard light source for spectroradiometer calibration. Therefore, the device was operationally used to calibrate end-user instruments during the final intercomparison.

3.2 Improving array spectroradiometer characterization

Array spectroradiometers are widely used in many applications due to their characteristics: portability, fast measurement (<1s), low cost. However, array spectroradiometers are single monochromators and therefore suffer significantly from stray light, biasing irradiance measurements typically in the UV-B wavelength range. This is a severe problem for measurements of solar UV radiation due to the sharp cut off of the solar UV spectrum as a consequence of ozone absorption. Therefore it is important to follow a) strict procedures when using array spectroradiometers for measuring spectral solar UV radiation, b) estimated the overall uncertainty budget, c) characterize and correct for straylight, d) calibrate the wavelength dependency and e) determine the linearity of the entire system.

A) Guidelines

In order to structure and summarize the required procedure **“A guide to measuring solar UV spectra using array spectroradiometers”** was newly developed by several project partners and published on the project web-page to be accessible to the end-user community. A brief overview of the document is given below:

Before an array spectroradiometer is used for measurements, it is necessary to determine:
- the relation between pixel number and wavelength
- the line spread function (incl. bandwidth) in dependence on excitation wavelength
- the pixel-structure of the dark signal (if appropriate)
- the nonlinearity
- the spectral responsivity (irradiance calibration).
- determination of temperature dependence of responsivity & wavelength (bandpass)

Ideally this data should be provided by the manufacturer, but usually the characterisation needs to be performed by the operator to achieve the required accuracy. Depending on application requirements, it might

be necessary to operate the instrument in a temperature controlled box and to measure the dark signal before each scan, thus an automated shutter has distinct advantages. Depending on the intention of the measurement, the integration time for each individual measurement and the number of repetitions has to be defined. The integration time should not be too high (avoiding overexposure), but setting it as high as possible will reduce the noise level. A high number of repetitions will also reduce the noise level, resulting in an averaging over a certain time interval.
After finishing a solar measurement, the raw data should be saved (together with information on time, location, integration time, number of repetitions, dark signal and temperature). To derive the final, calibrated spectral data the following steps are necessary:

1. Correction of the counts (of the dark and of the solar measurement) for nonlinearity
2. Subtraction of the dark signal (with its pixel-structure) from the entire measured signal
3. Conversion to a standard integration time including its nonlinearity correction
4. Stray light correction
5. Division by the responsivity function, resulting in [Wm-2nm-1]
6. Conversion of the pixel number to wavelength
7. Conversion to a uniform wavelength grid, determination and correction of any wavelength error, conversion to a standardised triangular bandwidth using the new developed algorithm “matShic”.

It is important to note that for the determination of the spectral responsivity by measuring a calibrated reference lamp the steps 1) to 4) have to be carried out too.

In analogy to the guideline summarized above **“A guide for the evaluation of the solar spectrum measurement uncertainty using array Spectroradiometers”** was developed by LNE and tested by several research partners and end-users during the final Intercomparison in July 2014 in Davos. The developed characterisation techniques to correct the measurement data from stray light led to complex correction process and uncertainty evaluation, which must take into account the contribution of this correction process. The measurement model considers the non-linear characteristics of the uncertainty propagation. Therefore uncertainty evaluation using the classical approach is not appropriate. New technique as described in the guideline should be used.
A Monte Carlo (MC) technique was applied to evaluate the uncertainty of Solar UV measurement performed with array spectroradiometer. LNE with the help of the partners of the project described the measurement model that is an important step of the MC technique.

In this measurement model stray light contribution is taken into account in the following equation

$$S_{Std} = S_{True} + S_{True}\, D$$

Where S_{Std} is the measured signal, S_{True} is the true signal, D is the matrix representing the stray light contribution. D is a square 2D matrix which diagonal elements are “0”. All these quantities are spectral values. The true signal can be obtained by inversing the equation above.
When dealing with this equation in the uncertainty evaluation we need to take into account the correlation between the signals spectral values and the D matrix elements. This can be addressed advantageously using the MC technique. Uncertainty evaluations are then performed using software that has been developed under the computer code Matlab with following input parameters:

- Spectroradiometer characterization results files and associated uncertainties: linearity, wavelength scale, stray light
- Measurement files for calibration and sun irradiance including dark measurements
- Uncertainties related to standard lamp: calibration, current power supply, distance measurement.

The software is available to the public on the project web-page and can be used to evaluate uncertainty in other applications as long as the measurement is performed with array spectroradiometers. The guideline displays a manual for the proper use of the software.

Summary: Objective achieved: The 2 guidelines support the end-user community using array spectroradiometers to follow a well investigated and tested procedure when measuring solar UV and to determine the uncertainty budget of their measurements. For the guidelines all knowledge obtained during the project from all different partners is included. Beyond the state of the art, the end-user community is provided with a detailed guidance, based on the recent research, for their operational and scientific work.

B) Stray light corrections, bandwidth and wavelength correction

One of the highest uncertainty components in the measurements by array spectroradiometers in the solar UV spectral range is caused by a poor suppression of the internally created stray light. A reduction of the stray light effect by up to two orders of magnitude may be achieved using a correction matrix based on line spread functions (LSFs) that can be determined with the help of spectrally tuneable lasers. However, the stray light corrections using the results of the LSF characterization are effective only as long as the spectral range of the instrument matches the spectral range of the array detector, typically a silicon-based charged coupled device (CCD), in use. Array spectroradiometers for the solar UV measurements may have a narrow spectral range. The simplest way of taking care of this out-of-range (OoR) stray light would be by using bandpass filters or other spectral pre-selection techniques that prevent the OoR radiation from getting into the instrument. For certain applications it may also be practical to subtract the OoR radiation by making an additional measurement with a long-pass filter in front of the entrance optics of the instrument. For the case that hardware modifications are not desired and feasible, an approach was implemented by PTB in collaboration with SFI-Davos and REG(IMU) to characterize the response of the instrument to the OoR radiation and to take it into account by means of a matrix for the OoR responsivity.

The contribution to the signal of every pixel of the CCD detector by the OoR stray light can be calculated numerically as

$$\mathbf{\Delta} = \mathbf{s}_{\mathrm{OoR}} \cdot \mathbf{E}_{\mathrm{OoR}} \cdot \delta\lambda \, , \tag{1}$$

provided that the responsivity of every detector pixel to the radiation from the wavelengths outside the spectral range (OoR) of the instrument, put in a matrix $\mathbf{s}_{\mathrm{OoR}}$, and the spectral irradiance outside the spectral range of the spectroradiometer, contained in a vector $\mathbf{E}_{\mathrm{OoR}}$, are known. $\delta\lambda$ represents the OoR wavelength step with which the OoR stray light data are available. The dimensions of the OoR responsivity matrix $\mathbf{s}_{\mathrm{OoR}}$ are *N*x*M*, where *N* is the number of pixels in the linear array detector and *M* is the number of wavelengths on a uniform grid throughout the OoR of the instrument, say every 1 nm. Then following the matrix formalism of Zong et al. the spectroradiometer data vector corrected for both the OoR and InR spectral stray light can be obtained as:

$$\mathbf{Y}_{\mathrm{IB}} = [\mathbf{I} + \mathbf{D}]^{-1} \cdot [\mathbf{Y}_{\mathrm{meas}} - \mathbf{\Delta}] = \mathbf{A}^{-1} \cdot [\mathbf{Y}_{\mathrm{meas}} - \mathbf{\Delta}] . \tag{2}$$

In order to calculate $\mathbf{\Delta}$ and to apply the correction of (2) the spectral irradiance $\mathbf{E}_{\mathrm{OoR}}$ outside the spectral range of the array spectroradiometer, up to 1100 nm in the case of silicon detectors, needs to be known for both the source used to calibrate the instrument and the source under test. For calibration sources such data is normally available. The OoR stray light estimation for a test source, i.e. the solar radiation, however, requires either measurements by an auxiliary spectroradiometer or some kind of extrapolation of the spectral content into the OoR spectral region based on the InR measurement data by the instrument. For this purpose one can use, e.g., radiative transfer model calculations or reference solar spectra normalized by the measurements in the overlapping spectral range. It can be shown, that in most cases the OoR irradiance does not need to be known very accurately.

To check the efficiency of the combined OoR and InR corrections, several solar UV instruments were characterized. One of them was of the type AvaSpec-ULS2048 (Avantes) operated by SFI Davos. The instrument, named AVOS, has a nominal spectral range from 280 nm to 440 nm wavelength and a spectral bandpass of 0.7 nm. As a detector, a Hamamatsu back-illuminated Si CCD with 2048 pixels is used in the device. Both the InR and the OoR stray light properties of the spectroradiometer were characterized at the PLACOS setup of PTB. The InR and OoR stray light properties of the AVOS instrument are shown in Figure 6.

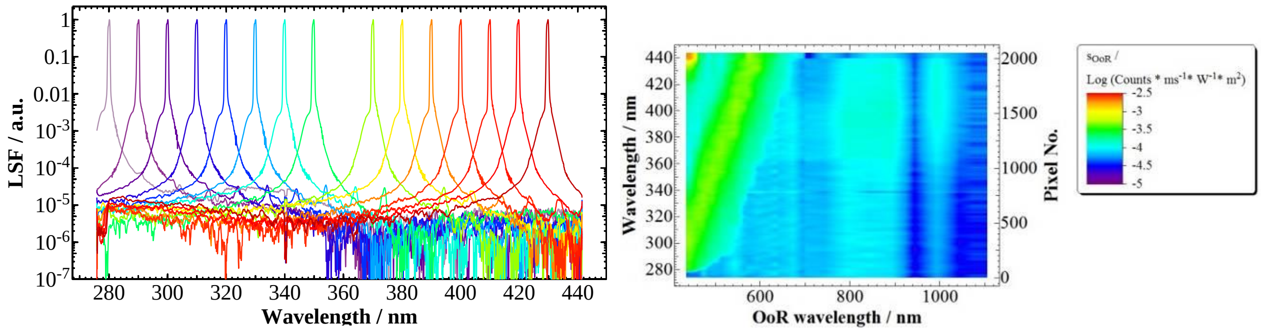


Figure 5: *a) Line spread functions of the AVOS spectroradiometer at several laser wavelengths. They are used to take into account internal stray light created within the spectral range of the instrument. b) Responsivity of the spectroradiometer with respect to irradiance at the out-of-range wavelengths, 440 nm to 1100 nm. This data was used to correct the OoR stray light contribution.*

Figure 6 shows the solar UV irradiance measured by the AVOS instrument, results of solely InR stray light correction as well as the combined OoR and InR stray light correction applied to the measurement data. For comparison purpose, the spectral irradiance measured by a reference Brewer spectroradiometer based on a double monochromator is shown as well. For this instrument, the OoR stray light contribution made about 2/3 of the whole stray light in the instrument. With the help of combined OoR and InR stray light corrections ca. 95% of the stray light contribution could be corrected.

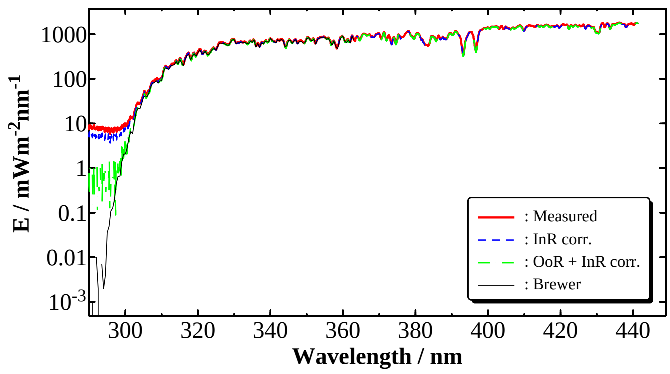


Figure 6: *Solar UV irradiance at SZA of 42° measured by the AVOS array spectroradiometer in a clear sky measurement campaign in Davos. Solid red curve is the solar spectrum without any stray light correction applied. Dashed blue and dash-dotted green curves are the solar spectra corrected for exclusively the InR and the combined OoR and InR stray light, respectively. Thin black curve shows the solar spectral irradiance measured with a Brewer spectroradiometer based on a scanning double monochromator*.

Since the full width half maximum of the slit functions of array spectroradiometers are variable with wavelength, the knowledge of the line spread function (LSF) obtained by the tuneable laser facilities are also important for the **bandwidth and wavelength homogenization** of spectra measured by array spectroradiometers. The new developed software "matShic" takes the variable slit function into account to create a bandwidth and wavelength homogenized spectrum. The algorithm is using an extraterrestrial spectrum specifically created within this project for the use of "matShic".

Both, the new extraterrestrial spectrum and the full software code implemented in Matlab are available from the project web-page. During the Intercomparison in July 2014 in Davos the end-users were introduced and trained to use the software to homogenize their solar UV spectra.

Summary: Objective achieved: One major problem when using array spectroradiometer for solar UV measurements is the contribution of stray-light. New Methods and devices to correct for the out-of-range stray light of solar UV array spectroradiometers has been developed and are now available for the community. New open source software "matShic" makes it possible to homogenize spectra measured by array spectroradiometers with respect to bandwidth and wavelength. There has been uptake of the new techniques by the end-users during or at the end of the project, which enalbles the end-user to improve their solar UV data.

C) Devices for wavelength scale and linearity

Wavelength:
Accurate wavelength calibration is a key parameter for solar spectral measurements. The aimed uncertainty is below 50 pm. Typically, spectrometers are calibrated with spectral emission lines. However, for small spectral ranges only few lines are typically available. In addition some of the spectral lines are caused by multiplets (i.e. at 313 nm, 365 nm, 404 nm and 408 nm), or can have very low levels (297 nm, 302 nm and 334 nm) and cannot be used by typical solar UV spectrometers.

Within this project two different approaches were realized that allows characterizing the wavelength scale accurately all over the UV (and visible) spectral range: METAS realized devices based on different Fabry-Perot etalons; VSL developed a wavelength ruler that is based on a one-stage Lyot filter. These devices show an oscillating transmittance behavior that can theoretically be modelled knowing the optical thicknesses of the device (see Figure 7 and Figure 8). If the temperature condition are controlled (typically to better than 2 °C) and geometry is fixed (angular alignment and beam divergence better than 0.5°) the devices can be used as absolute devices and deviations of the wavelength scale can be directly identified.

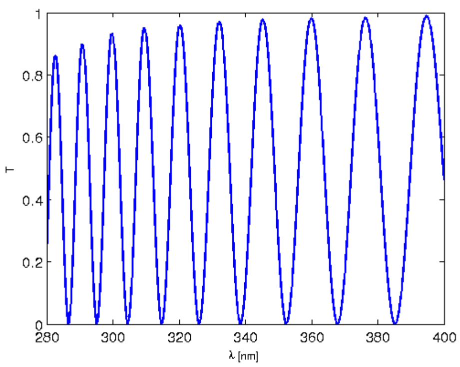


Figure 7: *Spectral transmittance of one stage Lyot filter*

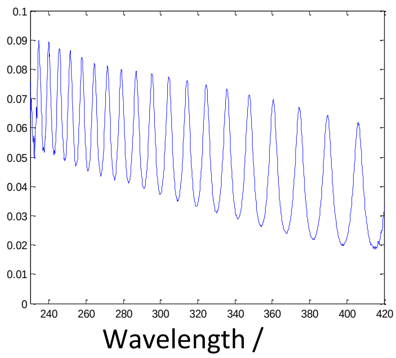


Figure 8: *Spectral transmittance of a Fabry Perot*

Theoretically the devices can be used with any kind of “white” light sources, but for best performance (i.e. to generate stable and powerful radiation in the UV range) a laser driven light source is recommended to be used. In a first step the transmittance is experimentally determined by measuring the spectral distribution of the light source with and without the filter. This transmittance is then compared to the theoretically modeled transmittance. If the optical thicknesses of the device are not known or the setup doesn’t respect the conditions for absolute device it is possible to use the device in combination with known spectral lines of a mercury lamp or one or several lasers. In this case an optimization algorithm has to be used to retrieve the effective optical thicknesses. Both devices has there advantages: Usually the modulation depth of the one stage Lyot filter is higher and therefore the device is less noise sensitive (particular for low light levels). However the setup is more bulky. The Fabry Perot etalon is a very compact optical element which can be easily integrated into an instrument. However the device is more noise sensitive. Both devices can reduce the uncertainty of the wavelength scale to below 50 pm. Figure 9 show the error of the wavelength scale of a particular spectrometer obtain be a Fabry-Perot devices. After correction the error reduces to with 20 pm (Figure 10).

Based on the research and development undertaken within this project, both devices may lead to a commercial product if a sufficient stable alignment and temperature control can be provided by an interested manufacturer.

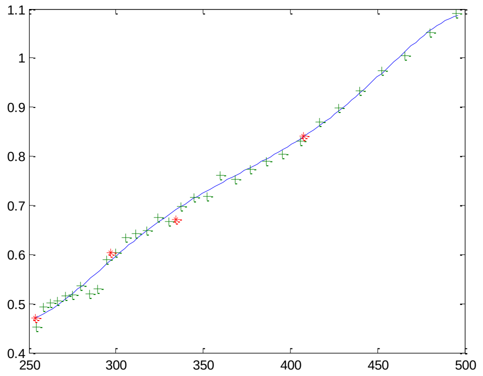


Figure 9: *measured wavelength error (in nm) in function of the wavlength (nm) prior correction.*

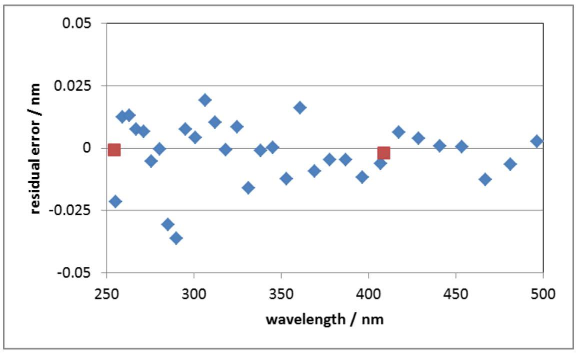


Figure 10: *Residual error after wavelength correction*

Linearity:
Terrestrial solar UV irradiance varies within the relatively narrow spectral range, 280 – 400 nm, over a large dynamic range, 5 to 6 orders of magnitude. Hence, the dependence between the measured solar UV irradiance values over the whole dynamic range and the respective signals of a spectroradiometer that is used for the measurements is required, i.e., the linearity of the instrument must be known. Residual deviations from the linear regime will yield errors both in absolute values as well as in relative spectral distributions of the measured solar UV irradiance.
In the case of compact array spectroradiometers, the linearity of the CCD instrument is typically characterized by exposing the instrument to the radiation of a stable source and varying the integration time of the detector. This is a simple but by far not complete characterization method. In fact, it accounts for the linearity of the signal processing electronics only. In principle, the linearity of such devices should be also tested by varying the spectral irradiance level over the whole dynamic range. For the radiometric characterization of the linearity of the spectroradiometers, the technical challenge consists in providing a radiation source, the spectral irradiance of which can be dynamically tuned over 5 to 6 orders of magnitude and reach the level of 1 W/m^2nm^{-1}. In the case of, e.g. halogen lamps, used for the calibration of the instruments, this is difficult.

Within the framework of this project, an approach to the linearity characterization of array spectroradiometers used for the solar UV radiation measurements has been chosen based on monochromatic sources tuneable over wide dynamic range with different setups at MIKES, METAS, PTB and VSL.

MIKES built a setup based on a single monochromator with two light sources (see Figure 11). The light exiting the monochromator is collimated and attenuated with interchangeable neutral-density filters in two consequent filter wheels. The light beam then continues to the device to be characterized through a beam splitter taking a fraction of the beam to a silicon photodiode serving as the linearity reference. PTB used for the linearity characterizations its tuneable laser source with the developed beam conditioning unit to generate high irradiance levels in the solar UV spectral range). The measurements are made also relative to silicon detector. Similar laser setup was used for the measurements at METAS as well. The setup built at VSL is mobile so that it can also be used outside of the VSL laboratories. It uses a laser with 373 nm wavelength as a source and a crossed-polarizer attenuator. The measurements are also made relative to a silicon photodiode.

To validate the VSL device before the UV intercomparison organized for the stakeholders of the project at PMOD/WRC, Davos, Switzerland in July 2014, where the VSL setup was to be used for the characterisation of the instruments, a comparison of the linearity measurements using the setups of MIKES, PTB and VSL was carried out in early spring 2014. In this intercomparison, two different array spectroradiometers were characterized at the three institutes. The measurements in irradiance-variation mode could be carried out within a dynamic range from $1{\cdot}10^{-4}$ $W/(m^2nm)$ to 2 $W/(m^2nm)$. The lowest measurable irradiance was limited by the responsivity of the instruments. Results of the linearity measurements at the NMIs were in a good agreement. Also results obtained by irradiance variation were consistent with those collected by varying the integration time of the instruments. Both instruments showed significant nonlinearities that seemed to be caused by signal processing electronics, i.e. analog-to-digital converter (ADC) and could be corrected as a function of ADC counts. Having this correction applied, no additional nonlinearity for irradiances of up to 2 W/(m^2/nm) could be detected (see Figure 12).

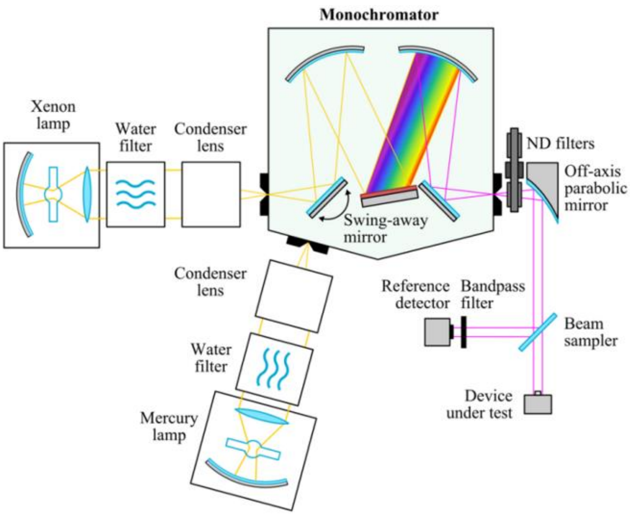


Figure 11: *Setup for linearity measurements built at MIKES*.

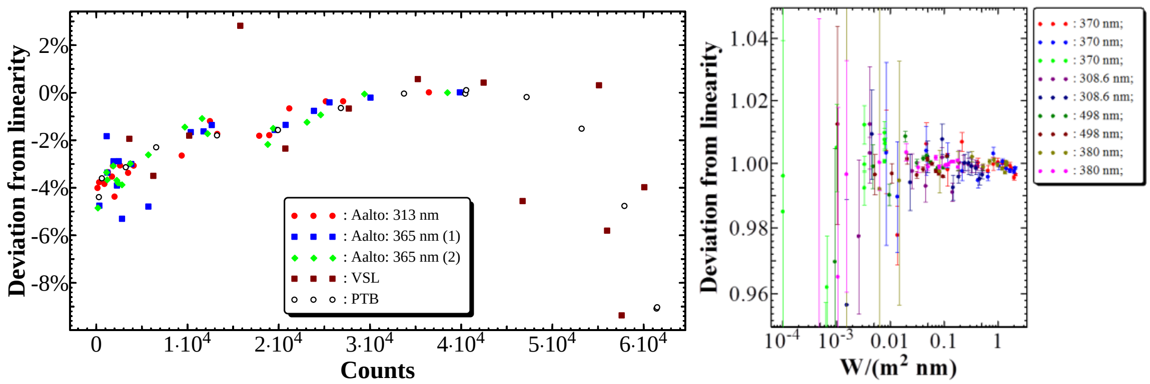


Figure 12: *Nonlinearities for an AvaSpec-ULS2048LTEC-USB2 spectroradiometer measured at Aalto, PTB and VSL and shown as a function of ADC counts. b) Residual nonlinearities of the instruments after a polynomial correction for the ADC nonlinearity. The measurements at the different wavelengths and irradiance levels were carried out at PTB.*

Summary: Objective achieved: Due to the different expertise of project partners two new approaches of determining the wavelength scale of array spectroradiometer with improved uncertainty was elaborated and can now be applied for operational use. Additionally the project partners jointly developed three methods to characterize spectroradiometers for the nonlinearity, which has been shown to be substantial regarding array spectroradiometer. The results of the research ist that the end-user community now posess new methods to find solutions to improve their array spectroradiometers as planned for the project.

3.4 Improving the QASUME reference spectroradiometer

A) Improved global entrance optics for solar UV spectroradiometers

In order to measure global UV radiation for all solar zenith angles, improved entrance optics in terms of cosine response are needed. New types of entrance optics were developed for spectroradiometers within the project. One of them is to be used with a spectroradiometer using fiber coupling, and the other one fits a Brewer spectroradiometer. To assist with the design of the diffusers, software for simulating the cosine response was developed. The new diffusers are based on novel quartz-based materials that were extensively studied.
The purpose of the diffuser element in a spectroradiometer or other radiometer is to collect radiation. Ideally the diffuser should have cosine response, i.e., for radiation directly incident on the diffuser the responsivity is at maximum, and when the angle is increased, the responsivity gradually approaches zero as a cosine of the zenith angle. The diffusers can be planar or shaped. Both designs were considered in the project.

Software for simulating diffusers

Figure 13 a) presents a model for a diffuser assembly showing all key elements that can be varied in the design process. The main component of the assembly is the diffuser element that is typically made of PTFE (also known under brand name Teflon) or Quartz. Diffuser housing attaches the diffuser element to the sensor, but it also has other functions, such as limiting the field of view. Weather dome protects the diffuser element from rain, but it also acts as a lens and therefore alters the optical behavior.
A software based on Monte Carlo algorithm was developed. The principle of the software is shown in Figure 13 b). To reduce time required for calculations, the rays are sent from the detector. Rays propagate, scatter, and are partially absorbed inside the diffuser element. This cycle is repeated multiple times until the ray encounters a diffuser–air interface, at which point the ray is split into transmitted and reflected rays. Finally, angular distribution of the rays exiting the outer surface of the diffuser, or the quartz dome, is analyzed to get the angular responsivity.

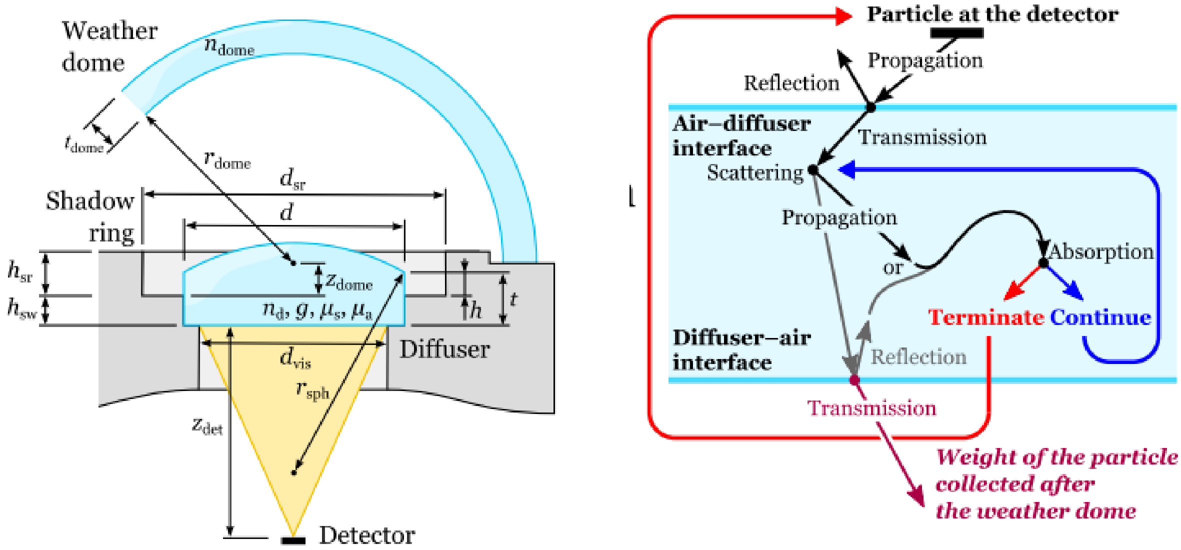


Figure 13: *a) Structure used for a diffuser assembly in the simulating software b) Workflow of the diffuser simulation algorithm.*

Optimization of diffusers by trial-and-error is time consuming. The software developed can significantly reduce this time. One initial angular responsivity measurement with the diffuser material chosen and known geometrical parameters is needed to derive material specific parameters. After this, angular behavior at other geometrical configurations can be calculated. The operating principle of the software has been published and the software is available on request at Aalto.

Material studies

The most often used material for diffuser elements is polytetrafluoroethylene PTFE. PTFE is a very good diffuser material but it has a few limitations. PTFE is a plastic and available in various forms. However, for

diffuser elements it has to be machined. As a plastic, PTFE turns slightly yellow with time. It also has a known phase transition that causes its transmittance to abruptly change as a function of temperature at around 19 °C. There are presently new quartz based materials available that can be used to make diffusers. These materials have bubbles inside the quartz that act as scattering centers. These materials overcome many of the limitations of PTFE. They are easier to get in shapes suitable as diffusers, they are stable what comes to photoyellowing, and they do not have the phase transition.
Various materials, both PTFE and Quartz based, were studied in the project. A laser based setup using a HeCd laser at 325 nm wavelength and a rotational stage was built. The samples were assembled in a prototype diffuser and measured for the cosine responsivity. Figure 14 presents the properties of these materials as a function of cosine error and transmission. Based on the results, one quartz material was chosen to be used with the new diffuser assemblies.

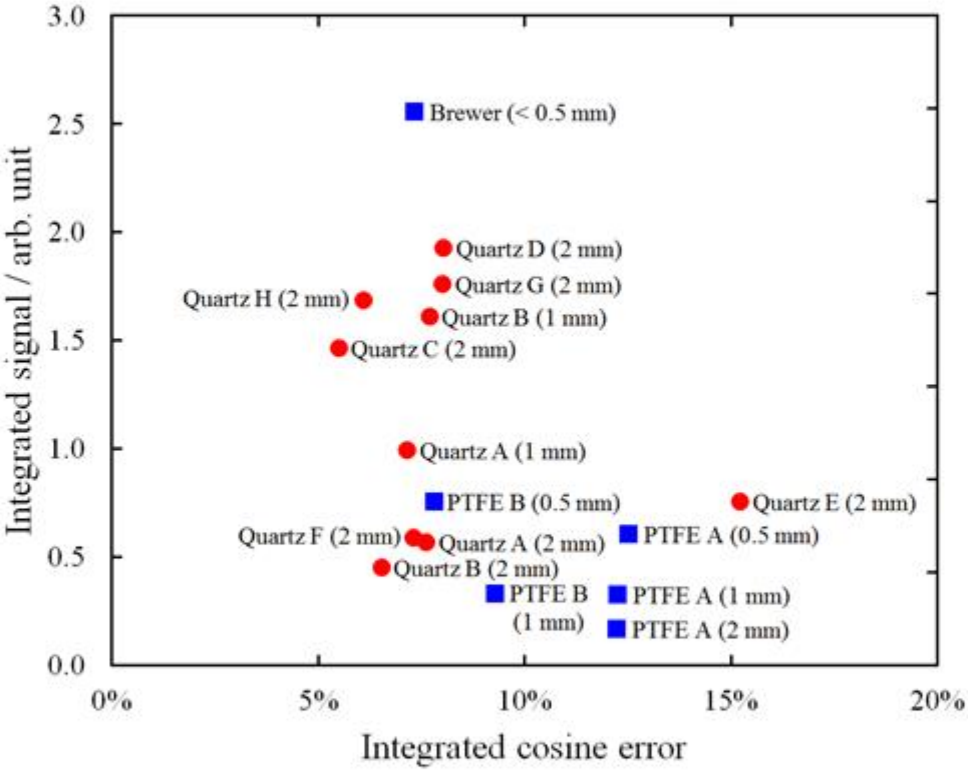
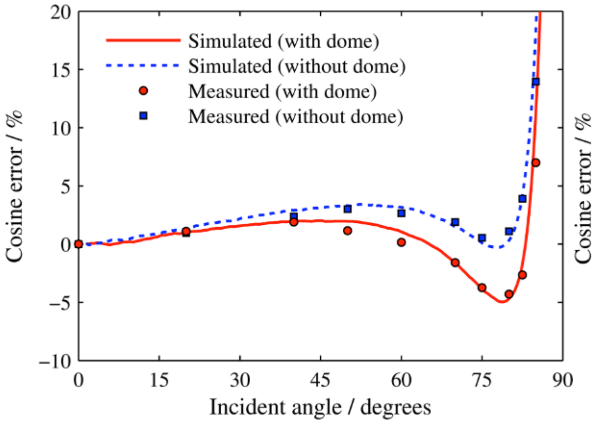


Figure 14: *The integrated signal level versus the integrated cosine error for each quartz (red circles) and PTFE (blue squares) sample at 325 nm wavelength.*

Diffusers with fiber coupling
Figure 15 shows the cosine responses for a new diffuser type that was developed for fibre-coupled spectroradiometers. The diffuser can be operated with or without weather dome and the design can be optimized for single fiber or fiber-bundles. The integrated cosine response of this design is f_2 = 1.4 %. The diffusers will be commercially available from CMS Schreder GmbH, Austria.



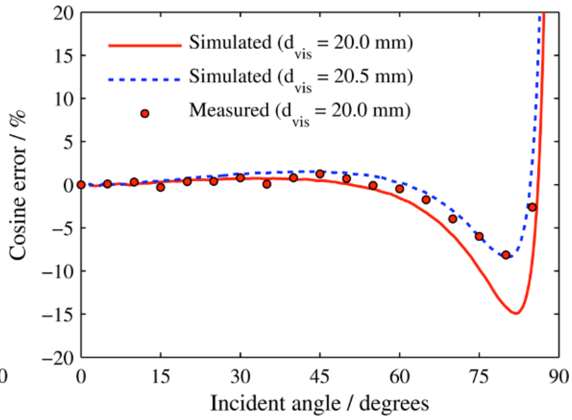


Figure 15: *Measured (symbols) and Simulated (lines) cosine errors for the new diffuser to be used with fibre entrance optics.* **Figure 16:** *Measured (symbols) and Simulated (lines) cosine errors for the new diffuser to be used with Brewer spectroradiometers.*

Diffuser for a Brewer spectroradiometer

Figure 16 shows the cosine responses for a new diffuser type that was developed for Brewer spectroradiometers. The measured integrated cosine response of this design is f_2 = 1.3 %. The diffusers will be commercially available from Kipp & Zonen, The Netherlands.

Summary: Objective achieved: New diffusors to be applied for fiber optics array spectroradiometers and Brewer scanning photometer have been developed and successfully tested within the project. As foreseen in the project, the new diffusors are available from the industrial partners, the software can be ordered on request at Aalto and the scientific background of both diffuser assemblies are published in literature to present the achievements beyond the state of the art.

B) QASUME II

In order to support more end-users with portable reference in-situ calibrations, a second portable reference spectroradiometer was developed by SFI DAVOS, based on the current QASUME spectroradiometer system. The improvements to the original instrument were developed in this project jointly with CMI, CMS and AALTO. They consisted of a new detector system based on two different technologies (solid state detector and photomultiplier) ensuring a better stability, and the development of a new entrance optic to reduce the uncertainties due to the deviations of the angular response from the nominal cosine response.

The Solid state detection system for QASUME II:

A new hybrid detection system (HDS) has been developed by CMI and SFI Davos in the framework of this project with the aim of improving the overall performance of the current reference UV solar spectroradiometer (QASUME) photomultiplier. The typical irradiance levels at the output of the double scanning monochromator (DSM) of QASUME range from 1 fW at 280 nm to about 1 nW starting from 320 nm to 400nm. The HDS is composed of latest generation UV-optimized photocounter (PC) from Hamamatsu H11890 in conjunction with state of the art Silicon photodiode (Si) with custom made high sensitive electronics based on the switched integrator principle (SIA). Both detectors PC and Si are impacted by a portion of the DSM output radiation that can be regulated adjusting their vertical position relative to the DSM output slit.
The PC H1189 is a USB-controlled small factor device ideal to fit in the DSM output slit with a sensitive area of 50 mm^2, it has a peak sensitivity at 400 nm of 5·105 counts/pW that drops to 3·105 counts/pW at 280 nm which is sufficient to detect even the lowest range of the solar UV spectrum . Its dark counts is below 40 counts/s and is linear up to 2·106 counts/s (Figure 17).
A microcontroller-driven switched integrator amplifier (SIA) has been developed by CMI which offers up to 7 order of magnitude of dynamic range and integration time generated on board that can be set by a controlling PC. In order to further extend the sensitivity of the SIA-based detection system to lower power levels a small area/low dark current silicon detector has been selected (Hamamatsu 1227 33BQ). The timing constraint of

1s for each measurement point given by the QASUME standard measurement procedure led to the selection of a 1pF integration capacitor with PFTE as dielectric material that offers the lowest leakage current, a critical parameter for the switched integrator amplifier in this context. Particular care has been taken to minimize any source of leakage current in the circuit: all the critical electric paths are in air. Furthermore to reduce noise pick up the connections between photodiode and amplifier have been made as short as possible and the all system is enclosed in a grounded aluminum shield. The latest prototype has shown excellent noise performance 3 fW/Hz½ and stability better than 5 fA of dark signal in 10 hours. The stability of the dark signal makes it possible to measure its value only at the beginning of the solar spectrum measurement.
The hybrid detection system offers the high sensitivity of the PC necessary to detect the portion of the solar UV spectrum with irradiance level below 0.1 pW in conjunction with the stable and linear behavior of the Si to cover the region with higher irradiance level (typically above 315 nm).

Furthermore, within the project INRIM achieved progresses in the development of ZnO detectors with reasonable response time, dimension of about 500 microns and 1000 times higher response than silicon detectors and a report was generated describing the characterization. It was so far not possible to obtain ZnO detectors with simultaneously high responsivity and short response times, which were suitable to be implemented in the QASUME II system. However, different manufacturing processes will be investigated to optimize the ZnO detectors to be applied for different further applications in the field of measuring low level irradiances.

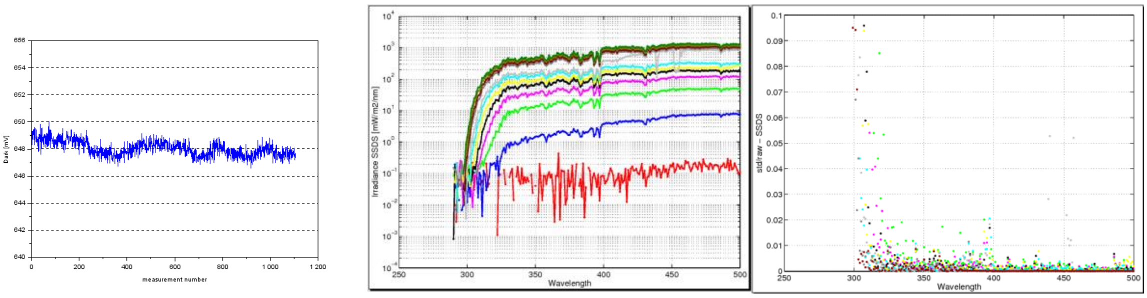


Figure 17: *a) Si dark signal stability over 40 days (integration time 0.1s), b) UV solar spectrum with Si detection system, c) Noise Si detection system.*

Summary: Objective achieved: A second portable reference spectroradiometer was developed, based on new detection systems and new diffusor material for the entrance optics. This new instrument and the improved existing portable reference (QASUME) allow more visits or end-users instruments worldwide to ensure the quality of solar UV measurements as aimed with this project. The new detection system offers the opportunity to detect low irradiance levels beyond the state of the art.

C) Adaptation of a Fourier transform spectroradiometer as reference instrument for solar UV irradiance measurements

The project aimed to investigate to ability of a different type of spectrometer (Fourier-Transform Spectroradiometer (FTS) to be used as a new portable reference. The aim was to offer high wavelength accuracy, low uncertainties for solar UV irradiance measurements and to perform fast measurements under rapidly varying environmental conditions ("cloudy sky"). The work of this task was a feasibility study for testing the suitability of an FTS as a possible alternative to scanning spectroradiometers like QASUME.

PTB has adapted and validated a commercially available Fourier Transform Spectrometer (FTS) for solar UV irradiance measurements. The first step was to modify the FTS – a Bruker FTS Vertex 80v – for measurements in the ultraviolet spectral range 280 nm to 400 nm by including UV detectors and an UV beam splitter. Furthermore, the FTS has been equipped with a global entrance optic to perform solar irradiance measurements. The spectral irradiance responsivity of the FTS equipped with a global entrance optic has been calibrated against a high-temperature black-body radiator and a secondary spectral irradiance standard lamp. Finally, the usability of the spectroradiometer for solar UV irradiance measurements has been investigated.

Fourier transform spectroradiometers have the capability to improve the dissemination of absolute irradiance scales due to specific advantages.

- Fourier transform spectrometers have a high throughput because of the circular aperture of these instruments (Jacquinot advantage). Furthermore, there are no diffraction losses to higher-order spectra as it is the case in grating spectrometers. It has been found that even semiconductor detectors (GaP or Si) can be used for calibrated solar irradiance measurements down to 360 nm because of the high throughput. However, below 360 nm a photomultiplier tube is necessary just as with QASUME portable travel standard.
- FT spectrometers cover broad spectral ranges with high resolution and high wavelength accuracy. Furthermore, the whole spectrum is measured simultaneously with a rate of typically one or two spectra per second at the chosen spectral resolution which is well below the resolution of QASUME. However, to get a reasonable SNR it is necessary to average the measured interferograms. It is an advantage that these calculations can be done flexibly after the measurement dependent on the demands on the SNR and on the solar variability. Interferograms obtained under stable solar irradiance conditions can be averaged over longer time periods. On the other hand, if the solar irradiance is quickly varying, the interferograms can be averaged over shorter periods to obtain the largest possible SNR.
- Modern FTS often use integrated HeNe lasers for the measurement of the position of the moveable mirror of the FTS interferometer. This laser can be used for the wavenumber calibration of the FTS. In this way, the wavenumber scale of the FTS is inherently traced to the SI with low uncertainties.

The following table shows the standard uncertainty of the calibration of the spectral irradiance responsivity of the FTS with a photomultiplier tube (Hamamatsu H10723-210) including a spectral UV filter (Schott UG5) performed in front of a black-body radiator at a temperature of 3010 K. The interferograms have been averaged over a time period of 20 min.

	Relative Standard Uncertainty / %			
Uncertainty contribution	**at 300 nm**	**at 350 nm**	**at 400 nm**	**at 500 nm**
Black-body temperature T	0.5	0.43	0.38	0.30
Black-body aperture diameter $2r_1$	0.50	0.50	0.50	0.50
Global entrance optic aperture diameter $2r_2$	0.0002	0.0002	0.0002	0.0002
Distance between black-body aperture and entrance optic d	0.43	0.43	0.43	0.43
Measurement noise	2.2	0.27	0.22	2.3
Combined uncertainty	**2.4**	**0.84**	**0.79**	**2.5**

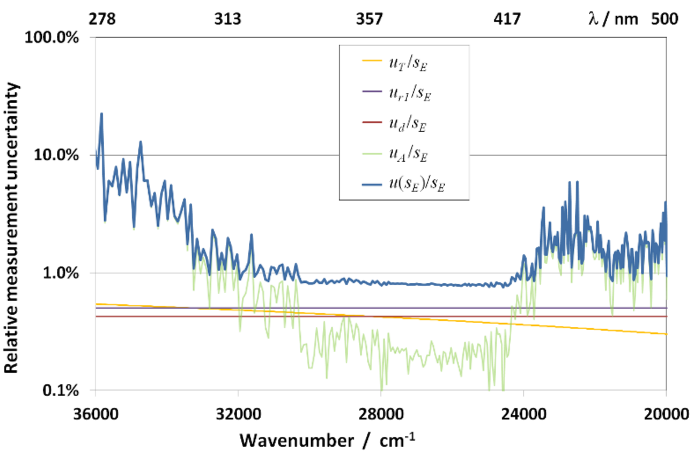


Figure 18: *Standard uncertainty of the spectral irradiance responsivity measurement when using the black-body radiator BB3200pg at a temperature of 3010 K for the FTS with photomultiplier tube and spectral filter UG5.*

The standard calibration uncertainty is around 0.8% in the wavelength range 320 nm to 420 nm. The uncertainty increases below 320 nm and above 420 nm because of the limited spectral range of the used photomultiplier tube and because of the limited spectral transmission range of the used spectral filter which is necessary to block the radiation from the internal HeNe laser and the broad solar radiation outside the investigated spectral range. A more suitable photomultiplier tube and spectral filter should be chosen for dedicated measurements below 300 nm. For comparison, the uncertainty of the QASUME calibration is 0.75% when using a transfer standard lamp. The uncertainty for an FTS calibration against a transfer standard is about 1%. It has to be mentioned that even with the FTS a daily irradiance responsivity recalibration against a transfer standard is recommended because of the use of the less stable photomultiplier tube as it is the case with QASUME.

The uncertainty budget for spectral solar UV irradiance measurements when using the FTS with a photomultiplier tube and spectral filter UG5 is shown in the following table. The measurements have been performed in Berlin on 03-Apr-2014, 10:30 UTC, and are averaged over 12 minutes. The spectral resolution has been reduced to the resolution of QASUME. The uncertainty for a solar UV irradiance measurement using the FTS is estimated to about 1.5% in the spectral range from 310 nm to 400 nm.

	Relative Standard Uncertainty / %			
Uncertainty contribution	**at 300 nm**	**at 350 nm**	**at 400 nm**	**at 500 nm**
Radiometric calibration	2.4	0.84	0.79	2.5
Transmittance of entrance optic[a]	0.60	0.60	0.60	0.60
Angular response of entrance optic[a]	0.40	0.80	0.80	0.80
Stability of spectral responsivity	1.4	0.50	0.79	4.0
Measurement noise	3.7	0.24	0.30	3.1
Combined uncertainty	**4.8**	**1.4**	**1.5**	**5.8**

[a]taken from QASUME uncertainty (solar zenith angle less than 60°)

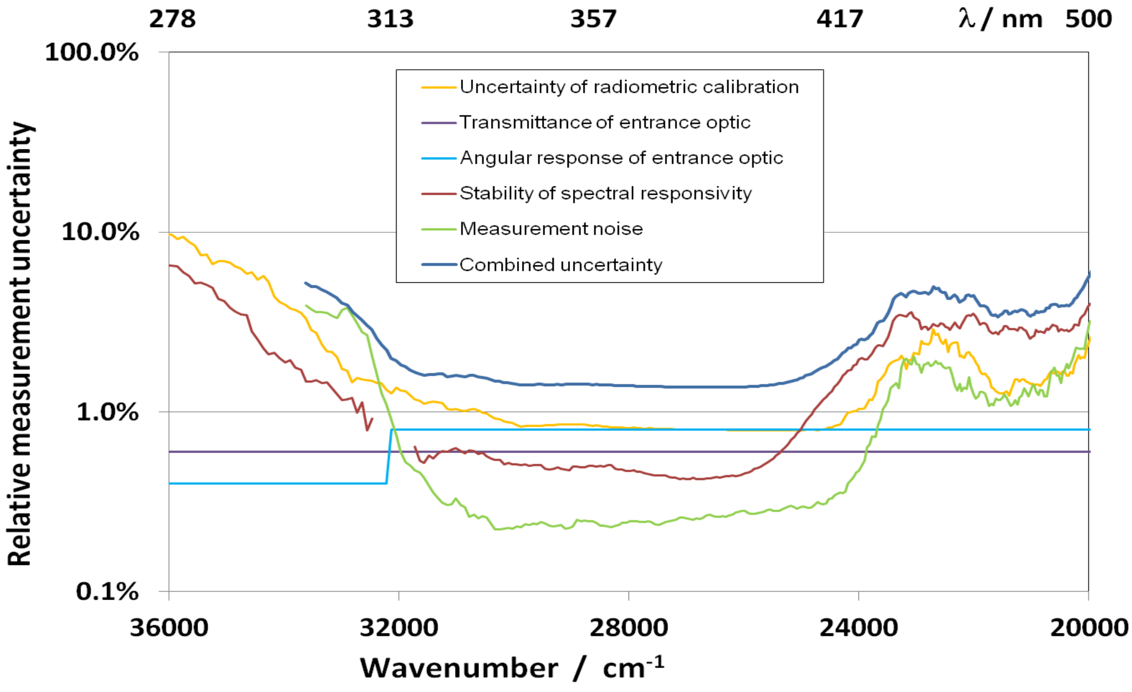


Figure 19: *Measurement uncertainty for a spectral solar UV irradiance measurement when using the FTS with photomultiplier tube and spectral filter UG5.*

The main characteristics of the FTS are:

- The wavelength scale of the FTS is direct traceable to the SI with an uncertainty ≤ 9 pm in the range 250 nm to 400 nm. There is no on-site recalibration or wavelength check necessary. The wavelength resolution can easily be chosen. The measurements have been performed with a spectral resolution of 160 pm to 320 pm in the spectral range from 280 nm to 400 nm. However, a resolution down to 2 pm is possible with the Bruker Vertex 80v.
- Semiconductor detectors are usable for absolute spectral solar UV irradiance measurements down to 360 nm. Below 360 nm a photomultiplier tube in combination with a spectral filter has to be used for absolute spectral solar UV irradiance measurements. The standard measurement uncertainty for solar irradiance measurements with the photomultiplier tube is about 1.5% in the spectral range from 310 nm to 400 nm (depending on spectral filter and solar variability).
- FTS interferograms can be averaged flexibly after the measurement depending on noise and solar variability. This enables an optimization of the uncertainty.

Summary: Objective achieved: The potential of the Fourier transform spectrometer Bruker Vertex 80v for use as a reference instrument for the measurement of solar surface UV irradiance has been investigated. The results revealed that the current status of the development may not allow using this technology as a reference instrument yet, the low sensitivity in the UV range needs to be further investigated.

3.4 Investigating the suitability of new technologies for solar metrology

A) Hyperspectral Camera

Deviations of global entrance optics from the desired angular response (cosine) seriously affect the accuracy of UV radiometers. In order to measure the corrections and implement a valid model of the emissivity of the sky measured by radiometers, it is important to realize an instrument, used as a reference, which collects as much information as possible of spectral and spatial distribution of sky irradiance. Ideally, the instrument should be able to observe the entire sky with high spatial resolution generating a calibrated emissivity spectrum in the UV for each point of the image at a given time. Furthermore the instrument must be compact and transportable. In practice the real instrument is a trade-off between spatial resolution, spectral resolution, measurement time and portability.

INRIM have realized a camera, based on a large convex spherical mirror coupled with quartz lens objective and a special CCD sensor, capable of observing the whole sky. A filter wheel made with 11 band pass filters allows to generating the irradiance spectrum of the light coming from each direction. Compared to classical spectro-goniometers the instrument generates a complete spectral map of the sky in few seconds allowing dynamic sky monitoring and thanks to its compactness can be easily transported allowing in situ calibrations.

Realization

The instrument is based on a UV sensitive CCD Camera equipped with a motorized filter wheel holding 11 filters having 10 nm nominal width and being uniformly distributed in the 300-400 nm range (see Figure 20)

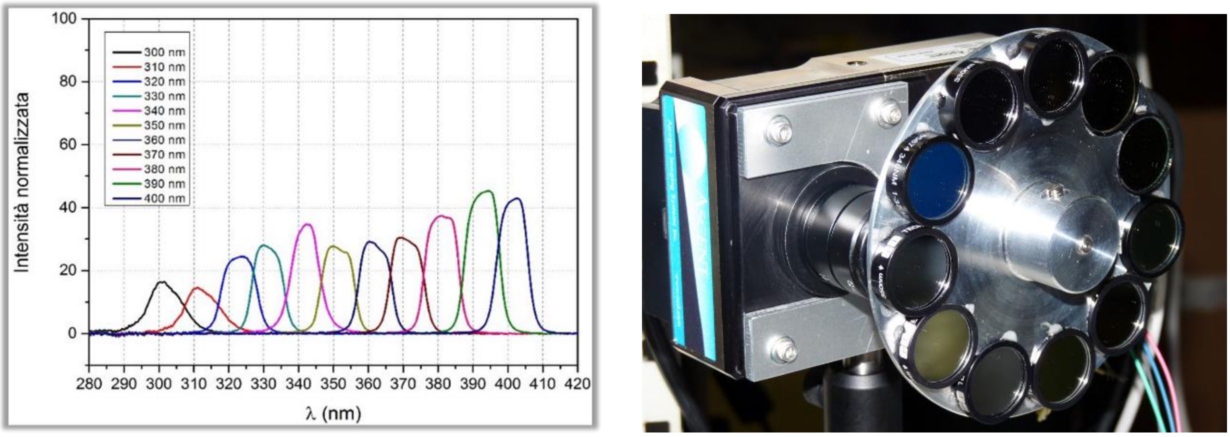


Figure 20: *Transmissivity function of the selected band-pass filters (left) mounted on a motorized filter wheel designed to minimize the shadow created by the camera itself (right)*

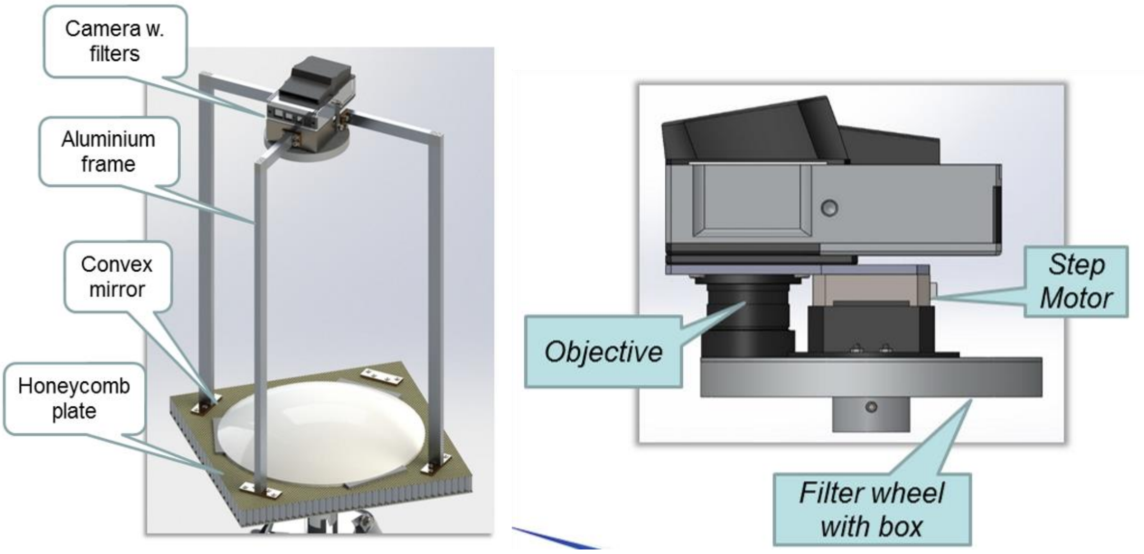


Figure 21: *Structure of the assembled instrument (left) with a detail of the camera assembly (right)*

Calibration

The mirror was made from glass and is coated with aluminium protected with quartz. The diameter of the mirror is 300 mm and the curvature radius is 262 mm. The objective of the camera is made from quartz lenses. The base of the instrument is a honeycomb plate on which the mirror is placed and an aluminium frame is fixed to hold the camera in the right position. The complete structure can be mounted on a tripod. A scheme of the instrument is in Figure 21.

The instrument has been calibrated for its spectral response and for spatial response. Spectral response calibration has been calibrated in collaboration with REG(IMU). The Musky (Multispectral UV sky camera) has been compared with a reference spectro-goniometer installed on the roof of Innsbruck Medicine University. The Musky has acquired several series of multispectral pictures while at the same time the reference spectrometer acquired a multitude of spectra in different portions of the sky (Figure 22). Later the results have been elaborated by comparing the portion of the multispectral images corresponding to the portion recorded by the reference instrument at the about the same time. The reference spectra have been resampled and weighted in order to have the same measurement spectral interval as Musky and the two curves are compared. The ratio of the two curves gives the calibration factor for each wavelength and each zenith angle. The variability obtained with the process is of the order of 10 % and can be mostly due to the non-ideal temporal coincidence of the measurements. Further spectral calibration will be carried out in the laboratory with LDLS source.

Spatial response has been calibrated by geometrical considerations supported by experimental realizations. The pixel to angle conversion matrix has been built with an uncertainty less than 1°.

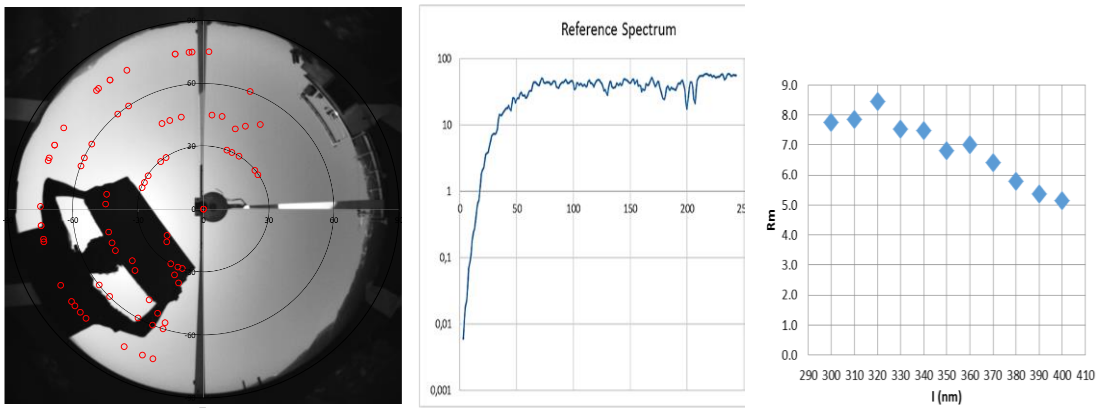


Figure 22: *One of the images taken with the Musky with the position acquired with the reference spectrometer (red dots). The ratio of the measurements allows to generating the calibration function (right).*

Dynamic range

The dynamic range is limited by the CCD and the camera (Ascent 4000 equipped with cooled Kodak KAI 4022 sensor). Because of the different responsivity versus wavelength and the variation in sky emissivity, the intensity of the image changes by a factor 100 or more from 300 to 400 nm. To compensate this while keeping good dynamic range for each image, acquisitions at different exposure times are recorded. In Figure 22 a typical recording set is displayed. From this, the spectrum of each of the ≈ 30 k pixel of the image is obtained by the combination of the three series normalized for the exposure time.

Specifications

Sky coverage: up to 83° Zenith angle
Spatial resolution: better than 1°
Spectral resolution: 10 nm
Spectral range: 300-400nm in 11 bands
Overall dimensions: 35x35x70 cm (tripod excluded)
Weight: < 10 kg
Image output: 512x512 pixels at 16 bit

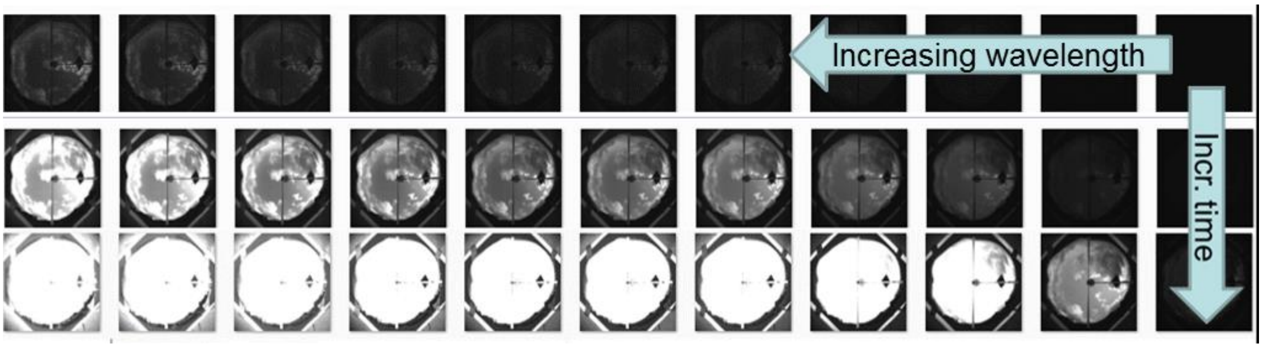


Figure 23: *A measurement set made from 33 pictures. Each row is the wavelength series decreasing from left to right from 400 to 300 nm. The exposure time is respectively 1, 10 and 100ms for the three rows.*

Hyperspectral Imaging in the UV

Based on previous experience at INRIM on hyperspectral imaging in the visible and IR regions experiments have been carried out to realize a UV fisheye hyperspectral camera in the UV. The hyperspectral approach has the advantage of high spectral resolution combined with high spatial resolution. Different prototypes have been realized but because of the uncertainty of the preliminary results it has been decided to realize the multispectral camera described above. Nevertheless promising results have been obtained. In Figure 23 an outdoor scene is recorded and elaborated with the INRIM's proprietary hyperspectral imager in the UV region. Both the spectral and spatial resolution can be appreciated.

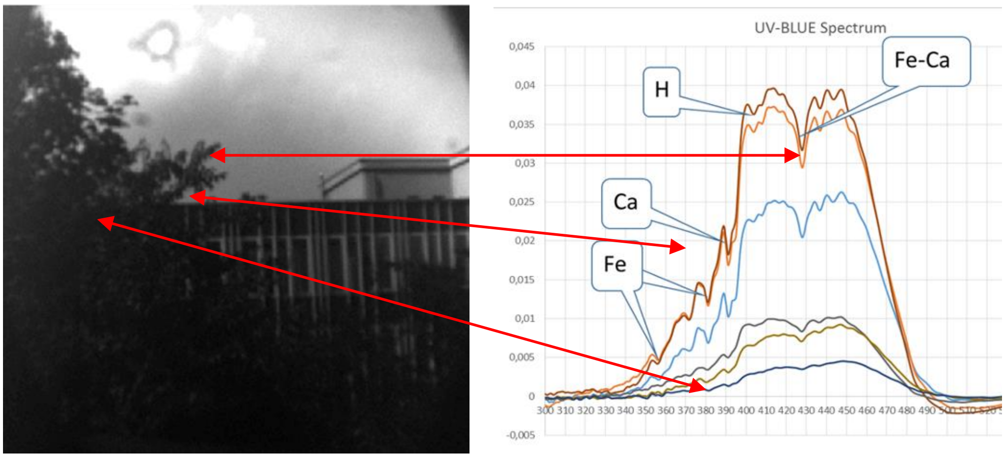


Figure 24: *Hyperspectral imaging in the UV. Left: a frame of the recorded scene, right: the spectra obtained for different pixels of the image.*

Summary: Objective achieved: In order to improve the cosine error off global entrance optics, an instrument was developed that collects as much information as possible of spectral and spatial distribution of sky irradiance. The built, characterized and tested instrument is now available for scientific investigations in the field of solar UV observations and can contribute to retrieve an improved cosine error, measuring the diffuse part of the global irradiance separately with a high spatial resolution in many different wavelengths. Researchers in the field of UV measurements are now applying this new system, resulting in a better understanding of the cosine response.

B) MEMS-Array-Spectroradiometer:

The solar ultraviolet spectrum captured by commercially available diode-array spectroradiometers is dominated by stray light from longer wavelengths with higher intensity. The implementation of a digital micro mirror device (DMD) in an array spectroradiometer enables the precise selection of desired wavelengths as well as the ability to reduce spectral intensity via selective mirror modulation, both reducing long wavelength stray light. As a collaborative work of CMI Prague, Czech Republic, SFI Davos, Switzerland, MSL, New Zealand and with cooperation with NIST Boulder, USA and Principal optics, UK, a prototype consisting of off-the-shelf components has been designed and assembled to verify the validity of the base concept. Furthermore the characterization measurements have been performed to confirm the throughput and image qualities such as spectral resolution and astigmatism.

Diode-array spectroradiometers provide a low-cost and effective alternative to expensive scanning double monochromator, yet their dynamic range is insufficient to accurately measure ultraviolet (UV) radiation. While diode-array spectroradiometers can complete the acquisition of the entire UV solar spectrum in few seconds, the portion of the spectrum below 300 nm is dominated by the stray light signal. The stray light originates from radiation with high intensities at longer wavelengths, which affects the signal at the detector pixels for wavelength regions with low irradiance levels. The high dynamic range of atmospheric solar UV radiation (approx. 6 orders of magnitude depending on atmospheric conditions between 290 nm – 440 nm) results in considerable bias of the low intensity at around 290 -320 nm measurements with conventional array spectroradiometers. In a previous study, it was demonstrated via libRadtran modeling that there is a 4 order of magnitude stray light contribution from wavelengths above the UV range of interest (290nm to 440nm) that would interfere with an accurate UV spectral intensity measurement. While the use of DMD's in spectroradiometer applications has been previously explored for visible light and infrared applications, in this project a novel micro mirror diode array spectroradiometer (µ-MUV) is assembled from off-the-shelf components to demonstrate the validity of the modelled stray light reduction concepts in the ultraviolet range. Initial modeling of a prototype using Zemax was used as the basis for the experimental design (Figure 25). The optical design was carried out with the main aim to preserve throughput of the optical system and to optimize its spectral resolution. The key elements of the model and subsequent prototype consist of a plain ruled 600 G/mm diffraction grating, a 1024x720 pixel XGA DLP micro mirror chip, a back-lit 2048x250 pixel CCD detector, and four spherical mirrors. The astigmatism generated by the use of off-axis spherics is exploited by binning the CCD camera's vertical pixels, effectively using it as a 1-dimensional array (Figure 26).

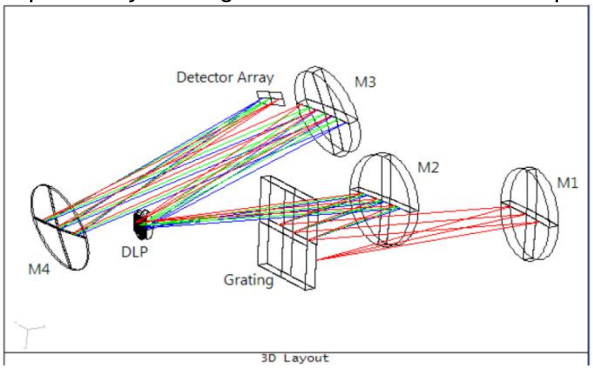


Figure 25: *Zemax schematic of the µ-MUV protot ype composed of 4 spherical mirrors, a 600 G/mm diffraction grating, DLP micro mirror chip, and CC D detector.*

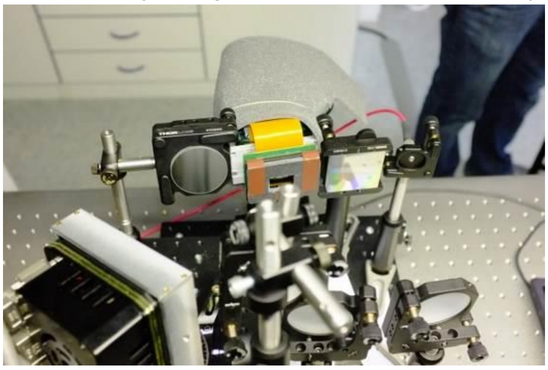


Figure 26: *Experimental setup of the µ-MUV prototype*

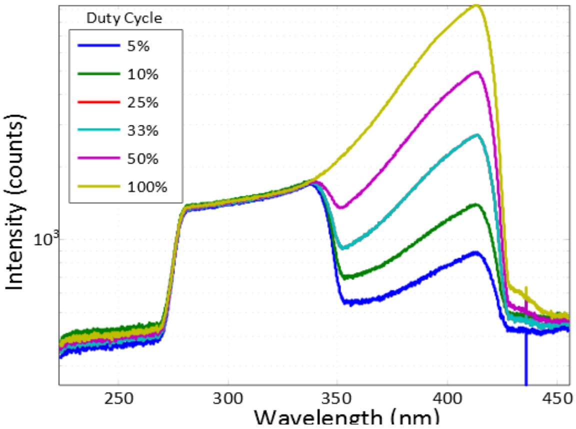


Figure 27: *Longer wavelength light modulate d via DMD to demonstrate dynamic range lev eling and stray light reduction.*

Implementation of a digital micro mirror device (DMD) could significantly reduce the impact of stray light using two techniques. The first includes levelling the dynamic range of the incoming radiation by selective wavelength modulation. The undesired wavelengths are modulated at high frequency creating an effective repetition rate, reducing their intensity and stray light contribution. The second method is to select a precise range of wavelengths using the DMD as an effective bandpass filter.

Using the whole DMD as just a mirror in the “on” position we are able to determine device specific parameters such as spectral resolution, bandwidth, and the slit function. Using a 407 nm laser the full width half maximum (FWHM) of the slit function of the spectroradiometer was determined to be 2 nm. This could be improved with reduced fiber width, effectively reducing the slit function. The spectral resolution was determined to be 0.2 nm based on the incident wavelength range and number of pixels illuminated. Basic light modulation techniques were implemented for initial stray light reduction, where 50% of the DMD was modulated at various frequencies. The portion with longer wavelengths was chosen to flatten the dynamic range and reduce stray light in the shorter wavelength region. Duty cycles ranging from 5% to 100% are shown in Figure 27. As the duty cycle decreases, the range in the “on” portion from 290 nm-350 nm subsequently decreases by a fraction of a percent. It is interesting to note that while the contribution in this range does demonstrate some stray light reduction, the reduction in amplitude of the background signal is more pronounced. Additional data were taken where spectral cut-off filters were placed directly in front of the detector identifying stray light contribution from wavelengths above 550 nm. Spectral range selection was demonstrated by scanning the DMD then reconstructing the full spectrum. Lastly, physical baffling was implemented to further reduce stray light contribution.

Summary: Objective achieved: The prototype of a novel array spectroradiometer based on DMD proofed the concept of light modulation for UV measurements. The prototype showed to the instrument developing community that the principle, which is beyond the state of the art of measuring radiation in general, may be applied for commercial instruments. So far no commercial product is produced based on this technology.

C) Array spectroradiometer with improved stray light using band pass filter

Array spectroradiometers suffer from stray light that can lead to large error in the short wavelength UVB range (280 - 300 nm) of the Sun spectral irradiance. Stray light can be characterized (spectral line-spread function method) using a tuneable laser and correction of the measured spectrum can be performed, by applying for instance the Zong method, to get the true spectrum. Even though improvement of measurement can be achieved using this method, the uncertainty is still large because of the uncertainty on the line spread-function characterization. Therefore a physical reduction of the stray light contribution is necessary to improve the SolarUV irradiance measurement uncertainty. This can be achieved by limiting the wavelength spectral range of the incoming beam inside the spectroradiometer (out of range). LNE has proposed based on a feasibility study from SFI Davos and other project partners to modify a commercially available array spectroradiometer (Jobin Yvon VS140) by adding specific bandpass filters. The spectroradiometer configuration is shown on figure 28. Two irradiance optics fitted with dedicated filters are connected to the spectroradiometer using a 2x1 fiber light guide.

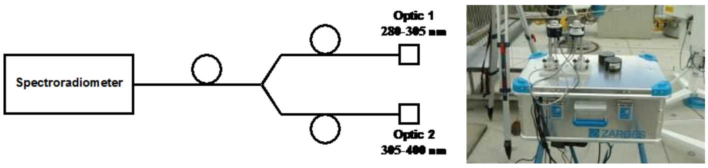


Figure 28: *Configuration and picture of the stray light improved array spectroradiometer.*

The optic 1 is fitted with a the SEMROCK 292 nm interference filter and a 3 mm thick UG11 filter for the measurement on the 280 nm-305 nm spectral range. The optic 2 is fitted with a 0.5 mm thick UG11 filter for the measurement on the 305 nm-400 nm spectral range. The optics is equipped with shutters to allow alternative measurements in the two spectral ranges. The modified spectroradiometer is characterized for stray light contribution by PTB using the tuneable laser facility that is not available at LNE.

The spectroradiometer has been tested during the comparison held at PMOD/WRC in Davos in July 2014. Typical spectrum of the sun is shown on Figure 29 a). The results show that the spectroradiometer has a four decade dynamic range measurement capability allowing good measurement down-to 300 nm and has shown superior results when compared to traditional array spectroradiometers participating at this intercomparison.

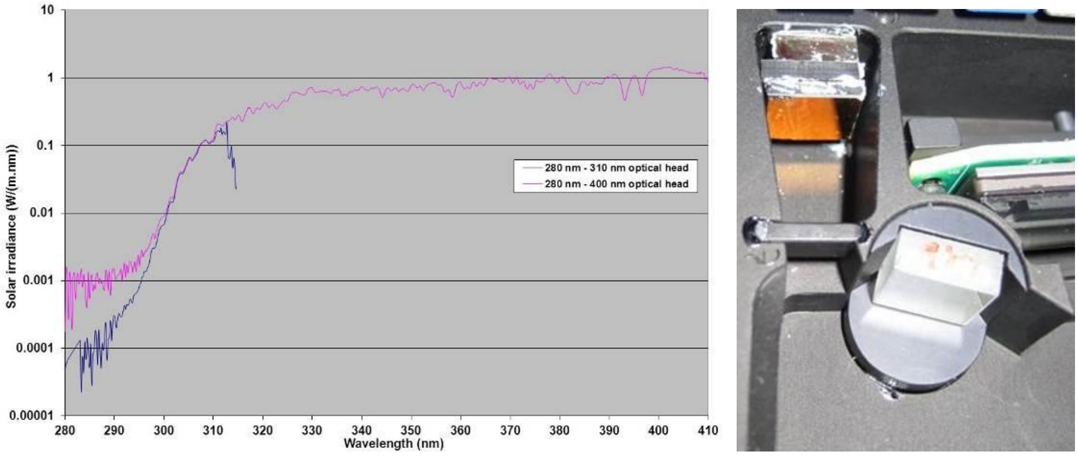


Figure 29: *a) Sun irradiance measured during the comparison in Davos revealing that one order of magnitude of stray light reduction can be achieved with this setup. b) DUG11X filter placed after the entrance slit of the AVOS array spectroradiometer.*

In the same context of physically reduce stray-light contribution using band pass filters. SFI Davos modifies a commercially available array spectroradiometer “AVOS” from Avantes with a DUG11X filter which blocks solar irradiance above 390 nm. Contrary to the setup by LNE the filter was placed in the instrument in the light path (Figure 29 b) showing similar results.

Summary: Objective achieved:The project aimed to investigate technical solutions to reduce the impact of straylight in array spectroradiometer. The spectroradiometer design using filters showed a significant stray light reduction and the principle can be implemented and adopted by an instrument manufacturer to improve their instruments. So far ther was no commercial uptake of this technology.

D) Intercomparison

The new techniques and methods developed within this project and described above were applied to end-users array spectroradiometers during the UV intercomparison held at Davos, Switzerland from 7 to 16 July 2014.

Using the new techniques following activities were performed:

- Comparison of global solar irradiance measurements from different instruments (array spectroradiometer, scanning spectroradiometers) with the QASUME reference spectroradiometer.
- On-site absolute spectral irradiance calibrations using traceable transfer standards,
- Linearity and wavelength characterizations of array and scanning spectroradiometers using new developed wavelength calibration devices,
- Slit function determinations using various laser sources,
- Angular Response determination of global entrance optics.

The results of the intercomparison revealed that array spectroradiometers, currently used for solar UV measurements, show a large variation in the quality of their solar UV measurements. Figure 37 presents the blind comparison of the end-users instruments as they are prepared by the operators for best possible measurements. The participants who were involved within the project showed significantly improved results than end-users who did not yet apply the new methods and techniques.

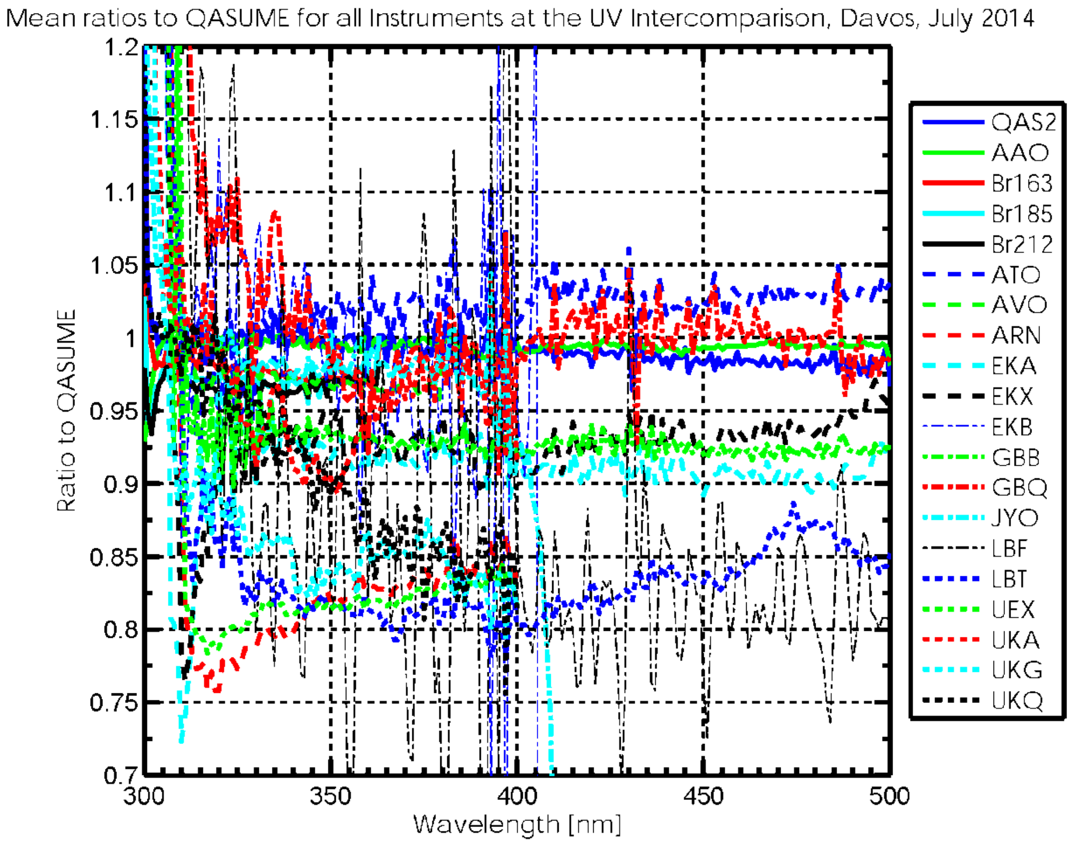


Figure 37: *Comparison of mean spectral ratios between the end-users instruments participated at the final intercomparison and the QASUME reference spectroradiometer.*

However, the results concerning array spectroradiometers are comparable to the overall quality of scanning spectroradiometers 10 years ago. In the meantime the quality of these spectroradiometers have been significantly improved and homogenized to a European wide comparable level. Starting from the activities from this project a similar homogenization can now be initiated for array spectroradiometers.

Summary: Objective achieved:The intercomparison showed that the new techniques developed in the project demonstrated the potential of using cost-effective array spectroradiometers for solar UV measurements. The results concerning array spectroradiometers are comparable to the overall quality of scanning spectroradiometers 10 years ago. In the meantime the quality of these spectroradiometers have been significantly improved and homogenized to a European wide comparable level. Starting from the activities from this project a similar homogenization can now be initiated for array spectroradiometers.

The project aimed to shorten the detector based traceability chain of the solar UV measurements to the SI unit and reduce the associated transfer uncertainties e.g. for the portable reference spectroradiometer known as 'QASUME' to provide traceable solar UV irradiance measurements with an uncertainty of 2 %.

The project further aimed to support the use of cost-effective array spectroradiometers in UV monitoring networks, where significant progress is needed in the characterisation of these devices.

4 Actual and potential impact

4.1 Metrology Achievements

Within this project metrological achievements for improving the traceability of solar UV measurements, stray light characterization and reduction, the wavelength calibration and the non-linearity determination of array spectroradiometers have been made.

- Concerning traceability of the spectral solar UV irradiance measurements, the goal was to realize a detector-based traceability chain allowing the calibration of the spectral responsivity of the portable solar UV spectroradiometer QASUME, operated by SFI Davos as world reference. The new metrology achievement of this calibration is the use of a reference detector. It was shown that the traceability route to the primary standard of optical power, the cryogenic radiometer, could be shortened. The associated uncertainties were 1% and validated using two independent methods. This achievement was highlighted at the recent NEWRAD conference held in Helsinki, 23-27 June 2014, with an invited oral presentation by one of the project partners. One additional outcome of the QASUME calibration campaigns at PTB using two in principle different calibration methods was that new information about the performance of the QASUME instrument was obtained.

  Furthermore, the project revealed that the Laser Driven Light Source (LDLS) can be used as a portable reference for calibration of solar UV spectroradiometers in the field to achieve similar uncertainties as with standard portable halogen lamps. Remarkably, the irradiance scale is much less sensitive to the distance from the entrance optics to the light source. Therefore this device provides a significant improvement to current methods.
- Having characterized the line-spread-functions of solar UV array spectroradiometers at different wavelengths within their spectral range and measured the response of the instruments to the out-of-range radiation the stray light contribution to the irradiances measured at, e.g. 300 nm wavelength could be reduced by more than a factor of 10. This is a significant contribution to the improvement of the measurement capabilities by the solar UV spectroradiometers typically having a narrow spectral range and, hence, dominated by the out-of-range rather than the in-range stray light. The established stray light correction methods known before the project have been concentrated on dealing only with the in-range stray light.
- The wavelength scale of array spectroradiometers can now be determined using 2 physically based devices (Fairy-Perot Etalon and wavelength ruler) and an algorithm based method (matSHIC) within uncertainties of a few picometers.

In summary, the uncertainties could be reduced from 5% to about 3% for the end-users measuring solar UV radiation in the field. This improvement is based on the newly investigated shortened traceability chain, the new portable light sources for calibration and the new methods and techniques to characterize and calibrate array spectroradiometers. Furthermore, the UV intercomparison confirmed the position of SFI Davos as the World Calibration Center for UV (WCC-UV) on behalf of the WMO. In the same context, the new QASUME reference spectroradiometer provides now a second portable reference standard for the quality assurance of solar UV irradiance of solar UV monitoring sites at a global level.

4.2 Dissemination Activities

Scientific Publications

The scientific results of the research undertaken during the development of the new devices, software and characterization techniques and environmental research have been published in 16 peer-reviewed articles in scientific journals. The publications supported the end-user information and trainings. In particular guidelines were published to provide a thorough manual how to use array spectroradiometers with reduced uncertainties in atmospheric UV measurements.

In order to focus additionally on the stakeholder information, the project partners and the REGs also disseminated their achievements in 2 Newsletters, UVnews 9 and UV news 10, of the Thematic Network for Ultraviolet Measurement, UVNet, with in total 15 articles. The mailing list of UVNet reaches 263 scientists working in the field of UV measurements. This list was used frequently to announce about the project activities such as workshops and the intercomparison.

The re-launch of the “UVNews” after 2006 was well appreciated by the solar UV community. The newsletters are available at http://metrology.hut.fi/uvnet/reports.htm and will be continued for the follow-up EMRP project Traceability for atmospheric total column ozone ATMOZ.

Conferences

In order to reach a wide audience, the project results were disseminated by all project partners, REGs, Collaborators and end-users with 48 oral and 15 poster presentations at conferences, symposia and workshops.

At an early stage of the project first results were presented and discussed at the International Radiation Symposia 2012 at a specific dedicated UV session. The symposia introduced the project partners from the National Metrology Institutes to the field of atmospheric radiation. The members of the two communities were discussing the scientific challenge of the project. The symposium was a good opportunity to focus the specific research of the project on the need for the end-users. The direct interaction resulted in positive feedback from both communities.

Specifically focusing on the end-user community working on UV radiation in the European north, the results were presented at the Northern Ozone Meeting (2013 and 2014) by several project participants. Again, the end-users were very interested to notice that an EMRP project was established to solve open problems in their specific field.

By the end of the project the impact in the scientific community was evident by several invited presentations at different conferences and meetings. In particular the NEWRAD 2014 conference was well represented by direct or indirect contributions originating from this project.

Workshops

The main podium for attracting end-users specifically working with solar UV instruments were the three workshops held in 2012, 2013 and 2014 and organized by SFI Davos and Aalto. The workshops were attended by about 50 to 70 participants, presenting results of the project and further studies from external partners. In particular, a representative from WMO and the chairman of the NEWRAD scientific committee, attended to be informed about the progress of the project.

The impact provided by these workshops was significant. Knowledge of the new developments was distributed effectively to the UV measurements community and the relevant stakeholders are now aware of the new developments in the field of solar UV radiometry. On request of the end-user participants the presentations are available on the project web page and should be accessible as an archive of new relevant information in the future (http://projects.pmodwrc.ch/env03/index.php/publications).

4.2 Early Impacts

Intercomparison

One major dissemination activity was the UV intercomparison held at Davos, Switzerland from 7 to 16 July 2014. The intercomparison was attended by a large number of participants from the user community. More than 25 instruments were operated on the measurement platform at the coordinator institute.

The participants of the intercomparison were trained to work with the new developed devices, methods and software developed in the project such as:

- UV LED based and laser driven light sources as new portable travel standards,
- two different wavelength calibration devices: a new software tool for stray light correction and bandwidth/wavelength homogenization for scanning and array spectroradiometers,
- uncertainty estimation tools for array spectroradiometers,
- The UV multispectral imager.

The training with the tools and devices developed during the project were very well received and the feedback from the user community was very encouraging, demonstrating the value of this activity to everyone attending the intercomparison and workshop.

In the same context of quality assurance the newly developed portable reference QASUME II is now prepared and tested during the intercomparison for worldwide intercomparisons of UV monitoring spectroradiometers. During the site-visits by the World Calibration Center for UV radiation (WCC-UV) at PMOD/WRC, the end-users have been trained with the new knowledge achieved eith this project, in order to ensure the quality end stability of their spectroradiometers.

Effective Cooperation

The project includes many examples of joint research, between project partners. In particular in the case of this environmental EMRP project, the coordinating organisation SFI Davos, serves as link between the Metrology and end-user communities, managing to extend the effective cooperation to collaborators and the end-user community.

By the cooperation with several National Metrology Institutes end-user array spectroradiometer have been thoroughly characterized for stray light with two different tuneable laser sources. The comparison of the different laser sources revealed the best method for characterization. The new characterization service was well received by the community and applied by several end-users. The benefit of the new characterizations was shown at the solar UV intercomparison assessing the quality of array spectroradiometers eith improved characterization.

In the same context, a sound cooperation between several institutions led to two different devices for wavelength calibration, which were tested by end-users. The two different wavelength calibration devices developed by EJPD and VSL were jointly analysed using QASUME data, which cannot be provided by the NMI themselves, resulting in a better understanding of the new devices. The results were jointly presented at the NEWRAD conference in June 2014.
By the analysis and discussion between different partners, the non-linearity of array spectroradiometers was considered as an important characterization and communicated to the end-users, who are now be aware to address this problem in order to improve their solar UV measurements.

The QASUME reference instrument from SFI Davos was calibrated several times by reference detectors using the tuneable laser facility at PTB (Braunschweig). This unique opportunity showed that the QASUME spectral irradiance scale remains stable to better than 1% for over a decade (2004 to 2014). QASUME also led the comparison between the new Fourier Transform Spectrometer developed for solar UV measurement at PTB (Berlin). QASUME was also used to validate the newly developed UV-LED source in field campaigns in La Reunion and Spain.

The project partners deepened their collaboration including REGs and collaborators by several visits and measurement campaigns at the different institutes. For example INRIM visited REG(IMU) for calibration of the new multispectral camera. LNE used data from several end-users to for the uncertainty budget software. The collaborations among partners and stakeholders were therefore very productive and scientific problems were discussed to ensure a goal-oriented achievement of the project’s objectives. Most of the collaborations did not exist prior to the project and collaborations with some of the partners are continued in a follow-up EMRP-project.

The main short-term impact focused on the end-users, which were trained during and at the end of the project using the new technologies and methods to improve their solar UV measurements in the field. The end-users are researchers in the field of UV radiation, national meteorology institutes to determine long-term UV trends in the atmosphere and health protection agencies monitoring UV radiation for human health protection as generally aimed within the project. From a long-term perspective, these end-users remarked the progresses of SFI Davos as leading experts in solar UV radiation observation on the Earth surface with improved uncertainty. The project also supported the UV community to homogenize their efforts for improving and preparing future results.

Standards

The project partners from the National Metrology Institutes strengthened the impact of the project by the representation at 15 standard meeting and committees:

For example, the technical committee TC2-51 of CIE received the “A guide to measuring solar UV spectra using array spectroradiometers” for preparing a document on the calibration, characterisation and use of array spectroradiometers. Moreover, the CIE-60 and TC2-17 appreciated the recommendations at the end of this project.

A second important platform for disseminating the results of the project was the EURAMET TCPR meeting, represented several times by one of the project partner chairing the TCPR.

Finally, the project was invited for presentation at the WMO TECO conference in October 2012 and the progress of the EMRP Project was presented as part of the activities of the UV working group of the international Radiation Commission (IRC) at the IRC business meeting on 7-8 July 2013.

A technical report describing the project results will be published by the WMO as an IOM report in the course of 2015.

These standards are the basis for the worldwide meteorology community to ensure the quality of solar UV radiation measurements and will guide laboratory UV applications outside environmental science in their selection of new technologies and methods.

4.3 Potential Impact

Specifically, the following impact was achieved:

- Reduced uncertainty of the primary reference spectroradiometer QASUME, which will provide improved traceability to UV monitoring stations and thereby better understanding of decadal UV changes.
- Validated fast solar UV irradiance spectra measurements, which will enable determination of cloud effects on spectral UV radiation and under rapidly changing conditions.
- Stray-light and bandwidth correction methods for characterised array spectroradiometers, which will allow the use of these robust and cost-effective instruments for UV exposure studies with known uncertainties.
- Global input optics and solid state detectors, which will allow end-users to significantly decrease the measurement uncertainties of their instrumentation.
- Significantly increased awareness among the user-community of the necessity of a thorough characterisation of array spectroradiometers before they are used for solar UV measurements.

Additionally, QASUME campaigns were performed to ensure the quality of the customer instruments on site (http://www.pmodwrc.ch/wcc_uv/wcc_uv.php?topic= qasume_audit) visiting several end-users in Spain, France and Finland. During these campaigns the end-users were introduced as an early impact on site to the developments of the project such as new bandwidth and wavelength homogenisation software matSHIC, new UV-LED portable source and general achievements of the project. This knowledge transfer will also be the aim during future QASUME quality assurance campaigns, at researchers-, national- and public health’s institutes.

From a long-term perspective, robust and cost-effective instruments that can be deployed as network instruments will be a unique European contribution to the topic of climate change and the challenges of addressing changes in solar UV radiation and its long-term effect on populations. This early and future impact enables the responsible agencies for their protection of human health as aimed in the project.

As a potential impact, it is further recommended that NMI should offer new characterization and calibrations services, such as e.g. tuneable laser sources for line spread function measurements and linearity determination. This impact leads for decision makings of the standards regulation bodies.

5 Website address and contact details

For the public visibility of the project a website has been established. The website kept the end-users informed about project achievements, collaborators opportunities, events and project meetings.

In a password-protected area information for the project partners has been shared and archived.

The website is available under with following web-site:

http://projects.pmodwrc.ch/env03/index.php

The main contact for the project is the project coordinator from SFIDavos: Physikalisch-Meteorologisches Observatorium Davos and World Radiation Center (PMOD/WRC), Dorfstrasse 22 7276 Davos-Dorf; www.pmodwrc.ch.

Dr. Julian Gröbner – JRP-Coordinator and Senior Research Scientist; Julian.groebner@pmodwrc.ch

Or

Dr. Luca Egli –Research Scientist; Luca.egli@pmodwrc.ch

6 List of publications

Following written publications have been published or submitted during the project:

[1] T. Pulli, P. Kärhä, and E. Ikonen, "A method for optimizing the cosine response of solar UV diffusers," *Journal of Geophysical Research: Atmospheres* 118, 7897-7904 (2013).

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